

**CONDITION MONITORING OF TURBINE BLADES
USING AIR-COUPLED GUIDED WAVES**

BY

AWAD ABDALLAH ALMOMANI

A Thesis Presented to the
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

December, 2024

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

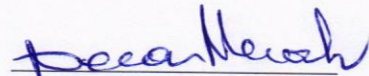
DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by Awad Abdallah Almomani under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **Master of Science in Mechanical Engineering**



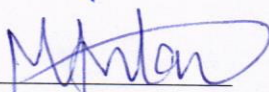
Dr. Fadi A Al-Badour
(Advisor)



Dr. Nesar Merah
(Member)



Dr. Samir Mustapha
(Member)



Dr. Mohamed A. Antar
Department Chairman



Dr. Suliman Al – Homidan
Dean of Graduate Studies



Dr. Salem Bashmal
(Member)



Dr. Muhammad Hawwa
(Member)

Date



© Awad

2025

*|To my family, whose unwavering support and encouragement have been the foundation of this
journey. This work is dedicated to you |*

ACKNOWLEDGMENTS

I am profoundly thankful to my advisor, Dr. Fadi Al-Badour, for his consistent support, mentorship, and profound knowledge that significantly contributed to my research progress. His perceptive advice and motivation have played a critical role in directing the development of my work.

I also express my heartfelt gratitude to Dr. Samir Mustapha for his steadfast assistance, mentorship, and expertise throughout my research journey. His thoughtful guidance and support have been crucial in giving shape to my research path.

My acknowledgment extends to the members of my research committee Dr. Salem Bashmal, Dr. Nesar Merah and Dr. Muhammad Hawwa for their advice and support throughout my research studies.

I am immensely grateful to my company, Siemens Energy, for the extensive support provided throughout my research endeavors.

I owe a debt of gratitude to my fellow scholars and colleagues for creating an engaging academic atmosphere and generously sharing their wisdom. The cooperative environment found within the Mechanical Engineering Department has significantly contributed to the breadth and rigor of my research.

I wish to convey my appreciation to my family for their steadfast support and patience throughout this demanding period. Their love and moral support have been the bedrock for my academic endeavors. Finally; I thank my friends who have been there for me, offering motivation, joy, and a necessary diversion at times - the value of your companionship during my academic journey is immeasurable.

This accomplishment stands as a tribute to the collective support and contributions of all those who had faith in and aided in bringing this project to fruition

TABLE OF CONTENTS

ACKNOWLEDGMENTS	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	ix
LIST OF TABLES	xii
NOMENCLATURE.....	xiii
ABSTRACT	xiv
ملخص الرسالة	xvi
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Scope of Work	4
1.3 Thesis Objective.....	5
1.4 Thesis Outline	5
CHAPTER 2 COMMON TURBINE BLADE FAILURES	7
2.1 Deterioration of Blade Coating	7
2.2 Erosion	9
2.3 Corrosion.....	11
2.3.1 Surface Corrosion:	12
2.3.2 Pitting Corrosion:	12
2.3.3 High temperature corrosion:	14
2.4 Fatigue Failure (Crack, Loss of Part & FOD).....	16
2.5 Blade Rubbing	18
2.6 Inspection and Maintenance Philosophy:	21
2.6.1 Maintenance Procedures	22
CHAPTER 3 BLADE HEALTH MONITORING TECHNIQUES	24
3.1 Blade Tip Timing:	24
3.2 Vibrational Monitoring:	27
3.3 Temperature Monitoring:	28
3.4 Acoustic Emission:	30
3.5 Ultrasound.....	31

3.5.1 Ultrasonic Guided Waves via Piezoelectric Transducers	32
3.5.2 Ultrasonic Stimulated Thermography	33
3.5.3 High Temperature Transducers	34
3.6 Pressure Monitoring:	36
3.7 Performance Monitoring:	37
CHAPTER 4 AIR-COUPLED ULTRASONIC GUIDED WAVES TECHNIQUE	39
4.1 Introduction	39
4.2 Principle of Air Coupled Guided Waves	40
4.2.1 Lamb Waves Characteristics	41
4.3 Non-Contact Lamb Wave Generation and Sensing Techniques	43
4.3.1 Air Coupled Transducers	43
4.3.2 Pulsed Laser	44
4.3.3 Scanning Laser Doppler Vibrometer (SLDV)	45
4.4 Air-Coupled Lamb Wave NDT Method	47
4.4.1 Lamb Wave Generation using ACT	47
4.4.2 ACT Lamb Waves for Non-Contact Non-Destructive Tests	49
4.5 Lamb Wave Propagation and Dispersion Curves Analysis	57
4.5.1 Lamb Wave Dispersion Curves	57
4.5.2 LAMB Waves in Multiple Layers	61
CHAPTER 5 EXPERIMENTAL INVESTIGATION OF DEFECT IDENTIFICATION USING AIR-COUPLED GUIDED WAVES	67
5.1 Experimental Setup	67
5.2 Incident angle optimization	68
5.3 Testing Blades with and without TBC	70
5.3.1 Discussion and results	73
5.4 Testing Blade with FOD (Material Loss)	75
5.4.1 Discussion and results	77
5.5 Time-Frequency Analysis	78
5.5.1 Analysis of Signals for TBC Removal Assessment	80
5.5.2 Analysis of Signals for Blade Material Loss Assessment	85
5.6 Conclusion	90
CHAPTER 6 FINITE ELEMENT MODELLING OF AIR COUPLED SYSTEM	92

6.1 2D Variable Thickness Plate Simulation	92
6.1.1 Module	92
6.1.2 Model Geometry and Material Properties.....	93
6.1.3 Model Boundary Conditions and Meshing	94
6.1.4 Simulation Results and Discussion	95
6.2 2D Airfoil Model	105
6.3 Effect of TBC -2D Simulation:.....	112
6.4 Validation.....	116
6.4.1 Plate with Varying Thickness Model.....	116
6.4.2 Airfoil Cross-Section Model.....	117
6.4.3 IN738 Plate with and without TBC.....	117
6.5 Conclusion Remarks	118
CHAPTER 7 CONCLUSIONS AND FUTUR WORK	119
7.1 Conclusions.....	119
7.2 Future Work	123
7.2.1 Environmental Factors	123
7.2.2 Sensors Optimization and Installation	123
References.....	126
Vitae	142

LIST OF FIGURES

Figure 1. Cycle Diagram of (a) Combustion Gas Turbine and (b) Steam Turbine (HP-LP Stages).	3
Figure 2. Gas Turbine Hot Components, transition duct, turbine blades and Vanes.	3
Figure 3. Thermal Barrier Coated Turbine Blade.	8
Figure 4. Healthy blade (a) Same blade after 24K EOH (b).	9
Figure 5. R2B TBC loss findings.	9
Figure 6. Turbine blades experiencing erosion-induced damage.	10
Figure 7. Erosion damage observed in aeroengine hot-section components.	11
Figure 8. Row 1 platform condition as found.	11
Figure 9. Pitting Corrosion.	13
Figure 10. Visual examination of a fractured blade, (a) original condition of blades assembly, (b) blade failure at the root, and (c,d) blade failure on the airfoil	14
Figure 11. Blades deterioration due to corrosion	15
Figure 12. Crack on blade (a) Crack caused by thermal fatigue in a gas turbine blade (b).	17
Figure 13. Turbine Row 1 Blades Clogged/blocked Cooling holes	18
Figure 14. Rubbing on Compressor blade (a) Blade's Tip Damage (b).	19
Figure 15. Blade Nomenclature.	22
Figure 16. Conventional Blade tip timing method.	26
Figure 17. Ultrasonic Stimulated Thermography.	34
Figure 18. The concept of Air-Coupled Guided Waves in a plate and their interaction with structural defects.	41
Figure 19. Pass-through (a) and (b) and pitch-catch (c) modes.	50
Figure 20. Dispersion curves of an IN738 plate. (a) Incidence angle; (b) Group velocity ; (c) Phase velocity.	61
Figure 21. Effect of Thermal Barrier Coating on Group Velocity of Guided Wave Modes in Inconel 738. Dashed lines represent the curves with TBC applied, Solid lines represent pure Inconel 738 at the same thickness. 1.41 thickness	65
Figure 22. Through thickness displacement profiles for Inconel 738 with TBC	66
Figure 23. Experimental Setup Diagram.	67
Figure 24. Gas Turbine Blades, TBC Coated (a) and without TBC (b).	68

Figure 25. (a) fifteen-cycles toneburst input signal with a center frequency of 100 kHz and (b) its frequency spectrum presented. _____	69
Figure 26. Optimal Incident Angle for Maximum SNR at Varying Excitation Amplitudes (200 Vpp, 300 Vpp and 400 Vpp). _____	70
Figure 27. Actual Experimental Setup: (1) RPR-Pulser-Receiver, (2) Rite RT-150, (3) Ultrat ACTs, (4) EXR054A Oscilloscope and (5) Gas Turbine Blade. _____	71
Figure 28. IN738 base metal - Gas turbine blades. _____	72
Figure 29. Alloy 247LC base metal - Gas turbine blades. _____	72
Figure 30. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Coated blade-IN738 base metal- obtained experimentally at two excitation amplitude. (a) 200 Vpp and (b) 400 Vpp. _____	73
Figure 31. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Coated blade-Alloy 247LC base metal- obtained experimentally at two excitation amplitude. (a) 200 Vpp and (b) 400Vpp. _____	73
Figure 32. Healthy and Cracked -IN738 base metal - Gas turbine blades. _____	76
Figure 33. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Cracked blade obtained experimentally at two excitation amplitude. (a) 200 Vpp and (b) 400 Vpp. _____	76
Figure 34. Raw A-Scan Signals, TBC-Free (a) and with TBC (b). _____	80
Figure 35. TFRs for signals with and without TBC under 200 Vpp Excitation. _____	81
Figure 36. TFRs for signals with and without TBC under 400 Vpp Excitation. _____	82
Figure 37. Feature signals -under excitation of 200 Vpp- obtained through different methods. _____	83
Figure 38. Feature signals -under excitation of 400 Vpp- obtained through different methods. _____	84
Figure 39. TFRs for signals for (a) Healthy Blade and (b) defected Blade under 200 Vpp Excitation. _____	86
Figure 40. TFRs for signals for (a) Healthy Blade and (b) defected Blade under 400 Vpp Excitation. _____	87
Figure 41. Feature signals -under excitation of 200 Vpp- obtained through different methods. _____	88
Figure 42. Feature signals -under excitation of 400 Vpp- obtained through different methods. _____	89
Figure 43. Geometric configuration of the air-coupled guided wave simulation model in COMSOL. _____	93
Figure 44. a fifteen-cycle Hanning windowed toneburst input signal with a center frequency of 100 kHz and b its frequency spectrum presented _____	96
Figure 45. Out of plane displacement at 50 mm (a), 130 mm (b) and 150 mm (c). _____	97

Figure 46. Normalized Amplitude of Transmitter and Receiver Signals	99
Figure. 47: Guided Wave Propagation in IN738 Blade: Healthy (a), Notched (b), and Internally Cracked (c) Scenarios at 209 μs	101
Figure 48. Comparison of Waveform Attenuation in a Plate with Notch (a) and Void (b) Defects	102
Figure 49. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Healthy plate obtained from the simulation (a) Full Received Signal and (b) Snapshot of 0-500 μs .	103
Figure 50. TFRs for signals for (a) Healthy, (b) Void-defected and (c) Notch- defected plates.	104
Figure 51. Geometric configuration of the 2D Airfoil cross-sectional and air-coupled guided wave simulation model in COMSOL.	105
Figure 52. Normalized Amplitude of Transmitter and Receiver Signals.	106
Figure 53. Guided Wave Propagation in IN738 Airfoil Cross-sectional: Healthy (a), Notched (b), and Internally Cracked (c) Scenarios at 163 μs .	108
Figure 54. Comparison of Waveform Attenuation in an Airfoil with Notch (a) and Void (b) Defects.	109
Figure 55. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Healthy plate obtained from the simulation (a) Full Received Signal and (b) Snapshot of 0-500 μs .	110
Figure 56. TFRs for signals for (a) Healthy, (b) Void-defected and (c) Notch- defected Airfoils.	111
Figure 57. IN738 Plate with TBC.	112
Figure 58. Normalized Amplitude of Pure INC738 (a) and IN738+TBC Signals (b).	113
Figure. 59. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Coated plate obtained from the simulation.	114
Figure 60. TFRs for signals for (a) Pure IN738, (b) IN738+TBC Plates.	115

LIST OF TABLES

Table 1. Summary of blade failures Modes.	20
Table 2. Overview of the characteristics and properties associated with different monitoring technologies.	38
Table 3. Material properties of TBC four layers.	65
Table 4. Time of Arrival (μ s)-TBC Effects.	75

NOMENCLATURE

$\vec{v}$: Velocity.
 $A_{0,1,2,\dots}$: anti-symmetric modes.
 $S_{0,1,2,\dots}$: symmetric modes.
 B_0 : out-of-plane motion
 B_1 : in-plane motion
 ρ : Density.
 E : Young's Modulus.
 p : acoustic pressure.
 f_c : center frequency.
 N : number of cycles.
 θ_i : incident angle.
 C_p : phase velocity.
 C_g : group velocity.
 C_e : energy velocity.
 u_1 : In-plane displacement.
 u_3 : out-of-plane displacement.
 d : thickness.
 ω : angular frequency.
 ξ : angular wavenumber.
 c_L : bulk longitudinal velocity.
 c_T : bulk shear velocity.
 Δt : time step.
 Δx : distance.
 ToA : time of arrival.
 ACT : Air-coupled transducers.
 $NACT$: Nonlinear Air-coupled transducer.
 LDV : Laser Doppler Vibrometer.
 FEM : Finite Element Method.
 TBC : Thermal Barrier Coating.
 DC : Dispersion Calculator.
 CFL : Courant–Friedrichs–Lewy.

ABSTRACT

Full Name : Awad Abdallah Almomani
Thesis Title : CONDITION MONITORING OF TURBINE BLADES USING AIR-
COUPLED GUIDED WAVES
Major Field : Mechanical Engineering
Date of Degree : December 2024

Gas turbines are undergoing advancements aimed at improving their performance. This include, but not limited to, elevating the pressure ratio created within the compressor and increasing the temperature at the turbine inlet. Consequently, these modifications result in diverse forms of component failures within the high-temperature zones of the turbine. This research focuses on leveraging guided wave technology for the early detection of faults in turbine blades, aiming to enhance the operational safety, reliability, and efficiency of gas turbines. Despite the potential of non-contact inspection techniques, limited attention has been given to the use of air-coupled guided waves for turbine blade evaluation. To address this gap, the study focused on developing and optimizing a non-contact air-coupled inspection system, with components chosen for their feasibility and performance, to explore air-coupled guided wave propagation in turbine blade structures through experimental testing and Finite Element Model simulations.

The results reveal that open or closed defects, significantly influence guided wave behavior, causing energy dissipation, reduced signal amplitude, and the appearance of a second dominant energy peak. Comparisons between healthy and defective blades confirmed the capability of air-coupled guided waves to detect and characterize anomalies. Additionally, the presence of TBC on turbine blades was found to delay signal arrival and reduce amplitude, attributed to the coating's viscoelastic nature, which dissipates Lamb wave energy. Signal processing tools, including the Normalized Hilbert Waveform with Bandpass Filtered Envelope and time frequency representations, were applied to extract key signal features, offering insights

into defect detection and material characterization. The analysis highlighted the influence of defect geometry, coating properties, and material conditions on wave propagation.

By advancing non-contact inspection methodologies, this research contributes to the gas turbine industry by providing a practical approach to guided wave applications. The findings underline the effectiveness of air-coupled guided waves in identifying structural defects and assessing material integrity, offering a valuable tool for enhancing condition monitoring and early fault detection in turbine blades.

ملخص الرسالة

الاسم الكامل: عوض عبدالله المومني

عنوان الرسالة: مراقبة الحالة التشغيلية لريشة التوربين باستخدام الموجات الموجهة عبر الهواء.

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: ديسمبر 2024

تخضع التوربينات الغازية لتطورات تهدف إلى تحسين أدائها، ويتضمن ذلك زيادة نسبة الضغط الناتجة داخل ضاغط الهواء ورفع درجة الحرارة عند مدخل التوربين. ونتيجة لهذه التعديلات، تنشأ أشكال مختلفة من الأعطال في المكونات الموجودة في المناطق ذات درجات الحرارة العالية في التوربين. يقدم هذا البحث على استغلال تقنية الموجات الموجهة للكشف المبكر عن الأعطال في ريش التوربين، بهدف تعزيز الأمان التشغيلي والموثوقية والكفاءة للتوربينات الغازية. وعلى الرغم من إمكانيات تقنيات الفحص غير التلامسية أخرى، الم ان استخدام الموجات الموجهة عبر الهواء في تقييم ريش التوربين محدودة. ولتغطية هذه الفجوة، ركزت الدراسة على تطوير وتحسين نظام فحص غير تلامسي يعمل عبر الهواء، مع اختيار المكونات بناءً على جدواها وأدائها، لاستكشاف انتشار الموجات الموجهة عبر الهواء في هياكل شفرات التوربين من خلال تجارب ومحاكاة باستخدام نماذج العناصر المحددة (Finite Element Analysis).

أظهرت النتائج أن الشقوق المفتوحة أو المغلقة تؤثر بشكل كبير على سلوك الموجات الموجهة، مما يؤدي إلى تشتت الطاقة، وانخفاض سعة الإشارة، وظهور قمة طاقة ثانية بارزة. وأكدت المقارنات بين الشفرات السليمة وتلك المعيبة قدرة الموجات الموجهة عبر الهواء على الكشف عن الشذوذات وتوصيفها. علاوة على ذلك، لوحظ أن وجود الغطاء الحراري على ريش التوربين يؤدي إلى تأخير وصول الإشارة وتقليل سعتها، وهو ما يُعزى إلى الطبيعة اللزجة والمرنة للطلاء، التي تؤدي إلى تبديد طاقة الموجات أثناء انتشارها. تم استخدام أدوات تحليلية، بما في ذلك Normalized Hilbert Waveform مع Bandpass Filtered Envelope و time-frequency representations ، لاستخراج الميزات الأساسية للإشارات، مما يوفر رؤى حول كشف العيوب وخصائص المواد. وأبرز التحليل تأثير شكل العيب وخصائص الطلاء وظروف المواد على انتشار الموجات.

من خلال تطوير منهجيات الفحص غير التلامسية، يساهم هذا البحث في فحص التوربينات الغازية من خلال تقديم نهج عملي لتطبيقات الموجات الموجهة. وتؤكد النتائج فعالية الموجات الموجهة عبر الهواء في تحديد العيوب الهيكلية وتقييم سلامة المواد، مما يوفر أداة قيمة لتعزيز مراقبة الحالة والكشف المبكر عن الأعطال في شفرات التوربين.

CHAPTER 1

INTRODUCTION

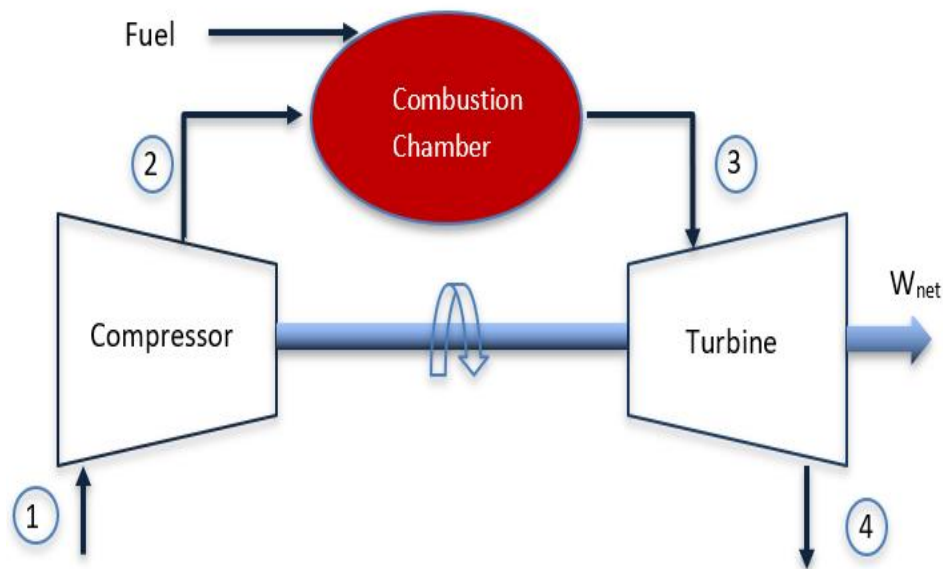
1.1 Background

Turbines are widely used for energy generation applications. They convert high pressurized flow to mechanical energy. Turbine shaft rotates due to the impact of the pressurized flow on turbine blades which are assembled to the shaft of the turbine. Figure (1.a) shows the core components of a gas turbine include a compressor, combustion chamber, and turbine. Compressor and turbine are connected through one shaft. The compressor increases the air pressure and then the air goes to the combustion chamber where the fuel is injected and mixed with the compressed air. Then, a combustor ignites the mixed flow, leading the gas to expand. This expanded air creates a lift force in the pressure side of the turbine blades and therefore, the shaft rotates which is known as the output work [1]. The blades of a steam turbine are driven by the high-pressure and high-temperature steam created by heating water in the boiler as shown in Fig. (1.b), this process results in the conversion of thermal energy into mechanical or rotational power. The shaft of steam turbines, employed in electricity generation, is split into three segments, high-pressure turbine, intermediate- pressure turbine and the output are subsequently channeled into the low-pressure [section [2]. The rotors of both gas and steam turbines are meticulously designed with fully-bladed configurations spanning their entire length, these blades are engineered with specific attributes tailored to accommodate varying levels of pressure and temperature in their respective environments.

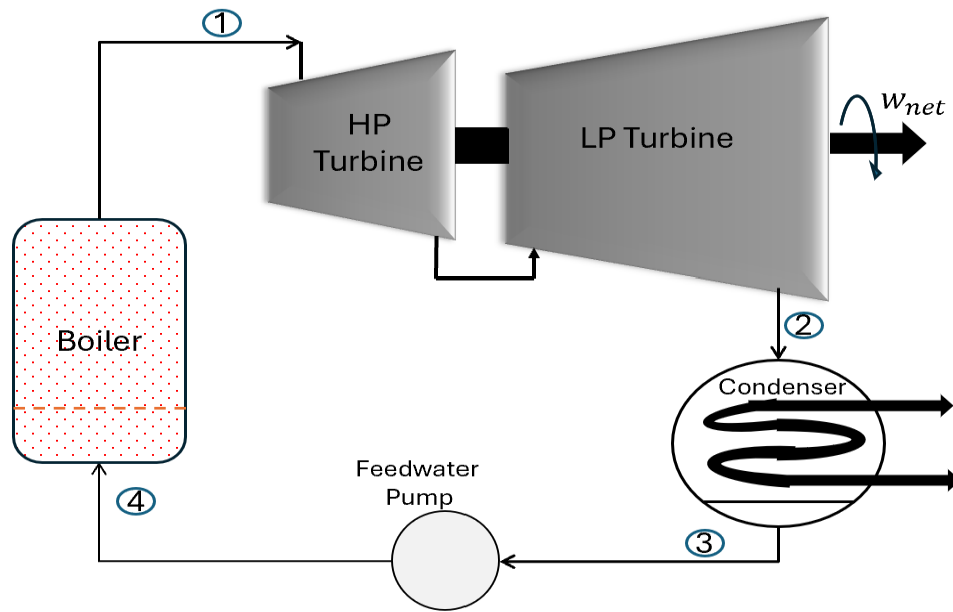
To produce the necessary mechanical energy, the turbine blades; shown in Fig. 2, are subjected to harsh conditions, such as high temperatures, severe strains, high pressure flows, and sometimes high levels of vibrations. Turbine blades are expected to experience efficiency and reliability degradation or loss of function over time in a variety of failure modes that affect turbine efficiency as a result of the above-mentioned variables. The primary mechanical and metallurgical abnormalities that lead to failure in turbine

blades are fatigue, foreign object damage (FOD), creep, corrosion, and erosion [3]. Operational factors like startup cycles, partial loads, and power output variations induce stresses, leading to fatigue and crack propagation. Additionally, fouling by contaminants or other objects is another possibility. At present, the absence of early detection methods for turbine blade failure causes turbine operating companies to perform emergency shutdowns when high vibrations are detected. This may happen occasionally when vibration sensors indicate excessive readings. The failure could be minor and resolved in a short period, or it could be severe, leading to extended service outages and significant losses in profitability and availability.

The implementation of Blade Health Monitoring (BHM) systems is crucial for real-time integrity assessment, enabling the early detection of critical issues. BHM systems enhance operational flexibility and improve turbine availability and reliability by reducing the likelihood of forced outages caused by blade malfunctions. Moreover, these technologies can optimize startup times through advanced monitoring capabilities, ensuring turbines operate within safe limits and reducing overall downtime.



(a)



(b)

Fig. 1. Cycle Diagram of (a) Combustion Gas Turbine and (b) Steam Turbine (HP-LP Stages).

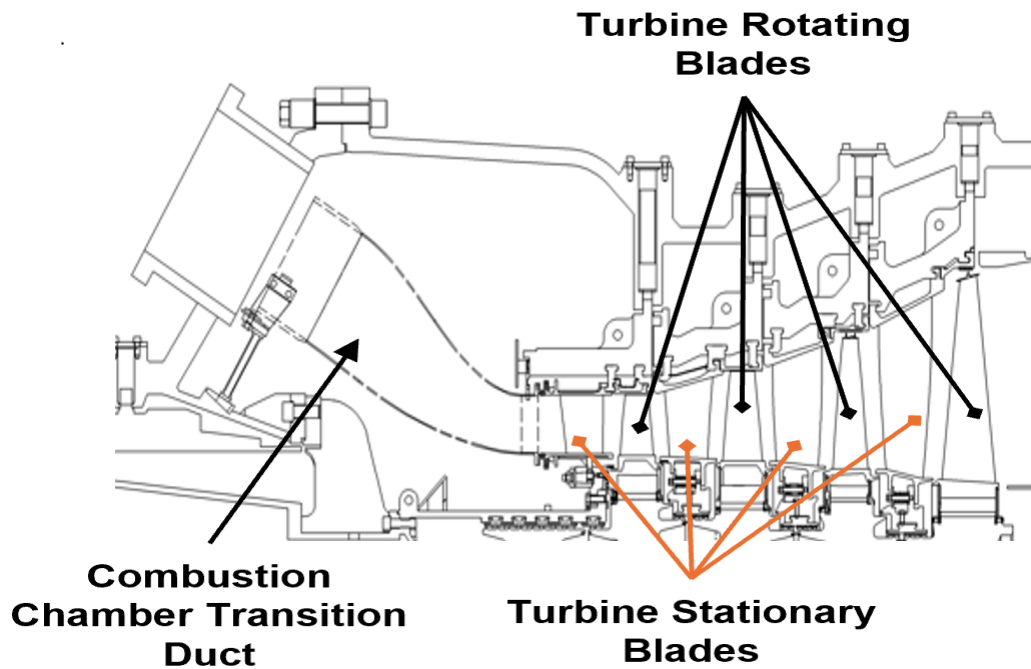


Fig. 2. Gas Turbine Hot Components, transition duct, turbine blades and Vanes.

1.2 Scope of Work

This thesis is dedicated to the exploration of guided wave technology as a means for the early identification of potential failures in turbine blades, with the ultimate goal of enhancing the efficacy, safety, and dependability of the gas turbine sector. Notably, the comprehensive exploration of the impact of utilizing non-contact guided waves for inspection of turbine blades in this context has been lacking in the existing literature, with only limited research published on this subject. Therefore, this research aims to bridge this gap in knowledge by analyzing the application of Air-coupled guided wave propagation in the structure of turbine blades through experimental research and simulations facilitated by the commercially available COMSOL software. Upon completing the experiment and simulations, components for the proposed non-contact air-coupled system for wave generation and detection were selected based on their feasibility and practical viability. Signature extraction tools, including the Normalized Hilbert Waveform with Bandpass Filtered Envelope, TFRs (STFT, CWT, and S-Transform), were utilized to analyze the received signals and extract critical features, enabling a thorough assessment of wave behavior and system performance. A detailed examination of the parameters pertinent to the proposed inspection system was conducted to refine the design of simulations and experiments. The initial target of this research is the identification of the most effective combination of parameters for the excitation and detection systems. This study also has involved the intentional introduction of various artificial defects to validate the effectiveness of the proposed methodology. Comprehensive analyses are undertaken to understand the propagation of waves through both air and solid media, along with the assessment of the waves' time of arrival (ToA) and signal amplitude. The study also has compared the signal profiles obtained from cracked turbine blades with those from undamaged blades. The overarching aim of this thesis is to furnish meaningful contributions to the field of condition monitoring within the turbine industry by advancing the application of non-contact inspection techniques, thereby enriching the body of knowledge on the use of guided waves for the early detection of blade faults.

1.3 Thesis Objective

The objectives of the ongoing research are outlined below:

Objective 1: Conduct a comprehensive literature review specific to this research, encompassing both industrial practices and current research endeavors in turbine condition monitoring techniques within the scope of this study, and establish connections and comparison between these methods and the earlier referenced studies in the literature above.

Objective 2: Developing a Finite Element Analysis (FEA) computational model to depict the propagation behavior of Air-Coupled Guided Waves interacting with turbine blades, incorporating potential defects.

Objective 3: Conducting an experimental work to investigate the wave propagation using Air-Coupled excitation and sensing system with turbine blades.

Objective 4: Utilizing the proposed model to identify specific blade crack features through analyzing changes in received wave signals, aiming to establish a reliable approach for detecting blade cracks using Air-Coupled guided waves.

1.4 Thesis Outline

Chapter 1 introduces the field of turbine operations, emphasizing the critical role that the proper design and monitoring of turbine blades play in ensuring the dependability of energy generation. It concentrates on the distinct obstacles associated with maintaining blade integrity and the complications that arise from the lack of early detection of defects.

Chapter 2 presents a comprehensive review of prevalent turbine blade failures, covering the most common issues such as thermal barrier coating (TBC) deterioration, erosion, corrosion, cracking, material loss, and blade rubbing. Furthermore, the chapter examines existing inspection techniques, and the maintenance procedures employed, underscoring their significance in ensuring the uninterrupted operation of turbines and the generation of electricity.

Chapter 3 comprises a detailed survey of the literature, addressing the current methodologies for monitoring the health of turbine blades. This includes an examination of techniques like blade tip timing, acoustic emission, ultrasonic testing, and the monitoring of blade performance metrics such as temperature, pressure, and vibrations. The chapter also delves into the effectiveness of each technique in identifying blade failures.

Chapter 4 discusses the use of Air-Coupled Guided Waves technique for condition monitoring. It covers the fundamentals of Lamb waves and details non-contact techniques for generating and detecting these waves, such as Air-Coupled Transducers, Pulsed Lasers, and Scanning Laser Doppler Vibrometers. The chapter then delves into the Air-Coupled Lamb Wave Non-Destructive Testing method, including wave generation and application for non-contact inspections, and concludes with an examination of Lamb wave dispersion and propagation in layered materials.

Chapter 5 focuses on the experimental development of defect detection and signal extracting methods. It examines the effectiveness of air-coupled guided waves in detecting two distinct types of faults: Thermal Barrier Coating (TBC) removal and cracks resulting from Foreign Object Damage (FOD).

Chapter 6 presents the creation of a 2D Finite Element Model (FEM) for an Air-Coupled System applied to a 2D representations of a blade model. It outlines the module, the model's design, material properties, boundary conditions, and meshing. The chapter concludes with simulation results, providing insight into the system's response.

Chapter 7 concludes the study and summarizes the findings. Also, it provides references and vitae

CHAPTER 2

COMMON TURBINE BLADE FAILURES

Turbine blades are manufactured from a range of materials, the choice of material hinges on diverse considerations including operational circumstances, temperature, and stress levels. High-pressure turbine blades are typically constructed from nickel-based superalloys, while low-pressure turbine blades are commonly made from titanium-based alloys [4], nickel-based superalloys are selected for their outstanding high-temperature strength, along with their resistance to corrosion and [oxidation [5]. Meanwhile, titanium-based alloys provide a favorable combination of strength, lightweight properties, and resistance to corrosion [6]. Despite the aforementioned causes, the turbine blade failures can occur due to issues like coating removal, erosion, corrosion and fatigue [7], potentially leading to serious consequences such as decreased efficiency, unplanned maintenance, and even catastrophic accidents. The areas of component contact in turbine blades, subject to both centrifugal and oscillatory vibrations, are susceptible to damage and the formation of cracks [8].

2.1 Deterioration of Blade Coating

Thermal barrier coatings (TBCs) are applied on turbine blades to improve their performance and longevity, they provide surface protection against high temperatures, prevent oxidation, and enable higher turbine inlet temperatures, enhancing gas turbine performance. However, there are several factors that may lead to either the removal or a decline in the effectiveness of these coatings, creating problems such as blade's cracks or erosion. As shown in Fig.3, TBC usually comprises a bond coat for adhesion (MCRA_{LY}, where M represents either nickel, cobalt, or a combination of both) and a thermal barrier layer, usually made of ceramics (ZrO₂-Y₂O₃ ranging 7~8 wt%), for thermal insulation. Coating failure may result from adhesion loss between the thermally grown oxide and bond coat [9] or oxidation occurring at the junction of the top coat and bond coat [10]. The process of coating oxidation is a major contributor to the degradation of turbine blades, which leads to the formation of oxides that are subsequently worn away due to erosion [11]. The

thermal barrier is more effective in regions with improved internal cooling, offering significant thermal protection advantages, this is unlike the leading and trailing edges, which can lead to damage and a change in the blade's color [12,13]. Figure 4 shows the difference between a turbine blade before and after 24,000 equivalent operation hours (EOH), the alteration in color to brown on specific blade areas and the erosive wear pattern on the airfoil surface are evident [14]. Figure 5 illustrates the TBC loss (as found) of the second stage of 260 MW gas turbine, it's reported that operating with level 1 findings poses no discernible risk. However, in cases of level 2 and 3, while damage might be localized in the blade, it is not anticipated how it will impact the operation. Detecting such issues is solely possible through a borescope inspection. following industrial practices, blades experiencing substantial TBC loss (exceeding 50% of the airfoil) will necessitate interim inspections prior to the planned outage, potentially affecting the gas turbine's operation and availability.

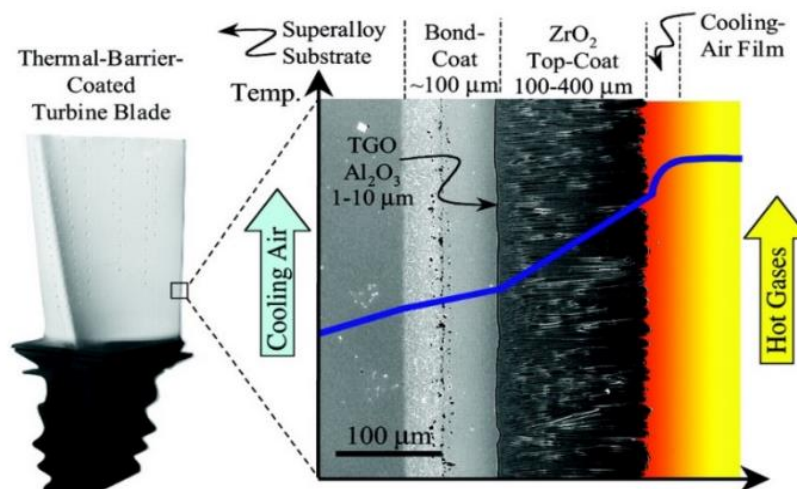


Fig. 3. Thermal Barrier Coated Turbine Blade [15]



Fig. 4. (a) Healthy blade and (b) Same blade after 24K EOH.[14]

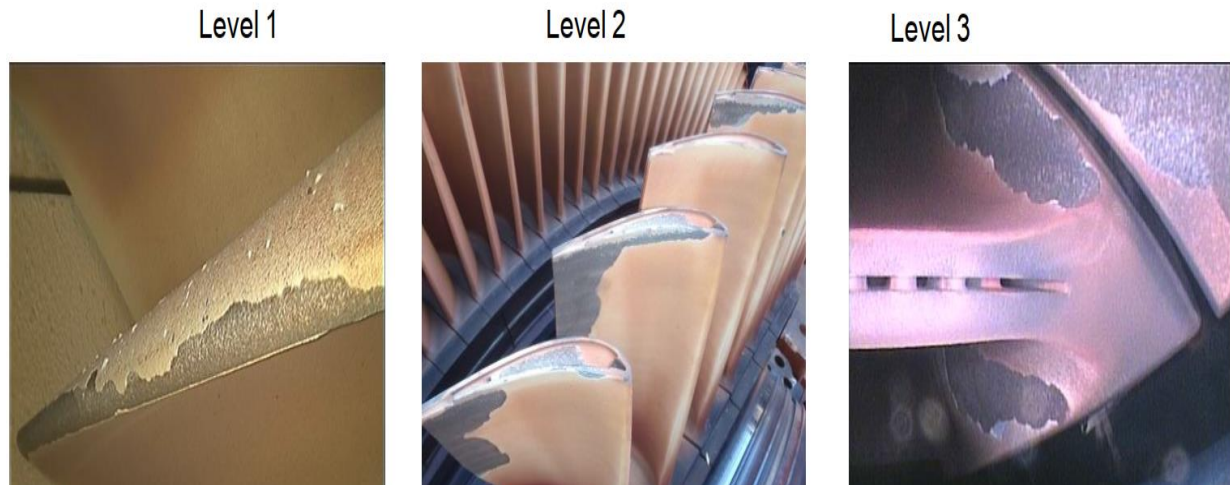


Fig. 5. R2B TBC loss findings

2.2 Erosion

Erosion refers to the degradation of a material, initiated at the surface, due to the mechanical impact of moving gases and steam carrying solid particles, or of liquids containing solid particles. Solid particle erosion is the process where material is gradually worn away as a result of the interaction between component surfaces and particles present in the working medium. The erosion rate is subjected to fluctuations based on the flow conditions of the erodent and the material of the blade's surface as described by Bonu et al [16], the erosion process is contingent upon the characteristics of the erodent particles,

including hardness, size, shape, direction, and velocity, as well as the properties of the material being eroded, whether it is ductile or brittle. Additionally, the erosion rate escalates with higher erodent velocities, and it also fluctuates when altering the angle at which the erosion occurs for both ductile and brittle materials. While the gas turbine is in operation, abrasive particles such as sand and dust infiltrate through the gas turbine inlet, causing an impact on the compressor and turbine blades. These particles have the potential to cause material loss from the compressor blades, resulting in erosion, along with damage to both the leading and trailing edges. Additionally, the particles can alter the shape and geometry of the turbine blade by adhering to it due to the extremely high temperatures involved [17]. Presby et al.[18] reported that due to the particle with lower speed, shallow craters are formed at the surface of N720 alumina composite, whereas deeper craters are created at higher velocities. Additionally, as the particle velocity increases, so does the depth of the crater for a specific particle size. Moreover, a rise in material removal is observed when particle size increases. Figures 6 and 7 highlights the impact of erosion on turbine blade damage. The evolution of turbine blade failure is marked by the loss of surface coating, resulting in extensive erosion-induced damage to turbine components, as vividly depicted in Fig.8.



Fig.6. Turbine blades experiencing erosion-induced damage[19].

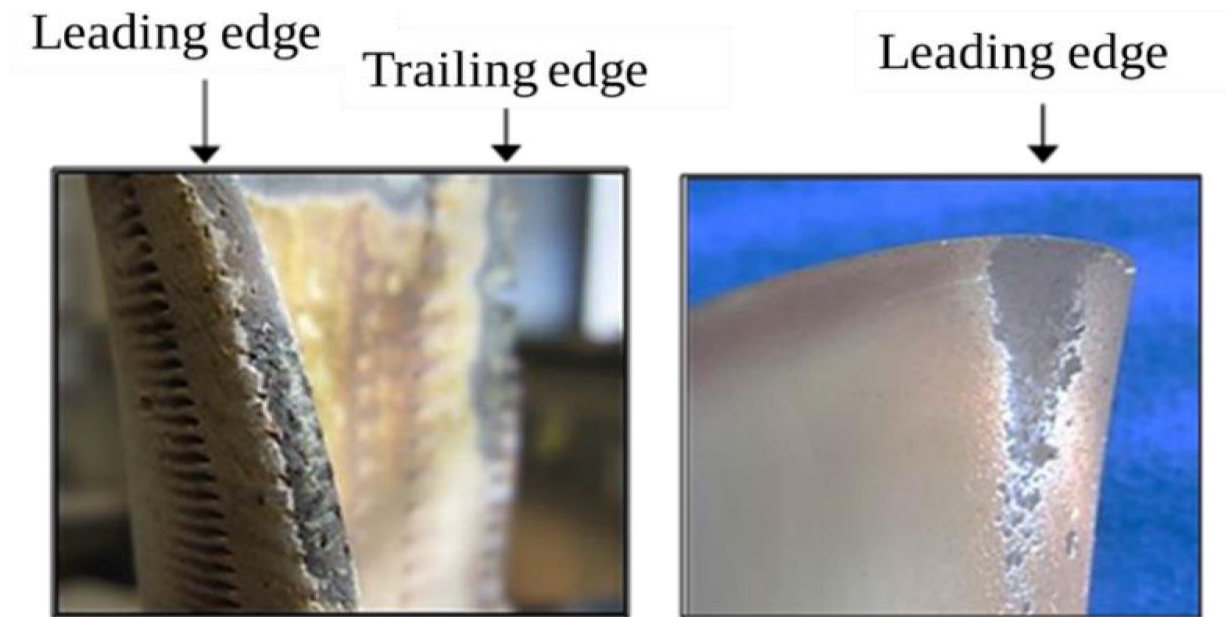


Fig. 7. Erosion damage observed in aeroengine hot-section components[18].

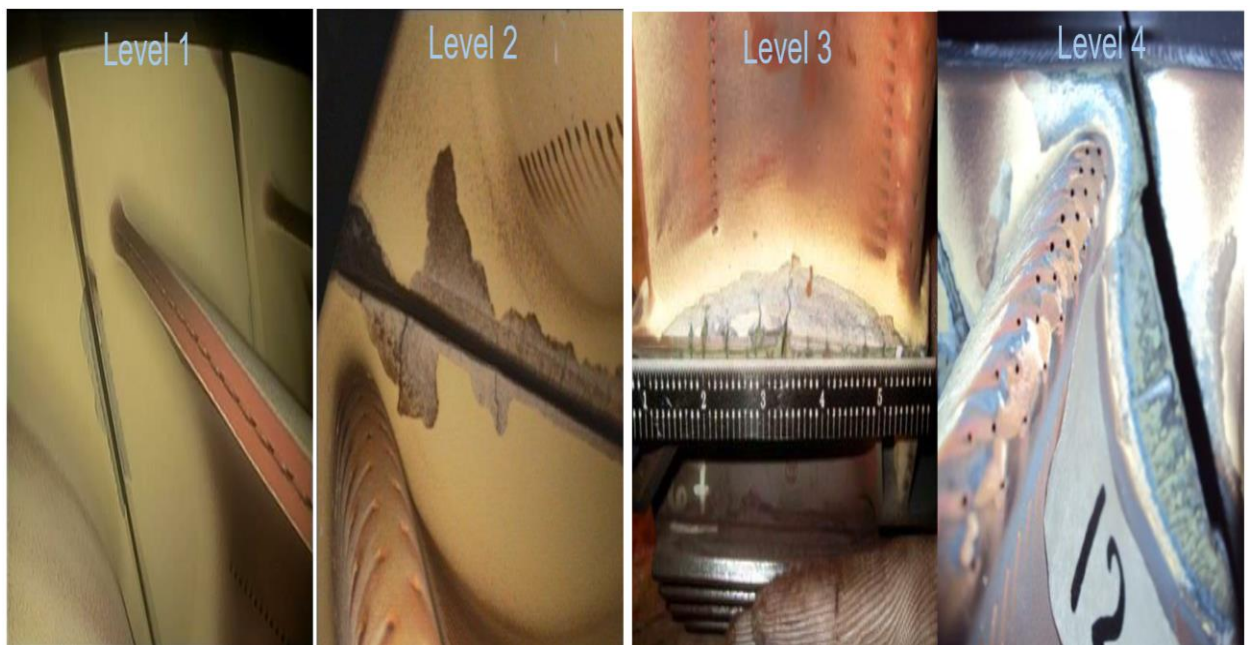


Fig. 8. Row 1 platform condition as found.

2.3 Corrosion

Corrosion arises from chemical reactions between internal components and various contaminants, which can include salts, acids, or reactive gases that are introduced into the system. In both, the steam turbine's low-pressure section and the gas compressor, blades are more prone to corrosion fatigue failure when

compared to their counterparts in the gas turbine or the steam high and intermediate pressure sections [20]. Common forms of corrosion observed in gas turbine blades necessitate a comprehensive understanding and effective strategies for their mitigation to ensure the longevity and optimal performance of these components.

2.3.1 Surface Corrosion:

Arising from either direct chemical or electrochemical reactions, this type of corrosion manifests as a general deterioration, often characterized by surface roughening, etching, or pitting of the metal. It is commonly accompanied by the presence of powdery corrosion byproducts.

2.3.2 Pitting Corrosion:

Pitting corrosion is a specific form of localized corrosive attack characterized by the development of small holes or pits on the metal surface as shown in Fig. 9. Pitting corrosion induces localized stress concentrations on blades and vanes, potentially leading to the initiation of cracking as a result of corrosion fatigue. Pitting corrosion arises when metal surfaces, including robust materials like high-strength stainless steel, undergo corrosive attack in harsh settings. It typically occurs in localized areas where a small portion becomes anodic due to the environment. Simultaneously, a cathodic area forms in another part of the metal. This sets off a form of galvanic corrosion, initially manifesting on the metal's surface but potentially advancing deeper, ultimately resulting in structural integrity compromise. This phenomenon is particularly critical for structures subjected to dynamic loads [21].

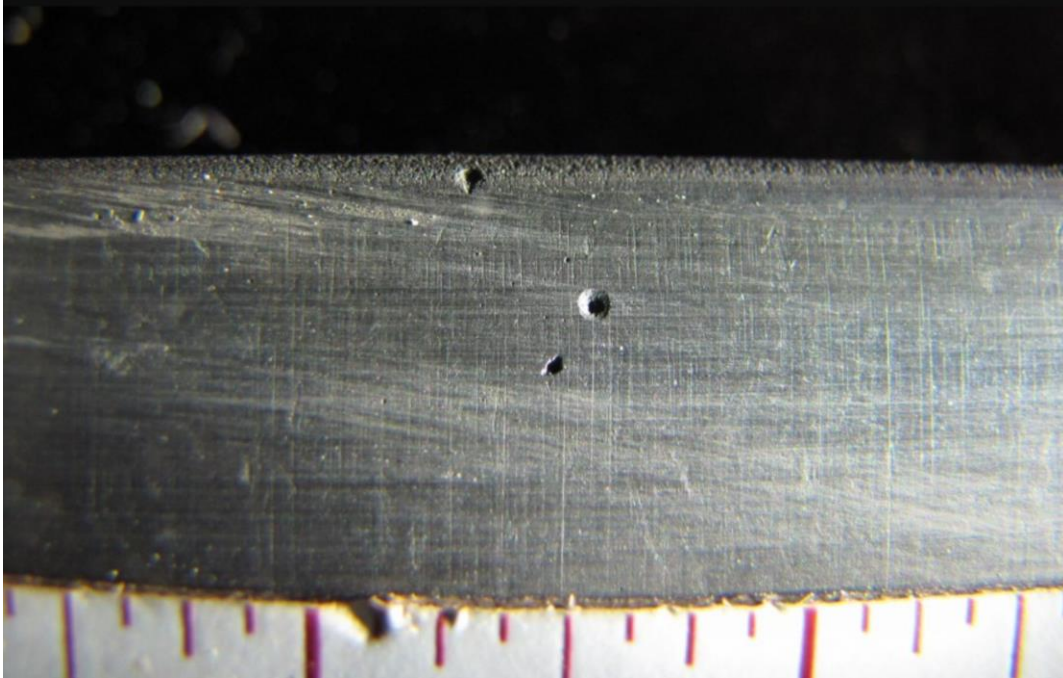


Fig. 9. Pitting Corrosion[22]

In the study conducted by Rajabinezhad et al. [23], a failure analysis was carried out on gas compressor blades constructed from the Nimonic-105 nickel-based superalloy. Two fractured blades from the compressor's second stage, one failed from the root and the other from the airfoil as depicted in Fig.10, underwent testing after approximately 20,000 hours of operation. The failed blades underwent examination of their microstructures utilizing optical and electron microscopes, phase identification was carried out using Energy Dispersive X-ray Spectroscopy (EDS). The investigation determined that the failure initially originated at the root, with corrosion-fatigue established as the predominant mechanism for the root failure. Furthermore; the analysis determined that the blade, which initially failed from the root, experienced a corrosion-fatigue failure, ultimately leading to the detachment of the airfoil from the root. Subsequently, the fractured piece collided with the adjacent blade during its trajectory, resulting in the fracture of the adjacent blade from the airfoil. The indentation observed at the airfoil's edge likely formed due to the impact between the flying broken piece and the airfoil. Ziegler et al.[24] conducted a similar experiment to investigate the failure analysis of a blade from the low-pressure turbine, which exhibited several pits along

its edges. It was concluded that the presence of pits, induced by a corrosive atmosphere, led to the development of residual stresses, ultimately triggering the initiation of intergranular micro-cracks.

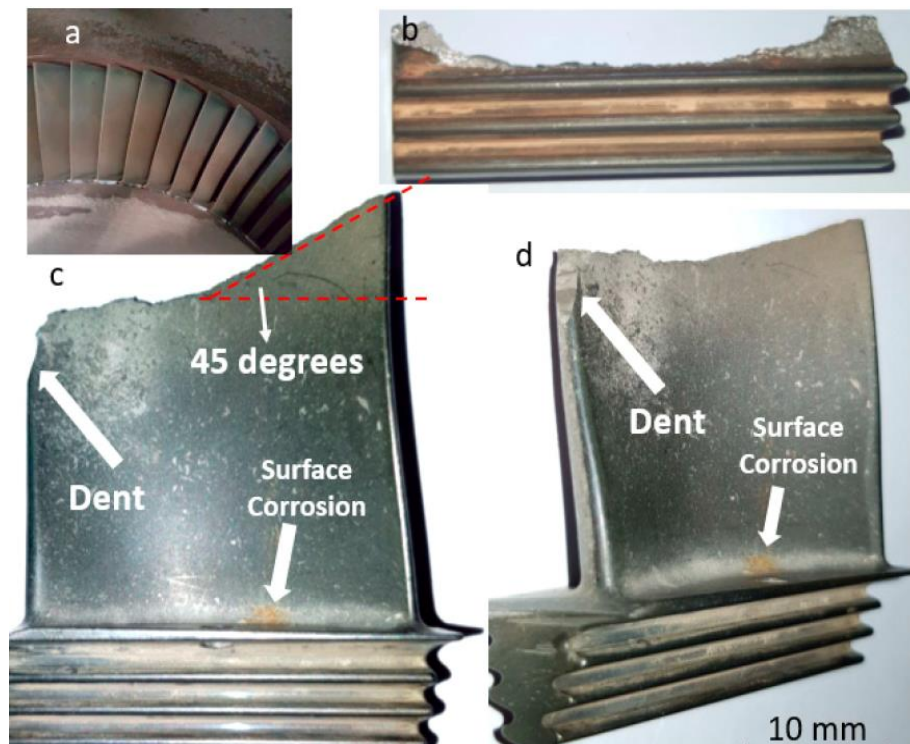


Fig. 10. Visual examination of a fractured blade, (a) original condition of blades assembly, (b) blade failure at the root, and (c,d) blade failure on the airfoil.[23]

2.3.3 High temperature corrosion:

Also known as high-temperature oxidation, pertains to the degradation of materials resulting from chemical reactions that take place at elevated temperatures. This form of corrosion is especially significant in settings where metals are subjected to high thermal conditions. It typically entails interactions with oxygen, sulfur compounds, or other corrosive substances at heightened temperatures, resulting in the deterioration of the material's surface and potentially posing a risk to its structural soundness. Corrosion is one of the main factors contributing to the deterioration of turbine blades, corrosion leads to a reduction in blade thickness, shortened blade chords, and an increase in surface roughness due to high-temperature oxidation [25]. Bannazadeh et al.[26] conducted an experiment to analyze the occurrence of a failure in a GE-F5 gas turbine

blade, which was constructed from the Inconel 738LC nickel-based superalloy. The fractured blade, located in the turbine's second stage and failing from the airfoil, underwent testing after approximately 65,000 hours of operation. The examination of the failed blade included assessing its microstructures through hardness measurements and examining the blade's chemical composition. The examination revealed severe pitting on the blade surface, accompanied by fatigue marks on the fracture surface, indicating that the crack originated from hot corrosion at the leading edge, propagated through fatigue, and ultimately culminated in fracture due to a reduction in cross-sectional area. Asadikouhanjani et al. [27] reported that the formation of hot corrosion pits on the blade's airfoil was attributed to the presence of a substantial amount of corrosive impurities in the air, which entered the gas turbine. This process, driven by the hot corrosion fatigue mechanism, led to the propagation of the pits and, ultimately, the fracture of the blade. According to Naga Bhushana Rao et al.[28], low-temperature hot corrosion at the root of the blades resulted in a notably rough surface with noticeable color changes. On the other hand, high-temperature hot corrosion at the tip of the turbine blade led to material loss and a reduction in its thickness. This reduction in blade thickness ultimately diminished the fatigue strength of the blade, culminating in the failure of the turbine blade.



Fig. 11. Blades deterioration due to corrosion [27]

2.4 Fatigue Failure (Crack, Loss of Part & FOD)

Turbine blades undergo frequent high dynamic and thermal stresses, causing a degradation in their original material properties, this leads to a weakening of the material, ultimately causing fatigue in the turbine blade. Fatigue is a prevalent factor contributing to gas turbine blade failures, accounting for 42% of all instances of gas turbine failures [29] and it can be categorized into thermal fatigue, low cycle fatigue (LCF) and high cycle fatigue (HCF) [30,31]. Low cycle fatigue occurs as a result of subjecting a material to high stress levels enough to cause plastic deformation whereas high cycle fatigue is caused by relatively low stress levels leading to primarily elastic deformation [32]. Fatigue failure invariably commences at a crack. Low Cycle Fatigue (LCF) encompasses the early onset of crack formation and an extended period of propagation. In contrast, High Cycle Fatigue (HCF) may be prompted by, or interplay with, additional forms of damage, including factors like foreign object damage (FOD), thermal fatigue, and LCF. Gas turbine blades are designed with internal cooling holes, and a cooling film covers the entirety of the blade surface to regulate high operational temperatures. However, owing to the harsh operational conditions and the combination of high thermal and pressure stresses, those cooling systems turned into significant problems, particularly when the cooling holes became clogged or blocked, potentially causing a fatigue in the turbine blades, resulting in the emergence of cracks around the cooling holes, as well as in the leading edge fillet and the root slot at the trailing edge[33]. Furthermore, operating at elevated temperatures can lead to the initiation of intergranular cracks originating from the boundaries between grains. These cracks then propagate until they reach a critical length, potentially culminating in a catastrophic fracture. Chen et al [34] examined how an aluminized coating influences the fatigue lifespan of turbine blades. An experiment was performed on turbine blades from an aero engine, involving combined low and high cycle fatigue tests. These assessments were conducted at 200 °C for a period of 2 hours, followed by a subsequent test at 950 °C for 5 hours. Findings revealed that the inner layer in the aluminized coating actually diminishes the blade's fatigue resistance. This inner layer was found to contain numerous cavities, which serve as the starting point for crack formation, ultimately resulting in a reduction in the lifespan of crack initiation.

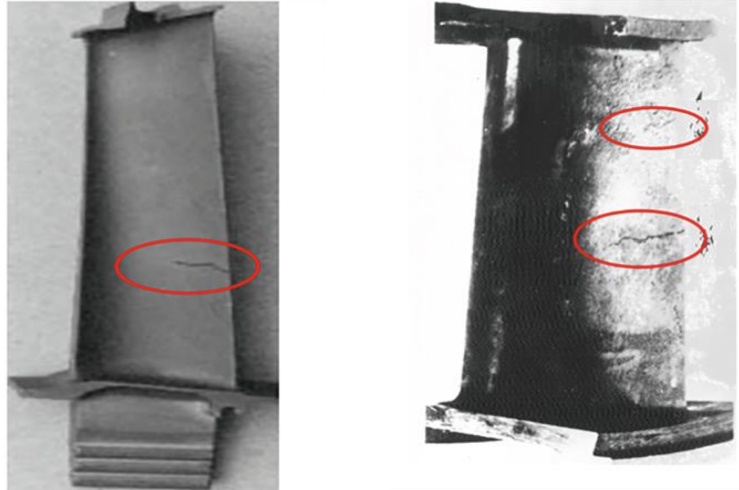


Fig.12. a) Crack on blade b) Crack caused by thermal fatigue in a gas turbine blade. [35]

The standard techniques for detecting cracks, which encompass visual inspection, magnetic particle inspection, fluorescent penetrant inspection, eddy current inspection, ultrasonic phased-array inspection, and acoustic thermography inspection, all mandate the turbine rotor to remain static during the examination. Figure 13 shows the Turbine Row 1 Blades Clogged/blocked Cooling holes (as found) of 260 MW gas turbine, it was reported that no impact on operation for level 1 clogging. Level 2 clogging not expected to affect operation, damage due to overheating will be concentrated in the blade, Debris clogging level 3 may lead to overheating and accelerated component distress that may lead to blade TBC loss, potential for cracks and material oxidation with the risk for leading to thermal fatigue with consequential moderate to significant damage to downstream turbine components as parts of the blade fragment and or liberate. Detecting such issues is solely possible through an inspection. Running with blades with level 2 or 3 blockage may require interim inspections prior to the planned outage, potentially affecting the gas turbine's operation and availability.

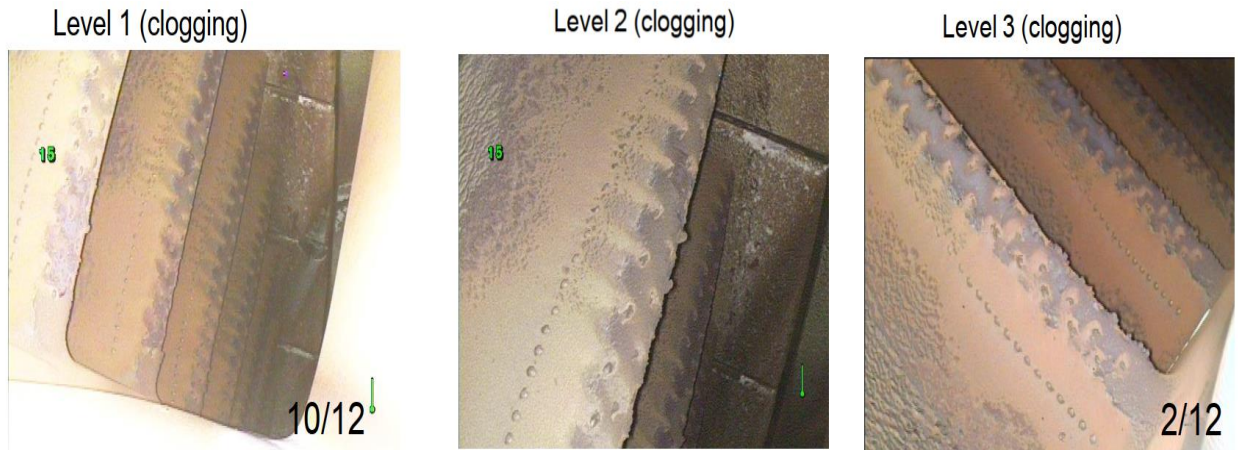


Fig 13. Turbine Row 1 Blades Clogged/blocked Cooling holes

2.5 Blade Rubbing

Blade rubbing, the contact and friction between blade and casing surfaces, has become more prevalent due to the heightened demand for greater efficiency in gas turbines. This is primarily driven by the design emphasis on minimizing operational clearance between rotating blades and the casing to maximize efficiency and minimize fuel consumption. These narrow clearances result in even minor alterations, such as blade expansion from thermal stress or bearing instability due to high vibration, causing certain blades to operate without adequate clearance, leading to rubbing. Existing rubbing force models often overlook blade bending deformation and coating wear effects. Kang et al. [36] proposed a rubbing force model that accounts for these factors alongside casing stiffness. They derived this model from the Archard wear model and assessed how casing stiffness, blade size, and coating properties influence rubbing force. Additionally, Tang et al. [37] introduced a new compound fault modeling technique encompassing centrifugal stiffening, spinning softening, and multiple failure modes, including rubbing faults. They developed an adapted rubbing force model for cracked blades and investigated various factors' impacts on rubbing behavior. Tang et al. [38] also explored the nonlinear vibration response of cracked blades experiencing rub-impact failure, proposing an updated rubbing model that considers different crack depths and locations. The consequences of blade rubbing can be extremely grave, potentially escalating to more damaging machinery failures such as Foreign Object Damage (FOD) resulting from fractured blade components.

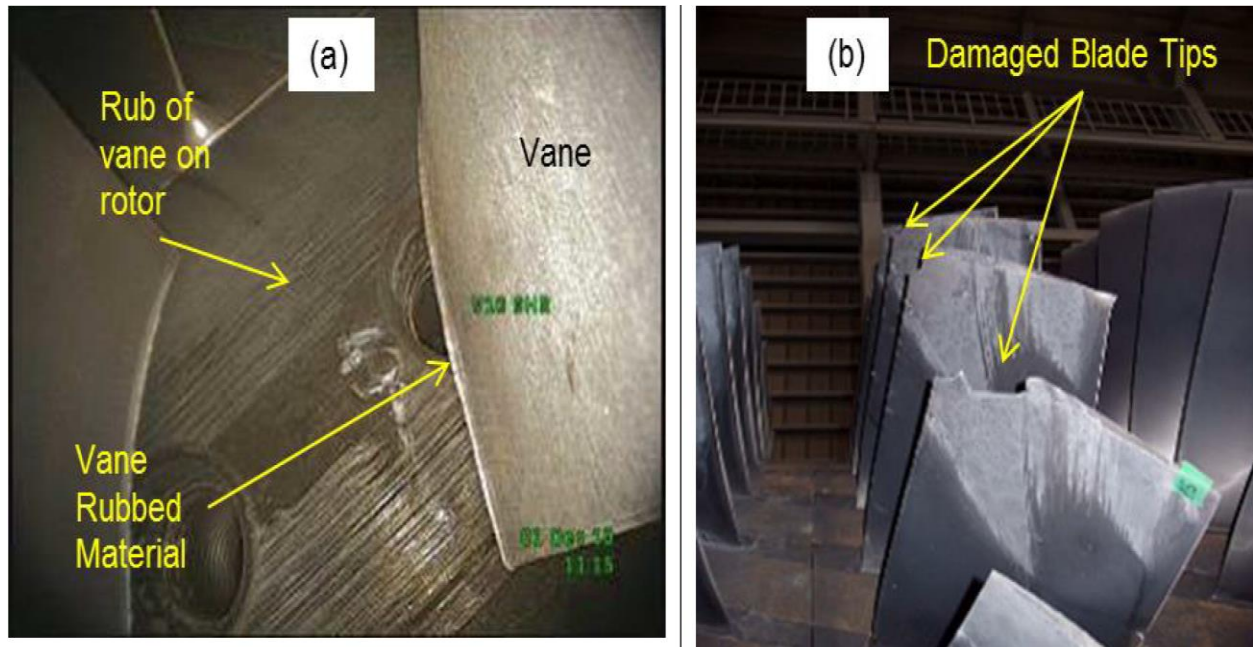


Fig. 14. a) Rubbing on Compressor blade b) Blade's Tip Damage. [39]

Table 1 illustrates a qualitative summary of aforementioned types of failures alongside their respective factors. The frequency of blade failure modes can significantly differ based on particular operating conditions, maintenance approaches, and other influencing factors.

Table 1- Summary of blade failures Modes.

Failure Type		Frequency of Occurrence	Blade Material	Fuel Type
TBC Loss [13-18]		Common in both blade airfoils and platform fillets.	Nickel-based superalloys (IN738 & CM247). Sub-Surface (Hast-X, Ni alloy & IN625). Bond Coat (e.g MCrAlY or Sicoat). TBC (ZrO ₂ and 6-8 at. %Y ₂ O ₃).	Natural Gas. Distillate Oil.
Erosion [20-22]		Occurs more often in dusty or dirty surroundings.	Titanium Alloys. Nickel-based superalloys.	All types.
Corrosion [24-32]	Oxidation	Common in high-temperature environments and occurs mostly at blade platform.	Nickel-based superalloys.	High-sulfur fuel.
	Stress Cracking	Less common but potentially serious. Typically happens at the blade platform and is regarded as the subsequent stage following oxidation.		
Fatigue [33-39]	General Fatigue	Common	Nickel-based superalloys. Titanium Alloys.	Natural Gas. Fuel Oil.
	Thermal	Occurs frequently in cyclic operations		Natural Gas. Fuel Oil.
	FOD	Varies based on operating environment		All types
	HCF	Frequent in high-speed operations.		Natural Gas. Fuel Oil.
Rubbing [40-42]		Common- Occurs at the tip of blade, particularly at the first row of blades.	Nickel-based superalloys.	Natural Gas. Distillate Oil.

2.6 Inspection and Maintenance Philosophy:

Examining and maintaining turbine blades is crucial for their performance, lifespan, and safety. Inspections typically occur during scheduled outages when the shaft is stationary. The widely used tool for these checks is the borescope camera, especially when the turbine casing remains intact. This camera can be inserted into the turbine to inspect internal damages. However, while less intrusive, it might not detect damage in unseen areas. Various methods exist to inspect turbine blades when the casing is open or the rotor is removed. Visual Inspection, the most straightforward approach, involves visually checking blades for visible damage like cracks or erosion. However, it has limitations as it might not detect internal or microscopic damages. An advanced turbine inspection method is Non-Destructive Testing (NDT), encompassing techniques such as ultrasonic, radiographic, and eddy current testing. While capable of identifying surface, near-surface, internal and microscopic damages, these methods demand specialized training and equipment. Finally; the Strip-Down Inspection method involves examining each blade separately after disassembling them from the turbine rotor. While it's the most comprehensive approach, it's also the most time-consuming and expensive method available. Various NDT methods and their attributes were examined by different authors. Mohammadian et al. [40] employed active thermography using various excitations like carbon dioxide (CO₂), hot air, and water vapor. These sources were chosen to identify residual ceramics formed during blade production. Another technique, the NDT Resonance Acoustic Method (RAM), is employed for inspecting gas turbine blades [41]. This method involves measuring the structural reactions of a component, which include a distinctive and quantifiable dataset of natural frequency (resonance) responses. Przysowa et al. [42] utilized the GE v/tome/x/m 300 system to conduct dimensional checks and internal examinations of turbine blades found in turboshaft engines. This inspection system, developed by GE Aviation under the Metals Affordability Initiative (MAI), employs specialized CT systems equipped with high-powered x-ray tubes, an automated blade feeder, linear Jupiter detectors, and GE Rhythm Review software.

2.6.1 Maintenance Procedures

Gas turbine blades are commonly sent for repair when they reach half of their expected lifespan. This maintenance usually involves cleaning to eliminate dirt and deposits, applying protective coatings to prevent corrosion or erosion, and addressing any damage by repairing or replacing affected blades. A design review is necessary for each area or feature to determine the repairability of the blade. Figure 15 shows blade nomenclature. It's important to follow the critical quality requirements for the blades which cover several key factors essential for blade performance. These encompass assembly guidelines, permissible distress at the blade root, seal slot measurements for both the seal pin and plate, clearance between the blade's angel wing and vane inner shroud, aerodynamics for maximizing hot gas flow efficiency, secondary and internal cooling airflow management concerning airfoil shapes, cooling hole sizes and orientations, and sealing elements affecting hot gas path efficiency, including squealer tip height, seal plate slots, and angel wing thickness. These specifications collectively ensure the optimal functionality and reliability of the turbine blades.

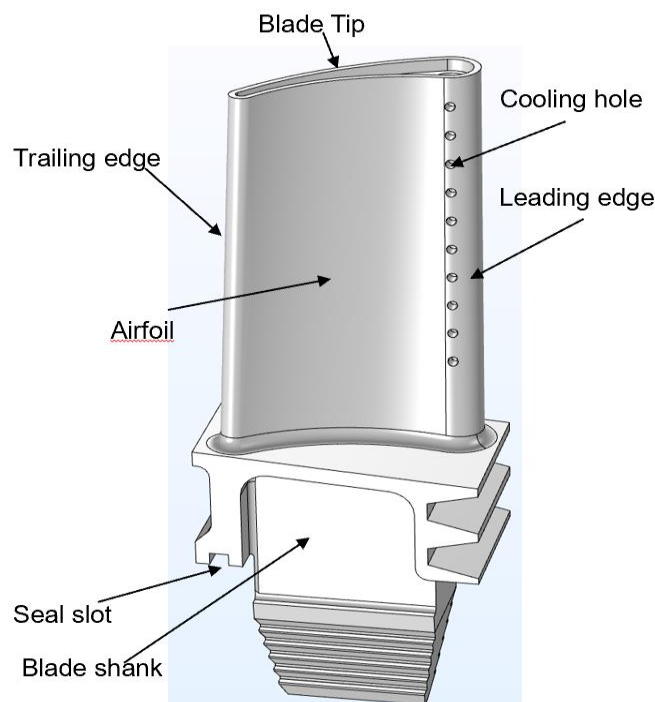


Fig. 15. Blade Nomenclature.

Alfred et al. [43] presented two advanced repair techniques for Nickel-based components in aircraft engines and gas turbines: hybrid brazing, a faster and superior process using thermal spraying, and single-crystal additive repair by laser cladding, allowing for the regeneration of expensive turbine blades through layer-by-layer material addition and laser melting.

The primary repair requirements involve ensuring the blade meets specifications, restoring its form, fit, and function to enable an extended service interval (typically 24,000/33,000 equivalent operating hours or 800/1,200 equivalent starts). However, repair poses challenges due to various factors: the alloys' inherent strengthening mechanisms that impede weldability, the intricate geometry of components making them prone to distortion, limitations in using high-strength fillers, longer intervals causing increased distress, and potential welding issues with superalloys, such as solidification and strain age cracking. Furthermore, routine inspections and maintenance procedures incur substantial costs, including direct procedure expenses and the associated downtime costs. Both necessitate turbine shutdowns, which may result in production losses.

CHAPTER 3

BLADE HEALTH MONITORING TECHNIQUES

Recent focus on gas turbine health monitoring systems aims to enhance engine health monitoring accuracy, diagnostics, and fault prediction. Implementing these systems has notably improved engine performance and enabled condition-based maintenance, enhancing overall equipment operation [44]. Blade Health Monitoring (BHM) functions by analyzing data obtained from systems that monitor Blade Vibration. It is designed to detect and monitor potential faults such as cracks in turbine blades, eliminating the necessity for physical inspections by continuously analyzing vibration data in real-time. There are several methods for turbine blade condition monitoring, Mevissen et al. [45] and Abdelrahman et al. [46] conducted an extensive analysis of the methods used in turbine blade condition monitoring. Below, these methodologies are discussed in depth.

3.1 Blade Tip Timing:

Blade Vibration Monitoring (BVM) or Blade Tip Timing (BTT) systems, as shown in Fig.16, analyze blade tip deflection by utilizing instruments to measure the actual time of arrival of a blade tip and contrasting this measured time with the anticipated arrival time if the blade were completely rigid. Subsequently, this data can undergo post-processing to ascertain the frequency response of the blades, their amplitude, and the correlated vibrational stresses. The conventional BTT approach utilized numerous probes, such as eddy current probes or optical sensors, and once per revolution (OPR) sensors to achieve the desired measurements, encountering several obstacles such as inadequate probes, a high likelihood of OPR sensor failure, improper layout, and low sampling frequency domain [47]- [48]. These challenges prompted researchers to focus on enhancing the BTT explored approaches and propose innovative methods to improve the accuracy and feasibility of BTT measurement. Haoqi et al. [49] proposed the phase-offset resonance identification (PHRID) method to identify resonance by extracting the vibration trend of probes with a special installation angle. They positioned two probes on the casing within a 0-90° angle range. This

placement aimed to accurately pinpoint the blade's resonance center and directly derive its resonance frequency from the time-based signal. Their conclusion highlighted the method's significance in extracting the blade's vibration parameters in real-time, especially under variable speed conditions. This obviates the need to convert signals to the frequency domain, leading to significant enhancements in computational efficiency. Another method is the single probe OPR-free BTT, which employs rotating including angle (RIA) as a signal analysis method for parameter identification instead of relying on tip displacement. It also constructs a sampling aliasing frequency (SAFE) map to assist in the identification process across various rotational frequencies [50]. The aforementioned method proved effective under steady, limited speeds and with fewer probes and sensors. However, its effectiveness diminishes when speed variations occur rapidly, making it challenging to generate the SAFE map. Ren et al. [51] introduced another technique that eliminates the requirement for the OPR probe. This method employs Multi-Probe linear fitting and Time of Arrival (ToA) linear correction to reduce errors in single probe linear fitting and correct calculation inaccuracies arising from nonlinear changes in rotation speed. Furthermore, the least-squares method has been applied to examine the inherent flaws stemming from imprecise linear fitting of the theoretical arrival time, caused by the vibration characteristics of the entire circular blades, in comparison to the actual arrival time. Cao et al. [52] made use of the distinct arrangement of components in the SAFE map and presented two BTT signal filtering approaches. The first method involves single-probe data detrending, which removes rotational frequency and its harmonics, enabling the extraction of synchronous vibrations. The second technique, tracking sliding bandpass filtering, aims to eliminate noise from the preserved signal (asynchronous vibration). Another method for identifying blade vibration parameters is the Waveform Mapping approach, which relies on mapping the sensor's static waveform and dynamic waveform obtained from BTT [53]. Fan et al. [54] introduced a technique involving polynomial fitting of OPR sensor data to estimate speed fluctuations within a single revolution. Subsequently, they introduced a Generalized Sine-Fitting (GSF) method that calculates blade vibration parameters using the equivalent probe angle correlated to rotor speed. Validation via numerical studies and experimental outcomes demonstrated reduced fitting uncertainties compared to conventional methods, significantly mitigating the impact of speed changes.

Another proposed technique involves a high-precision extraction method for the blade tip-timing signal using an eddy current sensor. This method scrutinizes factors influencing measurement accuracy and suggests enhancements to minimize errors. Specifically, it proposes a compensation method for errors resulting from tip clearance variation, introduces a denoising and shaping algorithm based on ensemble empirical mode decomposition (EEMD) to address errors caused by background noise, and recommends an optimal sensor installation position to mitigate errors arising from blade tip shape asymmetry [55]. Tocci et al. [56] introduced a state-space model tailored to simulate arrival time signals within blade tip-timing analysis. This mathematical model is proficient in creating synthetic tip-timing signals that faithfully replicate particular test conditions. These synthesized signals are subsequently employed to assess the post-processing software utilized in tip-timing analysis. This method allows for offline evaluation of the software, offering crucial insights into the uncertainties it introduces into user measurements. Moreover, this approach facilitates sensitivity studies on parameters impacting the accuracy of data analysis during testing. The fundamental limitations of BTT include significant under-sampling and rigid probe layout, impeding its practical application. Additionally, this method requires casing modifications for probe installation, which can affect turbine performance due to structural alterations, compounded by limited installation spots owing to the engine's complexity, resulting in an uneven probe distribution [57].

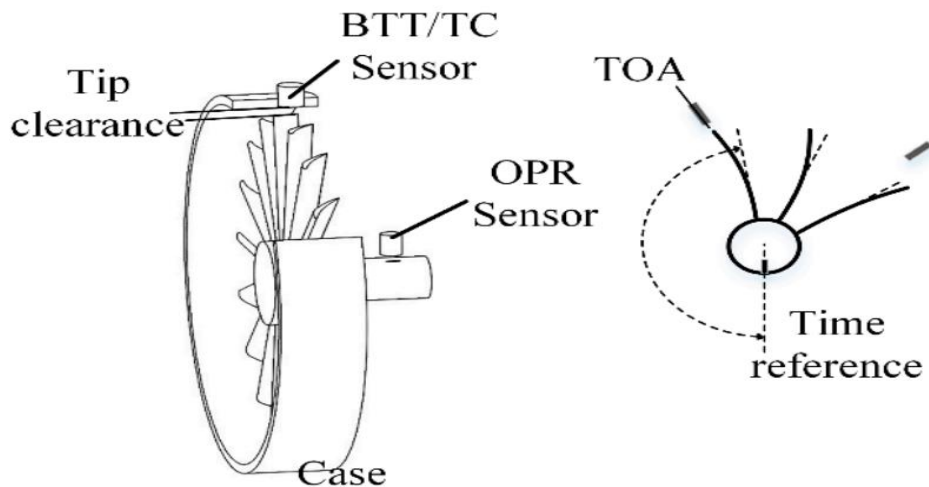


Fig. 16. Conventional Blade tip timing method [58]

3.2 Vibrational Monitoring:

Vibration measurement stands as the predominant method for monitoring the condition of rotating machinery overall. The rotational movement can be visualized as oscillations similar to sine waves, featuring specific frequencies and amplitudes. With knowledge of the shaft's velocity and the geometrical specifics of each equipment part, it becomes possible to determine the frequencies corresponding to the rotation of these components. This approach efficiently identifies significant blade faults like rubbing but lacks sensitivity in detecting minor issues such as alterations in blade geometry [46]. Continuous vibration monitoring allows for tracking changes in Blade Pass Frequency (BPF), its amplitude, and harmonics, offering valuable insights into the presence of blade rubbing. Vibrational monitoring techniques for gas turbine blade fault detection have been proposed in several studies. Ma et al. [59] studied the vibration response resulting from the rubbing between a rotating blade and casing during the run-up process with constant angular acceleration and the steady-state process. Their findings highlighted the method's efficacy in identifying blade rubbing, noting that blade-tip contact can lead to amplified amplitudes and harmonic resonance when the rotational frequency aligns with the blade's flexural dynamic frequencies. Wang et al. [60] also explored the efficiency of vibration analysis on the casing to identify blade-casing rubbing in a dual-rotor blade casing setup. Feng et al. [61] developed the Sparse Harmonic Product Spectrum (SHPS) technique for precise blade passing frequency computation from the broadband casing vibration of gas turbines. Their approach involved merging the Vold-Kalman filter with an adaptive parameter optimization process (AVKF) to distinguish blade-related vibrations from the overall casing vibrations. Moreover, they established a fault early-detection model by examining the spectrum of casing vibrations associated with blade performance. Utilizing healthy data, an Autoencoder was employed to establish a model for the blade's condition. The coefficient for pinpointing blade fault locations was derived from feature trend analysis and clustering analysis. The stage with the highest identification coefficient determines the precise blade fault location. Xiao et al. [62] introduced a technique named high-resolution harmonic product spectrum (HR-HPS) for precise extraction of the fundamental rotating frequency and computation of blade characteristic frequencies from gas turbine casing vibrations. Using the Vold-Kalman filter, they

reconstructed waveforms associated with the blade passing frequency, forming the basis of their proposed blade fault diagnosis framework, which exhibits higher sensitivity to fault severity compared to conventional features. An experiment testing blade fracturing faults was conducted to verify the proposed method. The findings indicated that the HR-HPS approach proved effective across different operating conditions, accurately pinpointing the moment of failure and offering early warnings for gas turbine blade fracturing faults. Ando [63] devised a method allowing the monitoring of turbine blades through the installation of pulsation or vibration sensors, primarily using piezoelectric sensors, on the stator side. This approach involved the examination of both radial and axial turbine blades to establish an appropriate measurement chain and analytical technique. It was concluded that the method proved effective for gas turbine monitoring by referencing pulsation amplitude levels during potential critical resonance occurrences under nominal conditions. Moreover; the approach underwent testing and assessment in a power plant for over a year. Soto-Ocampo et al. [64] introduced an economical data collection setup for monitoring the condition of rotating machinery via vibration analysis. They utilized a Raspberry Pi as the recording device and presented a case study that involved analyzing vibrations detected in a bearing across four levels of failure. This system boasts a high sampling frequency capability and can capture data from up to three channels, making it well-suited for vibration analysis in rotating machinery. The system's effectiveness was showcased through a case study that involved analyzing shearing vibrations across four different degrees of failure.

3.3 Temperature Monitoring:

As machines function, flaws like cracks or defects on the blades can produce heat because of heightened friction or alterations in stress. These irregularities cause changes in the thermal patterns of the blades, where temperature variations act as indicators for predicting potential faults on the blades ahead of time. Gas turbines are constructed with thermocouples positioned at every stage among the four stationary rows to measure temperatures. However, measuring temperatures in the high-speed turbine blades remains a significant focus of ongoing research. Three distinct temperature measurements methods are utilized to

detect various faults, with infrared thermography, pyrometry, and phosphor thermometry effectively identifying issues related to TBC degradation, fatigue, corrosion, and erosion [46,65]. Infrared thermography for detecting blade faults entails employing infrared cameras or sensors to assess the temperature spread over the turbine blade surfaces. Thermal flow imaging has the potential to enhance turbine blade defect detection, its advantage lies in detecting both surface and subsurface cracks, making it suitable for integrated quality control in mass production [66]. DeShong et al. [67] utilized the thermal images to examine the temperature distribution across blade surfaces, aiming to predict blade coolant flowrate. Sun et al. [68] detailed the pulsed thermal imaging – multilayer analysis technique, capable of evaluating property distributions over the entire surface of TBC samples and offer precise imaging of TBC parameters such as conductivity, thickness, or heat capacity, regardless of the number of coating layers.

The infrared pyrometer generates a signal by detecting and analyzing the infrared radiation emitted from turbine blades to determine their surface temperature. Gao et al. [69] introduced a mathematical framework aimed at gauging the surface temperature's shape function, specifically the emissivity of blades covered with TBC. This was achieved by analyzing the radiation captured through optical pyrometry. To validate this, an experiment was conducted wherein a multi-spectral optical pyrometer system was affixed to a gas turbine, while thermocouples were implanted into the shroud of a blade. The approach demonstrated its reliability and superior accuracy in temperature assessment. In gas turbine blade environments with intense heat and pressure, interference occurs due to combustion gases absorbing blade surface radiation and emitting more radiation than the turbine blades. Due to the aforementioned factors, Falsetti et al. [70] and Ketui et al. [71] provided an overview of errors related to measurement and reflection in infrared cameras and pyrometers. It was emphasized that three primary error sources include the target's emissivity, surrounding reflections, and the transparency of the optical pathway. Therefore, when measuring temperatures on reflective targets surrounded by surfaces at significantly higher temperatures, correction for reflection errors is crucial to ensure reliability. In conclusion; pyrometers offer temperature mapping without the need to install sensors directly onto a component's surface. However, they rely on optical access

and are susceptible to accuracy issues due to environmental factors unless specialized long wavelength pyrometers are utilized. The thermographic phosphor method relies on a history of thermal coating. It involves incorporating active rare earth ions, which can be part of the TBC. These unique materials emit light when stimulated by particular energy. Analyzing alterations in this emitted light allows surface temperature measurement without direct contact, proving valuable for challenging environments. Jenkins et al. [72] introduced a diagnostic method for measuring turbine blade temperature in an operating engine using thermographic phosphor coatings. The method involves laser-induced excitation of the phosphors and measuring the decay times of their luminescence.

3.4 Acoustic Emission:

Acoustic emission (AE) techniques are being used for early fault detection in rotating machinery, AE relies on transient elastic waves generated by the release of energy from material cracks, typically occurring within the frequency range of 100 KHz to 1 MHz, enabling the detection of machine defects through the unique crack growth-induced phenomenon detected by AE sensors. AE monitoring enables online identification of the condition of gas turbine engine blades, encompassing the detection of shaft cracks, blade rubbing, fatigue cracks, prognosis of crack expansion, and estimation of remaining fatigue life [73] [74]. Jo et al. [75] introduced an online method for diagnosing blade faults by acoustically detecting defects on rotating turbine blades. The researchers studied how blade faults, including partial loss and distortion, impact the amplitude of specific frequency components within received signals. They also quantitatively analyzed signal characteristics, such as attenuation concerning distance and reduction due to eccentricity. The findings indicated that partial loss of turbine blades reduces the area for sound reflection, resulting in decreased signal amplitude, while blade distortion leads to greater eccentricity between the transmitter and receiver, causing weaker detected signals. Additionally, the study validated the effectiveness of acoustic diagnosis in detecting both partial loss and distortion in turbine blades. Nashed et al. [76] investigated how altering fluid mechanical conditions in a functioning gas turbine affects Acoustic Emission (AE) and its origins. Their discoveries indicated that the sensitivity of AE allows for detecting subtle alterations in gas

turbine components, potentially spotting initial faults and tracing crack origins without invasive procedures. Additionally, AE effectively identifies rubbing occurrences between the rotor and stator. Later; Nashed et al. [77] discussed the use of AE monitoring in gas turbines for fault detection and condition monitoring and proposed a signal processing approach that involves extracting a time-series envelope and generating time-frequency features using a continuous wavelet transform. Zhang et al. [73] advocated for employing online acoustic emission (AE) monitoring specifically for gas turbine engine blades. Their experiments focused on fatigue crack development in both gas turbine engine blades and TC11 titanium alloy plates, establishing a correlation between accumulated AE detections and the length of fatigue cracks. By utilizing AE parameters, they were able to identify the stage of crack progression and forecast the extent of crack development as well as the remaining fatigue life based on AE energy. AE offers a cost-effective and straightforward approach to monitor the state of hot gas components, enabling early identification of blade fatigue cracks in comparison to vibration analysis, particularly as these cracks progress significantly [45]. However, signal attenuation poses a downside, and AE sensors are constrained by the high temperatures within gas turbines, restricting their application in the hot gas environment without active cooling.

3.5 Ultrasound

Gas turbine blade monitoring using ultrasound is an important technique for detecting cracks and defects in turbine blades. Non-destructive testing and structural health monitoring (SHM) processes are being used to identify initial cracks before catastrophic events occur [78]. Linear ultrasound methods can detect structural integrity by monitoring amplitude and phase fluctuations, but they may not easily detect closed or small cracks. Nonlinear ultrasound methods, on the other hand, can identify damages at an early stage by monitoring new signal components in the frequency spectrum [75]. Usually, an ultrasonic wave gets transmitted, and the signal bouncing back from a crack can help foresee potential failures. For gas turbines, the pertinent guided waves include Rayleigh and Lamb waves. Among these, Rayleigh waves are the most basic. They involve interconnected longitudinal and shear motions that travel at the same speed. Although Rayleigh waves excel in crack inspection, they come with the downside of requiring a coupling fluid.

Furthermore, it's crucial to recognize that higher-frequency waves have less penetration depth in materials compared to lower-frequency waves. This characteristic makes Rayleigh waves inadequate for detecting micro-cracks. Conversely, Lamb waves are elastic waves that move through solid plates, showcasing particle motion within the plane encompassing both the wave's direction and the plate's surface. These waves merge pressure and shear characteristics, proving valuable for identifying damage because they can traverse extensive distances and exhibit intricate behaviors. Several researchers have addressed the use of guided waves in detecting cracks at an early stage. Rau et al. [79] examined the identification of cracks at the turbine blade root employing ultrasonic Rayleigh waves. They conducted an experiment using water-based couplant transducers affixed to a γ -titanium aluminide turbine blade to detect cracks with a Signal to Noise Ratio (SNR) of 12dB. The results indicated that the ability to detect shallow flaws improves with increased frequencies due to shorter wavelengths and reduced depth of penetration. Additionally, employing higher transducer frequencies enhanced spatial resolution. Li Shitao et al. [80] suggested a technique employing ultrasonic detectors and probes attached to both ends of the turbine blade. These probes are linked to an ultrasound measuring instrument via a cable. The detection process relied on the propagation of generated guided waves along the blade, determining the scanning range based on the blade's length to detect echoes. This approach enabled efficient and reliable non-destructive testing to identify artificially induced blade cracks of varying sizes on the tested blades. Lane et al. [81] devised an ultrasonic array system to inspect single-crystal turbine blades in place. This system used phased arrays of ultrasound transducers, enabling precise control over excitation time and amplitude for each. Its purpose was to detect cracks in the turbine blade root's internal surface, a vulnerable area due to high operational stress. The system successfully identified artificial defects and notably improved the accuracy of detecting crack positions and sizes compared to standard single-element probes.

3.5.1 Ultrasonic Guided Waves via Piezoelectric Transducers

The utilization of piezoelectric transducers is widespread in generating and sensing guided waves. Structural health monitoring (SHM) system design encompasses choosing actuators and sensors,

determining their placement on the structure, and processing output signals after data collection [82]. Piezoelectric transducers are applied to create and measure flexural waves in plates, and their optimal frequencies are observed to detect damage [83]. Various methodologies, including guided wave techniques, are used for structural health monitoring (SHM) using piezoelectric transducers [84]. Flexible piezoelectric transducers with high piezoelectric constant have been fabricated and used for dynamic strain monitoring and ultrasonic guided wave sensing [85].

Other pathways under consideration involve the exploration and integration of ultrasonic sensors through hybrid methodologies, presenting alternative and diverse avenues for potential exploration and implementation.

3.5.2 Ultrasonic Stimulated Thermography

The core concept behind Ultrasonic Stimulated Thermography revolves around employing ultrasonic waves to elicit and observe thermal reactions within a substance by air coupled transducers, facilitating the identification of micro-crack. Mevissen et al. [86] developed an ultrasonic stimulated thermographic testing setup to detect cracks in turbine blades. This method employs ultrasound to induce frictional heat on crack contact areas, recorded by a thermal imaging camera. The temperature rise is quantified based on the electrical energy input to the actuator, aiding in crack topology comprehension and predicting preloads within the crack. Numerical analysis was performed to fine-tune the excitation frequency and comprehend the link between crack setup, local crack speed, and temperature rise. This approach enables effective detection of turbine blade cracks and enhances the efficiency of inspection schedules. Moreover; Finite element models were created to replicate findings and identify preloads on the crack surface and nearby plastic deformation. The research employed periodic sinusoidal excitation reaching a peak amplitude of 1000 N to replicate the piezo actuator's operation. Tests and measurements were carried out on turbine blades to identify the frequencies resulting in the most significant temperature elevation.

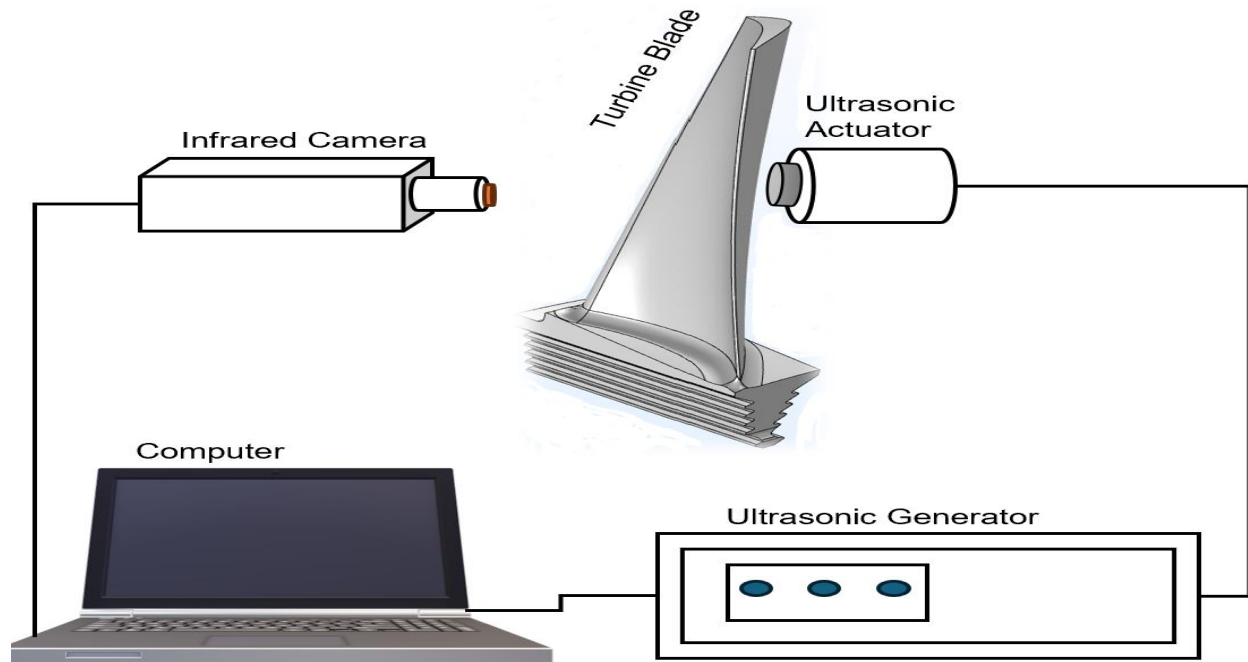


Fig. 17. Ultrasonic Stimulated Thermography. [87]

Jia et al. [87] investigated the importance of couplant selection and the rapid detection capabilities of explored the significance of selecting appropriate coupling agents and the swift detection capabilities of ultrasonic infrared thermography in identifying cracks within turbine blades. The study involved comparative assessments using various couplants, including no couplant, sheet metal, and medical adhesive plaster. Findings indicated that the selection of the coupling agent notably impacts detection efficiency, with medical adhesive plaster proving superior to sheet metal. Moreover, the experiment demonstrated that ultrasonic infrared thermography efficiently detects blade cracks within a mere second, given the acquisition frequency of 50Hz.

3.5.3 High Temperature Transducers

Mounting transducers onto turbine blades poses significant challenges, so utilizing high-temperature ultrasonic transducers provides potential solutions for managing the challenge of extreme temperatures in gas turbines and serves as a feasible approach to monitor turbine blades. Ensuring the sensors withstand the elevated temperatures is crucial, alongside maintaining effective acoustic coupling between the sensor and

the object being tested. Certain materials and sensors show potential for functioning at elevated temperatures. Microelectromechanical-system (MEMS) piezoelectric pressure sensor, utilizes aluminum nitride as its sensing material, allowing operation in extreme temperatures exceeding 1000 °C, enabling the capture of distinctive hypersonic-flow characteristics [88]. $\text{Ba}_2\text{TiSi}_2\text{O}_8$ single crystal sensor demonstrates effective sensing abilities and strong dependability even when exposed to high temperatures, reaching up to 650 °C [89]. Bouchy et al. [90] devised a compact piezoelectric ultrasonic transducer to be permanently exposed to high temperatures. The transducer was designed by including of a 12mm diameter 36° Y-cut lithium niobate piezoelectric crystal, generating a resonant frequency near 3 MHz. It features platinum electrodes (100 nm) with a 20 nm titanium adhesion layer deposited via physical vapor deposition. A mineral-insulated wire with nickel conductors drives the transducer, secured by silver paste. The backing layer comprises powdered steel 17-4PH with calcium aluminate cement and the casing is stainless steel 304 with a screw-on cap. An experiment was conducted to evaluate the efficiency of the transducer which was connected to a signal generator (Agilent 33500B series), the described transducer design effectively monitored steel block thickness even at elevated temperatures. Its performance remained consistent even after prolonged exposure to high temperatures for 2 months. Without an acoustic coupling layer, the piezoelectric transducer successfully measured the thickness of a 32 mm steel block in a 750°C environment for at least 72 hours. It endured multiple thermal cycles and sustained functionality in temperatures above 550°C for a few months. However; the study used a transducer without a matching layer, but in practice, adding a tailored matching layer can boost efficiency or negate the need for bonding the transducer. Moreover; A thermocouple is necessary to adjust velocity and ensure accurate thickness measurement. Amini et Al. [91] also designed high-temperature ultrasonic transducer using a piezoelectric element made of lithium niobate single crystal. The authors investigated the acoustic coupling of the piezocrystal to the backing element made of porous zirconia and matching layer using high-temperature adhesives and brazing alloys, and stable bonding and clear signals were obtained using an aluminum brazing alloy. It was found that the designed transducer effectively served its intended purpose, recording clear echo signals even up to 800°C.

Another explored concept entails adapting Acoustic monitoring techniques for temperature monitoring in turbine blades, employing waveguides in conjunction with high-temperature ultrasound transducers for temperature measurement. Waveguides and buffer rods offer a means to separate transducers from severe conditions. Yule et al. [92] explored the use of ultrasonic guided waves for temperature monitoring in turbine blades and nozzle guide vanes in aerospace turbomachinery. It was concluded that employing waveguides to mitigate temperature effects on transducer operation appears to be the most suitable approach for attaching transducers to a vane. The use of waveguides becomes impractical in situations where there's limited space around the pipework or where elevated temperatures persist within roughly 50 cm of the structure being examined [90].

3.6 Pressure Monitoring:

Turbine blade fault detection natural from casing pressure is a non-trivial task. However; leveraging pressure field distortion around rotating blades aids in diagnosing blade deformation faults. Pressure transducer signals within the gas turbine's inner casing offer superior insights on fouled and twisted blade conditions than vibration probes [46]. Cox et al. [93] determined the natural frequency of rotor blades using both turbine engine casing pressure and vibration sensors. Ratz et al. [94] employed externally positioned accelerometers to gauge casing vibration responses and correlate them with internal blade vibrations in gas turbines. Their experimental work on a simplified test turbine showcased that the spectrum of internal pressure and casing vibration signals holds data useful for estimating rotor blade natural frequencies. Forbes et al. [95] introduced a contactless analytical method for estimating rotor blade natural frequencies using casing vibration measurements at a singular engine operating speed. Implementing this method for operational gas turbines is deemed challenging due to the complexity of installing pressure sensors on the surface of turbine blades.

3.7 Performance Monitoring:

Monitoring gas turbine performance is essential to avert failures. This involves analyzing performance parameters like heat rate and structural vibration to detect faults and anticipate the turbine's remaining lifespan. Advanced condition monitoring systems use operational gas turbine data to track performance and identify potential issues. Variations in pressure and flow rate ratios, along with reduced isentropic efficiency in the turbine and compressor sections, could signal a decline in system performance [96]. Tahan et al. [97] conducted a review of gas path performance monitoring methods, examining various failure modes like fouling, corrosion, and erosion in gas turbines. They explored the potential for detecting these issues through performance monitoring. Panov et al. [98] investigated how the wear and tear of gas turbine components like the compressor, combustor, and turbines affected engine performance as they aged. This degradation occurred gradually over the engine's lifespan. The gradual development of physical issues during prolonged operation led to a decline in performance metrics, resulting in observable changes in engine parameters like temperature, pressure, speed, and fuel consumption. They developed a tool to estimate performance and a dynamic model for real-time monitoring and adjustment of the engine's performance. Table 2 illustrates a qualitative summary of aforementioned methods alongside their respective characteristics.

Table 2- Overview of the characteristics and properties associated with different monitoring technologies.

Blade Monitoring Technique	Monitoring Parameter	Fault Detection Mode	Characteristics & Properties
Blade Tip Timing [51-61]	Tip Clearance Time of Arrival	Rubbing Crack	Installation Challenges-Casing Modification. Opting for sensors can be a complex task. Pricey setup.
Vibrational [50], [63-68]	Blade Pass Frequency	Rubbing Crack	Pricey setup. Not sufficiently attuned to detect minor malfunctions.
Temperature [50], [69-76]	Temperature	TBC Loss Fatigue Corrosion Erosion	Early fault detection. Opting for sensors can be a complex task.
Acoustic Emission [77-81]	Acoustic signal	Crack	Signal weakening is a disadvantage. Restrictions using in hot gases without cooling. Pricey setup.
Ultrasound [82-96]	Linear Methods- Amplitude & phase fluctuations. Non-Linear Methods- Signal components in the frequency spectrum	TBC Loss Crack	Challenging to implement in operational environments. Works in hybrid systems with other methods for better accuracy.
Pressure [50], [97-99]	Engine Casing Pressure	Rubbing Crack	Challenging to implement in operational environments.
Performance [100-102]	Efficiency. Pressure and flow rate ratios.	All Types of failure modes	Many sensors are needed. Extensive data and computations are necessary.

CHAPTER 4

AIR-COUPLED ULTRASONIC GUIDED WAVES

TECHNIQUE

4.1 Introduction

The maintenance of gas turbine engines in power generation and aero-derivative industrial applications is a significant concern, with condition monitoring recognized as a critical factor in preventing unscheduled downtime. A primary maintenance objective is the early detection of material defects and damage in components that could lead to failure during their service life. Online monitoring systems are extensively employed to assess the mechanical integrity of the engine core, particularly the turbine, with the primary aims of preventing unplanned engine removals, minimizing operational and capital costs, and transitioning to condition-based maintenance. The main objectives are to further prolong the lifespan of components and maximize service time. Efforts in developing monitoring systems for the turbine are focused on detecting blade failures as severe blade faults can lead to consequential damage to other blades and potentially catastrophic engine failure. Moreover, a failed blade can be both costly and hazardous, reducing turbine efficiency and increasing emissions. Conventional non-destructive evaluation methods commonly employed for monitoring engine components typically involve direct physical contact on the surface using transmitting and receiving transducers. However, the transmission of vibrational energy into the solid material can result in power loss due to impedance mismatch, as well as dispersion and attenuation of the wave caused by varying speeds of certain frequencies. This can pose challenges in signal processing and analysis, often requiring specialized expertise to interpret the data for damage assessment. Nonlinear ultrasonic methods have indeed been gaining increasing popularity in recent years due to their high sensitivity to micro-damage, such as incipient fatigue cracks, compared to classical linear methods. This increased sensitivity makes nonlinear ultrasonic methods valuable for detecting and monitoring structural health and integrity [99]. Nonlinear Air-coupled transducer (NACT) method provides a significant

advantage by eliminating the necessity for physical contact with the specimen and enabling easier excitation of guided wave modes, facilitating swift inspection of extensive areas. A study by Yilmaz et al. [100] highlighted the differences between ACT and traditional contact methods, showing that while immersion techniques and contact methods offer superior defect detection and sizing accuracy, ACT remains a valuable tool. The authors found that ACT successfully visualized four defects out of five and demonstrated higher defect sizing accuracy compared to guided wave inspections, despite challenges with certain defect locations. While ACT may have lower sensitivity and sizing precision than traditional methods, its non-contact nature, efficiency, and ease of use make it an attractive option for fast, preliminary inspections, especially when surface preparation or direct contact is not feasible. This is especially beneficial for the examination of turbine blades, which often possess complex shapes and are challenging to inspect due to their elongated, slender geometries across various frequencies. This key advantage renders air-coupled guided wave technology appropriate for in situ components without requiring the removal of coatings to access the substrate. Furthermore, the technology holds promise for inspecting components with intricate geometry and/or composite materials, such as fan and turbine blades. Thus far, the majority of guided wave applications have focused on uncomplicated components, such as straight sections of pipework.

4.2 Principle of Air Coupled Guided Waves

Air-coupled guided waves have emerged as a promising method for inspecting structures, utilizing ultrasonic waves to identify potential defects. The technique commences with the generation of Lamb waves, a specialized type of ultrasonic wave suitable for plate-like structures like turbine blades. These elastic waves can travel extended distances with minimal energy loss, making them well-suited for this purpose[101]. They exhibit high sensitivity to various forms of damage, such as delamination, debonding, and cracking[102]. This method involves the stimulation of guided ultrasonic waves within a structure. These waves travel through the structure, and any alterations in their travel characteristics can indicate possible flaws or damage. For instance, a fracture in the blade could lead to a reflection and dispersion of the wave or part of the wave scatters at the edge of the damaged area, leading to changes in the wave. These

changes can be measured and analyzed to infer details about the damage [103]. As depicted in Fig. 18, a Lamb wave traveling through the thickness of the plate interacts with a defect, causing partial reflection and the remainder to pass through. Air-coupled transducers can be used to excite and detect the waves, removing the necessity for direct contact with the blade. This approach is especially beneficial in scenarios where access to the blades is restricted or where contact methods might risk causing additional harm.

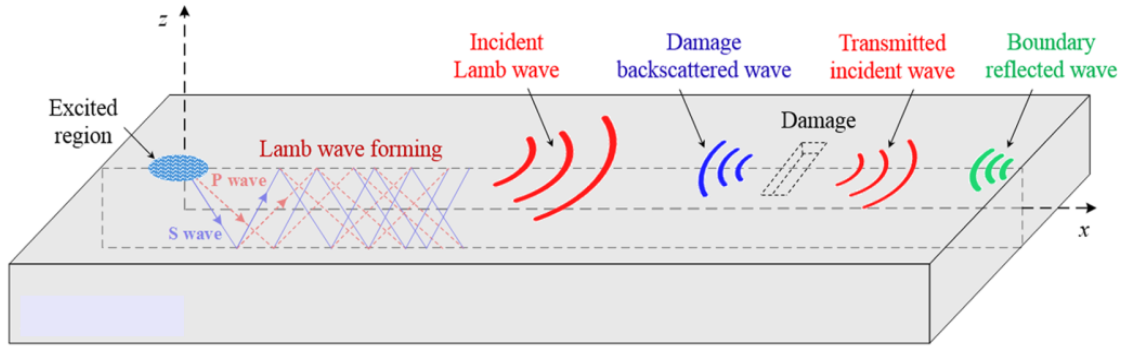


Fig. 18. The concept of Air-Coupled Guided Waves in a plate and their interaction with structural defects [104]

4.2.1 Lamb Waves Characteristics

Lamb waves are types of guided elastic waves that exhibit different modes, such as symmetric and anti-symmetric modes, each characterized by distinct wave behaviors. The Lamb wave mode is extensively utilized for assessing the mechanical integrity of thin plates due to its ability to propagate over long distances parallel to the surface, making it a common choice in nondestructive testing [105]. When Lamb waves are generated, multiple modes can propagate at the same time, each with unique characteristics. Symmetric modes (S_0 , S_1 , S_2 , etc.) have displacements that are symmetric about the plate's mid-plane. The fundamental symmetric mode, S_0 , has the lowest frequency for a given wavelength and travels the fastest, while S_1 , the first higher-order symmetric mode, travels slower than S_0 . On the other hand, antisymmetric modes (A_0 , A_1 , A_2 , etc.) have displacements that are antisymmetric about the mid-plane. The fundamental antisymmetric mode, A_0 , typically exhibits a higher frequency than the symmetric mode S_0 for the same wavelength, with A_1 , the first higher-order antisymmetric mode, propagating at a slower

speed than A0. The fundamental symmetric mode, S0, is especially advantageous for detecting both surface and subsurface defects due to its high sensitivity and rapid propagation speed while mode A0 is effective in identifying defects that impact the plate's thickness, such as delamination or disbands, owing to its elevated frequency and enhanced sensitivity to variations in thickness [106]. Piezoelectric transducers are commonly used for both excitation and detection purposes, emitting a normal mode at the transducer plate, transmitting through the plate, and subsequently being detected at another location on the same surface. Furthermore, Laser Doppler Vibrometer (LDV) can be utilized to measure the out-of-plane velocity of the Lamb wave mode propagating at a distance from the excitation region. Lamb wave generation and detection methods can be categorized based on their installation requirements into two groups: contact-based methods, which necessitate the use of liquid or solid couplants (e.g., piezoelectric wafer active sensors), and non-contact methods (e.g., pulsed laser, air-coupled transducers), where physical contact is not necessary. Contact and non-contact approaches offer distinct advantages depending on the application requirements. The propagation of signals along a plate to distant points results in purely crest or trough characteristics, akin to those of an infinite plate. Lamb waves offer valuable insights into material properties such as thickness, wave speed, attenuation, and density, as well as the detection of structural discontinuities like cracks or voids. Additionally, Lamb waves find applications in secure communication between physically secured devices in hostile environments, utilizing metallic components to convert plate wave energy into surface wave elastic energy. Unlike normal or shear waves, Lamb waves can exist across a wide frequency spectrum and exhibit dispersion, where wave phase velocity varies with frequency. Signal amplitude is significantly influenced by signal frequency, and coherent wave addition from different thickness modes can diminish signal detectability. Therefore, precise measurement of wave velocity and mode identification are crucial for reliable interpretation of Lamb wave signals.

Lamb waves are essential in a range of applications including nondestructive testing, structural health monitoring, and wireless sensing, which led several researchers to explore contact and non-contact Lamb wave excitation and sensing for diverse purposes. Kishore et al. [107] used PZT sensors affixed to an

aluminum plate to generate and detect Lamb waves. They compared signals from plates with different defect orientations to those from defect-free plates, demonstrating distinct differentiation among various types of defects. Sedaghati et al. [108] employed Lamb wave propagation via ultrasonic probes to conduct in situ measurements of both the location and dimensions of circular corrosion defects in thin plates. Bharati et al. [109] utilized lamb waves for wireless data communication in enclosed metal structures. Sathyanarayana et al. [110] utilized lamb wave propagation for detecting impact damage in carbon fiber reinforced plastic (CFRP) laminates and it was concluded that the propagation of lamb waves can be influenced by the material composition and orientation. The subsequent section (4.3) provides an in-depth discussion on Lamb wave methods that function without direct physical contact.

Overall, Lamb wave NDE methods offer a versatile approach for detecting, locating, and sizing defects in various materials and structures, making them valuable tools in industries requiring non-destructive testing and structural health monitoring applications.

4.3 Non-Contact Lamb Wave Generation and Sensing Techniques

In scenarios where entry to the framework is restricted, utilizing contact methods increases the likelihood of worsening damage, or when surface conditions prevent bonding materials from adhering to contact sensors, employing non-contact approaches becomes essential. Common non-contact ultrasonic transducers include pulsed lasers, ACT, and scanning laser Doppler vibrometer (SLDV).

4.3.1 Air Coupled Transducers

Air-coupled transducers (ACT) have emerged as a promising technique for non-contact NDE, using air as the medium for both the actuation and sensing of ultrasonic waves in structures. The development of air-coupled transducers focused on addressing the challenges of inefficient ultrasound transmission between the transducer and the test piece across the air gap, primarily due to the significant impedance mismatch at the transducer-air and air-specimen interfaces. Additionally, ultrasonic attenuation in air is much greater than in traditional couplants, particularly at high frequencies. To mitigate the substantial impedance

disparity between piezoelectric materials and air, 1-3 type piezoelectric composites—comprising polymer (epoxy resin or polyurethane) and piezoelectric ceramic—can significantly lower acoustic impedance. As a result, this enhances the transmission efficiency of ultrasound from the transducer to the air [111]. Wu et al. [112] developed an air-coupled ultrasonic transducer with a single matched layer utilizing a hollow polymer microspheres/epoxy resin system, which enhanced the transducer's sensitivity by 20.9 dB. Zhou et al. [113] investigated the impact of double matching layers and various bonding layer materials on transducer performance. They modeled a transducer comprising a 1-3 piezoelectric composite, with the first matching layer made of hollow glass microspheres, epoxy, curing agent, and diluent, and the second matching layer made from polypropylene foam. Their study concluded that the fabricated air-coupled ultrasonic transducer demonstrated a 20% higher amplitude than commercially available products and effectively identified defects in non-metallic materials. Zhang et al. [105] documented that capacitive Micromachined Ultrasonic Transducers (CMUT) exhibit potential in mitigating the acoustic impedance mismatch problem, enhance bandwidth and output pressure in air-coupled applications, enabling wide bandwidth and high output pressure generation, rendering them appropriate for air-coupled applications in defect detection based on Lamb waves. To enhance signal quality in ACT sensing, a data acquisition system incorporating a super low-noise, narrow-band tunable pre-amplifier was used, significantly improving the low-energy ACT ultrasonic signals caused by the substantial impedance mismatch between air and solid. In this research, ACT will be used for non-contact actuation, with further details on its application in NDT provided in Section 4.4 onwards.

4.3.2 Pulsed Laser

The pulsed laser (PL) facilitates the generation of Lamb waves by causing a rapid localized increase in temperature within the material. This leads to either the generation of thermoelastic ultrasonic waves or the creation of strong ultrasonic waves through ablation. Controlling wave generation is achievable by adjusting laser pulse parameters such as power, duration, and wavelength, tailored to the structure and surface condition of the target material [114]. Utilizing the PL ultrasonic technique enables the generation

of specific narrowband modes, like A0 and S0 modes, by modulating the scanning speed of the continuous-wave laser to align with the phase velocity of the intended mode [115]. Furthermore, optimizing the spatial distribution of the laser source can also improve the excitability of Lamb modes, particularly Zero-Group Velocity (ZGV) resonances in isotropic plates [116]. Pulsed laser technology is effectively employed for detecting damage in diverse materials, as evidenced by various studies highlighting its utility in non-destructive evaluation. For example, a two-step approach utilizing laser interferometry integrates guided waves with high-frequency bulk waves, enabling efficient inspection of carbon fiber-reinforced structures [117]. Moreover, Wang et al. [118] utilized a picosecond pulsed laser for ultrasonic actuation, allowing for ultrahigh-resolution detection of multi-scale damage in carbon fiber-reinforced composites. Furthermore; Wu et al. [119] demonstrated the use of PL to generate ultrasonic waves for detecting defects in aluminum plates, achieving high spatial resolution and comprehensive full-field data acquisition. Collectively, the aforementioned studies underscore the importance of pulsed laser technology in improving the accuracy and efficiency of damage detection processes across various materials. Nevertheless, PL actuation has some drawbacks. Pulse energy must be carefully controlled within the thermoelastic range to prevent surface burning, as excessive laser power can lead to destructive outcomes . According to Hosoya et al. [120] the use of laser-thermoelastically generated Lamb waves presents two significant practical challenges. Firstly, these waves exhibit small amplitudes, necessitating extensive signal averaging to improve the signal-to-noise ratio, which limits their application for large-area damage detection (e.g., in aircraft or ships). Secondly, determining the threshold for laser-thermoelastic regime activation is complex, as it depends on multiple factors such as material properties, laser parameters, and polarization, making it difficult to establish a precise threshold, particularly in scenarios where the target structures are fully submerged in a medium that absorbs the laser beam.

4.3.3 Scanning Laser Doppler Vibrometer (SLDV)

SLDV serves as a widely utilized sensor for measuring vibration characteristics of surfaces and the out-of-plane velocity of the Lamb wave mode propagating at a distance from the excitation region without physical

contact. It operates based on the principle of the Doppler effect, where the frequency of light reflected from a moving surface is shifted compared to the incident light frequency. The SLDV emits a laser beam onto the surface of interest, and the reflected light, if the surface is vibrating, undergoes a frequency shift due to the Doppler effect. This reflected light is combined with a reference laser beam to create an interference pattern, which is then detected by a photodetector. The interference pattern contains information about the frequency and amplitude of the surface vibration. Additionally, the SLDV may scan across the surface to obtain vibration data at different points, allowing for spatial mapping of vibrations. This technology enables precise measurements of surface vibrations without physical contact, making it suitable for various applications such as structural health monitoring, non-destructive testing, and acoustic measurements. In NDE applications, the SLDV sensor finds utility in detecting flaws or structural deficiencies, particularly within plate-like structures. This involves applying a continuous sinusoidal input of singular frequency to the material under scrutiny, often via a piezoelectric transducer. Subsequent analysis of the material's response by the SLDV allows for the identification of diverse forms of damage, such as impact damage in composites, fatigue-induced cracks, and thinning of aluminum walls [121] [122]. This method offers the benefit of delivering sufficient energy to the test structure, leading to a notable enhancement in the signal-to-noise ratio without the need for repetitive measurements. Furthermore, it guarantees operational safety by employing a low-power class 1 laser. It is important to highlight that advancements have been made in the development of SLDV for specialized applications, including the detection of shallow defects ($\leq 5\%$) and its adaptation for use with dry-coupled interdigital transducers [123]. Nonetheless, a limitation of this technique is its potential incapacity to detect minor defects or early stages of wall-thinning due to slight variations in wavenumber. To overcome this challenge, alternative methods have been proposed, such as multi-frequency local wavenumber analysis and guided-wave image fusion technology. Despite its intricacy and certain constraints, SLDV continues to stand as a potent instrument for monitoring structural health and diagnosing damage. SLDV has been employed in various studies focusing on NDE and SHM. Fakhri et al. [124] investigated damage localization in 3D-printed plates by inducing guided waves through surface-mounted piezoelectric transducers, with sensing conducted by SLDV. Segers et al. [125] explored

the integration of nonlinear vibration filtering, angular bandpass filtering, and error map construction to precisely localize in-sight and out-of-sight damages in composite plates by utilizing SLDV for comprehensive full wavefield measurements.

The non-contact nature of PL and SLVD has led numerous researchers to utilize them for damage detection and localization. Ma Z & Yu L [126] suggested a non-contact approach utilizing PL for Lamb wave generation and SLDV for Lamb wave detection. This proposed system facilitated the inspection of defects in aluminum plates, offering swift inspection and health monitoring techniques for emerging structural systems. Tian et al. [127] presented a noncontact PL-SLDV system for Lamb wave phased arrays, facilitating distant inspection and adaptable array setups. This system utilized PL for Lamb wave generation and SLDV for signal capture, for damage detection in 1 mm aluminum plates. Additionally, an enhanced delay-and-sum (DAS) imaging algorithm was devised for receiver phased arrays, incorporating Lamb wave dispersion to enhance resolution. Compton et al. [128] Presented a non-contact system incorporating a PL for excitation and SLDV for Lamb wave sensing to study sensing parameters and surface enhancements, achieving high-frequency Lamb waves (<600 kHz) in plates thinner than 1 mm, demonstrating the system's efficacy in thickness measurement.

4.4 Air-Coupled Lamb Wave NDT Method

4.4.1 Lamb Wave Generation using ACT

Air-coupled transducers generate longitudinal waves in air striking the plate, which are partially reflected back into the air and partially refracted into the plate, where they produce longitudinal and transverse waves that reflect within the plate and couple to form Lamb waves, their advantage lies in their non-contact operation, ensuring high reproducibility in measurements [129]. The generation process begins with an air-coupled transmitter, oriented at a specific angle to produce a pure Lamb mode. This wave then propagates along the structure, potentially interacting with any defects present. For successful excitation of Lamb waves, an optimal angle is required when the phase velocity in an object under a test is greater than the

sound velocity in air [130]. Several researchers have examined material dispersion curves to precisely determine the optimal angle of orientation for the ACT to generate a pure A0 Lamb mode at specified frequencies. Harb et al. [131] utilized a non-contact method employing an ACT for actuation and an LDV for sensing, applying Snell's law to derive Lamb wave dispersion curves in isotropic solids and directly obtaining phase velocity and frequency wavenumber dispersion curves for a 6061-T6 aluminum plate in air. The authors conducted experimental work to determine the optimal incident angle of an ACT to generate pure A0 Lamb mode waves within the frequency range of 60 to 250 kHz. The transducer was incrementally rotated from 0° to 25° while excited with a five-peaked toneburst signal centered at 60 kHz, and the resulting signals were recorded and averaged over 10 readings. This process was repeated for each 10 kHz increase in center frequency up to 250 kHz. Subsequently, out-of-plane velocities were measured using LDV for various frequencies and incident angles. The incident angles corresponding to maximum out-of-plane velocity for each excitation frequency were recorded and plotted to generate an incident angle versus frequency curve. For instance, incident angles of 14° and 11° were determined to maximize out-of-plane velocity for excitation signals with center frequencies of 100 kHz and 200 kHz, respectively. The A0 Lamb wave mode dominated in a 6061-T6 aluminum plate, exhibiting pronounced behavior within specific angle ranges 10° - 20° for frequencies of 100 and 120 kHz, and 8° - 13° for frequencies of 200 and 240 kHz. Furthermore, leveraging the incident angle frequency-dependent curve and the known speed of sound in air, the researchers directly derived phase velocity and frequency wavenumber dispersion curves for a 6061-T6 aluminum plate through the application of Snell's law. Moreover, a correlation between Lamb wave group velocity and incident angle was established, facilitating the direct plotting of group velocity dispersion curves from the incident angle frequency-dependent curve. It was noted that the group velocity falls within the range of 2 to 2.5 km/s for frequencies spanning from 100 to 120 kHz. Drywall et al. [132] employed an ACT-LDV actuation and sensing system to investigate the optimal incident angle (θ) of an air-coupled transmitter for inspecting aircraft engine blades, typically composed of titanium and nickel alloys. Their goal was to maximize the signal-to-noise ratio (SNR) at a specified configuration. The experiment assumed a transmitter lift-off distance of approximately 15 mm, with the elastic wave field

generated by the ACT being recorded using the LDV system across a range of angles (θ) from -45° to $+45^\circ$, with 0° representing the planar angle. The study revealed that the highest SNR was achieved at an incident angle of $15^\circ \pm 0.5^\circ$. Fan et al [133] employed dispersion curves to determine the optimal angle of 12.75° for the ACT, enabling it to induce the A0 mode in an aluminum plate using a frequency excitation of 300kHz. Optimal slope angles for effective A0 mode generation were determined numerically and experimentally for aluminum and CFRP plates using ACT with a 40 kHz frequency [134].

4.4.2 ACT Lamb Waves for Non-Contact Non-Destructive Tests

ACT technology is extensively employed in NDE applications for inspecting various materials and structures. Numerous researchers [136], [138-148] have used ACT to detect flaws, cracks, delamination, and other structural defects as this technique offers significant advantages for inspecting delicate, complex, or large surfaces, such as composite materials, metals, and aerospace components, without requiring direct contact with the material. ACT techniques are classified into pass-through and pitch-catch modes as shown in Fig. 19. In the pass-through mode, the transmitter and receiver are positioned on opposite sides of the sample, allowing the receiver to capture pulses that traverse along the material. Pitch-catch is often synonymous with through-transmission, where one transducer serves as a transmitter and the other as a receiver, generally placed on opposite sides of the specimen. However, pitch-catch can also involve positioning both transducers on the same side, with the receiver detecting signals that propagate through the material, a setup commonly adapted for pulse-echo methods. In both techniques, time of flight (TOF) and signal attenuation are critical for identifying defects. Pitch-catch is particularly effective in testing complex materials like CFRP composites, offering advantages over traditional backwall echo methods [146]. Conversely, through-transmission enables a comprehensive inspection of internal defects, avoiding the blind zones that can limit reflection techniques [147]. Harb et al. [135] utilized a non-contact methodology integrating ACT to induce the fundamental anti-symmetric Lamb wave mode (A0) in an isotropic aluminum plate, coupled with Laser LDV for measuring the out-of-plane velocity of the propagating A0 mode. Their experimental work involved dense data sampling and employing frequency-

wavenumber filtering to segregate forward-propagating waves from any backward reflections. Additionally, they employed zero-lag cross-correlation (ZLCC) signal processing in the frequency domain for damage imaging. Their analysis concentrated on comparing the A0 Lamb wave mode measured along the plate with and without damages, along with assessing ZLCC values of forward and backward wavefields across all scanning points. They noted a significant increase in cross-correlation values (I) at damaged regions compared to undamaged areas, depicted through contour maps plotting discrete I values. Their findings underscored the effectiveness of frequency-wavenumber filtering in generating and measuring a

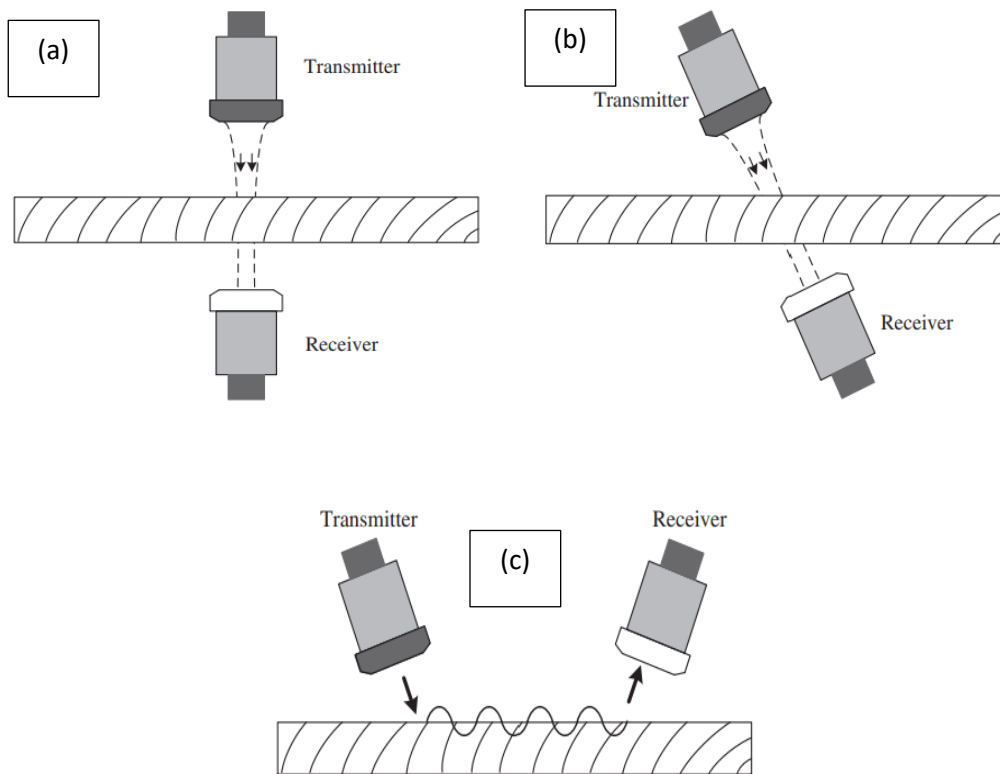


Fig. 19. (a) and (b) Pass-through modes and (c) pitch-catch mode.

comprehensive wavefield, capturing backscattered waves from minor damages and structural boundaries, exhibiting varied propagation angles relative to damage orientation. Moreover, ZLCC imaging accurately identified damage locations, estimated minor damage areas, and delineated damage orientations, highlighting the potential of the hybrid system and associated analytical techniques for structural damage

detection and characterization. Fan et al. [133] utilized a hybrid non-contact system, consisting of an ACT and LDV, to identify the location, size, and shape of circular flat-bottom holes and a rectangular groove defect in a 1.5 mm thick aluminum plate. The incident angle of the ACT, with a central frequency of 200 kHz; required to excite the fundamental anti-symmetric mode (A0), was determined from the dispersion curves to be 12.75° . The researchers applied the local wavenumber approach to calculate the average wavenumber distribution in the isotropic thin plate. By combining the wavenumber with the phase velocity dispersion curve, they were able to detect the defect features and quantify the damage depth. Bustamante et al. [136] explored two non-contact systems for non-destructive inspection and flaw detection in CFRP and aluminum plates, a hybrid laser with air-coupled ultrasound and a purely air-coupled ultrasonic system. The authors employed ACTs with a central frequency of 1 MHz and determined the incident angle based on Snell's law. Due to differences in excitation modes, energy required to generate guided waves, and acoustic impedance, they conducted two distinct experiments, one experiment used an ultrasonic laser for actuation and an ACT for detection to inspect aluminum plates, while the other utilized two ACTs, one for excitation and the other for sensing, to inspect defects in a CFRP plate. A-scan and B-scan techniques were used to detect the presence, size, and location of defects by examining changes in amplitude and anomalies in the B-scan signals. In areas with defects characterized by reduced stiffness, the leading wavenumber of the A0 mode was found to increase, while the measured amplitude signal decreased to its lowest point over the defect and reached its peak in regions without defects. This reduction in amplitude over the defect region was attributed to the mode conversion of Lamb waves into other modes, which resulted in a decrease in the measured amplitude of the S0 mode. Jiang et al. [137] conducted an experiment to detect knots and cracks in wood panels with thicknesses ranging from 10 to 40 mm, utilizing an air-coupled ultrasonic system. They employed a pass-through inspection technique, positioning transducers 75 mm away from the test piece and using a center frequency of 200 kHz. The transmitter was excited using sinusoidal and Barker-coded signals. The signals received by the receiver were filtered and amplified to produce a response signal, after which a matched filter was applied for pulse compression through cross-correlation between the received and excitation signals. The amplitude (C-scan) images of the sample using both excitation signals were

generated, demonstrating that both methods were effective for knot detection. However, the size of knots detected using only sinusoidal excitation was significantly smaller than the actual defect size due to the system's limited precision and noise interference. In contrast, the image size resulting from excitation with Barker-coded signals closely matched the actual size of the defects. Furthermore, the results from the sinusoidal excitation indicated a lack of detection capability when combined defects were present. In contrast, the Barker-coded excitation exhibited much higher resolution, enabling the distinction of combined defects, as evidenced by different colors at the edges of both defects. The study concluded that the application of the Barker code method enhances measurement accuracy compared to using a sinusoidal signal. Additionally, TOF (D-scan) images of various defect types were presented, revealing that while the TOF method could detect combined defects, it was less effective than the amplitude method for identifying knots and cracks. Rommeler et al. [138] explored defect detection in polymer pipes made of polyvinylidene difluoride (PVDF) and polypropylene (PP) using an ACT system for excitation and sensing. Two ACT transducers were utilized, each with a central frequency of 200 kHz, one with a 25 mm active diameter serving as the transmitter and the other with a 12.5 mm diameter as the receiver. The transmitter was excited using three cycles of a sine wave, windowed by a Gaussian envelope. The study examined how different Lamb wave modes, particularly the A0 mode, could be excited and detected depending on the transducer angles. Using a polymethylmethacrylate (PMMA) plate (300 mm long, 100 mm wide, and 3 mm thick), they determined that the optimal angles for exciting the S0 and A0 Lamb modes were 9° and 19°, respectively. The researchers scanned PVDF and PP pipes with and without defects using a single-sided pitch-catch setup and successfully detected defects with diameters of 4 mm, 2 mm, and 1 mm, reporting that signal amplitude decreased as defect size increased and wall thickness decreased. However, defects with a 0.5 mm diameter could not be detected. Additionally, they compared the experimentally obtained phase and group velocities of the A0, S0, and A1 Lamb wave modes with numerical simulations, concluding that measured values were slightly higher by 4% than the computed ones for PVDF, while for PP, the simulated results were approximately 10% higher than the experimental values. Wang et al. [139] introduced a nonlinear defect index paired with an adaptively weighted (AW) imaging algorithm for the

detection of small-scale defects in in-service CFRP plates. Their experimental setup involved two ACTs, operating at a center frequency of 200 kHz for both excitation and sensing, on T300/QY8911 CFRP plates. A 400 V_{pp} sinusoidal pulse signal modulated by a Hanning window with a center frequency of 200 kHz and a 5-pulse period was applied to the transmitter. To simulate delamination defects, a 0.05 mm polyethylene film layer was inserted between the 10th and 11th layers of two CFRP plates, creating artificial delamination defects with diameters of 20 mm and 10 mm. The results revealed a notable decrease in time-domain maximum amplitude in regions with defects compared to defect-free areas. For the 20 mm defect, the nonlinear defect index demonstrated a smoother and more stable amplitude profile at defect-free positions, reducing the likelihood of false positives compared to the linear defect index. For the 10 mm defect, the nonlinear defect index showed greater sensitivity, with enhanced boundary clarity around the defect. Additionally, for the 20 mm defect, both indices achieved low measurement errors (8.1%, 7.2%, 7.3%, and 6.5%) and high imaging SNRs (28.3 dB, 28.6 dB, 30.1 dB, and 31.4 dB). However, with the 10 mm defect, the linear defect index presented higher measurement errors (22.4% and 20.6%) and reduced SNRs (17.8 dB and 17.6 dB), likely due to environmental noise, resulting in potential misinterpretation. In contrast, the nonlinear defect index sustained low errors (8.1% and 7.8%) and favorable SNRs (25.9 dB and 26.9 dB), with a 67% reduction in error, underscoring its suitability for precise characterization of smaller defects independent of the imaging algorithm applied. Asokkumar et al. [140] applied the air-coupled through-transmission technique to assess the size and shape of internal defects in a glass fiber-reinforced plastic (GFRP) composite plate. Using a 2D guided wave model in COMSOL, they defined the GFRP plate as a 3.2 mm thick isotropic solid with a 305 mm width, modeled in an air medium. Two 300 kHz ACTs with 14 mm diameters were employed, exciting plane waves with a 10-period Hanning-windowed sine burst at 100 Pa. A void defect was introduced, generating leaky Lamb waves in the air and a reflected A₀ mode in the GFRP plate; signals at the receiver showed lower amplitude and slight delay in the presence of the defect. Experimentally, the authors tested the air-coupled through-transmission method using a 750 V, 10-period rectangular pulse to generate two C-scan images, an 8 J impact defect (60 × 50 mm²) and a 12 J impact defect (60 × 80 mm²). The transducers were stationary while the plate moved with

1 mm scanning increments in both directions. Findings indicated that the 8 J defect spread across fibers perpendicular to the roving direction, whereas the 12 J defect extended along fibers, appearing concealed with central protrusion. Moreover, detailed B-scan imaging was used to further characterize the internal defects. The B-scan approach involved incrementally moving the scanner along the y-direction by 1 mm steps over a 100 mm distance to capture the response across different angles. This method provided clear indications of defect orientation and extent within the GFRP plate. For the 12 J impact defect, the B-scan images highlighted the damage's anisotropic nature. When scanning at an angle of 86° , the B-scan was able to capture the long side of the defect, effectively revealing its larger extent along the roving fiber direction. In contrast, scanning at 35° allowed for the detection of the shorter side of the defect, providing a clearer understanding of the defect's actual shape and orientation within the composite material. This B-scan methodology thus demonstrated its utility in identifying both the size and directional characteristics of impact-induced defects in composite plates, enhancing the accuracy of defect characterization.

Ambrozinski et al. [141] conducted an experiment on two 1.2 mm thick, 4-ply CFRP plates, using air-coupled transducers in pitch-catch mode to detect crack and delamination. A broadband chirp signal (100–500 kHz) was used for excitation, and signals were cross-correlated via matched filtration. The transmitter angle was set to 17° to enhance the A0 mode, while a 4° incident angle enhanced the rapid S0 mode. The study examined S0 and A0 modes' interactions with defects through B-scan and C-scan images. B-scan results showed distinct diffraction and weak reflections of the S0 mode at the defect, with a sharp RMS amplitude drop at 130 mm, indicating the crack. A clear A0 mode also showed significant amplitude decay after the crack, highlighting the S0 mode's faster propagation and lesser decay compared to A0. Signal perturbations and increased A0 attenuation due to delamination were noted, with C-scan results showing higher attenuation along the delamination edges than its center. Moreno et al. [142] explored the application of an ACT excitation-sensing system to evaluate sandwich composite plates, focusing on antisymmetric Lamb waves induced specifically in the upper CFRP layer. The authors created a 2D finite element model in COMSOL, and conducted two experiments with 250 kHz ACTs set at a 12° incident angle, exciting the transmitter with a 5-cycle toneburst signal. Artificial square-shaped defects were introduced, and

corresponding C-scan images were generated and analyzed. FEM simulations confirmed the presence of antisymmetric Lamb waves and longitudinal waves within the transmitter's air wedge, where multiple reflections occurred. Consequently, a third, higher-amplitude signal emerged due to complex amplitude variations with changing incident angles, as also observed experimentally. The C-scan imaging approach reveals that amplitude changes in the AWL mode pulse effectively detect flaws like disbonds and delaminations in the upper CFRP layer of a sandwich plate. Increased amplitude at the CFRP-foam boundary indicates disbonds, attributed to interrupted wave leakage, while decreased amplitude suggests separation from the boundary, likely due to phase velocity shifts with thickness reduction. This highlights C-scan imaging's utility for inspecting impact-prone areas in composite structures. Wandowski et al. [143] proposed simulating acoustic wave generation and elastic wave propagation in composites using FEM and SEM methods. FEM modeling in COMSOL simulated acoustic wave generation with ACT, and extracted acoustic pressure data was converted into loads for an SEM model of a delaminated composite panel. Elastic wave propagation in the CFRP panel was analyzed using in-house SEM software with GPU-based parallel computation. The panel, measuring 500 x 500 x 3.9 mm, comprised 40 unidirectional CFRP layers. A resonant transducer at 40 kHz was modeled in FEM, and delamination was introduced via node separation in SEM. Three ACT angles were tested: $\theta = 0^\circ$ generated symmetrical waves, while $\theta = 30^\circ$ optimized A0 mode in the direction across fibers, producing distinct energy concentrations at delaminations. Results indicated that ACT at $\theta = 30^\circ$ toward the top produced the highest RMS amplitude, likely due to alignment with reinforcing fibers, while $\theta = 0^\circ$ yielded symmetric energy distribution optimal for low-frequency waves. Higher-frequency behavior remains an area for further study. Li et al. [144] conducted nondestructive testing of monocrystalline silicon solar cells, a single-sided, air-coupled ultrasonic system was applied to generate Lamb waves and detect leaky Lamb waves propagating in air. Monocrystalline silicon solar cells, each with dimensions of 125 mm x 125 mm and a thickness of approximately 158 μm , were analyzed. Theoretical dispersion curves helped determine the appropriate incident angle for A0 mode excitation, targeting a 35° angle that was then experimentally confirmed as optimal within a 36° - 38° range. This range enabled the effective propagation of Lamb waves through the solar cells, allowing the

assessment of artificial cracks by tracking amplitude variations in both circular and lateral scanning patterns. In the circular scanning phase, wave amplitudes varied periodically, reflecting the anisotropic nature of the material, and distinguishing between through-thickness and non-through cracks based on wave scattering patterns was possible. Lateral scanning allowed precise crack length estimation using cross-correlation coefficients with a 0.97 threshold, demonstrating the system's ability to detect and characterize cracks based on wave scattering patterns. The study's results contribute to the validation of air-coupled ultrasonic testing for crack characterization in anisotropic, thin silicon layers. Reichle et al. [145] investigated the use of air-coupled ultrasound in the non-destructive testing of pultruded profiles within the pultrusion manufacturing process. In their study, ultrasound examination was conducted with probes at a center frequency of 207 kHz, with the optimal incident angle experimentally determined to achieve the highest signal-to-noise ratio at 4.7° . To assess detection capability, they introduced artificial defects such as fiber misfeeds, incomplete fiber impregnation, and fiber bundle tears. The study described multiple ultrasound scanning methods, including A-scan, B-scan, and C-scan, to visualize and analyze the internal profile structures. In C-scan imaging, defect-free profiles consistently appeared as homogeneous blue regions, whereas defects were characterized by amplitude variations. The authors noted, however, that all defect types produced similar effects on the ultrasound signal, complicating defect classification based solely on ultrasound data.

Air-coupled ultrasonic technology provides considerable benefits for defect detection across various industries, especially within non-destructive testing (NDT) applications. Its non-contact approach is ideal for inspecting materials that cannot tolerate direct coupling or where physical contact is unfeasible. Key advantages include its versatility for inspecting diverse materials like composites and thin profiles without coupling agents, and a reduced risk of damage to sensitive surfaces. Air-coupled systems also offer effective defect localization through signal amplitude variations and facilitate rapid scanning via multi-transducer setups, achieving speeds similar to traditional immersion methods [148]. However, despite its advantages, challenges such as signal attenuation and environmental noise remain; thus, continuous advancements in

transducer design and advanced signal processing techniques—such as time-frequency analysis and high-resolution direction-of-arrival estimation—are critical to improving detection accuracy and ensuring the reliability of air-coupled inspections [149,150].

4.5 Lamb Wave Propagation and Dispersion Curves Analysis

Recently, guided wave testing emphasize accurate lamb wave field modeling to improve rapid, non-destructive inspections in complex structures. Plates, with different traveling Lamb wave modes, pose unique challenges in wave propagation modeling compared to simpler shapes like beams or cylinders. The characteristics of Lamb wave travel depend on material properties, boundary conditions, and selected wave modes, making precise simulations crucial for effective visualization and transducer placement. This includes studying dispersion curve structures to understand singularities and establishing criteria for selecting optimal Lamb wave modes in complex geometries.

4.5.1 Lamb Wave Dispersion Curves

The unique geometry of turbine blades facilitates the propagation of Lamb waves at ultrasonic frequencies. Lamb waves, a form of elastic wave, occur in thin plates where the wavelength is on the order of the material's thickness. These waves are guided by the material's upper and lower surfaces, combining longitudinal and shear vertical wave components to enable continuous propagation. Lamb waves are plane strain waves occurring in a free plate, where the traction force must be zero on both the upper and lower surfaces. As entry angle and frequency vary, different mode structures emerge at each point. Due to their dispersive and multi-modal nature, analyzing Lamb waves is challenging, particularly in structures with variable thicknesses, which further complicates wave behavior and interpretation. Dispersion curves can be obtained numerically by solving the Rayleigh–Lamb wave equations, which are known as dispersion relations. These equations specify the propagation velocity (or velocities) of waves at particular frequencies within a plate and are governed by the Rayleigh-Lamb equation. The dispersion relations of group or phase velocities in terms of frequency depend on the structure and material properties. The Rayleigh-Lamb wave

equations describe the propagation of Lamb waves in isotropic plates as outlined in Rose's book [151]. The classic presentation of these equations can be expressed as follows:

$$\frac{\tan(qd)}{\tan(pd)} = -\frac{4\xi^2 qp}{(q^2 - \xi^2)^2} \quad \text{for symmetric modes} \quad (4.1)$$

$$\frac{\tan(qd)}{\tan(pd)} = -\frac{q^2 - \xi^2}{(4\xi^2 qp)^2} \quad \text{for antisymmetric modes} \quad (4.2)$$

Where q and p are given by

$$q = \sqrt{\left(\frac{\omega}{c_T}\right)^2 - \xi^2} \quad (4.3)$$

$$p = \sqrt{\left(\frac{\omega}{c_L}\right)^2 - \xi^2} \quad (4.4)$$

where ξ is angular wavenumber, d is the thickness, ω is angular frequency, c_L is bulk longitudinal velocity and c_T is bulk shear velocity.

$$\text{The angular wavenumber } (\xi) = \frac{w}{Cp} \quad (4.5)$$

The phase velocity (Cp) is related to the wavelength by the simple relation:

$$C_p = \left(\frac{\omega}{2\pi}\right) \lambda \quad (4.6)$$

The group velocity of a guided wave refers to the speed at which a wave packet travels, specifically the rate at which energy is conveyed. It is determined using a well-established equation.

$$C_g = \frac{d\omega}{d\xi} \quad (4.7)$$

where ω represents the circular frequency ($=2\pi f$), and ξ denotes the wavenumber of the guided wave.

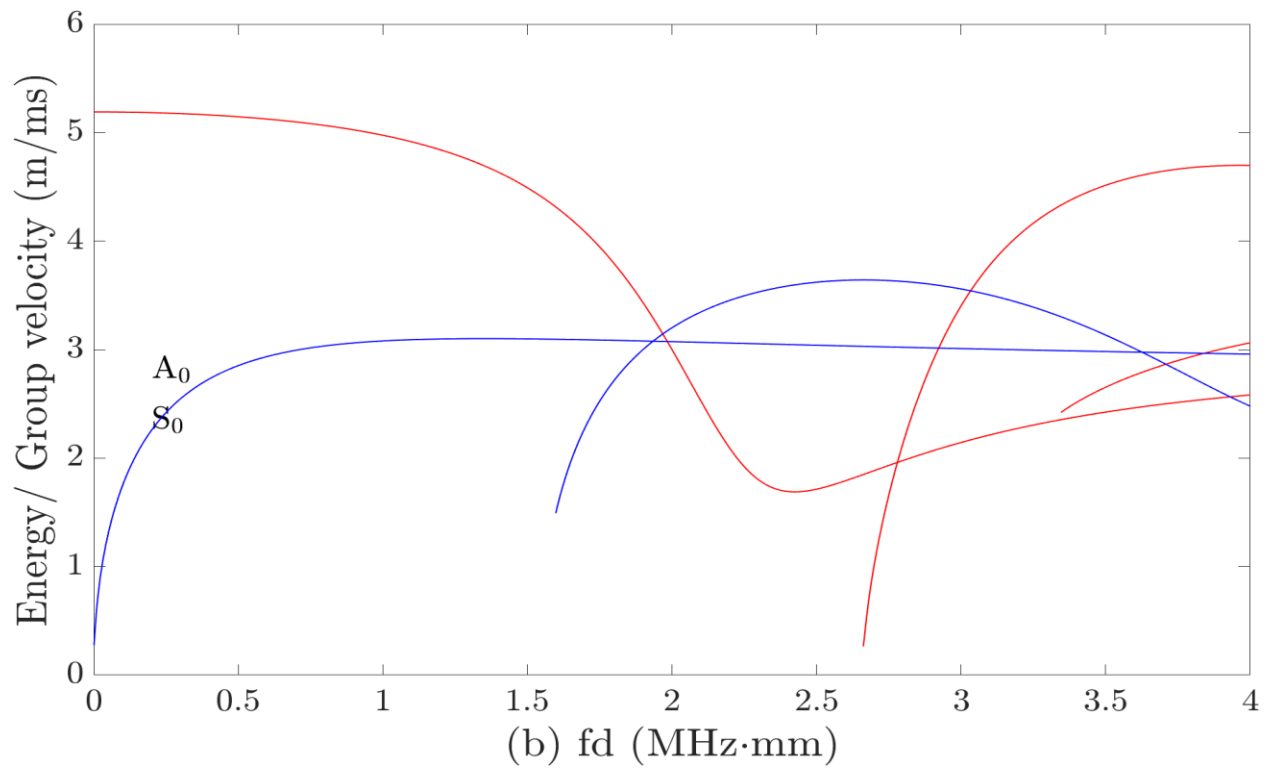
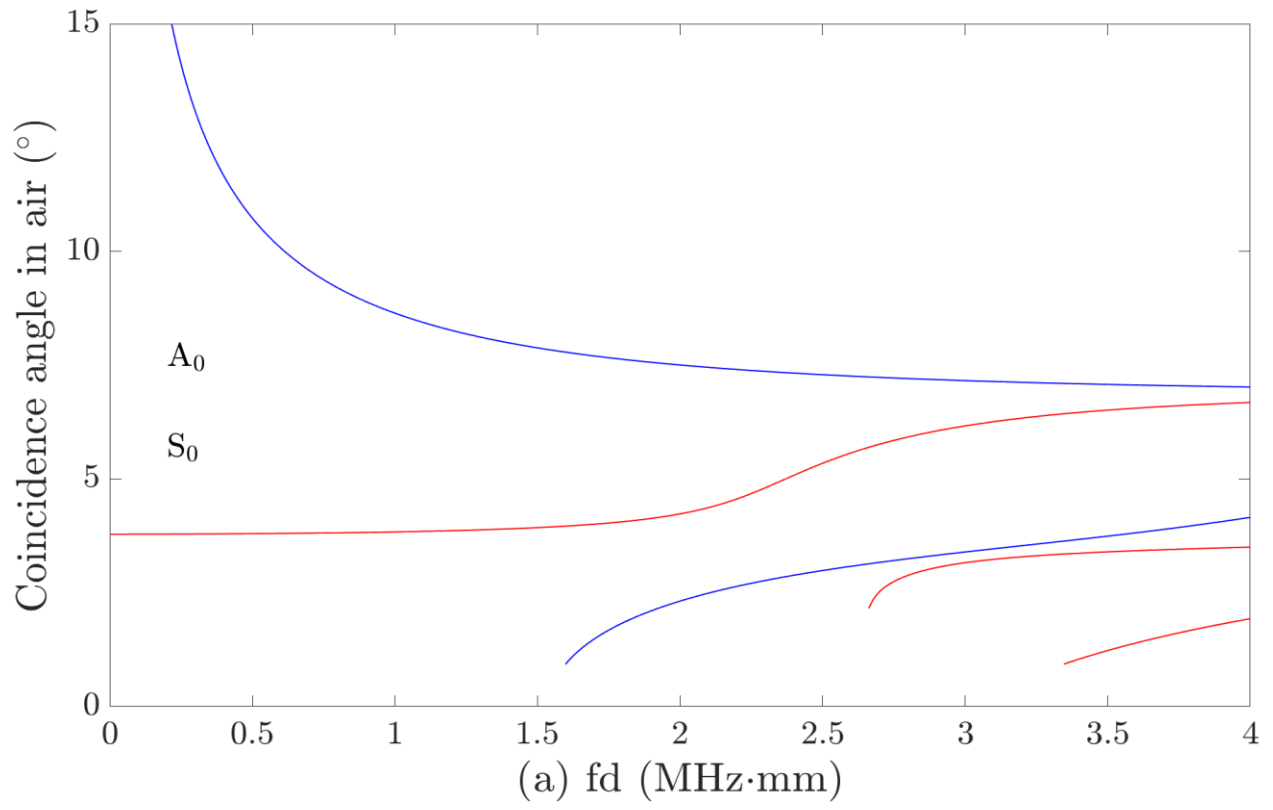
$$C_g = C_p^2 \left[C_p - (fd) \frac{dC_p}{d(fd)} \right]^{-1} \quad (4.8)$$

where fd represents the product of frequency and thickness. It is important to note that when the derivative of C_p with respect to fd equals zero, C_g equals C_p . Additionally, as the derivative of C_p with respect to fd approaches infinity (i.e., at the cutoff point), C_g approaches zero.

The turbine blade examined in this study is composed of Inconel 738 (IN738), with a thickness ranging from 10 to 20 mm. Figure 20 illustrates the theoretical dispersion curves for IN738, which were generated using the Dispersion Calculator (DC) [152]. The suitable range of incident angles for the 100kHz ACT to excite the A0 mode in the IN738 turbine blade, given the variation in thickness, is between 7.3 and 9 degrees as illustrated in Fig. 20.a. The phase velocity falls within the range of 2150 to 2690 m/s, while the group velocity lies between 3030 and 3100 m/s as illustrated in Fig. 20.b and Fig. 20.c respectively. According to the DC manual, Eq. (4.8) is inadequate for use in the DC for two main reasons. First, group velocity is meaningful only in non-dissipative systems, as attenuation from viscoelasticity or fluid-loading makes the wavenumber complex, rendering Eq. (4.7) invalid. In contrast, energy velocity remains applicable in both attenuated and non-attenuated scenarios, with group and energy velocity being equivalent in the latter. Second, Eq. (.7) provides only the group velocity in the wave propagation direction, whereas the DC focuses on calculating energy velocity. The energy velocity components ce_1 and ce_2 are derived from the ratios of power flow P_j to the total energy E_{tot} .

$$\vec{c}_e = \frac{1}{E_{tot}} \begin{bmatrix} P_1 \\ P_2 \\ 0 \end{bmatrix} = \begin{bmatrix} ce_1 \\ ce_2 \\ 0 \end{bmatrix} \quad (4.9)$$

$$c_e = |\vec{c}_e| = \sqrt{ce_1^2 + ce_2^2}. \quad (4.10)$$



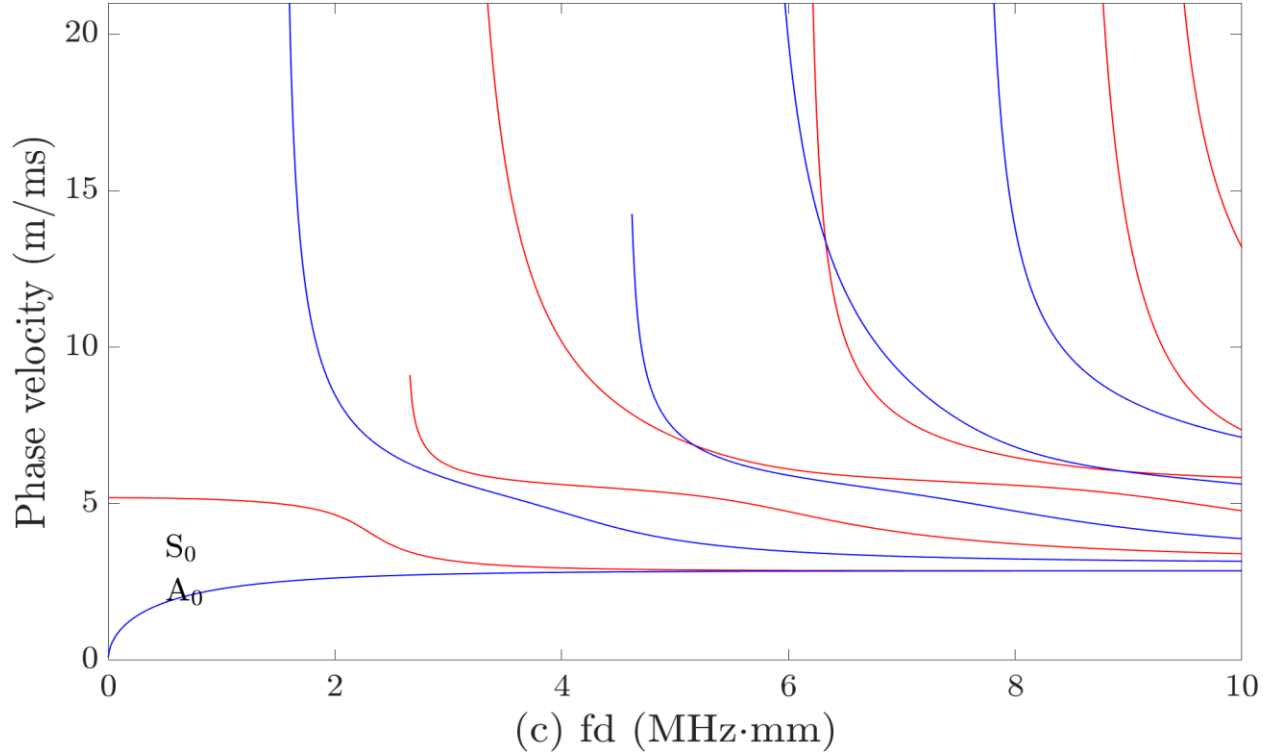


Fig. 20. Dispersion curves of an IN738 plate. (a) Incidence angle; (b) Group velocity ; (c) Phase velocity. The blue lines represent the antisymmetric modes and the red lines represent the symmetric modes.

4.5.2 LAMB Waves in Multiple Layers

A turbine blade with a TBC illustrates one of the many applications where guided waves in multilayered structures offer significant value. Additional uses encompass painted surfaces, layered aircraft components, diffusion or adhesive bonds, and detecting ice or contaminants across solid-fluid interfaces. In such media, Lamb waves interact with each layer's boundaries, forming complex wave modes that vary with layer properties and thickness. These waves' unique dispersion characteristics make them highly effective for detecting defects, assessing bond quality, and identifying delamination, especially in applications like TBCs on turbine blades, bonded composites, and multilayer aircraft coatings. The derivation of dispersion relations in multilayered structures uses various mathematical approaches, each designed to account for the specific structural characteristics and material properties of each layer. The thickness, density, and Lamé constants of each layer are represented by h^n , ρ^n , λ^n and μ^n , respectively. These methods enable detailed

analysis of wave propagation in complex layered configurations, allowing for precise predictions of dispersion behavior. According to Rose's book [151], two main methods for assembling boundary conditions are commonly used which are the global matrix and transfer matrix methods. These methods are essential for solving wave propagation problems in multilayered structures. The global matrix method constructs a single matrix applicable to any number of layers (elastic, viscoelastic, isotropic, or anisotropic), offering stability across a wide range of fd values, though it requires extracting roots from a large-order determinant, making it computationally intensive. The transfer matrix method, simplifies calculations by eliminating unknowns from intermediate layers, focusing only on external boundary conditions through matrix multiplication. However, at high fd values, where upper layers have minimal effect on lower layers, the method can become ill-conditioned, causing numerical instability. Different researchers have applied a variety of methods to derive dispersion relations in multilayered structures. Huang et al. [153] employed the Stroh formalism to derive dispersion relations for film bulk acoustic resonators, which consist of layered elastic electrodes on the top and bottom and a central piezoelectric layer. This approach systematically links the variables at the top and bottom of each layer, enabling comprehensive analysis. Moreover, the dual variable and position method complements this approach by efficiently combining basic cases for various layer configurations, facilitating the automated derivation of dispersion relations in complex structures like film bulk acoustic resonators. Gao and Zhang [154] employed the precise integration method (PIM) and the Wittrick–Williams algorithm to compute dispersion relations in layered media. By transforming the problem into a standard eigenvalue format, these methods improved numerical stability and accuracy. Additionally, Asif et al. [155] used variational methods to examine the effects of factors such as interface imperfections and foundation characteristics on dispersion relations. This approach provided valuable insights into the behavior of elastic waves within multilayered structures, particularly under long-wave, low-frequency conditions.

The DC calculator [152] is employed to examine how thermal barrier coatings impact wave propagation. As discussed in section 2.1, TBCs typically consist of multiple layers, a bond coat for adhesion (MCrAlY,

where M denotes either nickel, cobalt, or a combination of both) and a ceramic thermal barrier layer, commonly composed of $\text{ZrO}_2\text{-Y}_2\text{O}_3$ (7-8 wt%) for insulation. TBCs significantly influence the amplitude and frequency of wave propagation due to their unique material properties and structural characteristics [156]. The interaction between ultrasonic waves and TBCs can be understood through various factors, including porosity, mechanical behavior, and temperature gradients. Zhang et al. [157] found that TBCs show a linear relationship between porosity and longitudinal wave velocity, with higher porosity leading to a decrease in wave velocity. The morphology and distribution of pores within the coating play a crucial role, influencing the ultrasonic reflection coefficient and thereby affecting the amplitude of reflected waves. According to Tassini et al. [158], the mechanical properties of TBCs, particularly yttria-stabilized zirconia, display amplitude-dependent behavior that enhances their damping characteristics. This damping effect can modify the amplitude of wave propagation, thereby making TBCs effective in diminishing vibrational energy transmission in turbine applications. In a non-symmetric laminate like thermal barrier coatings (TBCs), wave modes lack a distinct symmetric or antisymmetric character, particularly when the layers exhibit significantly different material properties and, consequently, varying wave speeds. As a result, these modes are designated using the symbol B, as suggested by The Dispersion Calculator [152], instead of classifying them as either symmetric (S) or antisymmetric (A).

A standard TBC, as described in [15], is utilized to obtain the dispersion curves and through thickness displacement profiles in order to examine the influence of TBCs on wave propagation. The material properties of TBC four layers considered in this study are listed in Table 3. Figure 21 presents a comparison of group velocity curves for various wave modes in Inconel 738, both with and without a TBC. The solid lines represent the group velocities for pure Inconel 738, while the dashed lines show the behavior when a TBC is applied. With the addition of TBC, the wave modes in pure Inconel undergo a transformation, the A0 and S0 modes shift to B0 and B1 modes, respectively, while the A1 and S1 modes transform into B2 and B3 modes. Notably, the B0 mode with TBC does not converge towards the Rayleigh wave speed at high frequency-thickness products, as the A0 mode does in pure Inconel. Additionally, the prominent peaks

observed in the $A1$ (now $B2$) and $S1$ (now $B3$) modes are significantly diminished with TBC application, indicating that these modes will likely be less distinguishable in the time domain for the coated material. Overall, the TBC layer alters the group velocity characteristics of Inconel 738 by changing mode behaviors and reducing the prominence of certain wave modes at higher frequencies. As noted in [159], the presence of a coating or an increase in its thickness leads to a reduction in phase velocity. This phenomenon can be attributed to a decrease in the equivalent stiffness of the material, which subsequently lowers the equivalent longitudinal and transverse wave velocities. Furthermore, it is highlighted that the $A0$ mode with the presence of TBC exhibits greater dispersion compared to the $S0$ mode, aligning with the findings from Fig. 21. Mehrabi et al. [160] found experimentally that the addition of a coating results in a slight delay in the signal's arrival and a decrease in amplitude relative to the coating's thickness. This is due to the viscoelastic properties of the coating, which lead to the dissipation of energy from the Lamb waves as they propagate. This energy leakage into the coating reduces the amplitude of the received signal, demonstrating the significant impact of such coatings on signal attenuation. Figure 22 shows through-thickness displacement profiles for five modes at frequency-thickness values corresponding to maximum energy velocity. At low frequency-thickness values, modes $B0$ and $B1$ resemble the single-material modes $A0$ and $S0$, with $B0$ exhibiting strong out-of-plane motion (Fig. 22a) and $B1$ showing in-plane motion (Fig. 22b). For higher modes, particularly $B2$, the YSZ top coat displays significant through-thickness displacement (Fig. 22c), due to its lower Young's modulus compared to other TBC materials. This increases the modes' sensitivity to TBC surface defects. Higher-order modes like $B5$, $B7$, and $B9$, although advantageous for selective excitation, show less displacement and are thus less sensitive to defects, resulting in lower signal amplitudes.

Table 3. Material properties of TBC four layers

Layer	Thickness (mm)	Material	Young's Modulus (GPa)	Density ($\frac{kg}{m^3}$)	Poisson's ratio
Ceramic Top-Coat	0.3	$ZrO_2 - 8\ wt\% Y_2O_3(8YSZ)$	48	6000	0.1
Thermally Grown Oxide (TGO)	0.01	$\alpha - Al_2O_3$	380	3980	0.23
Bond-Coat	0.1	NiCrAlY	200	7500	0.3
Substrate	1	Inconel 738	200	8110	0.29

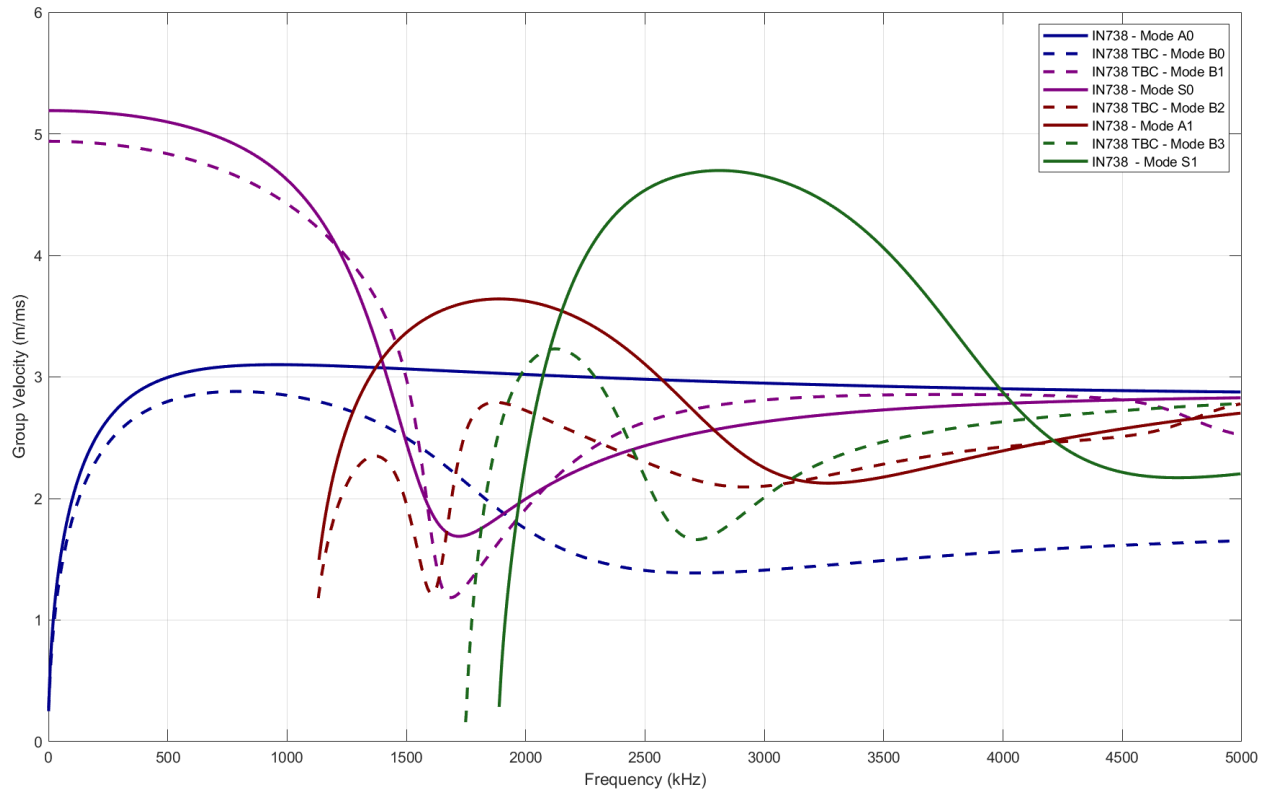
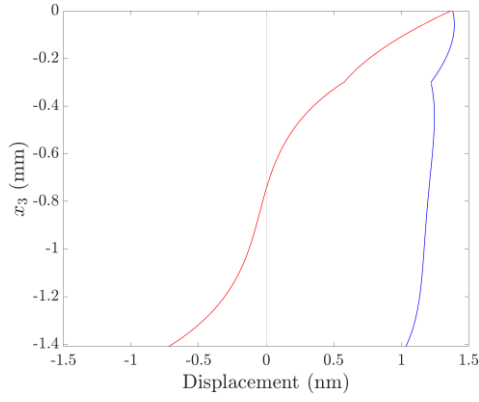
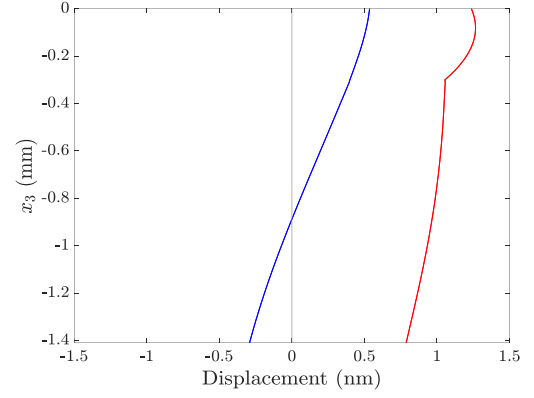


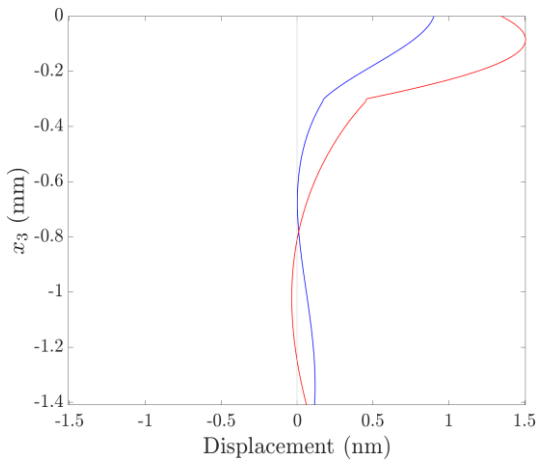
Fig. 21. Effect of Thermal Barrier Coating on Group Velocity of Guided Wave Modes in Inconel 738. Dashed lines represent the curves with TBC applied, Solid lines represent pure Inconel 738 at the same thickness. 1.41 thickness



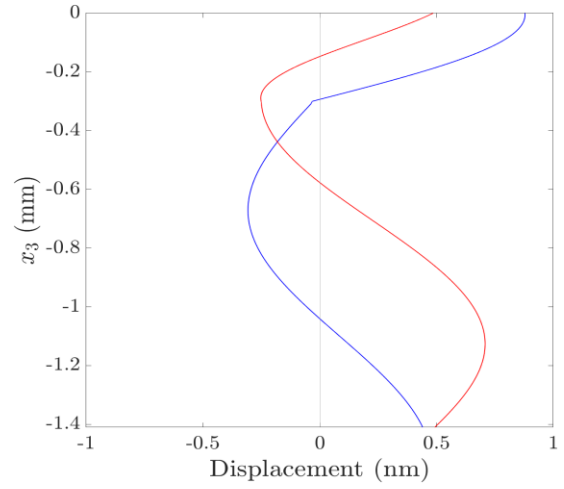
B0 Displacement – 1 MHz.



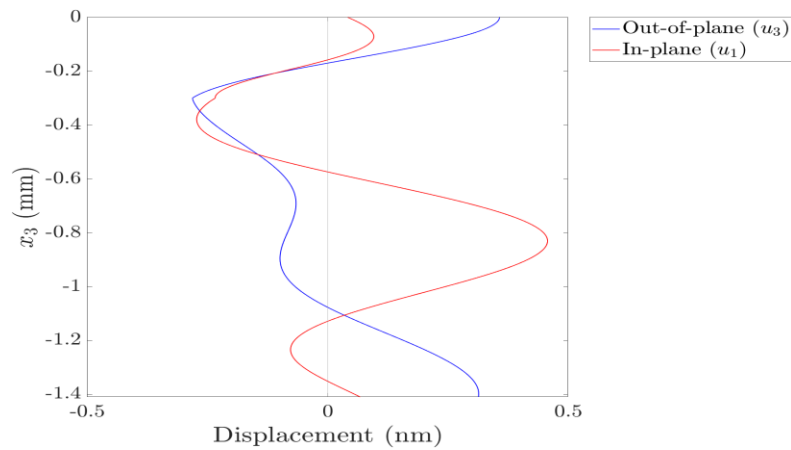
(b) B1 Displacement – 1 MHz.



(c) B2 Displacement – 2.4 MHz.



(d) B3 Displacement – 2.4 MHz.



(e) B5 Displacement – 4.4 MHz.

Fig. 22. Through thickness displacement profiles for Inconel 738 with TBC.

CHAPTER 5

EXPERIMENTAL INVESTIGATION OF DEFECT IDENTIFICATION USING AIR-COUPLED GUIDED WAVES

5.1 Experimental Setup

The experimental setup, illustrated in Fig. 23, involves testing several gas turbine blades made of Nickel-based superalloys specifically, Inconel 738, Rene-80 and 247 LC, with and without TBC coating, as shown in Fig. 24. For testing, an air-coupled transducer (ACT) system with two high-performance, circular piezocomposite ultrasonic transducers (Ultrason ACT NCG100-D25) were used in a pitch-catch mode. These transducers have a nominal frequency of 100 kHz and an active area of 25 mm. The ACT excitation is provided by a RITEC RPR-4000 pulser-receiver. To minimize reflections from high transducer impedance, the RT-150 termination is placed between the RPR-4000 output and the transmitter input, ensuring a stable toneburst shape. The air-coupled receiver was connected to a RITEC RSP-50K-1M-60DB pre-amplifier. The processed output from the system was captured using a KEYSIGHT EXR054A digital oscilloscope.

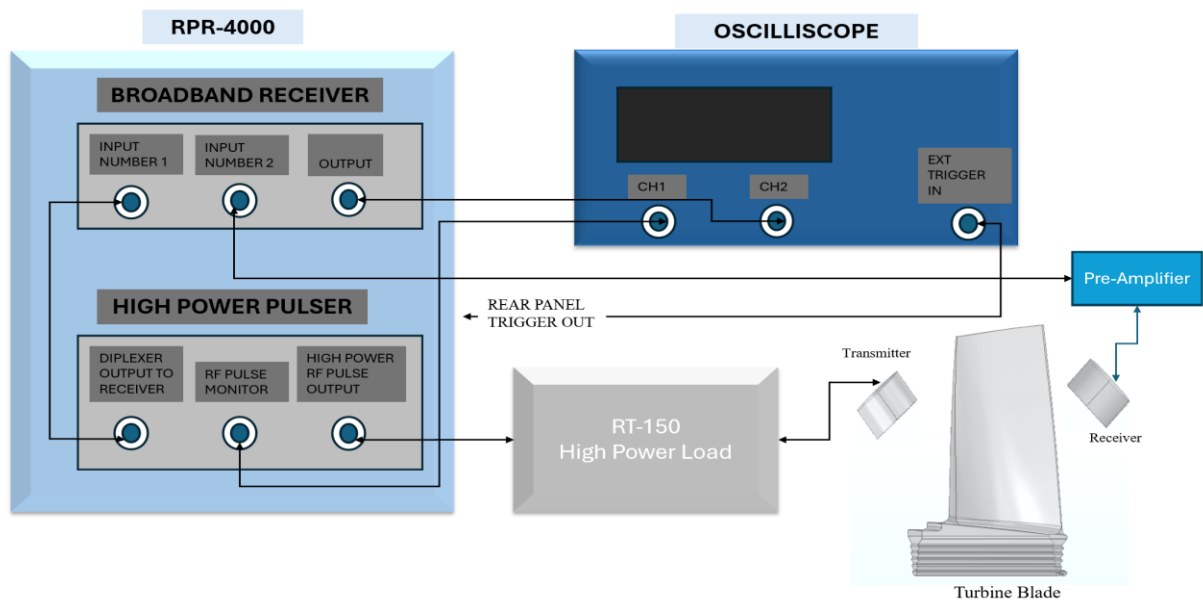


Fig. 23. Experimental Setup Diagram.

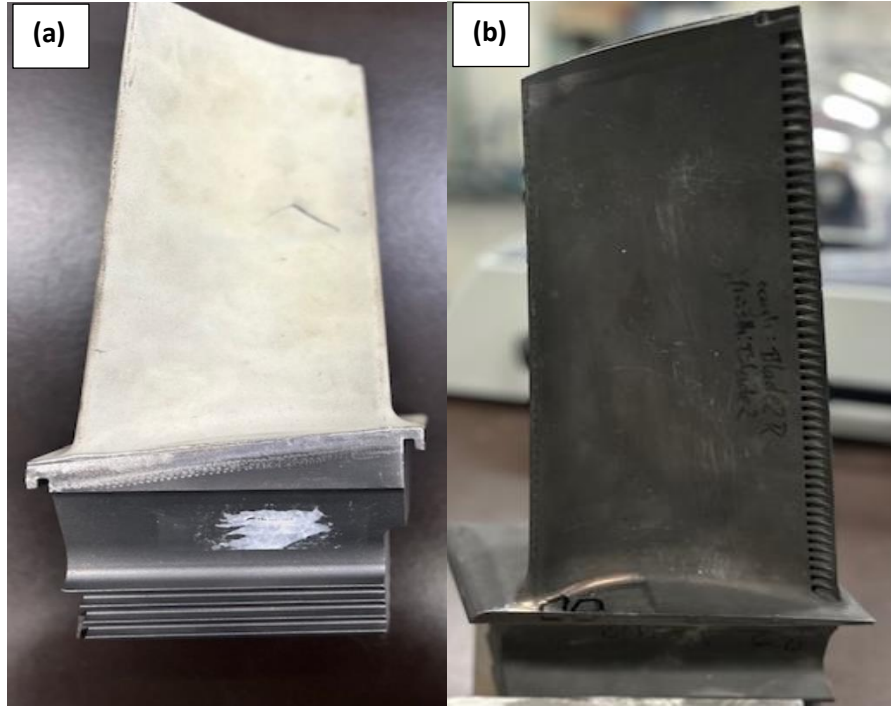


Fig. 24. Gas Turbine Blades, TBC Coated (a) and without TBC (b).

5.2 Incident angle optimization

The purpose of this initial experimental investigation is to accurately determine the ideal orientation angle for the ACT to produce a pure A0 Lamb wave mode within the 80–120 kHz frequency range of the transmitting transducer.

In the slanted transmission setup, the acoustic energy transmitted at a given incident angle θ is dependent on the phase velocity in both the sample (C_p) and the surrounding air (C_{air}). However, due to the geometric complexity of components like the turbine blade analyzed in this study, calculating the exact angle θ analytically is challenging. Consequently, as in the work of Dyrwal [132], the optimal angle θ was identified experimentally by iteratively adjusting the angle to achieve the maximum signal-to-noise ratio (SNR).

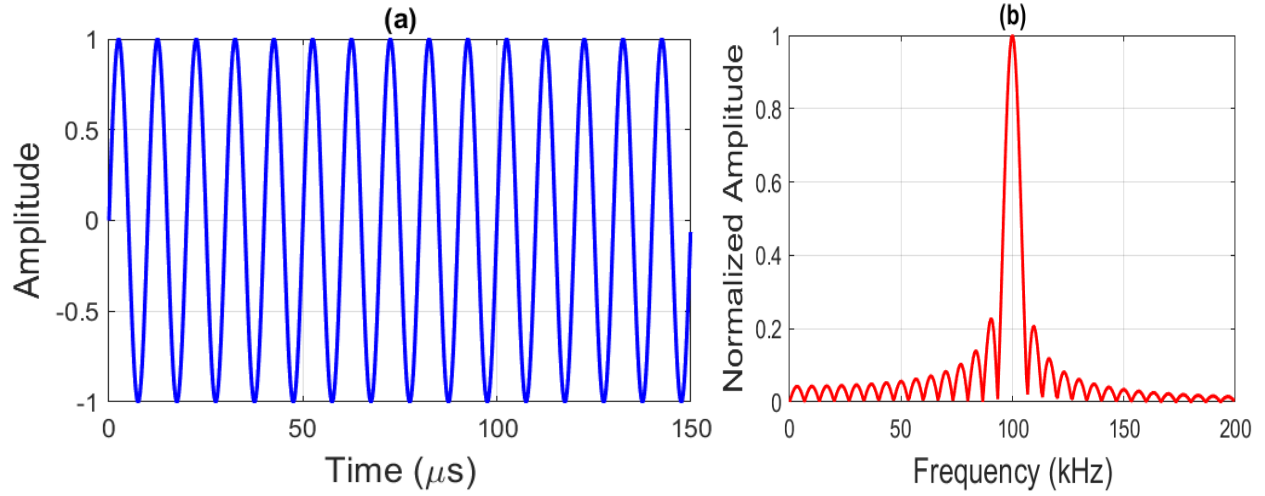


Fig. 25 (a) fifteen-cycles toneburst input signal with a center frequency of 100 kHz and (b) its frequency spectrum presented

The transmitter and receiver were positioned 20 mm away from the blade surface and 100 mm apart. The experiment began with an incident angle of 0° , where the transducer's face was positioned perpendicular to the blade surface. Using the internal signal synthesizer of the RPR-4000, the ACT transmitter was excited with a fifteen-cycle toneburst signal at a center frequency (f_c) of 100 kHz shown in Fig. 25, and the signal was received by the ACT receiver. To find the optimal orientation, the transducer angle was increased in 1° increments from 0° to 20° , and signals were recorded at each step. This initial angular scan, from 0° to 20° , was conducted with an excitation amplitude of 200 Vpp. For subsequent scans, the amplitude was raised to 300 Vpp and 400 Vpp, enabling a comparative assessment of SNR at each amplitude and angle. The optimal angle θ was determined by identifying the angle that produced the highest signal-to-noise ratio (SNR), defined by Eq. (5.1):

$$SNR = 20 \log_{10} \left(\frac{V_{signal}}{V_{noise}} \right) \quad (5.1)$$

where V_{signal} is the absolute peak amplitude of the signal region, and V_{noise} is the standard deviation of the noise. This SNR criterion was employed to select the angle that maximized signal clarity. The plot in Fig. 26 shows the SNR as it varies with the angle of incidence. For each excitation amplitude level (200, 300, and 400 Vpp), the angle of incidence that yields the peak amplitude for the generated A0 mode is

recorded, and these values are used to create an incident angle curve. In this case, Fig. 26 reveals that the optimal SNR is achieved at an incident angle of $\theta = 10^\circ$ across the different excitation amplitudes.

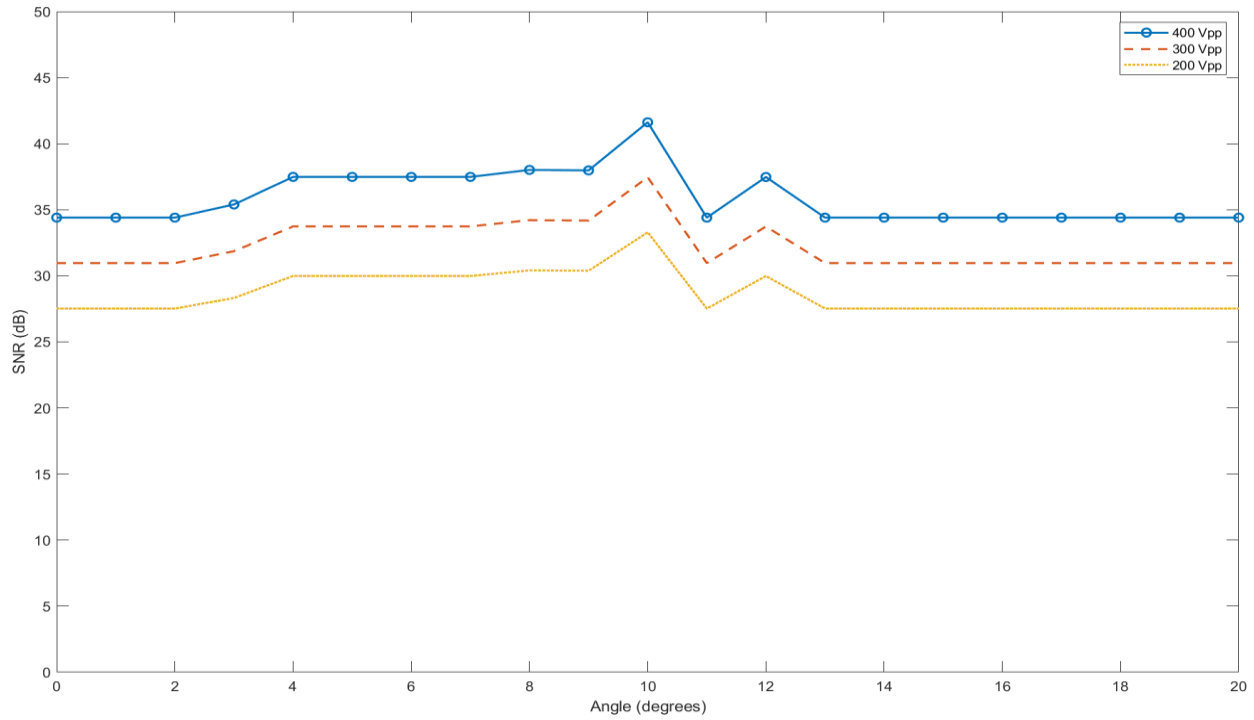


Fig. 26. Optimal Incident Angle for Maximum SNR at Varying Excitation Amplitudes (200 Vpp, 300 Vpp and 400 Vpp).

5.3 Testing Blades with and without TBC

TBC removal is a common failure mode observed in gas turbine blades, as extensively documented in the literature. Therefore, understanding the behavior of guided waves in the presence of TBC, as well as in scenarios where TBC has been removed, is crucial. This knowledge aids in assessing the integrity of the blade, detecting early-stage damage, and evaluating the impact of TBC failure on wave propagation characteristics. The ACT system, as previously detailed, is utilized to assess the impact of TBC on two different gas turbine blade designs. The first pair of blades is constructed from IN738, while the second pair is made from Alloy 247 LC. The experimental setup, depicted in Fig. 27, positions the ACT at a 10° angle and the receiver at -10° , as found through experimentation to yield the highest amplitude for the A0 mode of interest. The receiver is directly connected to an oscilloscope for signal analysis. The transmitter-

receiver separation, measured from the front membrane to the inspected blade, is fixed at approximately 20 mm. The blade under inspection is placed vertically on a specialized mounting fixture. Following the same excitation reported in section 5.2, a fifteen-cycle toneburst signal with a center frequency (f_c) of 100 kHz was used to excite the ACT transmitter, utilizing the internal signal synthesizer of the RPR-4000.

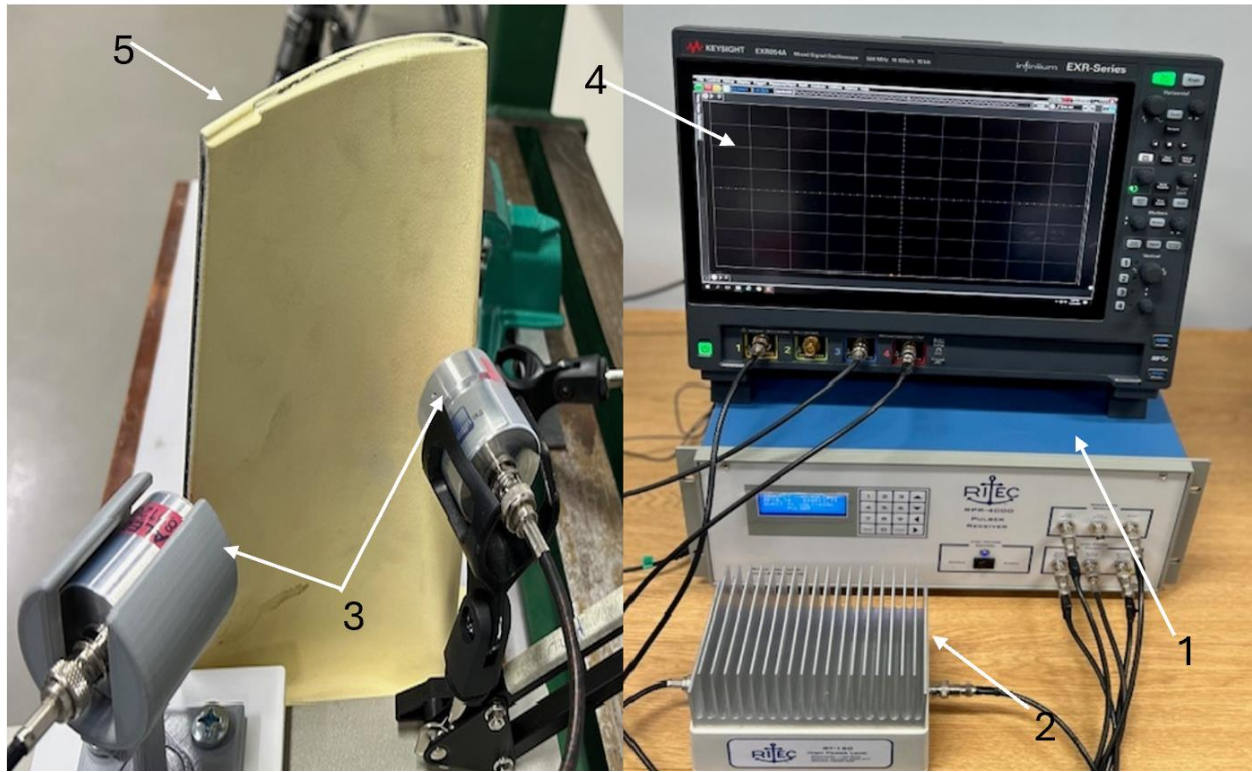


Fig. 27. Actual Experimental Setup: (1) RPR-Pulser-Receiver, (2) Ritec RT-150, (3) Ultrasonic ACTs, (4) EXR054A Oscilloscope and (5) Gas Turbine Blade.

The initial test was performed on two gas turbine blades made of IN738, one with TBC coating and the other without as shown in figure 28. The airfoil is approximately 200 mm in length and 100 mm in width. This model of blade is used in a gas turbine which may provide up to 80 MW power. Another test was performed on two gas turbine blades made of Alloy 247 LC, one with TBC coating and the other without as shown in Fig. 29. The Airfoil is approximately 250 mm in length and 120 mm in width. This model of blade is used in a gas turbine that provides up to 260 MW power.



Fig. 28. IN738 base metal - Gas turbine blades.



Fig. 29. Alloy 247LC base metal - Gas turbine blades.

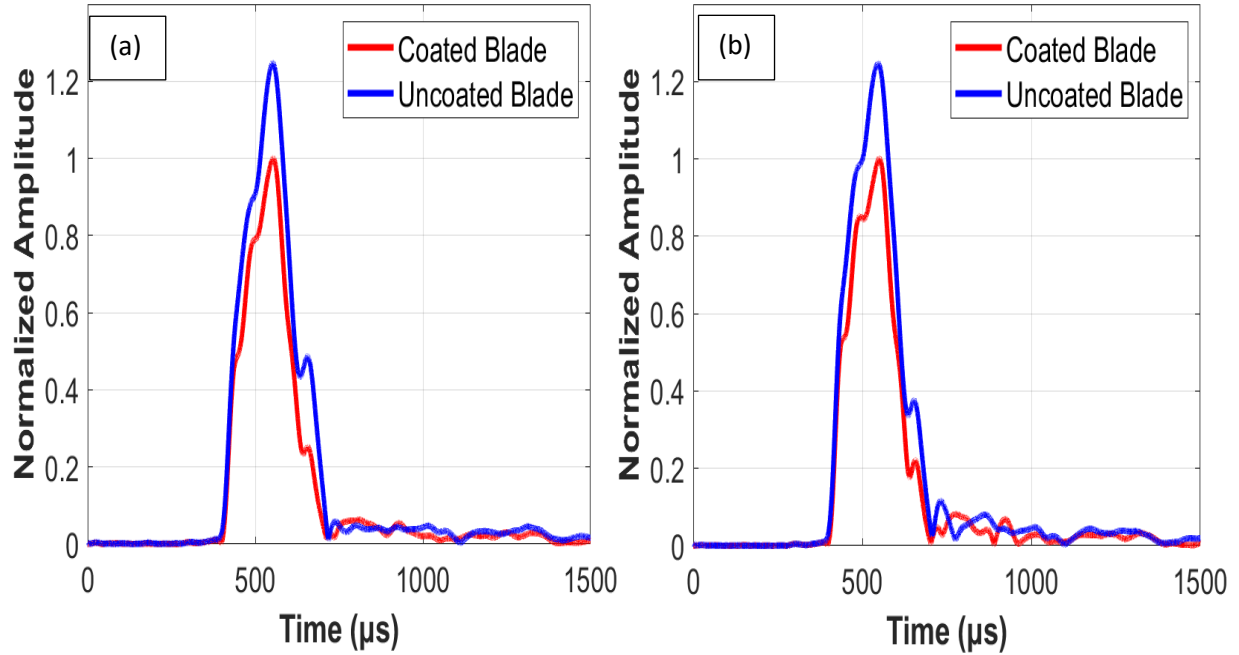


Fig. 30. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Coated blade-IN738 base metal- obtained experimentally at two excitation amplitude. (a) 200 Vpp and (b) 400 Vpp.

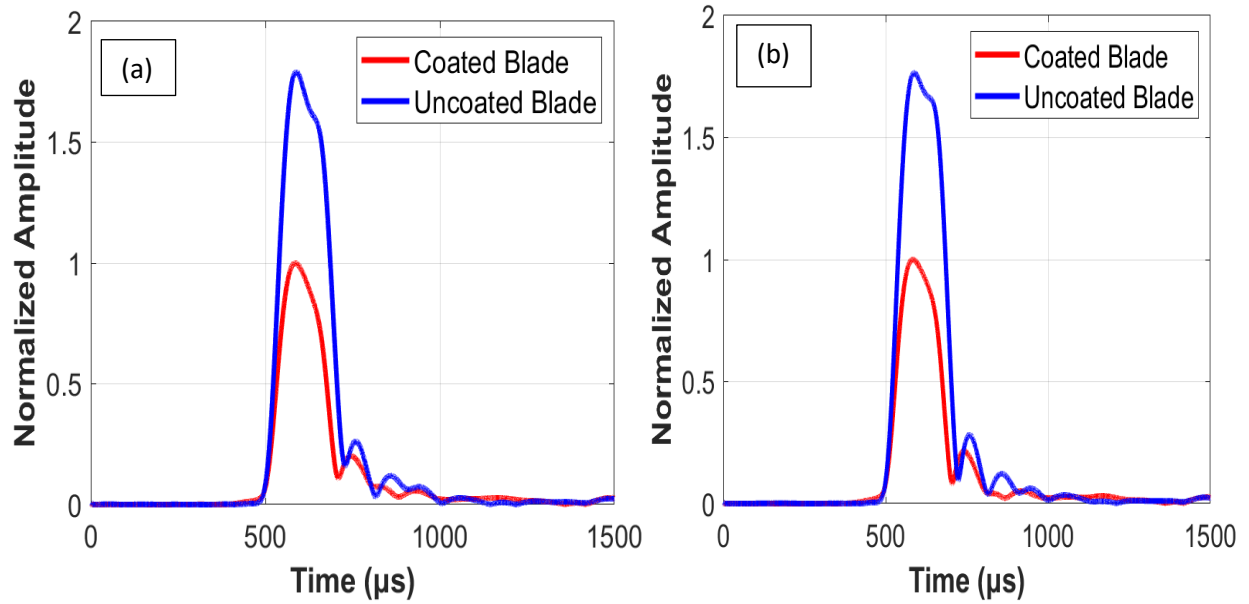


Fig. 31. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Coated blade-Alloy 247LC base metal- obtained experimentally at two excitation amplitude. (a) 200 Vpp and (b) 400 Vpp.

5.3.1 Discussion and results

Figures 30 and 31 (a) and (b) present the filtered Hilbert-transformed waveforms corresponding to excitation levels of 200 Vpp and 400 Vpp at a center frequency of 100 kHz, applied to a turbine blade with

and without a thermal barrier coating (TBC). Normalizing these waveforms relative to the coated blade provides a clearer insight into the underlying wave propagation phenomena. A bandpass-filtered frequency range of 80–120 kHz, chosen to center around the air-coupled transducer's operating frequency of 100 kHz.

The behaviour of Lamb waves within the turbine blade is influenced by factors such as acoustic impedance, waveguide geometry, and material properties, with viscoelastic effects playing a particularly critical role. The addition of the TBC and increased propagation distances result in increased energy absorption by the coating, which manifests as reduced wave amplitudes and a slight delay in signal arrival times, consistent with established findings in the literature [159,160]. Moreover, The general trend of amplitude reduction remains consistent across both cases (200 Vpp and 400 Vpp), suggesting that the primary influence of the TBC stems from its material properties rather than the excitation amplitude. The results indicate that the TBC layer further contributes to attenuation and scattering of the guided waves, leading to a decrease in the received signal amplitude. Additionally, the TBC modifies the wave mode characteristics, potentially reducing the efficiency of energy coupling into specific modes that are most effective at propagating through the substrate. This combination of attenuation, scattering, and altered wave mode characteristics collectively leads to a substantially weaker signal in air-coupled experiments conducted on TBC-coated turbine blades.

For further analysis, all the normalized received signals are plotted to extract the TOA of each received signal in relation to the excitation-normalized toneburst. The data reveal that the presence of the coating leads to a slight delay in the TOA of the signal, with the delay reaching up to approximately 27 μ s when compared to the TOA in the uncoated condition as shown in table 4. This observed delay can be attributed to the effects of the coating on wave propagation. Specifically, literature findings indicate that the presence of a coating, or an increase in its thickness, can reduce the phase velocity of the propagating waves. This reduction in phase velocity results in a slower propagation of the wave through the material, causing a slight delay in the signal's arrival time. The consistency of this observation with previously reported results further

confirms that the coating plays a significant role in modifying wave propagation characteristics, impacting both the amplitude and timing of the received signals.

Table 4. Time of Arrival (μ s)-TBC Effects

Blade Type	TBC	TOA @200 Vpp	TOA @400 Vpp	Time delay @200 Vpp	Time delay @400 Vpp
IN738 Base Metal	Yes	544.3	541.8	1.5 μ s	3.2 μ s
	No	542.8	538.6		
Alloy 247LC Base Metal	Yes	577.8	575.3	25.8 μ s	26.8 μ s
	No	552	548.5		

5.4 Testing Blade with FOD (Material Loss)

Cracks induced by foreign object damage (FOD) represent a prevalent failure mode in gas turbine blades, highlighting the importance of evaluating the sensitivity of air-coupled guided waves to such defects. Two turbine blades with identical design and material properties were tested: one featuring FOD damage and another in pristine condition, as shown in Fig. 32. The observed crack was approximately 1 mm wide and 4 mm long. Following the same experiment setup reported in the previous section. A transmitter-receiver pair, spaced 100 mm apart and positioned 20 mm from the blade surface at angles of $\pm 10^\circ$, was used to excite the A0 mode. The blades were mounted vertically on a specialized fixture mount. The transmitter was excited by a fifteen-cycle toneburst signal with a center frequency (f_c) of 100 kHz generated by the internal signal synthesizer of the RPR-4000.



Fig. 32. Healthy and Cracked -IN738 base metal - Gas turbine blades.

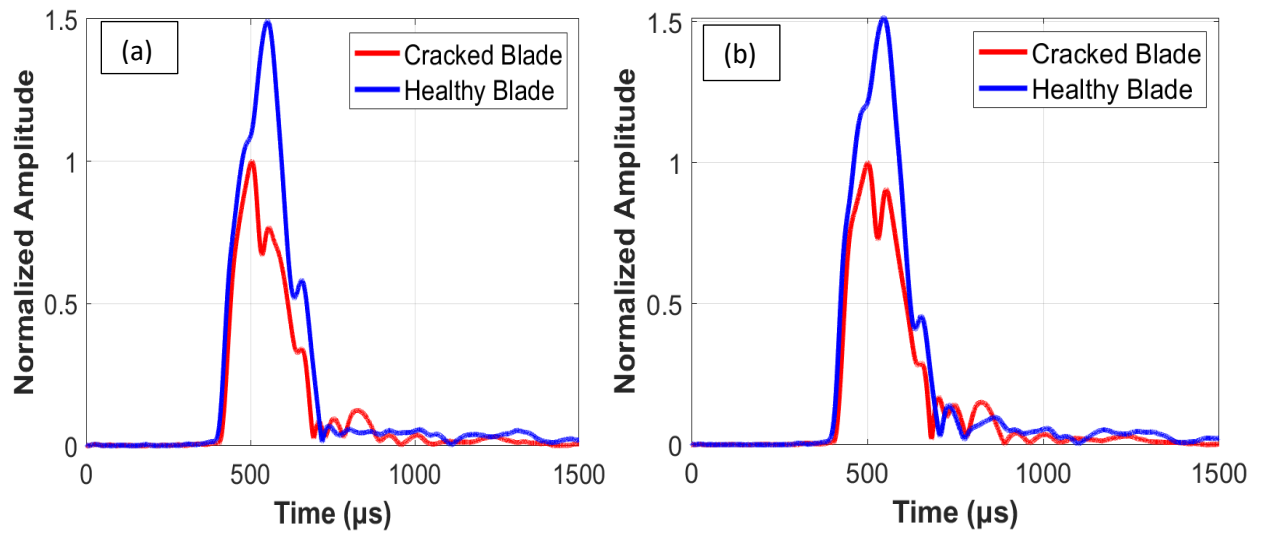


Fig. 33. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Cracked blade obtained experimentally at two excitation amplitude. (a) 200 Vpp and (b) 400 Vpp.

5.4.1 Discussion and results

The normalized Hilbert waveforms with a bandpass-filtered envelope, shown in Fig. 33, provide a clear visualization of how the presence of a crack impacts guided wave propagation, in which the normalization is relative to the cracked blade's peak amplitude. The results indicate that the peak amplitude resulted from the first direct arrival signal of the healthy blade is noticeably higher than that of the cracked blade, this reduction highlights the energy dissipation caused by the defect, aligning with findings in the literature that suggest a partial loss of the turbine blade reduces the reflective area, leading to decreased signal amplitude [75,136,139]. It is important to note that when Lamb waves traverse regions of varying thickness, both reflected and transmitted waves are generated. These waves may experience multiple interactions, including repeated reflections and transmissions between sections with differing thicknesses. Since the exact reflection and transmission coefficients are generally unknown, the resulting signal is a complex composition. It includes the direct arrival of waves, scattering signals caused by damage, mode-converted components, and edge-reflected signals. Notably, the damage-induced scattering signal appears as the second dominant wave mode [161]. This observation aligns with the analysis in Fig. 33, where multiple modes are visible, with the second dominant peak being more pronounced in the case of a crack compared to the waveform from an undamaged blade. The overall waveform trends remain unchanged despite increasing the excitation voltage from 200 Vpp to 400 Vpp, but the higher voltage amplifies the second dominant wave mode. While the normalized amplitude in both conditions remains proportional, the energy dissipation in the cracked blade appears more evident at higher excitation levels due to greater wave interaction with the defect. Additionally, the cracked blade exhibits a longer post-peak tail and increased oscillations, which can be attributed to wave scattering and reflections generated by the crack, effects that are minimal in the healthy blade. These post-peak features further highlight the disruptive influence of the crack on wave propagation.

This analysis focuses on a bandpass-filtered frequency range of 80–120 kHz, chosen to center around the ACT operating frequency of 100 kHz. By isolating this range, the analysis ensures that the most relevant

frequency components for defect detection are emphasized, as this range effectively balances wavelength sensitivity and spatial resolution for turbine blade diagnostics. Within this range, the energy distribution for the cracked blade shows a noticeable reduction, underscoring the impact of the defect.

By normalizing relative to the cracked blade's peak amplitude, the comparison further emphasizes the extent of energy loss caused by the defect. The observed amplitude differences, and post-peak oscillatory behavior collectively demonstrate the utility of guided wave analysis for damage detection and structural health monitoring in critical applications like turbine blades.

5.5 Time-Frequency Analysis

While the A-Scan analysis discussed earlier offers a fundamental approach to interpreting signal characteristics in the time domain, the utilization of a time-frequency representation (TFR) provides a more advanced and comprehensive tool by transforming a one-dimensional time-domain signal into a two-dimensional function of time and frequency, TFR enables a detailed characterization of time-frequency information, offering enhanced insight into signal behavior [162]. The Short-Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT), and S-Transform (ST) are prominent methods for analyzing non-stationary signals, each with distinct advantages and limitations. Their comparative effectiveness hinges on their time-frequency resolution capabilities and adaptability to signal characteristics. STFT analyzes signals by performing multiple Fourier transforms over specific time intervals, generating a spectrogram that illustrates the temporal evolution of frequency components. However, its fixed time-frequency resolution, governed by the Heisenberg uncertainty principle, limits its effectiveness for signals with rapidly changing dynamics, making it more suitable for those with relatively stable frequency content [163,164]. On the other hand, CWT provides variable time-frequency resolution, allowing for detailed localization of transient features by adjusting the resolution based on the frequency being analyzed. This flexibility makes it particularly useful for signals with fluctuating frequency content [165]. The ST further improves upon both STFT and CWT by incorporating a differential frequency window, which enhances energy localization and is especially effective for capturing abrupt amplitude

variations in noisy environments. Research shows that the ST often surpasses both STFT and CWT in energy localization and robustness to noise [166]. While STFT is efficient and straightforward to implement, its inability to handle highly non-stationary signals highlights the advantages of CWT and ST for analyzing complex and transient behaviors. Therefore, selecting the most suitable method depends on the specific characteristics of the signal and the required level of analysis detail. The application of STFT, CWT, and ST in fault detection has gained significant attention due to their effectiveness in analyzing nonstationary signals. STFT was particularly utilized in wind turbines and industrial applications [167], while ST was effectively utilized for detecting faults in mechanical systems, such as bearings [168,169], engine fault diagnosis [170] and in power distribution system and voltage source converters [171], [172]. Han et al. [173] introduced a comprehensive methodology for signal processing and imaging that leverages TFRs such as STFT, CWT, and S-Transform to analyze ultrasonic A-scan signals obtained from ACT system with non-stationary and dynamic characteristics. The approach involves extracting key features from the TFR, including feature time (t_0), feature frequency (F_c), energy-frequency curves (EFC), energy-time curves (ETC), and direct maximum ridge energy distribution curves (DMR-EDC), which collectively capture the transient and dynamic nature of the signals. Using a simulated Gaussian-modulated ultrasonic signal, the study demonstrated how these features effectively mitigate noise, preserve signal details, and enhance the accuracy and stability of signal analysis. These extracted features are then utilized to improve the quality and efficiency of imaging, offering a robust framework for ultrasonic signal interpretation and analysis.

In this study, we adopt the aforementioned approach, employing TFRs such as STFT, CWT, and S-Transform to analyze ultrasonic A-scan signals and extract key features, including EFC, ETC, and DMR-EDC. These features are used to compare the energy differences, as well as signal amplitude between coated, uncoated, healthy and cracked blades. This method facilitates the characterization of time-varying and frequency-dependent signal attributes, enabling enhanced analysis and understanding of the underlying phenomena. Fig. 34 (a) and (b) show the raw signals received from the A-Scan ACT testing. It is clear that,

although there are amplitude differences between the two signals, the raw signal is affected by noise interference. This interference complicates the identification of key differences between the signals and may result in some features being overlooked.

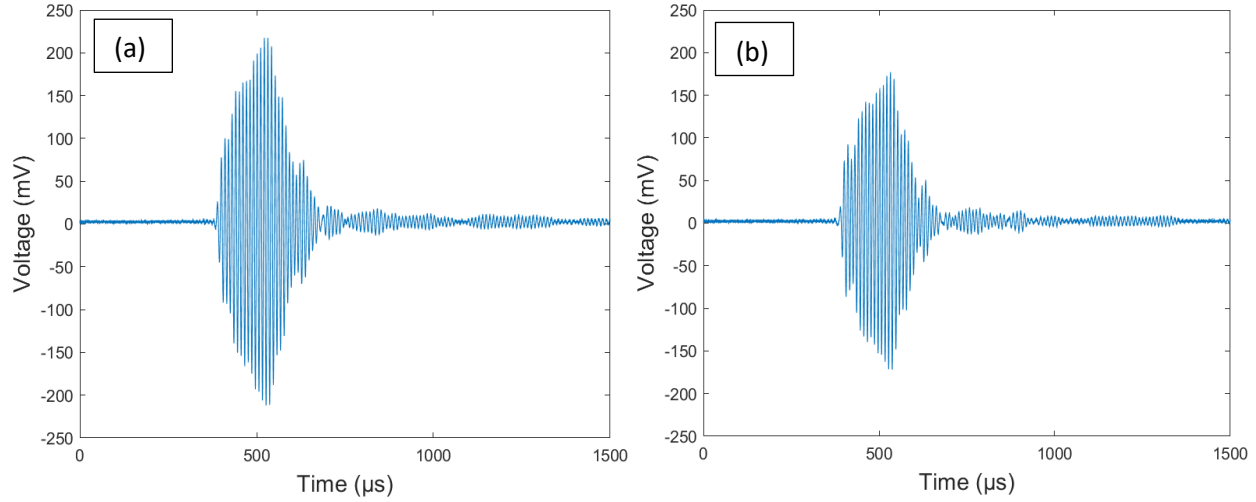
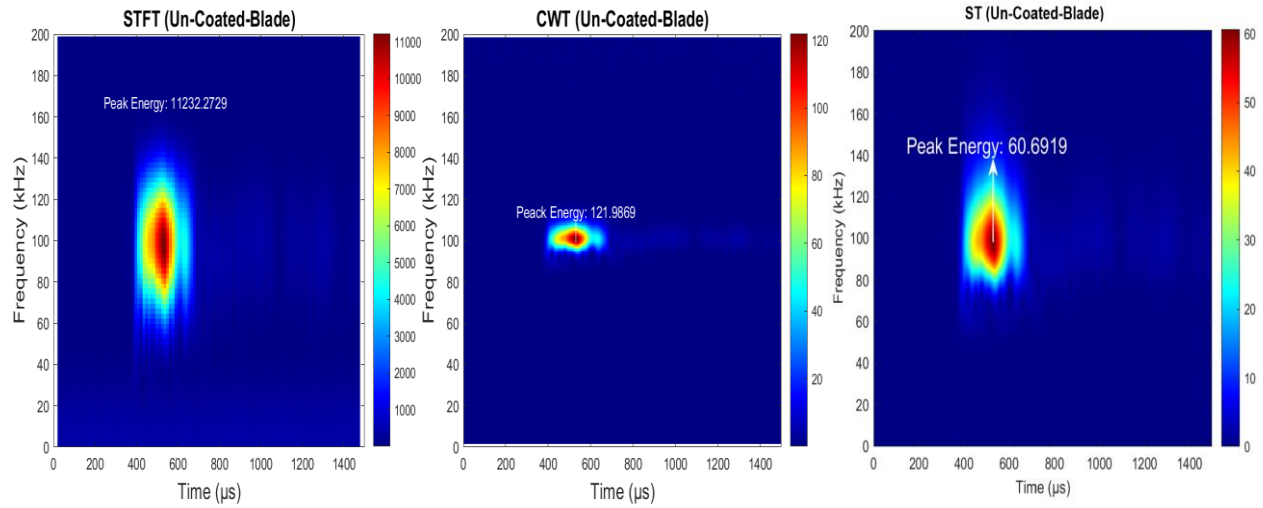


Fig. 34. Raw A-Scan Signals, TBC-Free (a) and with TBC (b)

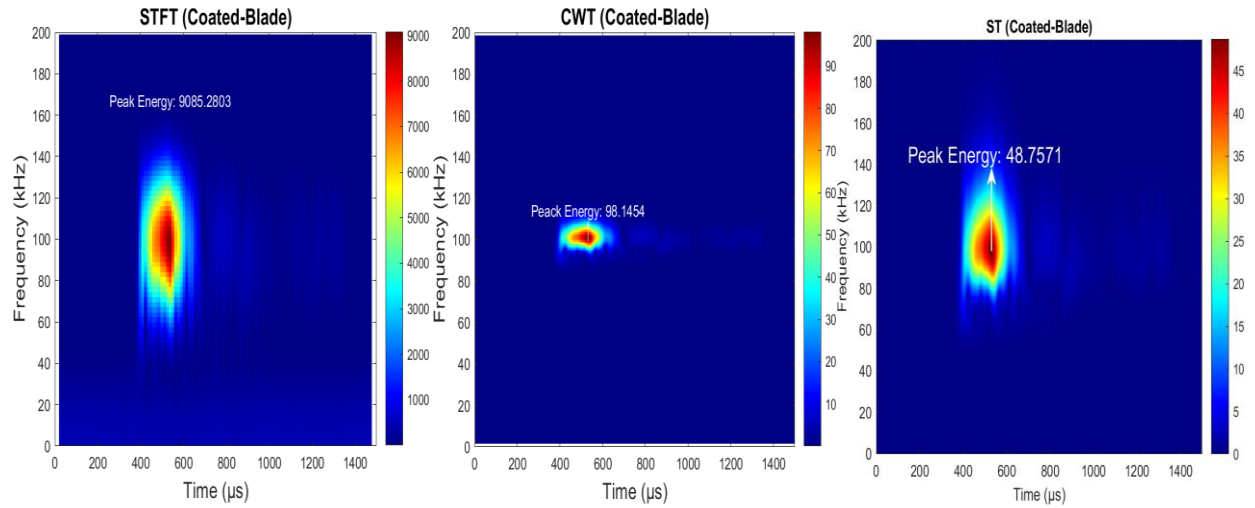
5.5.1 Analysis of Signals for TBC Removal Assessment

In order to assess how the presence or absence of TBC affects signal behavior, time-frequency transformations are applied to signals with and without TBC using STFT, CWT, and S-Transform. The resulting TFR, depicted in Fig. 35 and Fig. 36 respectively, reveals that regions of higher energy are concentrated around 100 kHz, corresponding to the frequency of the transducer utilized. While the TFRs for signals with and without TBC exhibit similar time and frequency distributions, notable discrepancies are observed in energy levels at corresponding positions, with the uncoated blade showing more concentrated energy and the coated blade exhibiting reduced intensity and broader dissipation due to damping. The energy values at peak points, highlighted in Fig. 35 and Fig. 36, demonstrate these differences. This energy variation serves as a distinguishing feature, enabling the differentiation between TBC-present and TBC-free signals based on the energy disparities within the TFR. The general trend of

energy reduction remains consistent across both cases (200 Vpp and 400 Vpp), suggesting that the primary influence of the TBC stems from its material properties rather than the excitation amplitude.

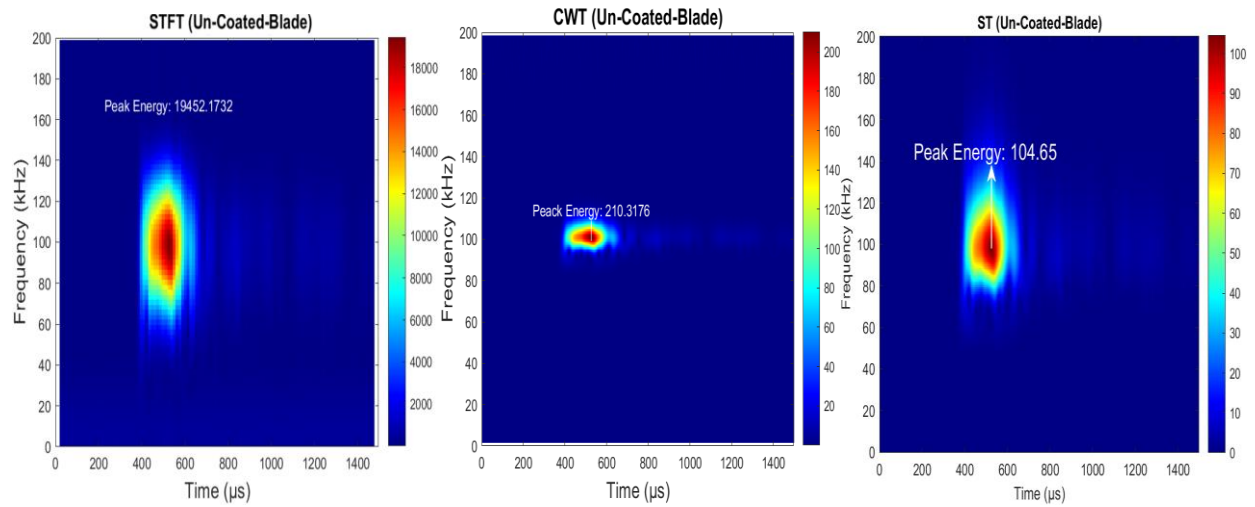


(a) TFRs of signals without TBC

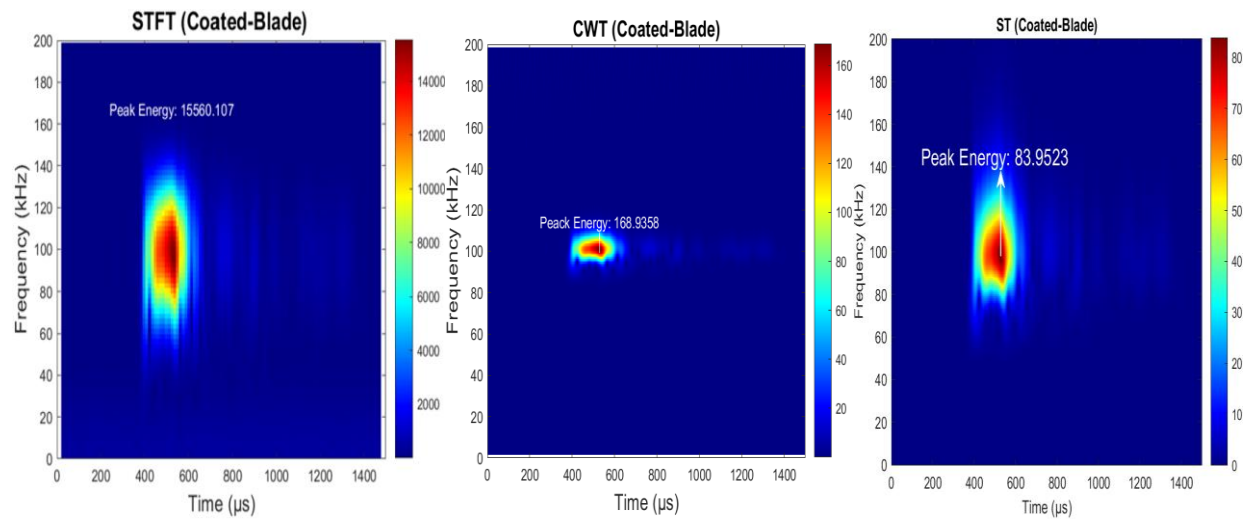


(b) TFRs of signals with TBC

Fig. 35. TFRs for signals with and without TBC under 200 Vpp Excitation

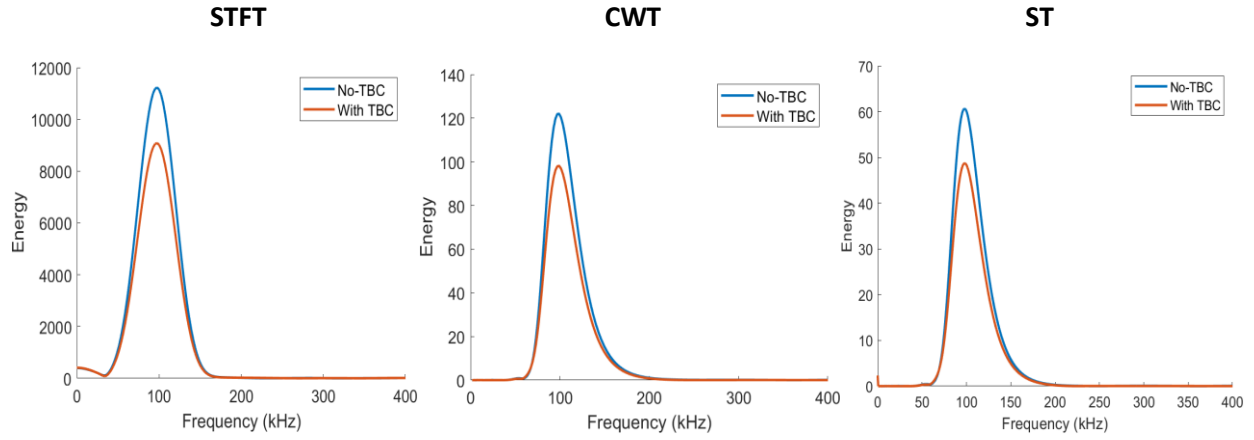


(a) TFRs of signals without TBC

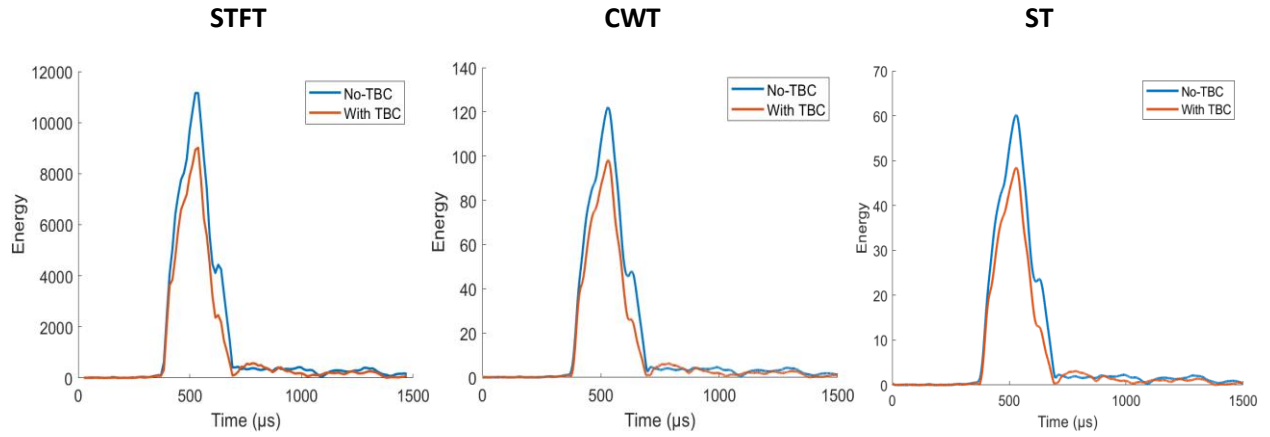


(b) TFRs of signals with TBC

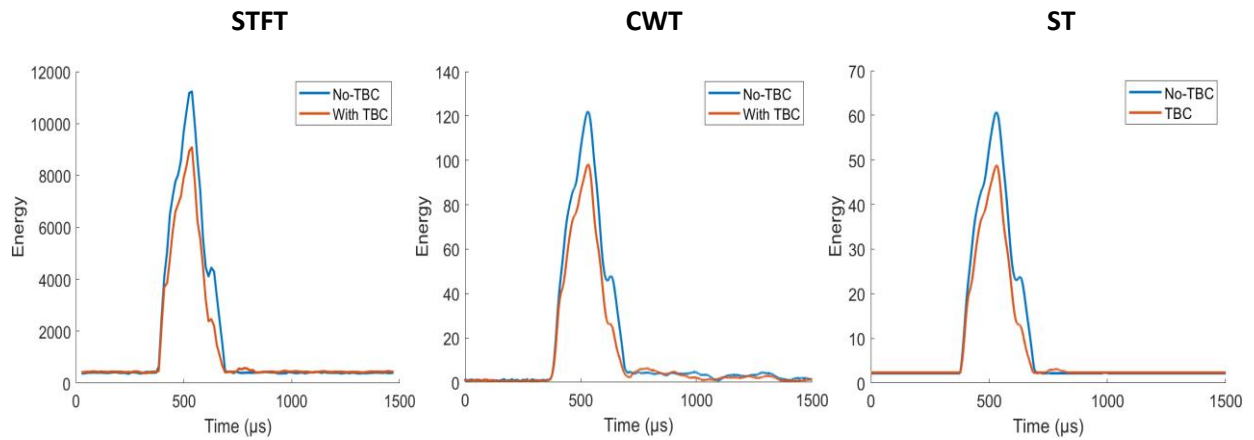
Fig. 36. TFRs for signals with and without TBC under 400 Vpp Excitation



(a) EFC at Time of Peak Energy

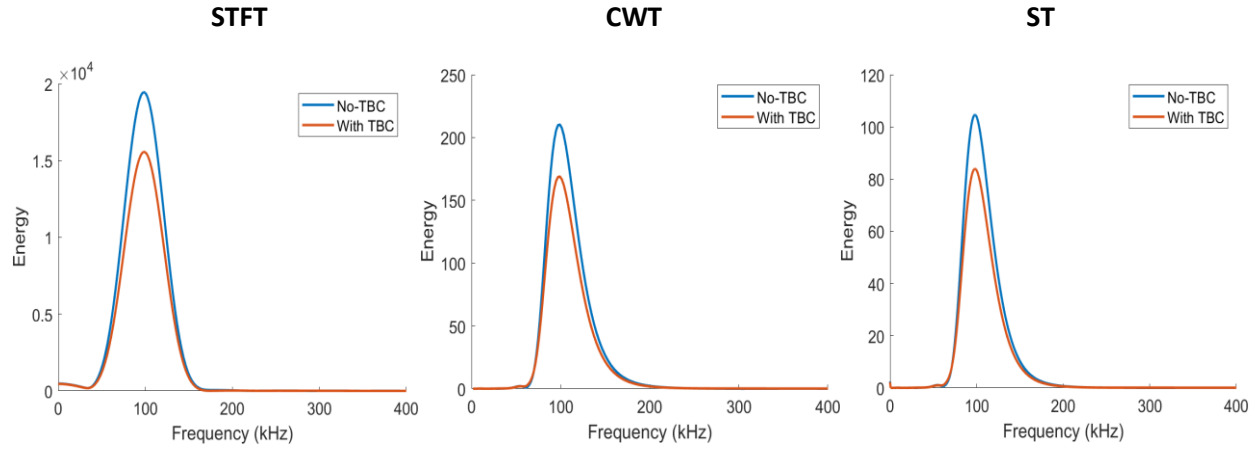


(b) ETC at ($F=F_c$)

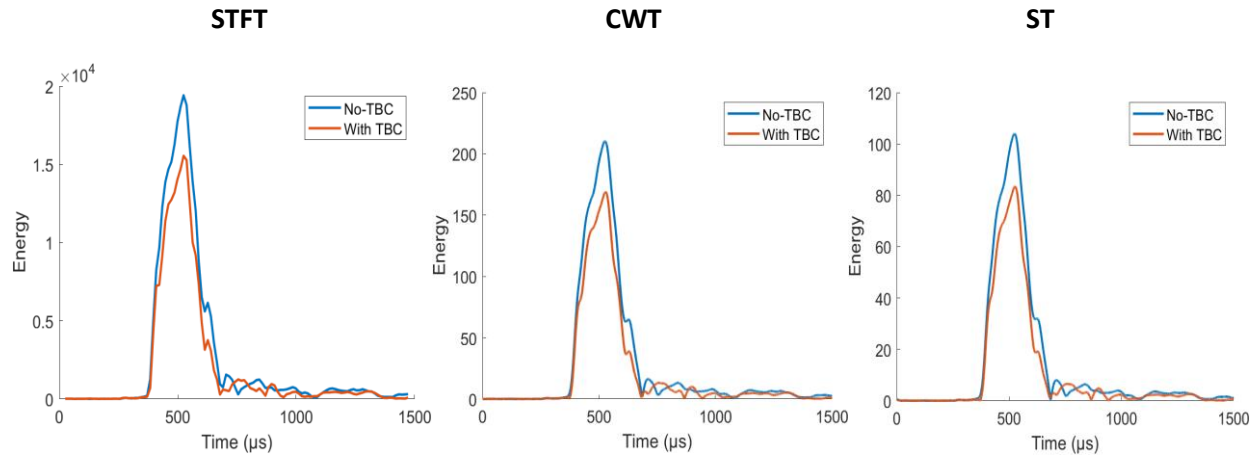


(c) DMR-EDC Feature Signal

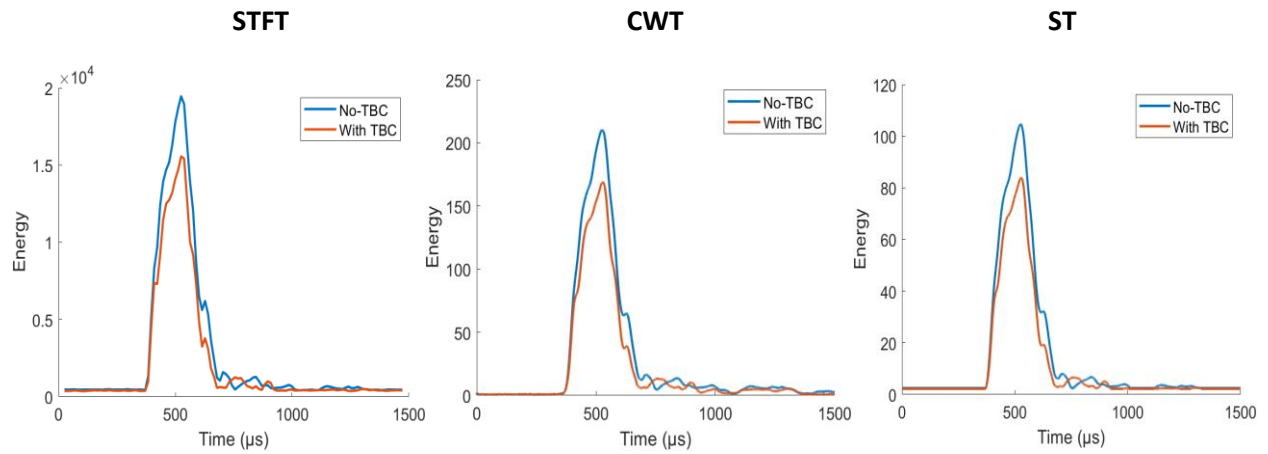
Fig. 37. Feature signals -under excitation of 200 Vpp- obtained through different methods



(a) EFC at Time of Peak Energy



(b) ETC at ($F=F_c$)



(c) DMR-EDC Feature Signal

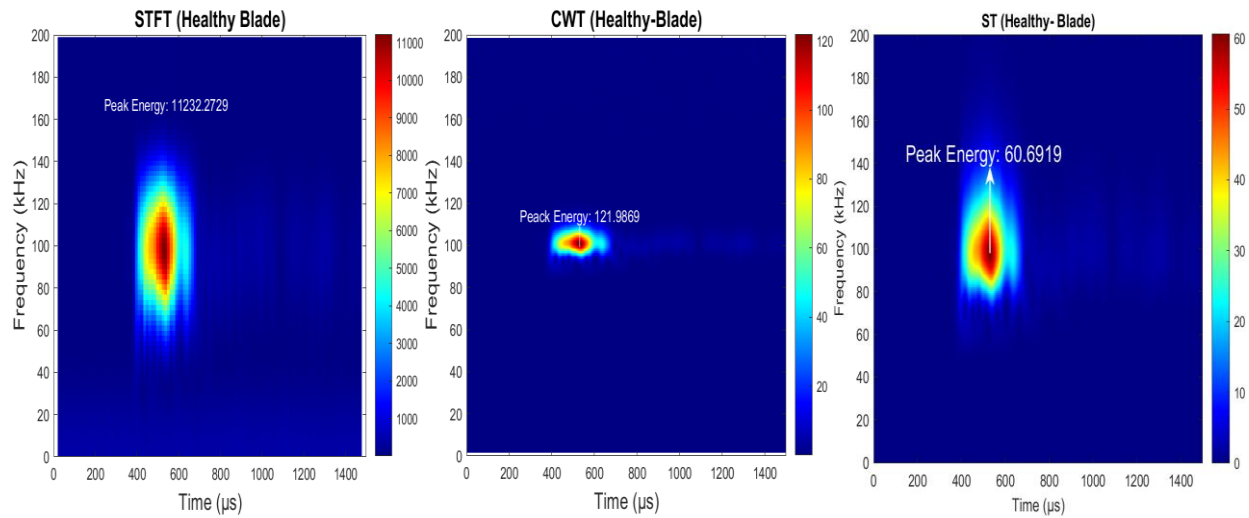
Fig. 38. Feature signals -under excitation of 400 Vpp- obtained through different methods

To evaluate the effectiveness of the extracted feature signals influenced by TBC, the EFC, ETC, and DMR-EDC features for both TBC-present and TBC-free signals are examined. The results are presented in Fig. 37 (a)-(c) for 200 Vpp excitation and Fig. 38 (a)-(c) for 400 Vpp excitation. The analysis reveals that the extracted feature signals are more streamlined and better represent the underlying characteristics of the system, effectively capturing the relevant details of both TBC-free and TBC cases. A distinct energy difference is observed between the TBC-free and TBC signals. Furthermore, the general trend of energy reduction is consistent across both excitation levels (200 Vpp and 400 Vpp), suggesting that the primary impact of TBC is due to its material properties, not the excitation amplitude. The feature extraction process effectively generates a smooth feature signal that captures the amplitude variation patterns for both TBC-free and TBC cases. The energy dissipation and reduced signal amplitude observed with TBC are consistent with literature findings, which show that TBC reduces wave velocity and causes energy leakage and diminishes the amplitude of the received Lamb wave signal during propagation.

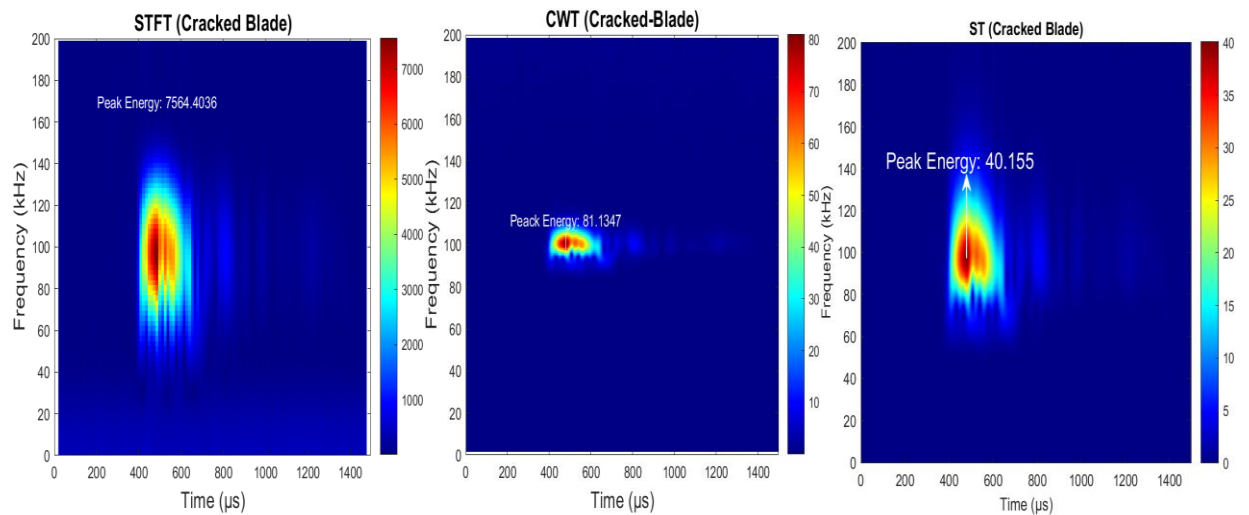
5.5.2 Analysis of Signals for Blade Material Loss Assessment

The analysis of signals for assessing blade material loss, specifically caused by FOD, involves examining how changes in the blade's material properties influence the transmitted acoustic signals. By comparing the signals from blades with and without FOD, differences in energy distribution, attenuation, and signal patterns can be identified. As stated in section 5.4.1, unaffected blades typically show higher signal amplitude, indicating efficient acoustic wave propagation and minimal material degradation. In contrast, blades with FOD exhibit reduced signal amplitude and increased energy dissipation, suggesting the presence of material loss or damage that disrupts the acoustic signal transmission. These alterations can provide valuable insights into the extent of the damage. To validate these findings and gain further insights into the guided wave behavior resulting from material loss, we will employ the same method outlined in section 5.5.1. The resulting TFRs, shown in Fig. 39 and Fig. 40 under 200 Vpp and 400 Vpp respectively, indicate that areas of higher energy are focused around 100 kHz, which corresponds to the frequency of the transducer used. It can be noted that the STFT, CWT and ST spectrograms reveal significant differences

between the healthy and cracked blades in terms of energy distribution and attenuation. The peak energy under both excitations shows a reduction of $\sim 35\%$, indicating that the crack is the primary cause of energy attenuation, rather than any variations in excitation amplitude. The healthy blade demonstrates a more concentrated and intense energy region, while the energy pattern in the cracked blade is more diffuse or fragmented, with a lower intensity and less defined peak energy concentration. This is likely due to the effects of scattering and dispersion caused by the crack. The decrease in energy and the spread of spectral content act as clear markers of structural damage, with the variations in peak energy and wave characteristics offering a measurable approach for detecting cracks.



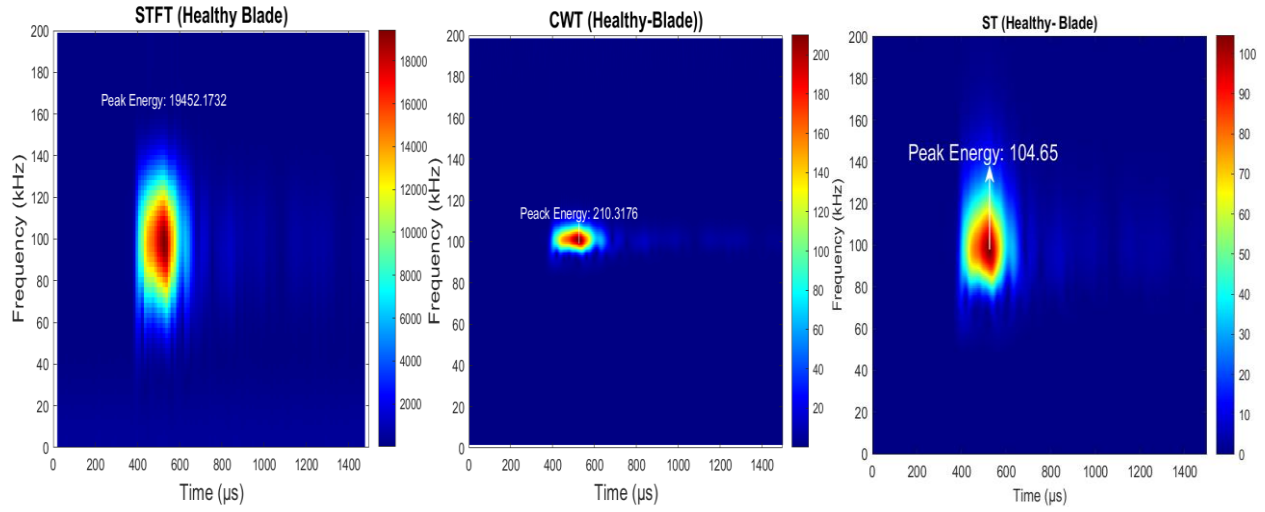
(a) TFRs of signals of Healthy Blade



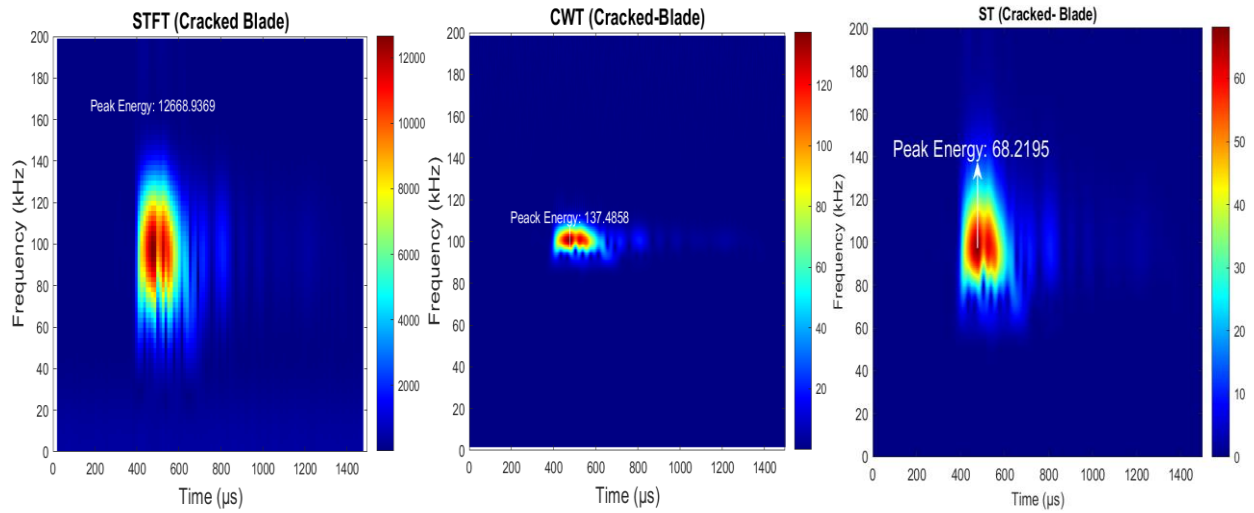
(b) TFRs of signals of defected Blade

Fig. 39. TFRs for signals for (a) Healthy Blade and (b) defected Blade under 200 Vpp

Excitation



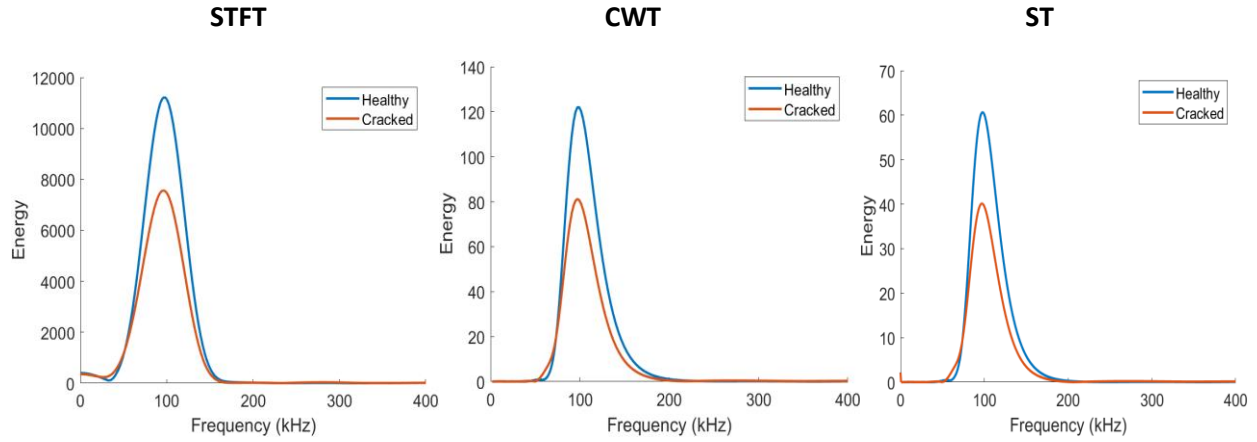
(a) TFRs of signals of Healthy Blade



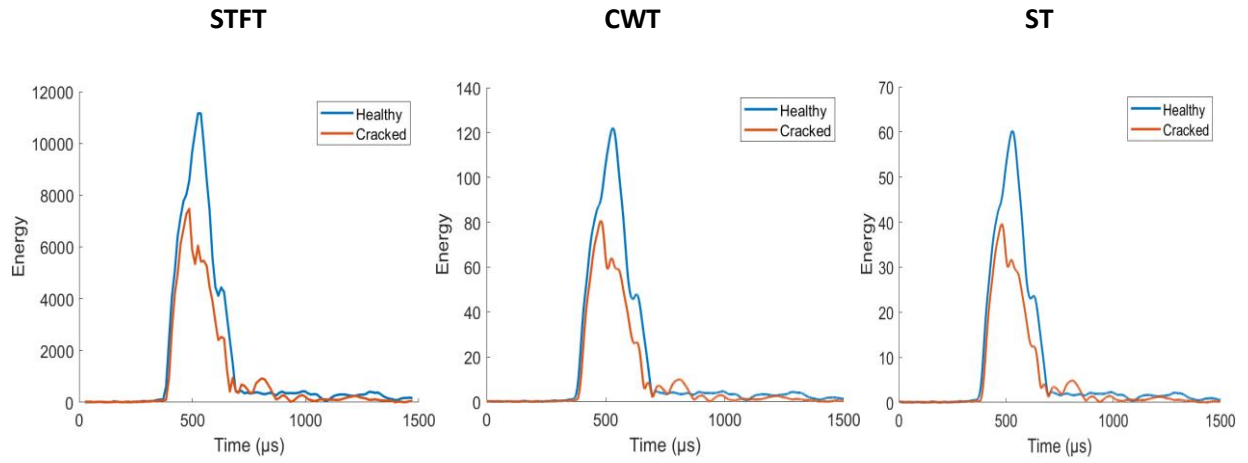
(b) TFRs of signals of defected Blade

Fig. 40. TFRs for signals for (a) Healthy Blade and (b) defected Blade under 400 Vpp

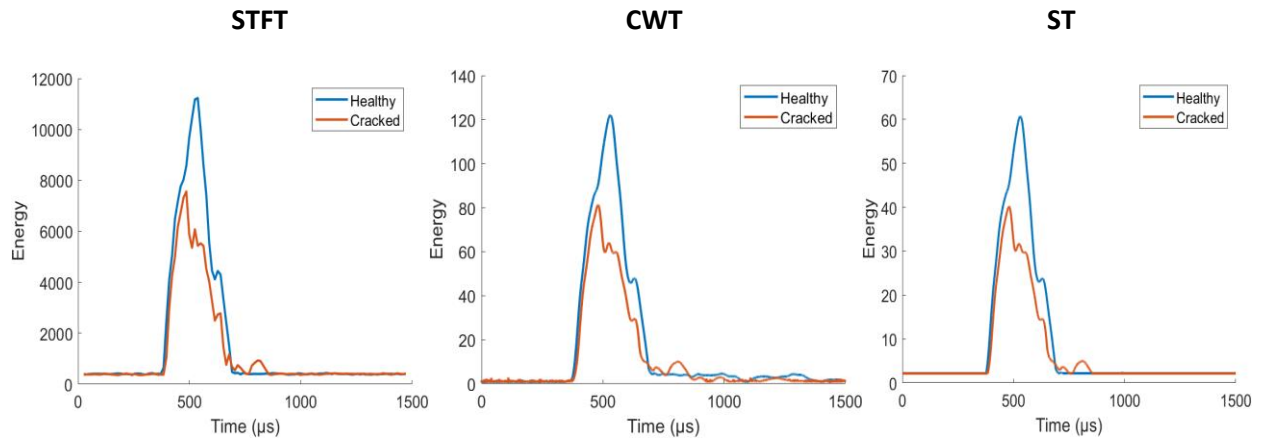
Excitation



(a) EFC at Time of Peak Energy

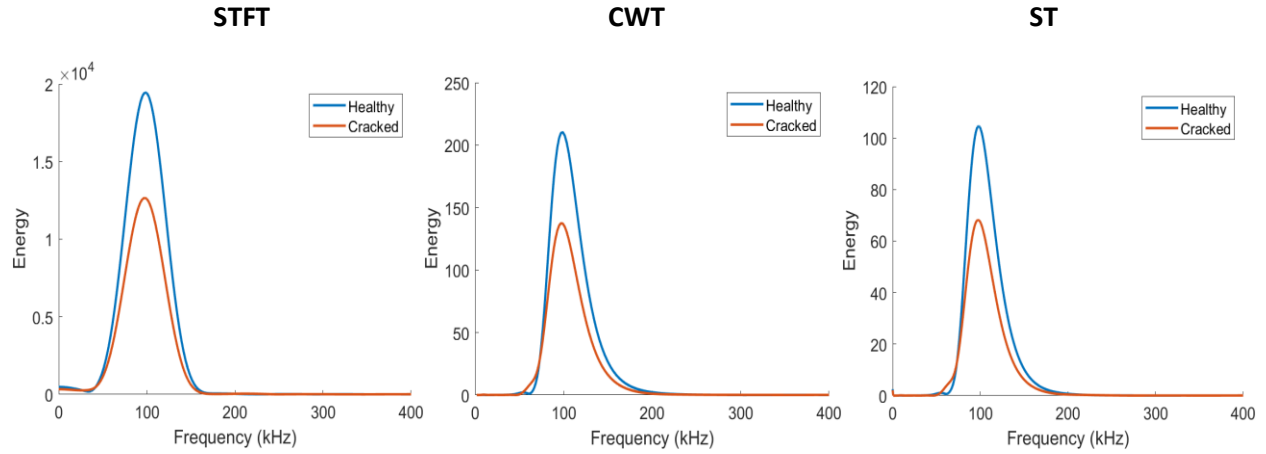


(b) ETC at ($F=F_c$)

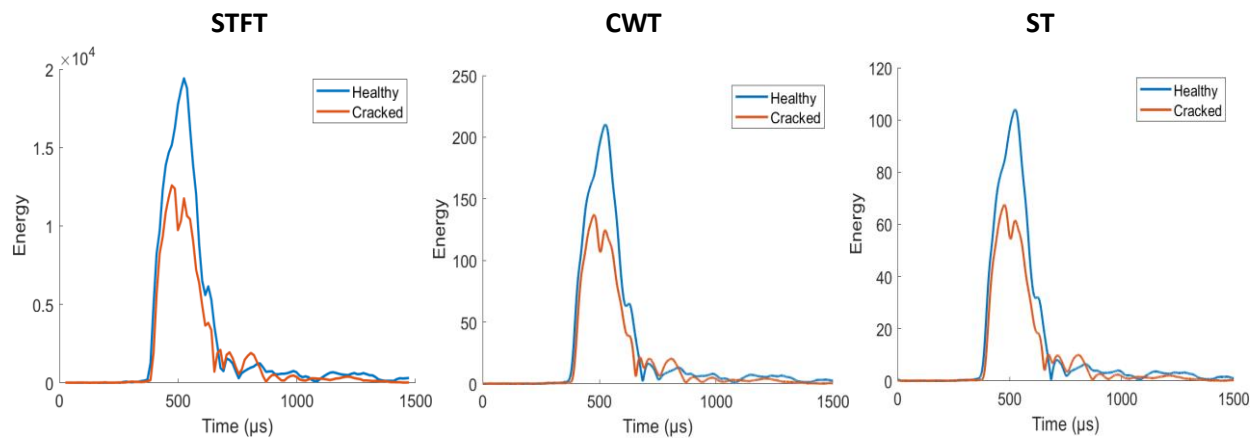


(c) DMR-EDC Feature Signal

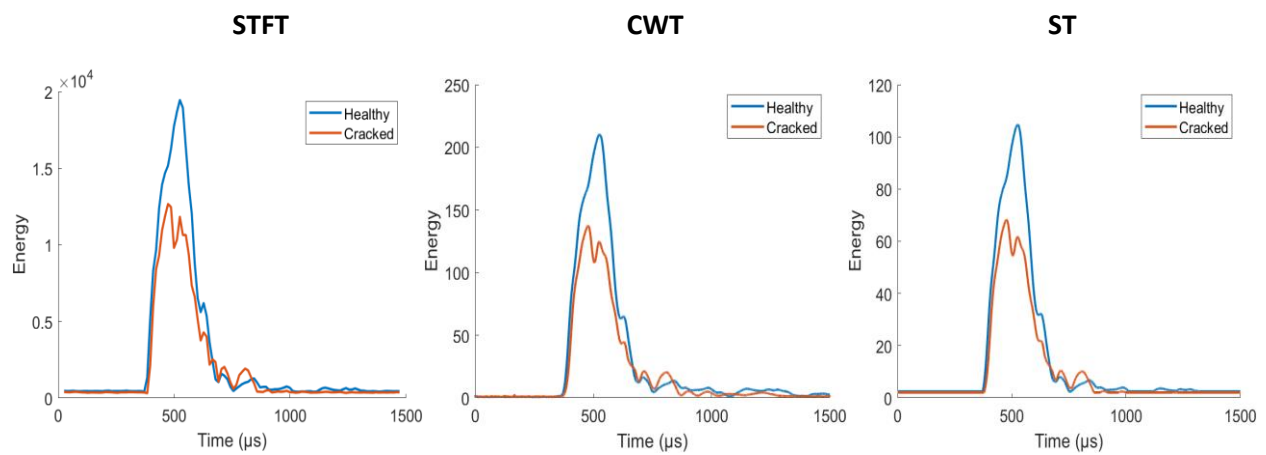
Fig. 41. Feature signals -under excitation of 200 Vpp- obtained through different methods



(a) EFC at Time of Peak Energy



(b) ETC at ($F=F_c$)



(c) DMR-EDC Feature Signal

Fig. 42. Feature signals -under excitation of 400 Vpp- obtained through different methods

In order to determine the effectiveness of the extracted feature signals for defect identification, the EFC, ETC, and DMR-EDC features were analyzed for both defective and defect-free signals. The results are presented in Fig. 41 (a)-(c) for 200 Vpp excitation and Fig. 42 (a)-(c) for 400 Vpp excitation. The analysis shows that the extracted feature signals are more concise and effectively capture the underlying characteristics of the system, highlighting the key details of both defect-free and defective conditions. A clear energy difference is observed between the defect-free and defective signals. Moreover, increasing the excitation amplitude from 200 Vpp to 400 Vpp amplifies the differences between the cracked and healthy cases. While the energy peak in both conditions remains proportional, energy diffusion in the cracked blade becomes more noticeable at higher excitation levels, likely due to greater wave interaction with the defect, in agreement with the findings in section 5.4.1. The feature extraction process successfully generates a smooth signal that reflects the amplitude variation patterns for both defect-free and defective cases. The amplitude reduction and the presence of a second dominant peak caused by the crack are consistent with the findings outlined in section 5.4.1.

5.6 Conclusion

This study successfully demonstrates the effectiveness of a fully non-contact method using air-coupled transducers for guided wave excitation and sensing to investigate the effects of TBC removal, material loss due to FOD, and structural defects on turbine blades. By incrementally adjusting the transducer angle from 0° to 20° and analyzing signals at each step, an optimal incident angle of 10° was identified based on the highest signal-to-noise ratio (SNR).

The study reveals significant differences between uncoated and coated, as well as healthy and cracked signals. The uncoated blade exhibited higher peak energy, indicating more efficient wave transmission and reduced attenuation compared to the coated blade, where the TBC led to energy dissipation and scattering. Similarly, the cracked blade displayed a ~35% reduction in peak energy relative to the healthy blade, attributed to energy attenuation caused by scattering and dispersion. These observations were obtained through advanced signal processing methods, including normalized Hilbert waveforms bandpass-filtered

envelopes, and time-frequency representations like STFT, CWT and ST. Additionally, feature extraction techniques such as EFC, ETC, and DMR-EDC effectively captured amplitude variation patterns across TBC-free, TBC-coated, defect-free, and defective cases.

Overall, these findings underline the potential of air-coupled guided waves for applications in NDT and SHM, offering quantifiable metrics for defect detection and assessment in coated, uncoated, healthy and defected turbine blades. These findings provide valuable insights for monitoring structural integrity, optimizing wave propagation, and understanding the implications of coatings and cracks on blade performance.

CHAPTER 6

FINITE ELEMENT MODELLING OF AIR COUPLED SYSTEM

6.1 2D Variable Thickness Plate Simulation

6.1.1 Module

A 2D simulation was developed using COMSOL Multiphysics to investigate guided wave propagation in a turbine blade, along with the interaction of these waves with different defect types. This simplified 2D setup was chosen as it provides sufficient accuracy for time-of-flight analysis and insights into wave-defect interactions. The simulation utilizes the Acoustic-Solid Mechanics Interaction Module to accurately capture air-coupled guided wave dynamics. In the air domain, pressure (P) is defined as the dependent variable, and transient analysis is applied to solve the system. In the solid mechanics domain, a plane strain condition is used, with u and v as the dependent displacement variables, appropriate for the plate's geometry. At the air-solid interface, energy is exchanged through a bidirectional coupling, enabling acoustic pressure waves in the air to interact with mechanical displacements in the solid. This coupling mechanism supports both the generation and detection of guided waves through the air medium.

The problem geometry is defined using a simple 2D model that includes the transmitter, receiver, plate, and surrounding air as illustrated in Fig. 43. The materials and boundary conditions for each geometry and phase are specified, and then the domain is meshed into small elements to achieve an accurate solution.

As described in the literature, the air-coupled guided wave method operates by generating ultrasonic longitudinal waves in air through an angled air-coupled transmitter, which then directs these waves toward a waveguide. Upon interacting with the waveguide, the waves undergo interference, transforming into guided Lamb waves that propagate through the plate-like sample. As the guided waves move within the waveguide, they cause mechanical disturbances in the adjacent air, producing leaky Lamb waves detectable

by an air-coupled receiver. This technique allows multiple wave modes to be excited concurrently at specific frequencies, enabling selective mode excitation and targeted inspection for particular defect types. Adjusting the incidence angle, θ_i , enables the generation of specific guided wave modes. The angle can either be directly derived from the dispersion curves shown in Figure (19.a) or calculated using Snell's law, as shown in equation (6.1).

$$\theta_i = \arcsin\left(\frac{C_{air}}{C_p}\right) \quad (6.1)$$

In this equation, C_p denotes the phase velocity of the mode in the IN738 plate obtained from the dispersion curves, while C_{air} represents the speed of sound in air.

6.1.2 Model Geometry and Material Properties

Figure 43 presents the 2D model, where the air domain is depicted in blue and the turbine blade in gray. In this setup, the turbine blade is specified as a solid isotropic material made of Inconel 738, with a thickness varying between 10 and 20 mm and a width of 200 mm, while the air domain is modeled as a fluid medium.

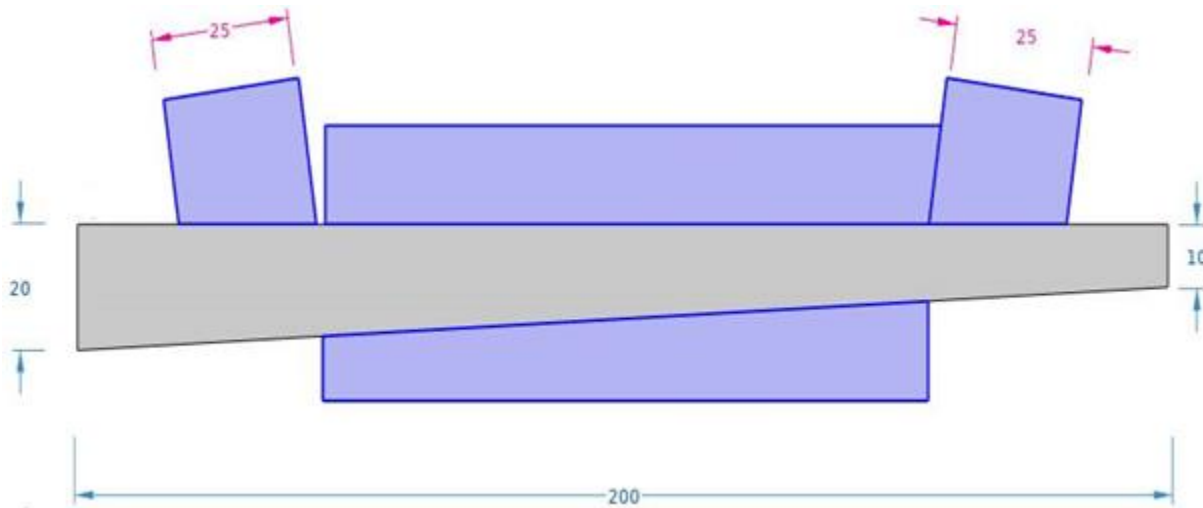


Fig. 43. Geometric configuration of the air-coupled guided wave simulation model in COMSOL, dimensions in[mm]

The air domains are modeled above and below the plate to capture the wave propagation and its interaction with defects. The transmission and reception domains in the air were designed as rectangles with a width of 25 mm and 20 mm away from the top surface of the plate, matching the diameter of the 100 kHz transducer utilized in the experiment, and were positioned 100 mm apart. These rectangles are oriented at angles of 10° and -10° with respect to the y-axis to efficiently generate and receive the A0 mode at 100 kHz as found experimentally. The IN738 plate possesses elastic properties of a Young's modulus of 200 GPa, a Poisson's ratio of 0.29, and a density of $8110 \frac{kg}{m^3}$. Turbines operate in extreme conditions with temperatures reaching approximately 1000°C. However, to align with experimental conditions, the air properties used for simulations are set to a temperature of 21°C, with a density of $1.2041 \frac{kg}{m^3}$ and a velocity of 343 m/s.

In this study, two types of defects were considered: a U-notch with a 6 mm radius, representing material loss [174], and a void, representing internal cracks [175], to observe potential mode conversion and leaky Lamb waves from the defect. A defect-free model was also used for validation.

6.1.3 Model Boundary Conditions and Meshing

The acoustic-structure boundary condition from COMSOL is utilized at all interfaces between solid materials and air. This condition guarantees the continuity of normal displacement and normal stress while ignoring tangential stress at the interface. The boundary between air and vacuum is represented as a plane wave radiation condition, which models an infinite medium and eliminates reflections. The two vertices on the left side of the plate, characterized as linear boundaries, are fixed, which reflects a realistic situation where the turbine blade is fixed on its thicker side. At the transmitter and receiver, classified as planar wave excitation at the air boundary, the transmitter is driven by a fifteen-cycle Hanning windowed toneburst signal centered at a frequency of 100 kHz.

For meshing, the elements need to be small enough to ensure a reasonably accurate solution. To select a proper meshing; it's essential to note that the wavelength in air at 100 kHz is approximately 3.43 mm whereas the wavelength for Lamb Waves in Inconel 738 with varying thickness at the same frequency is

from 21.5 to 26.9 mm based on the phase velocity obtained from the dispersion curves. As per the COMSOL guidelines [176], to effectively simulate wave behavior, a minimum of 10 linear finite elements for each wavelength needs to be used. This means that the element size should not exceed one-tenth of the minimum wavelength in each domain to achieve an accurate solution at the specified frequency. Consequently, a triangular mesh size of 0.3 mm is used for the air domain, while a size of 1 mm is applied for the solid domain.

After defining the mesh, the model is solved for 1500 μs , enabling the wave from the transmitter to generate a Lamb wave in the plate that reaches the receiver. The time step for wave propagation determined to be 0.1 μs using the Courant–Friedrichs–Lewy (CFL) condition [177], as described in Equation (6.2).

$$\Delta t = \frac{C \cdot \Delta x}{v} \quad (6.2)$$

Where: Δt is the time step size, C is CFL number (often set between 0.1 and 0.5 for stability; typical values are 0.1 to 0.25), Δx is the mesh size (0.3 mm) and v is $v_{air} \approx 343 \text{ m/s}$.

6.1.4 Simulation Results and Discussion

In this section, the results from the FEM simulation are analyzed to evaluate the efficiency of guided waves in detecting various defect types. This involves examining wave propagation through air and solid materials, as well as analyzing the time of arrival (ToA) of the waves. The input signal is a fifteen-cycle narrowband toneburst centered at 100 kHz (Fig. 44), used to produce a smoothly tapered excitation that helps reduce spectral leakage and provides a more localized response in the time-frequency domain. The excitation signal $S(t)$ is defined by Equation (6.3).

$$S(t) = \frac{P}{2} \left(1 - \cos \frac{2\pi f_c t}{N} \right) \sin(2\pi f_c t) \left(t < \frac{N}{f_c} \right) \quad (6.3)$$

Where P is the pressure amplitude of the excitation signal which is 200 Pa, f_c is the center frequency of the transmitted signal and N is the number of cycles. The method of plane wave generation is used to create

the A0 mode in the IN738 plate, with the resulting leaky Lamb waves being captured at the receiver boundary.

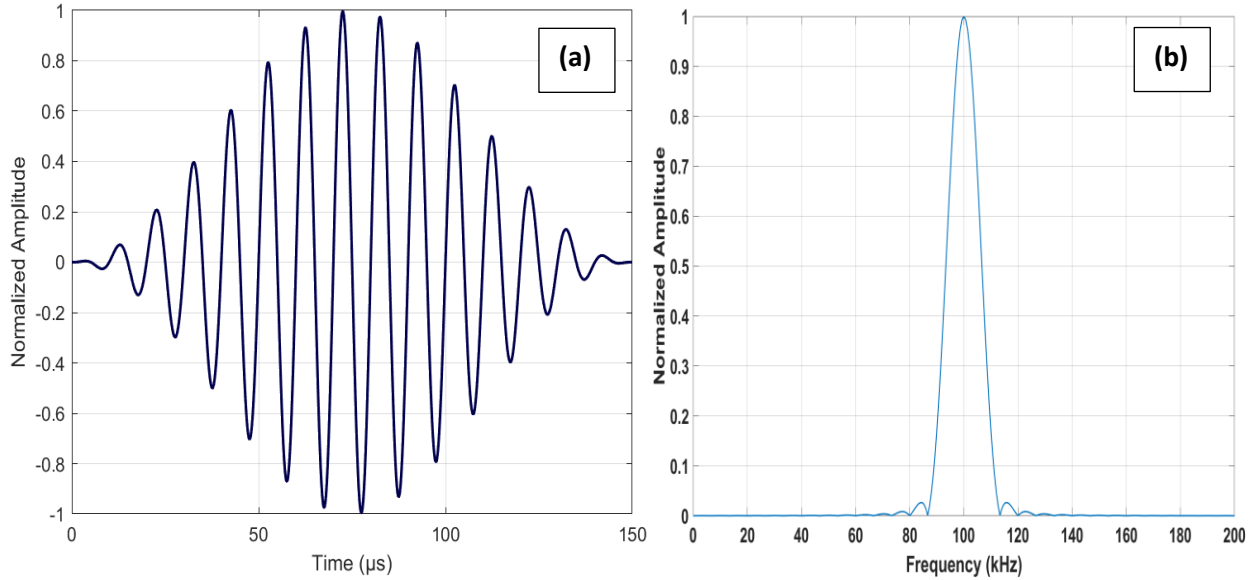


Fig. 44. (a) fifteen-cycle Hanning windowed toneburst input signal with a center frequency of 100 kHz and (b) its frequency spectrum presented

In the FEM simulation of a healthy blade, the group velocity (C_g) of the A0 mode at 100 kHz is calculated by plotting out-of-plane displacement at various points (50, 130, and 150 mm) (Fig. 45). By identifying the first peak of the initial wave group reaching the receiver, C_g is calculated as the distance traveled (Δx) divided by the time of flight (Δt). Between the first two points, where $\Delta x = 80$ mm and $\Delta t = 23.1$ μs, the group velocity is 3,463.2 m/s. For the first and third points, with $\Delta x = 100$ mm and $\Delta t = 29.2$ μs, the group velocity is 3,424.66 m/s. Comparing these values to the average group velocity from the dispersion curves in section 6.3.1, where $C_g \approx 3,080.00$ m/s, reveals a difference of roughly 12%. This variation can be explained by minor errors in the FEM simulation, as well as the fact that the dispersion curves assume a flat plate with uniform thickness, not accounting for any thickness variations.

Figure 46 displays the excitation signal alongside the received signal. In order to determine the time of arrival (ToA) from the simulation results, the initial wavefront is identified by locating the first significant

peak in the A-scan data. The Hilbert envelope is subsequently applied to the signal to isolate the wave group with the highest energy. This method enables an accurate measurement of the ToA, as it more effectively captures the propagation time of the dominant wave group, even in the presence of multiple reflections or overlapping signals. The peak-to-peak method [178], supported by the Hilbert transform, proves to be especially suitable for this type of analysis.

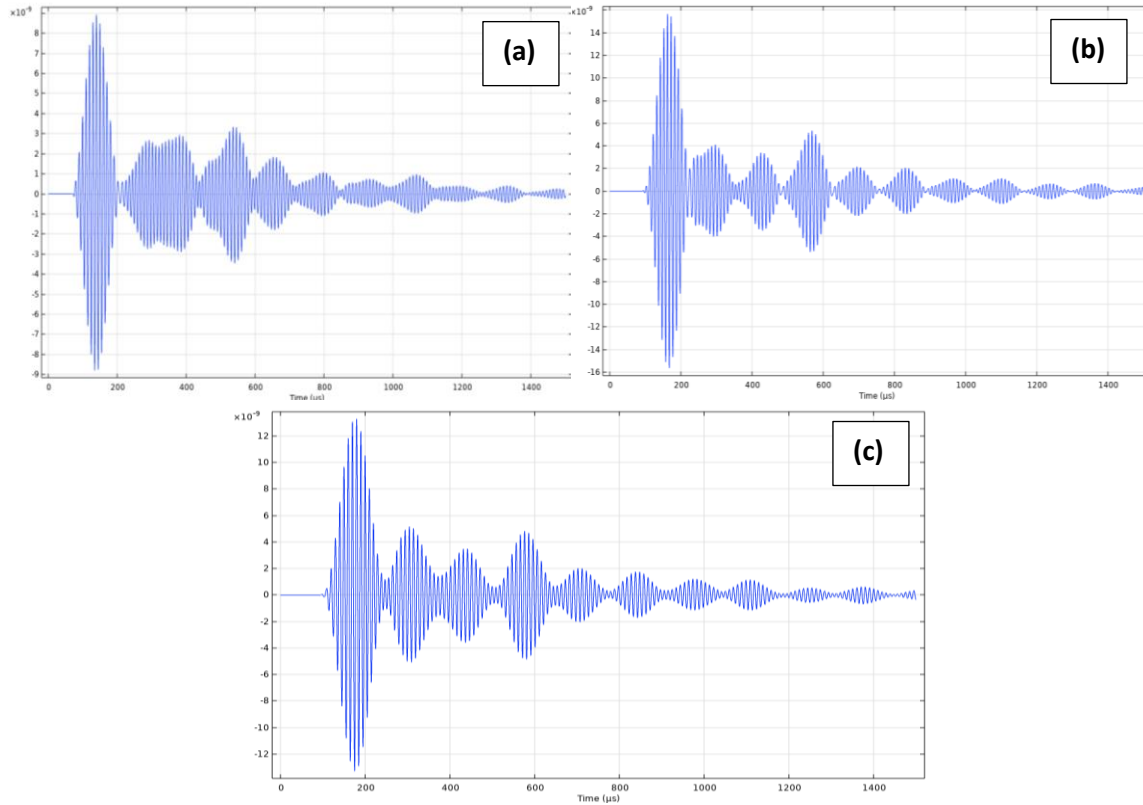


Fig. 45. Out of plane displacement at (a) 50 mm , (b) 130 mm and (c) 150 mm.

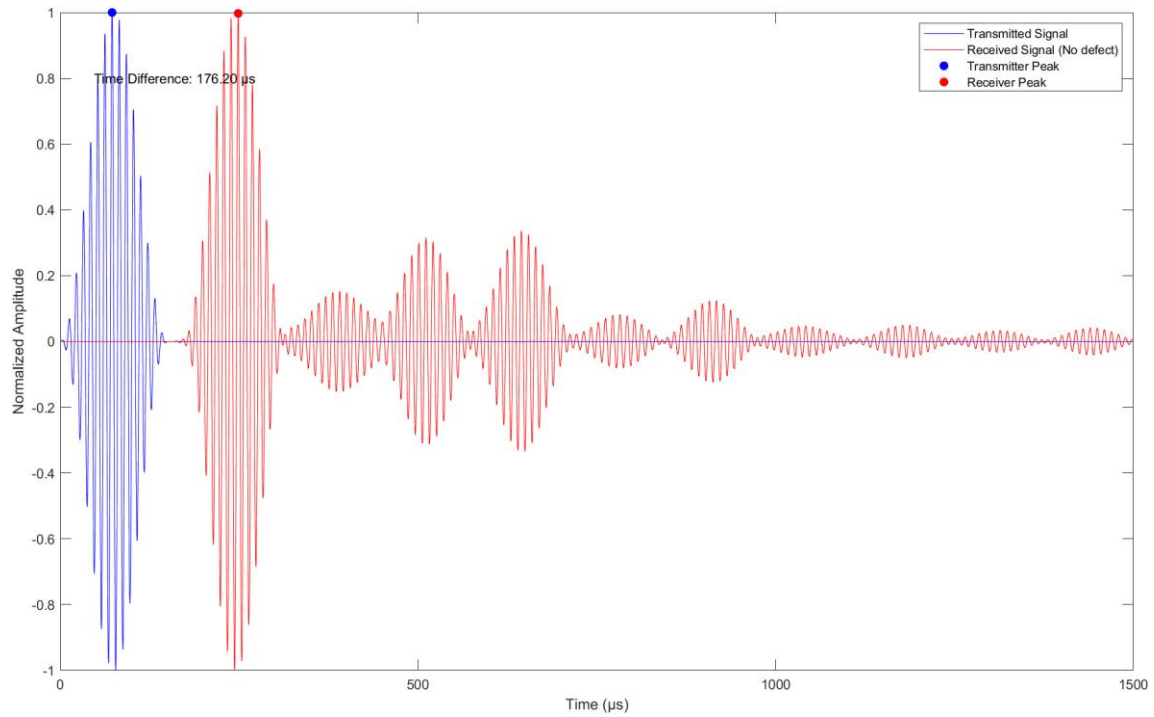
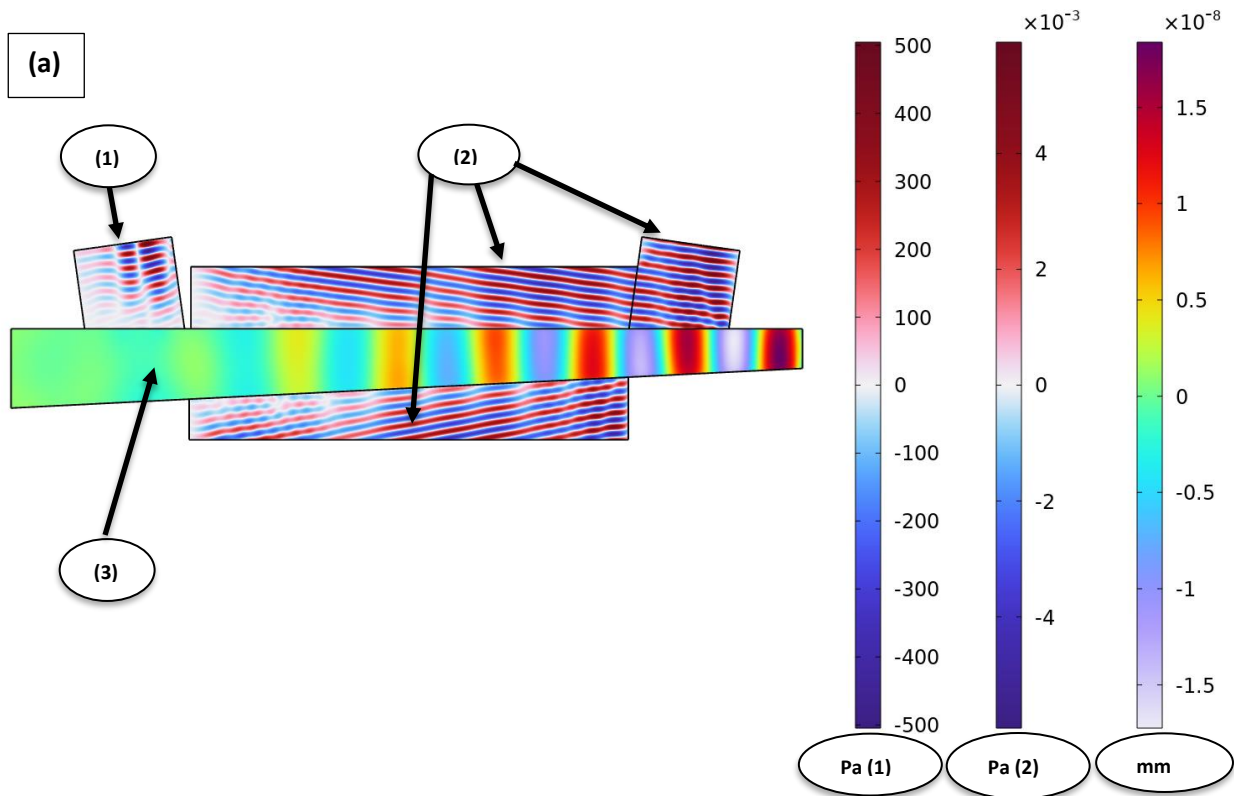


Fig. 46. Normalized Amplitude of Transmitter and Receiver Signals

When analyzing plates or thin structures, both the length and thickness of the material can significantly influence the time of arrival (ToA). The ToA is dependent on the path taken by the wave, which may involve traveling through the thickness of the plate or reflecting along its length. For instance, using group velocity obtained from dispersion curves, the ToA for an IN738 blade is analytically calculated to be 160 μs ; however, this value shows a slight discrepancy with the simulated ToA from COMSOL, which is 176 μs . Calculating ToA analytically for a plate with thicknesses ranging from 10 mm to 20 mm is complex due to the various factors impacting wave propagation. As the thickness changes, the wave travels faster in thinner sections (10 mm) and slower in thicker areas (20 mm), leading to a variable ToA. COMSOL simulation is better equipped to account for these thickness variations, allowing the wave's path to adapt accordingly. Additionally, changes in wave modes and reflections, which are prevalent in such plates, can further influence wave speed and contribute to an increased ToA. These complexities are captured in the COMSOL simulation, thereby explaining the longer ToA observed in the results.

Figure 47 displays the propagation of guided waves through an IN738 blade under three scenarios: a defect-free plate, a plate with a notch defect (6 mm radius), and a plate with an arbitrary internal crack (void) at a simulation time of 209 μ s. The wave propagation in the air domain is depicted by acoustic pressure in Pascals, whereas in the IN738 plate, it is shown as normal displacement in millimeters. The amplitude at the reception area (2) is reduced compared to the excitation area (1) due to transfer losses during interaction with the solid plate. In the case of the healthy plate, the waves propagate smoothly, maintaining a clear and continuous wavefront. The presence of internal defect induces localized scattering, characterized by distinct reflection and refraction patterns, which enhances its detectability using guided waves. In contrast, the material loss caused by FOD (U-Notch defect) leads to complex scattering, resulting in more diffuse reflections and interference patterns. This produces a broader distribution of wave amplitude with lower peak values, suggesting the presence of an open crack. Additionally, the sharp edges of the notch defect lead to a notable reduction in pressure amplitude at the receiver, generating high-intensity reflections that facilitate identification of this defect type. In Fig. 48, the waveforms recorded at the receiver boundary are compared for three cases: a signal without defects, a signal with a notch defect (Fig. 48.a), and a signal with a void defect (Fig. 48.b). The signal without defects serves as the baseline, representing the normal wave propagation through the material. The multiple modes shown in Fig. 48 are consistent with the discussion in section 5.4.1, emphasizing that Lamb waves propagating through regions of varying thickness generate complex signals due to repeated reflections, transmissions, and mode conversions. When a notch defect is present, the received signal exhibits a higher amplitude attenuation. This suggests that the notch causes more significant scattering or absorption of the wave energy, leading to a more substantial reduction in the signal strength. In contrast, the signal in the presence of a void defect shows less attenuation compared to the notch defect. This indicates that while the void alters the wave propagation, it does not attenuate the signal as severely as the notch, aligning with wave energy strength shown in Fig. 47 and with the findings in the literature that suggest a partial loss of the turbine blade reduces the reflective area, leading to decreased signal amplitude and increase energy attenuation. For further analysis, the normalized Hilbert waveforms with bandpass filtered Envelope, with frequency range of 80–120 kHz, relative to the healthy

plate signal are plotted in Fig. 49, it can be noted that the waveform for the healthy material displays a single dominant peak with smooth decay, indicating minimal scattering or disruption, serving as a baseline for comparison. In contrast, waveforms from void and notch defects show reduced amplitude, with the notch signal exhibiting the most significant attenuation. The second dominant peak is evident in both void and notch cases but is more pronounced in the void due to smoother wave interactions and less scattering as clearly evident in Fig.49.b. Notches, representing sharp edges or cracks, causing greater amplitude reduction and energy redistribution across modes. Conversely, voids induce relatively less attenuation, allowing more transmitted wave energy to contribute to the second peak. These observations highlight the differing impacts of defect geometry on Lamb wave propagation and agrees with the findings from the literature and the experiment that the second peak in the received signal would refer to the damaged signal.



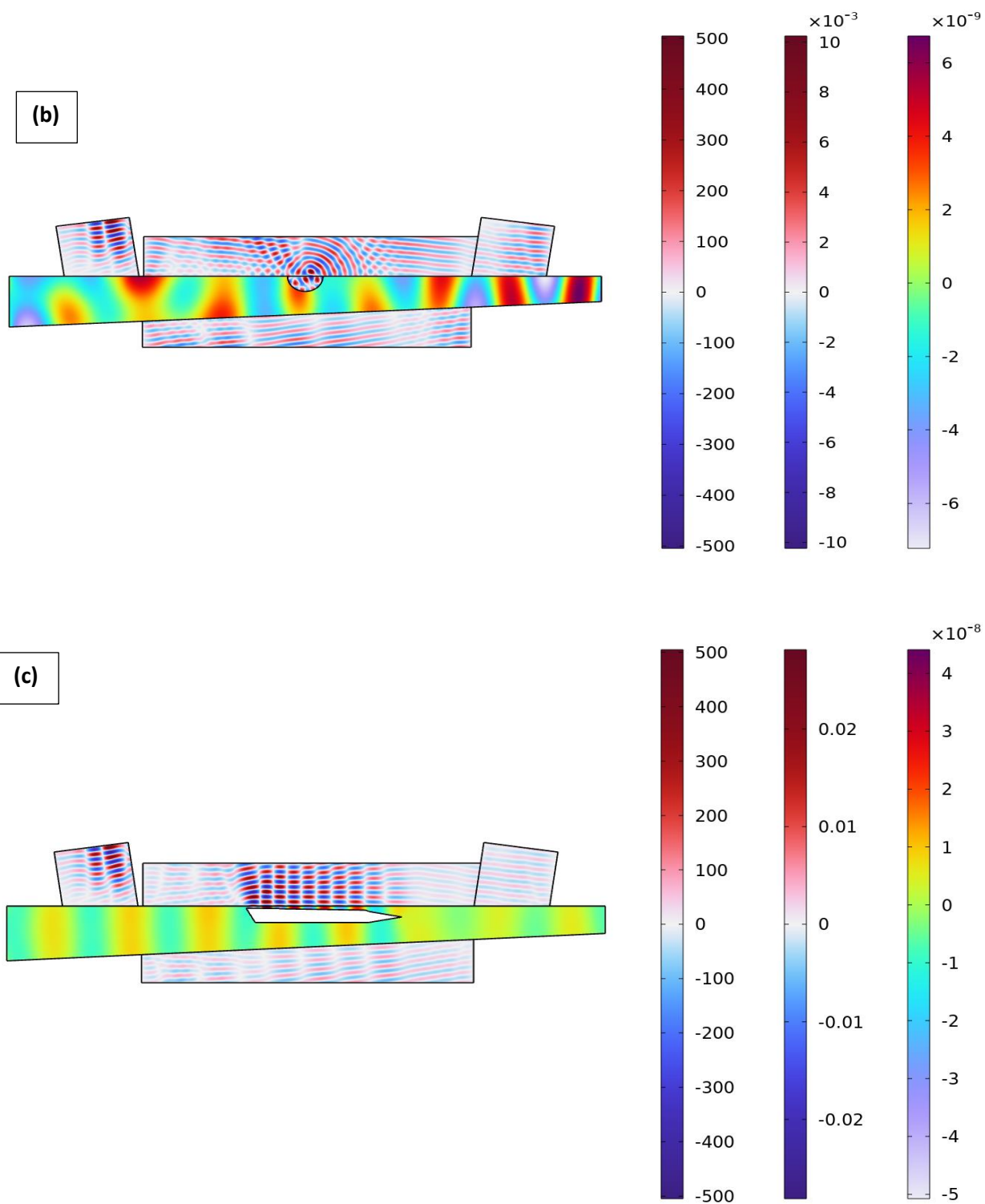


Fig. 47. Guided Wave Propagation in IN738 Blade: Healthy (a), Notched (b), and Internally Cracked (c) Scenarios at 209 μ s

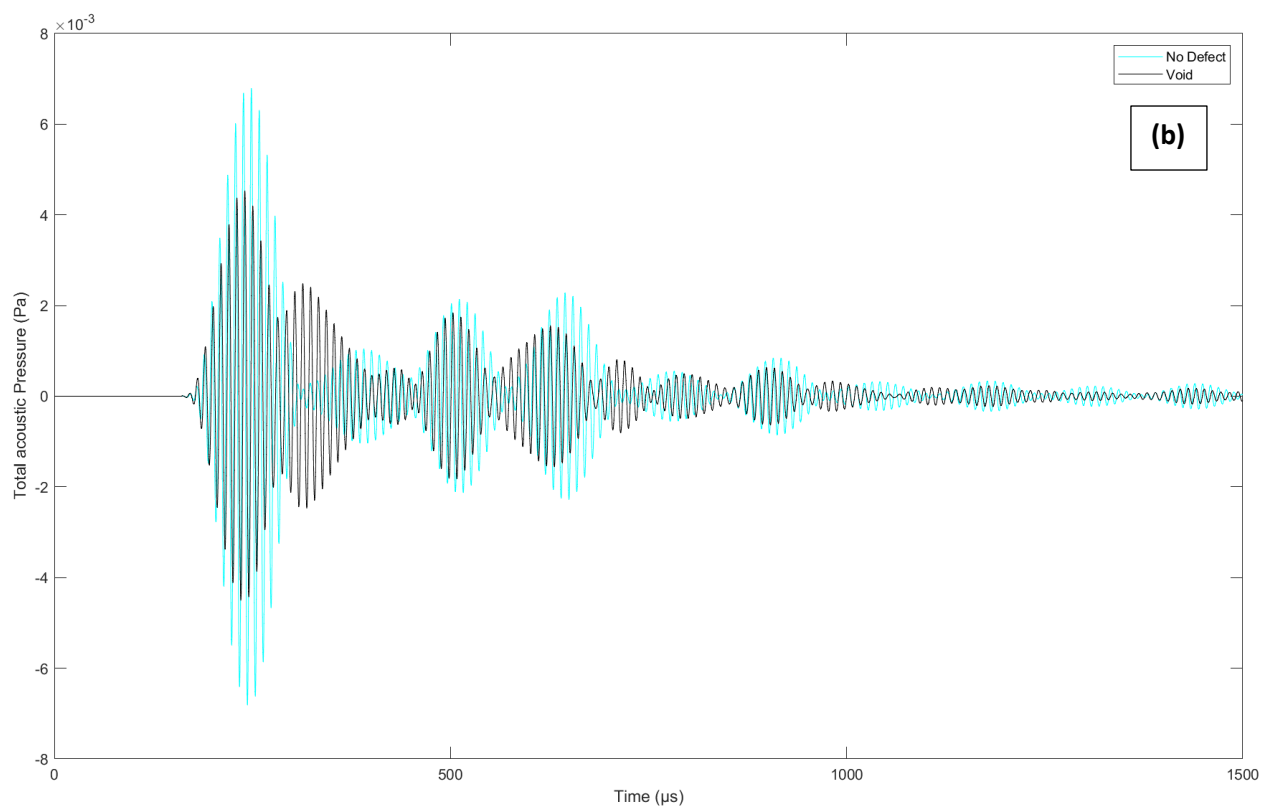
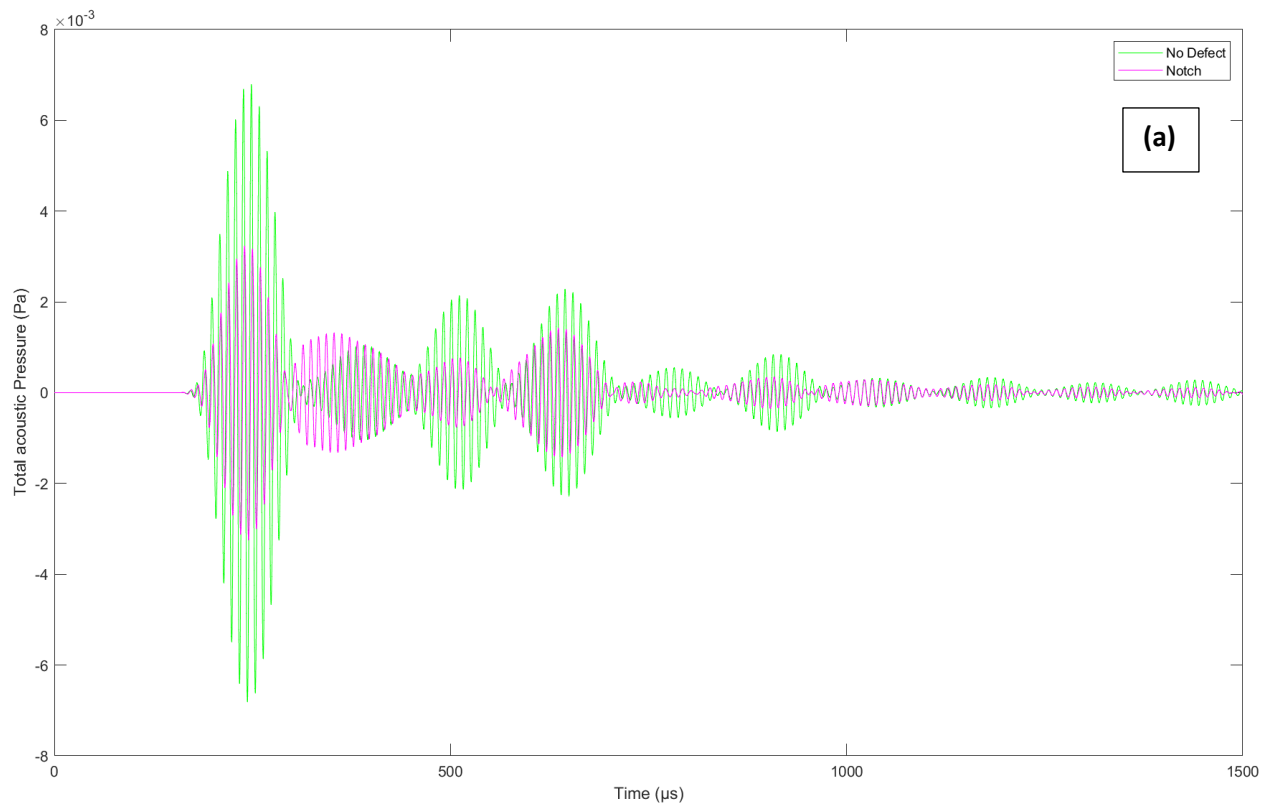


Fig. 48. Comparison of Waveform Attenuation in a Plate with Notch (a) and Void (b) Defects

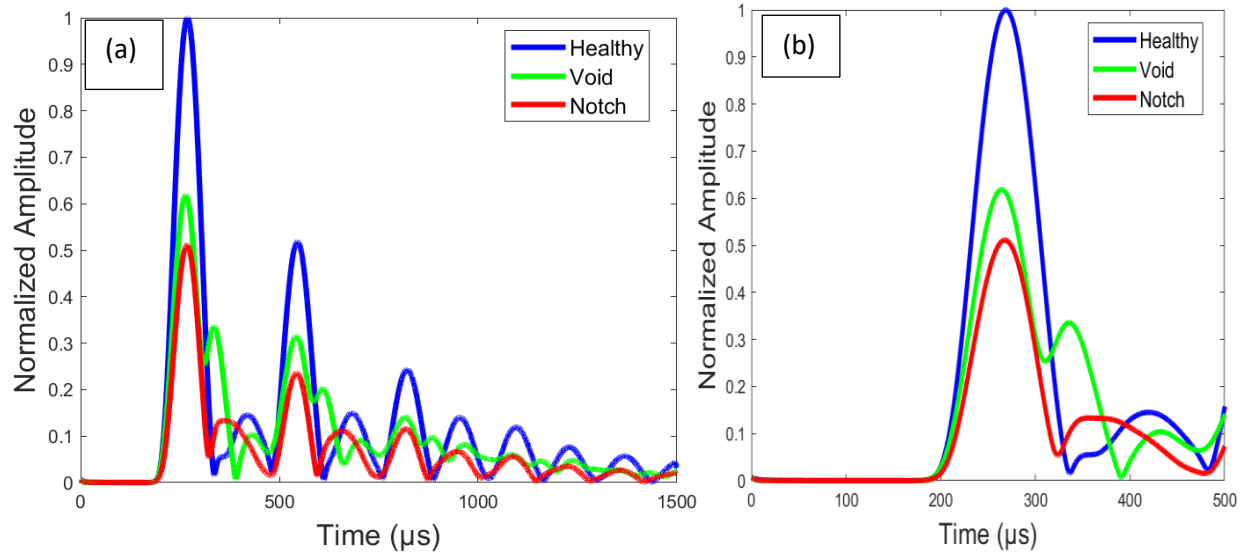
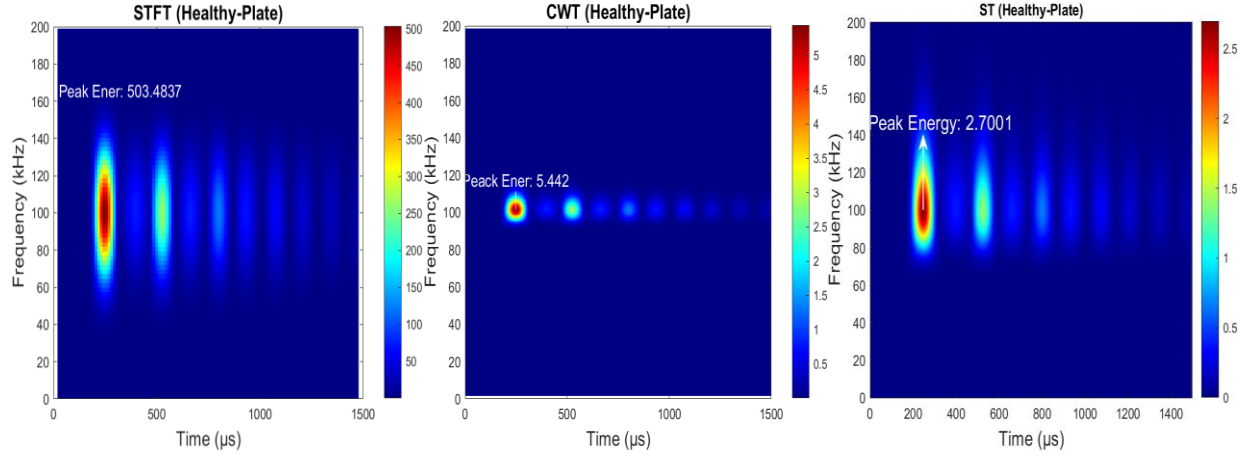
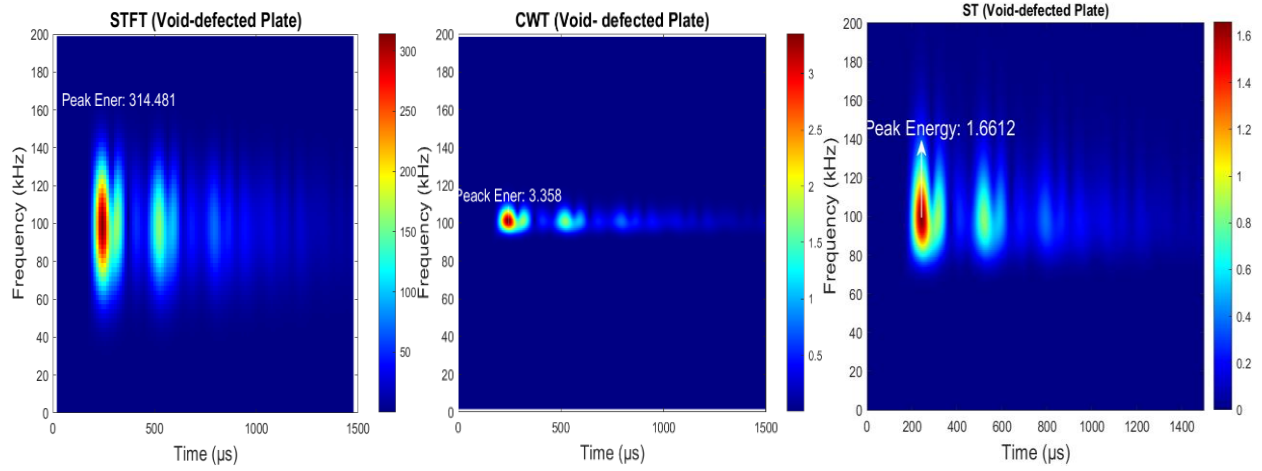


Fig. 49. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Healthy plate obtained from the simulation (a) Full Received Signal and (b) Snapshot of 0-500 μ s.

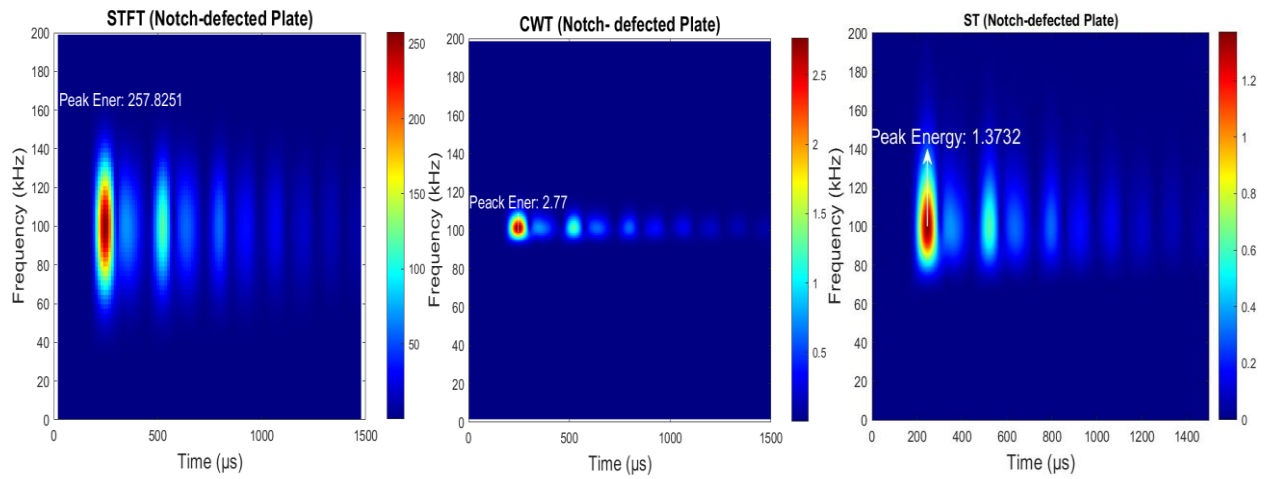
Defect assessment analyzes how material changes in blades influence acoustic signals. Healthy plates exhibit higher amplitudes and efficient wave propagation, while defective plates show reduced amplitudes and increased energy dissipation, indicating closed cracks or material loss. These signal variations help pinpoint the location and severity of damage. To further investigate guided wave behavior in defective blades, the TFR method is employed. As shown in Fig. 50, the TFRs reveal concentrated energy around 100 kHz, matching the transducer frequency. STFT, CWT, and ST spectrograms highlight notable differences in energy distribution and attenuation between healthy and defective plates. The healthy plate demonstrates the highest peak energy, while the void-defected plate shows moderate energy loss, and the notch-defected plate has the lowest peak energy due to significant wave scattering. A second energy peak, indicating defects, is more distinct in the void-defected compared to the U-Notch defect plate due to smoother wave interactions and reduced scattering.



(a) TFRs of signals of Healthy plate



(b) TFRs of signals of Void-defected plate



(c) TFRs of signals of Notch-defected plate

Fig. 50. TFRs for signals for (a) Healthy, (b) Void-defected and (c) Notch- defected plates.

6.2 2D Airfoil Model

In order to study the air-coupled wave propagation in the complex geometry of a turbine blade, a 2D cross-sectional model of the airfoil is used, representing the top view of the blade, as illustrated in Fig. 51. Similar to the previous setup, air domains are modeled both above and below the plate to capture wave propagation and its interaction with defects. The transmission and reception domains in the air are placed 60 mm apart and designed as rectangular regions, each with a width of 25 mm to match the dimensions of the 100 kHz transducer used in the experiment and positioned 20 mm above the top surface of the plate. The rectangles are oriented at angles of 10° and -10° relative to the y-axis to optimize the generation and reception of the A0 mode at 100 kHz. The same material properties, boundary conditions, and meshing approach are applied in this model to investigate the wave propagation.

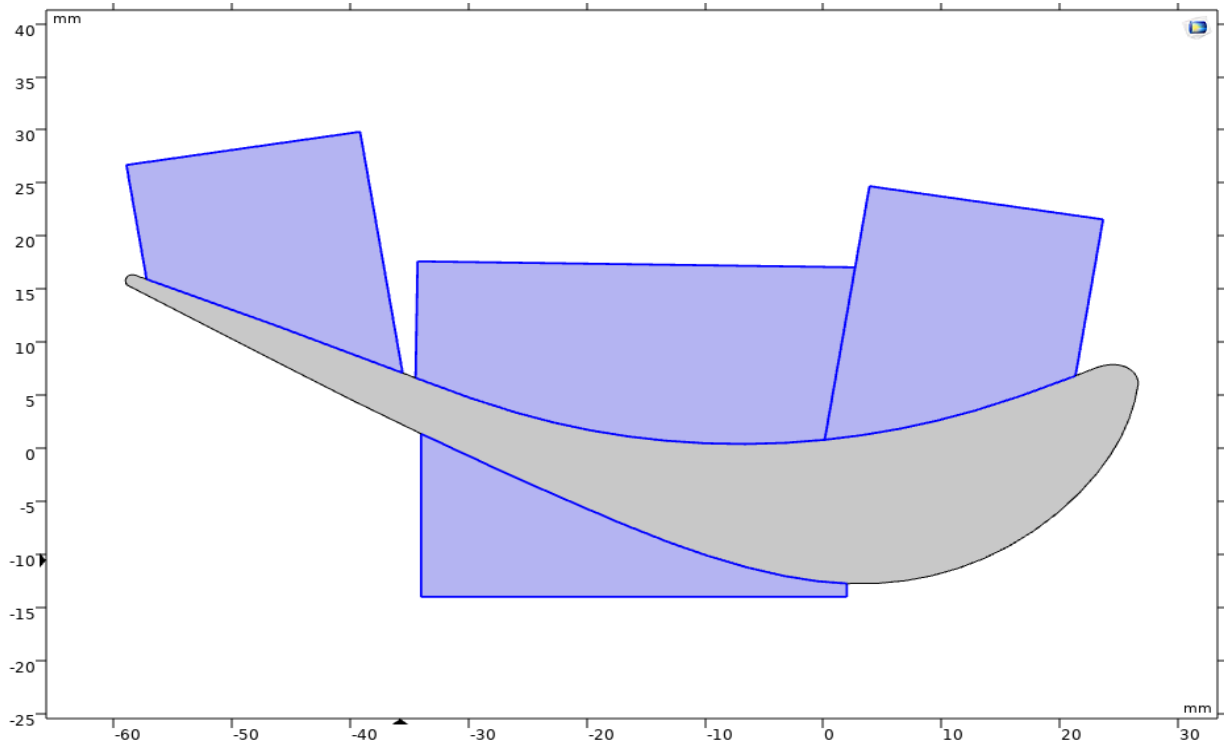


Fig. 51. Geometric configuration of the 2D Airfoil cross-sectional and air-coupled guided wave simulation model in COMSOL.

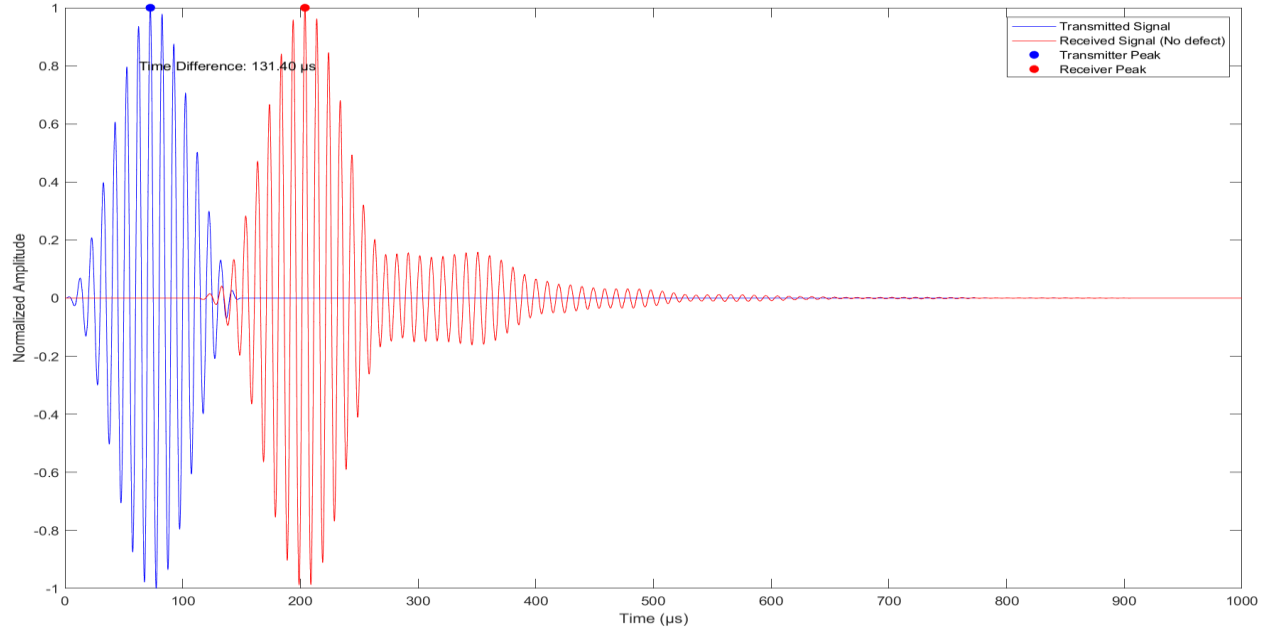


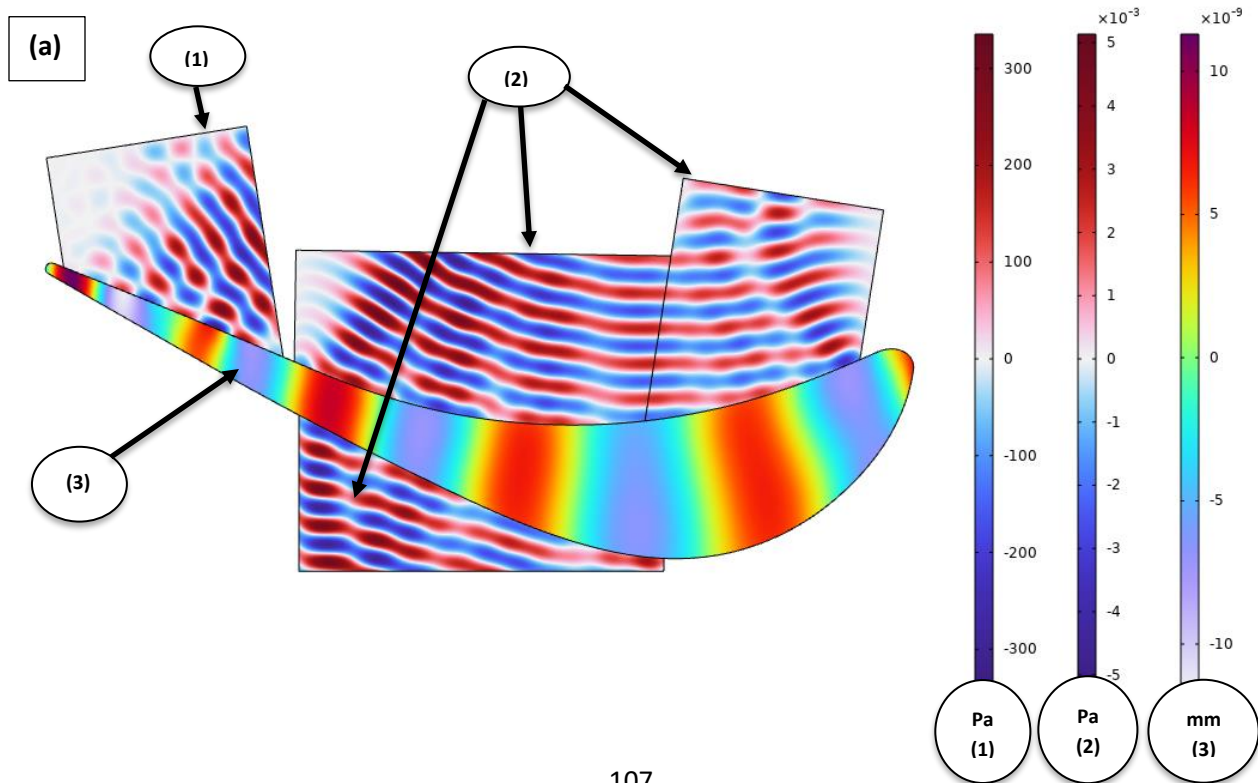
Fig. 52. Normalized Amplitude of Transmitter and Receiver Signals

As demonstrated earlier, the ToA of the guided wave signal is significantly affected by the airfoil's complex geometry, as the material thickness changes along the wave's path, the ToA depends on the wave's route, which involves traveling through the plate's thickness or reflecting along its surface. For instance, the analytical ToA for an IN738 airfoil is calculated as 118 μs , while the COMSOL simulation predicts a ToA of 131.4 μs , as shown in Fig. 52. COMSOL simulations can better handle thickness variations by adapting the wave's path accordingly. It also accounts for changes in wave modes and reflections, which can affect wave speed and increase the ToA, explaining the longer times observed in the results.

The guided wave propagation in the IN738 airfoil cross-section, analyzed at 163 μs , reveals distinct behaviors under three scenarios: healthy, notched, and internally cracked as shown in Fig. 53. The wave propagation in the air domain is depicted by acoustic pressure in Pascals, whereas in the IN738 airfoil, it is shown as normal displacement in millimeters. The amplitude at the reception area (2) is reduced compared to the excitation area (1) due to transfer losses during interaction with the solid plate. In the healthy condition, the wave travels smoothly with a uniform distribution and minimal disturbances, reflecting

normal behavior in a defect-free medium. In the notched condition, featuring a U-notch with a 4 mm radius, the external notch disrupts the wavefront, causing localized reflections and scattering that redistribute the wave energy and alter its amplitude near the defect. In the internally cracked condition, the wavefront experiences less disruptions, energy attenuation and amplitude reduction compared to the notched scenario.

In Fig. 54, the waveforms recorded at the receiver boundary are compared for three different conditions: a signal without defects, a signal with a notch defect (Fig. 54.a), and a signal with a void defect (Fig. 54.b). The signal without defects serves as the baseline, representing typical wave propagation through the material. The presence of a notch defect leads to significant waveform attenuation and greater distortion, likely due to the sharp edges of the notch scattering the wave more intensely. On the other hand, the void defect causes a more moderate attenuation with less waveform distortion, indicating that the smoother geometry of the void results in less scattering. These findings demonstrate that the notch defect has a more noticeable impact on the wave's amplitude and shape, making it easier to detect, while the void defect produces subtler changes. This comparison underscores the potential of acoustic waveforms in identifying and distinguishing different types of defects.



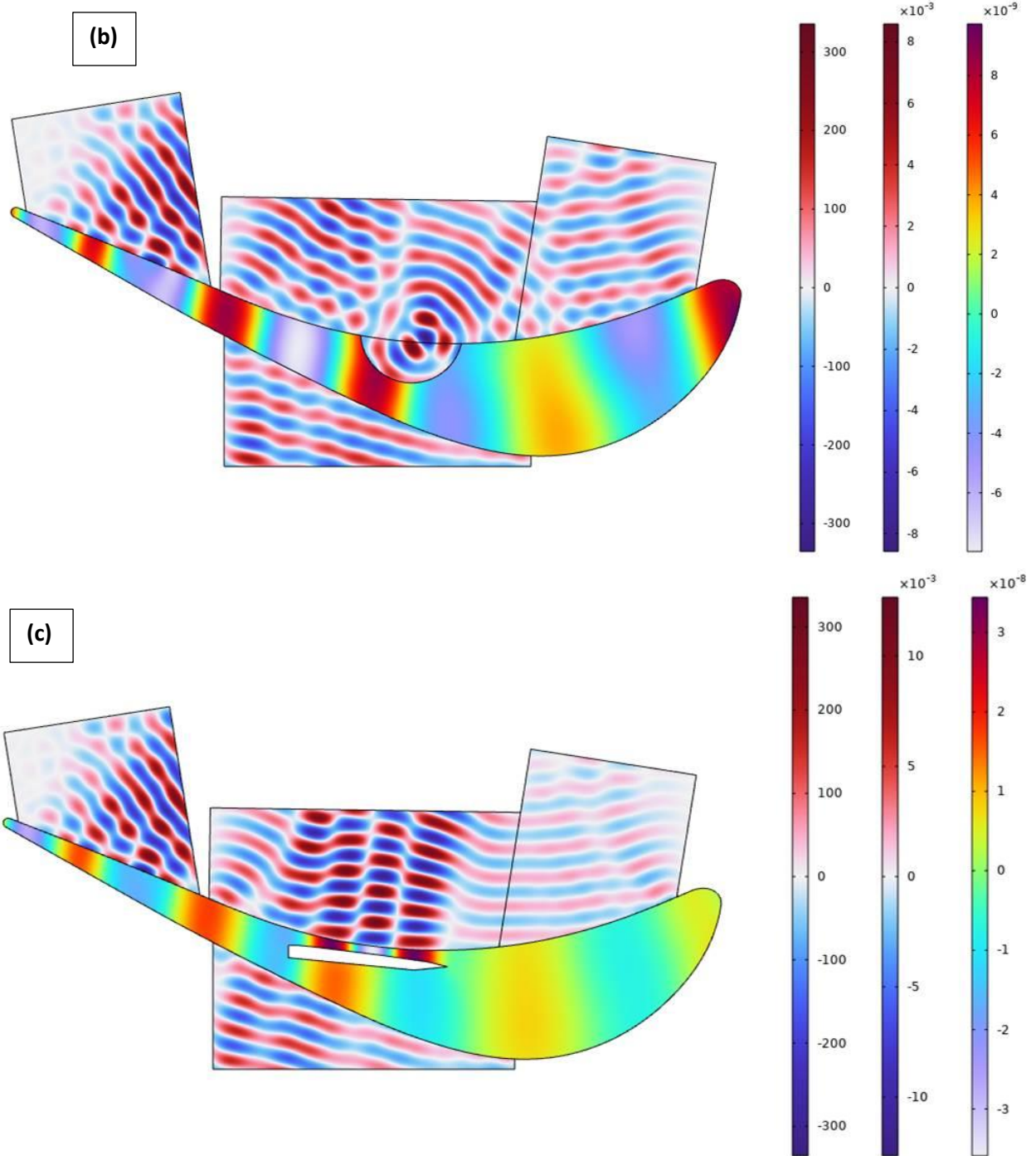


Fig. 53. Guided Wave Propagation in IN738 Airfoil Cross-sectional: Healthy (a), Notched (b), and Internally Cracked (c) Scenarios at 163 μs

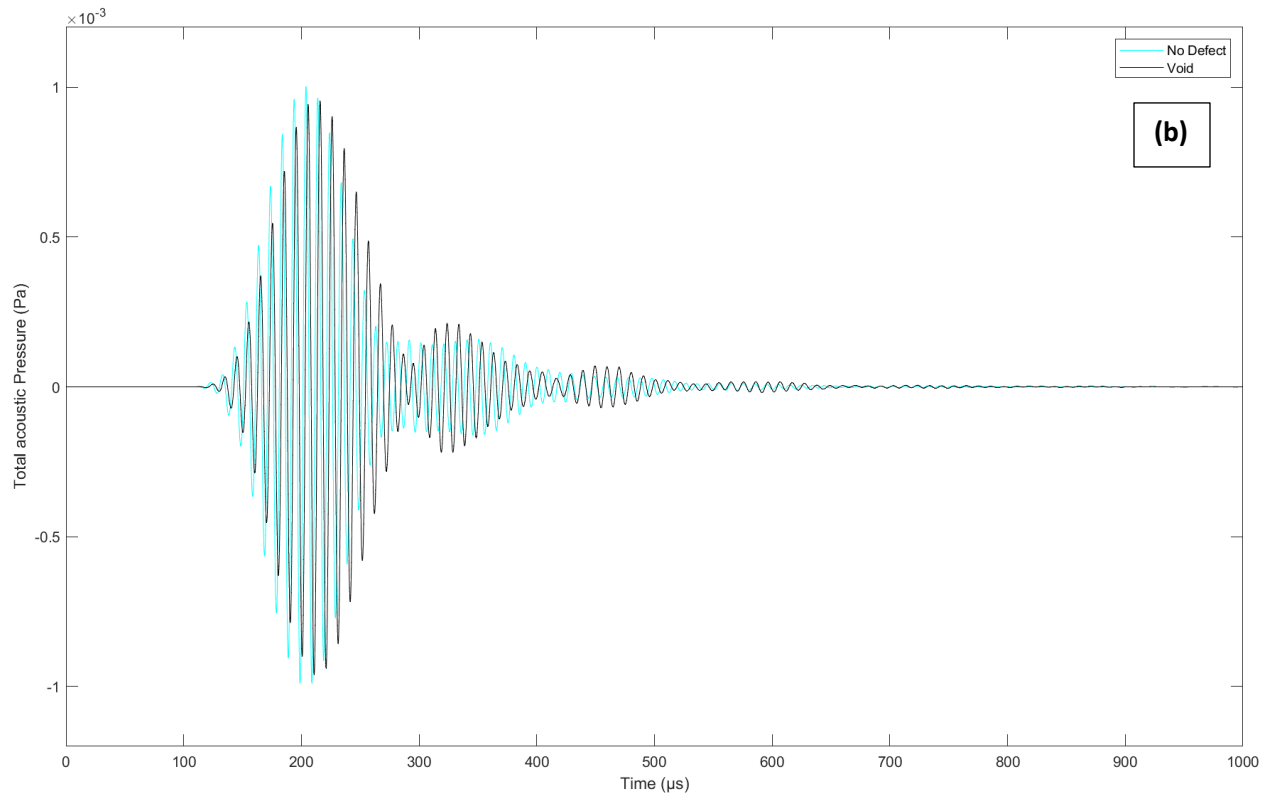
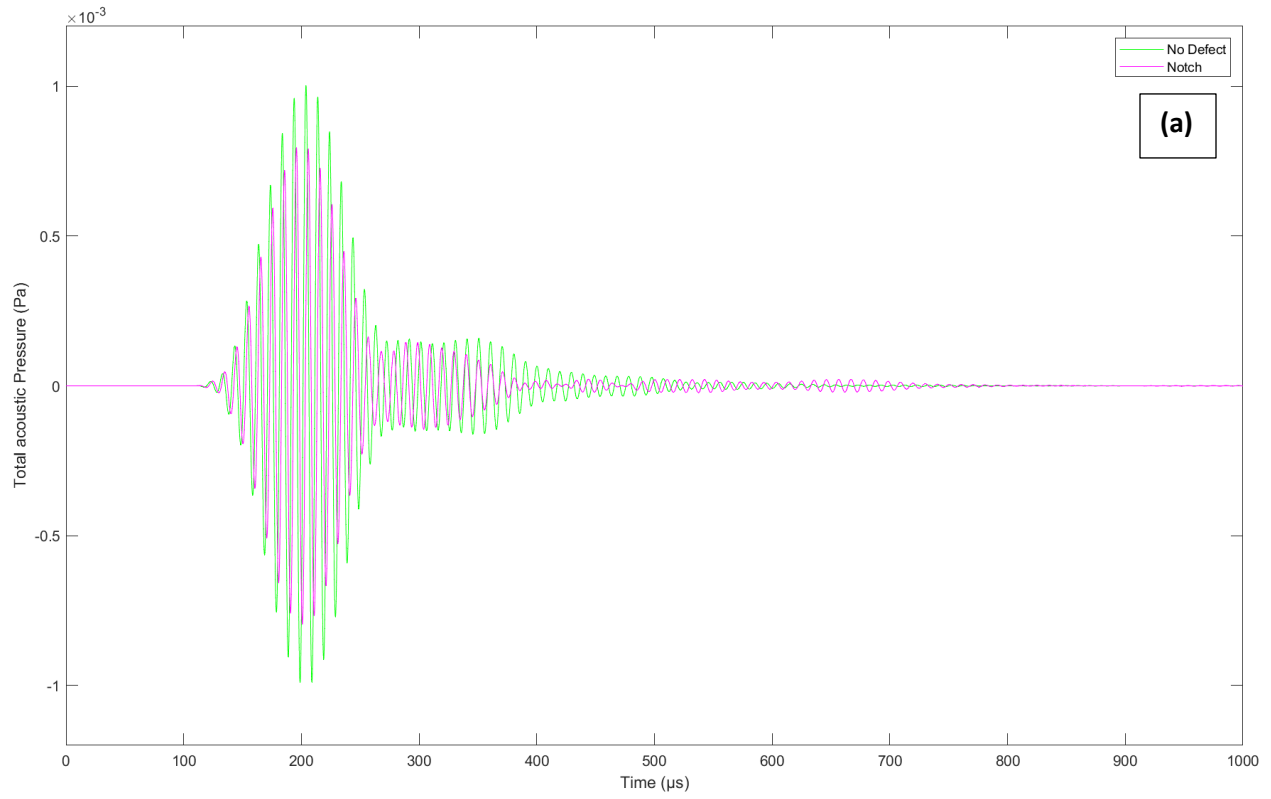


Fig. 54. Comparison of Waveform Attenuation in an Airfoil with Notch (a) and Void (b) Defects

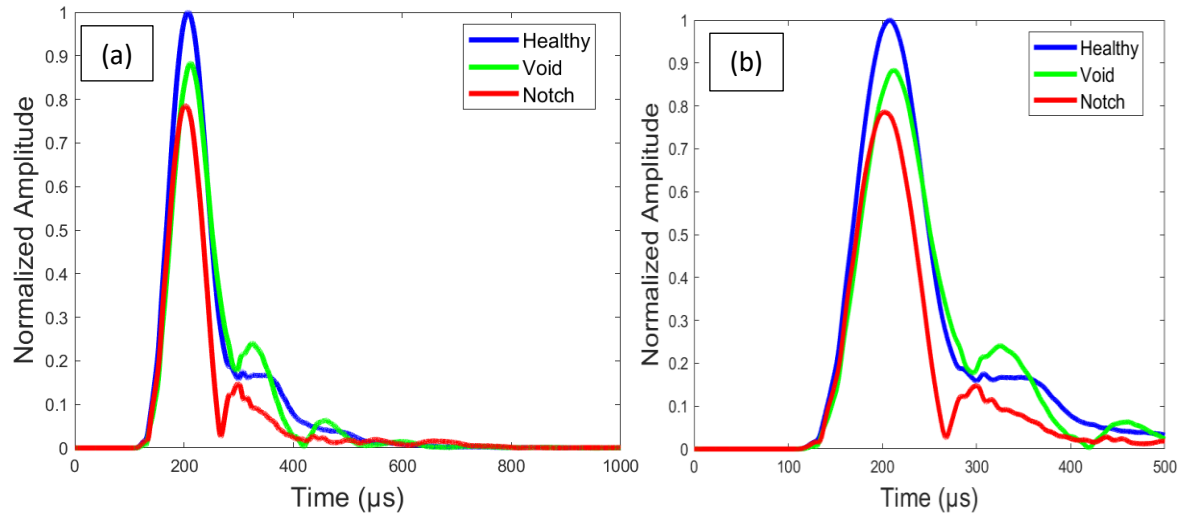
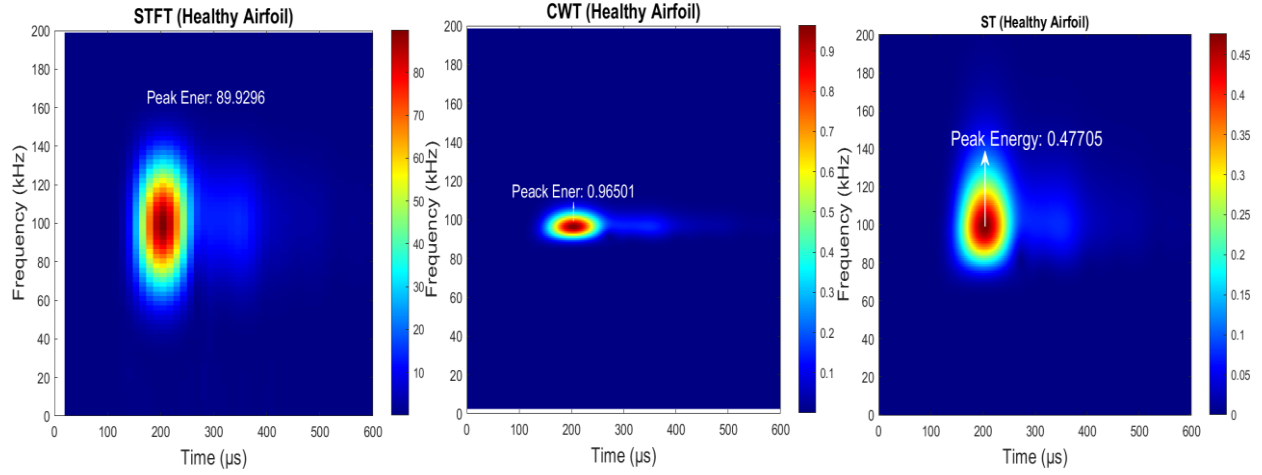
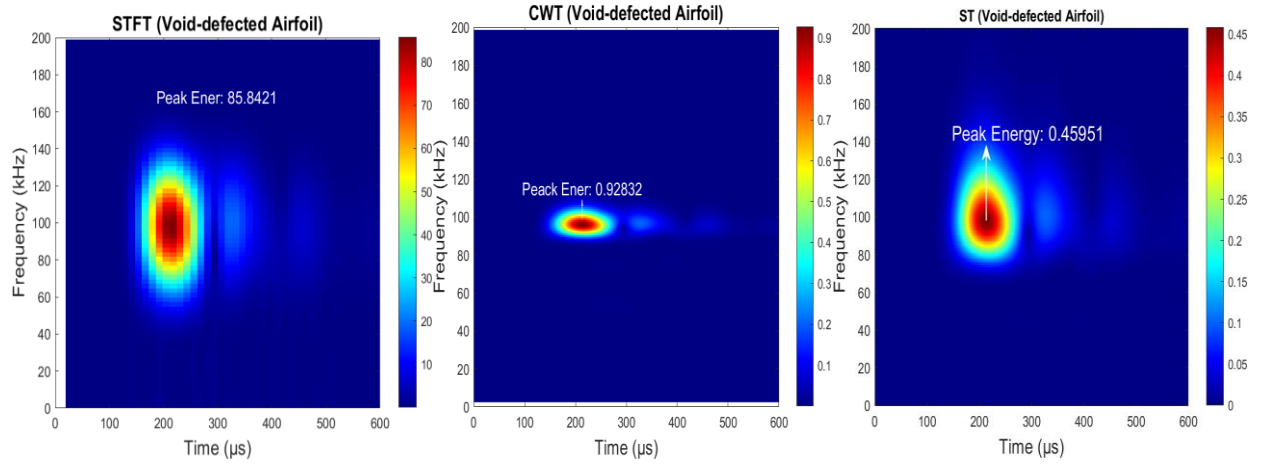


Fig. 55. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Healthy plate obtained from the simulation (a) Full Received Signal and (b) Snapshot of 0-500 μ s.

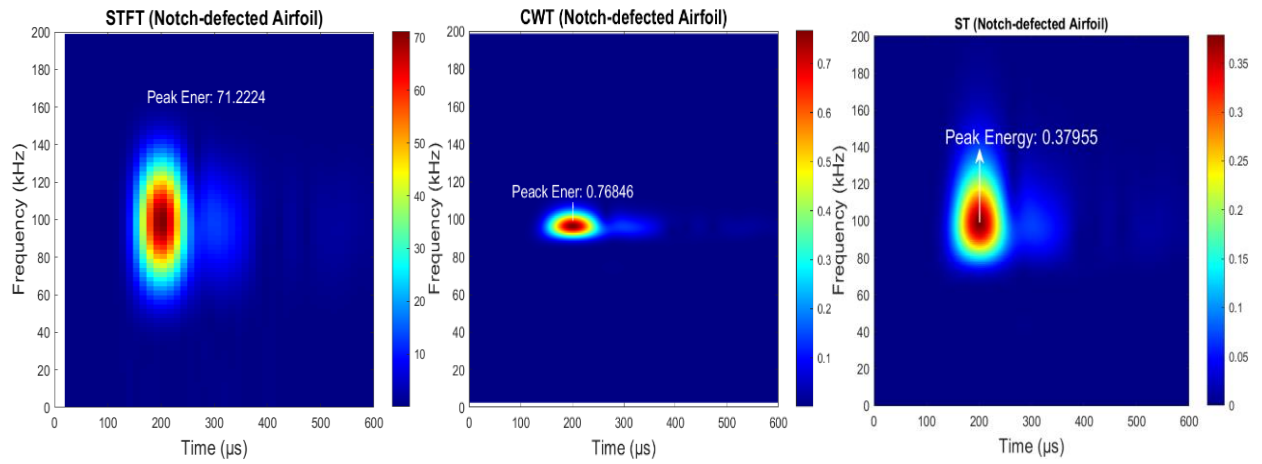
Figure 55 presents normalized Hilbert waveforms with bandpass-filtered envelopes, with a frequency range of 80-120 kHz, relative to the healthy plate. The healthy material shows a single dominant peak with smooth decay, indicating minimal disruption. In contrast, void and notch defects reduce amplitude, with the notch showing the most significant attenuation. A second peak, more pronounced for voids due to smoother wave interactions, highlights the differing effects of defect geometry. Notches, with sharp edges, cause greater energy scattering, while voids allow more energy transmission. These findings align with literature and experiments, confirming the second peak as indicative of damage and the open crack would reduce the reflective area causing higher amplitude attenuation. To further analyze guided wave behavior in defective airfoils, the TFR method is applied. Fig. 56 shows energy concentrated around 100 kHz, consistent with the transducer frequency. STFT, CWT, and ST spectrograms reveal differences in energy distribution and attenuation between healthy and defective plates. The healthy plate exhibits the highest peak energy, while the void-defected plate shows moderate energy loss, and the notch-defected plate displays the lowest peak energy due to pronounced wave scattering.



(a) TFRs of signals of Healthy Airfoil



(b) TFRs of signals of Void-defected Airfoil



(c) TFRs of signals of Notch-defected Airfoil

Fig. 56. TFRs for signals for (a) Healthy, (b) Void-defected and (c) Notch- defected Airfoils

6.3 Effect of TBC -2D Simulation:

To explore the impact of the presence of TBC on air-coupled guided wave transmission, two basic 2D structures are simulated using COMSOL Multiphysics. These simulations aim to assess the observations noted in section 4.5.2 and corroborate experimental results. The configuration for the simulations is depicted in Fig 57, which illustrates a plate composed of Inconel 738, both with and without the application of TBC, each maintaining a consistent thickness of 1.41 mm, in which the TBC thickness is 0.41 mm, and width of 200 mm. The transmission and reception domains in the air were designed as rectangles with a width of 25 mm and 20 mm away from the top surface of the plate, matching the diameter of the 100 kHz transducer utilized in the experiment, and were positioned 100 mm apart. These rectangles are oriented at angles of 13° and -13° with respect to the y-axis to efficiently generate and receive the A0 mode at 100 kHz as obtained from the DC calculator. The used IN738 and TBC material properties and thickness of consisting material are the same as presented in Table-3. The air properties used for simulations are set to a temperature of 21°C , with a density of $1.2041 \frac{\text{kg}}{\text{m}^3}$ and a velocity of 343 m/s.

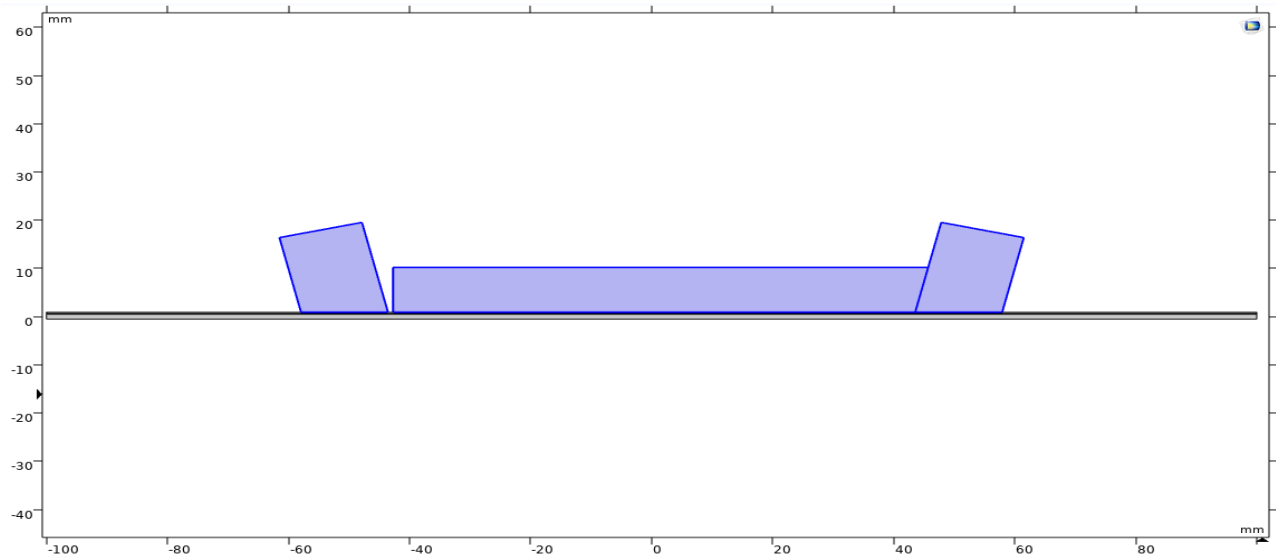


Fig. 57. IN738 Plate with TBC

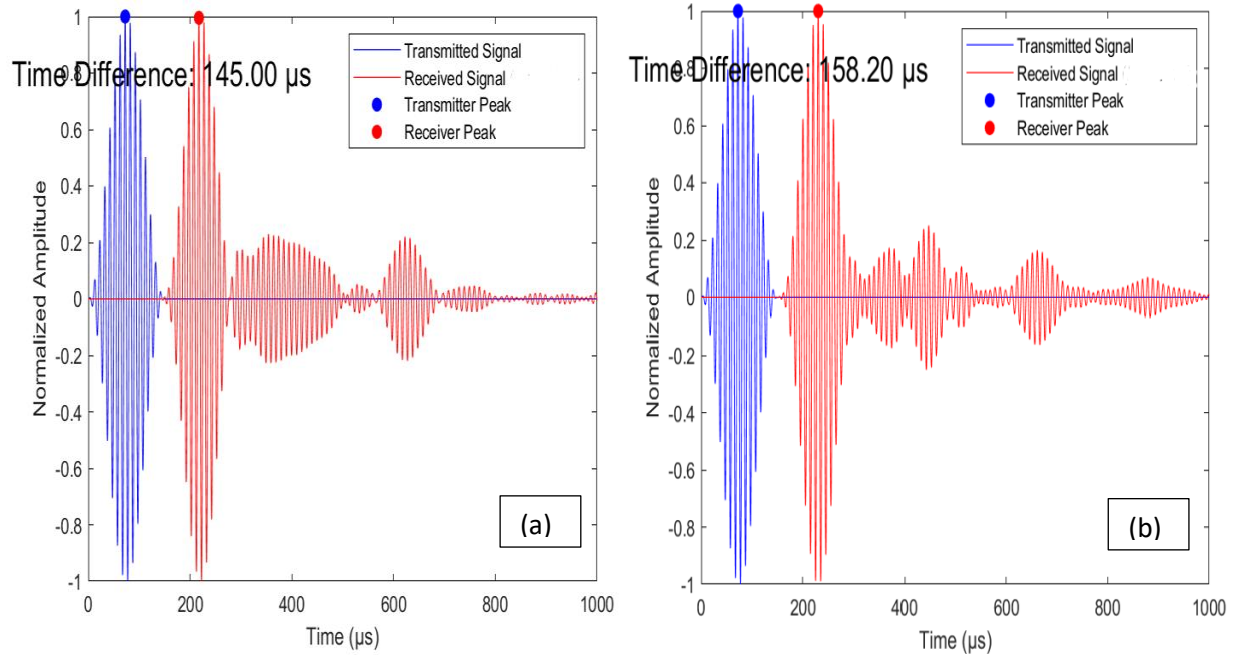


Fig. 58. Normalized Amplitude of Pure IN738 (a) and IN738+TBC Signals (b).

Figure 58. presents the normalized received signal for pure IN738 and IN738 with a TBC coating. The results show that the addition of the TBC coating introduces a slight delay in the signal's arrival. This delay, measured at 13.2 μs, is attributed to the coating's impact on wave propagation as discussed in the literature, which is likely due to changes in material properties such as wave velocity and energy interaction with the coating layer.

Figure 59. presents the normalized Hilbert waveforms with bandpass-filtered envelopes for an IN738 plate with and without the presence of TBC. Normalizing these waveforms relative to the coated plate provides a clearer insight into the underlying wave propagation phenomena. A bandpass-filtered frequency range of 80–120 kHz, chosen to center around the air-coupled transducer's operating frequency of 100 kHz. The addition of the TBC results in increased energy absorption by the coating, resulting in a slight reduction in wave amplitude and a noticeable delay in signal arrival, aligning with findings from the literature. Furthermore, the TBC alters wave mode characteristics, potentially decreasing the efficiency of energy coupling into the modes that are most effective at propagating through the substrate.

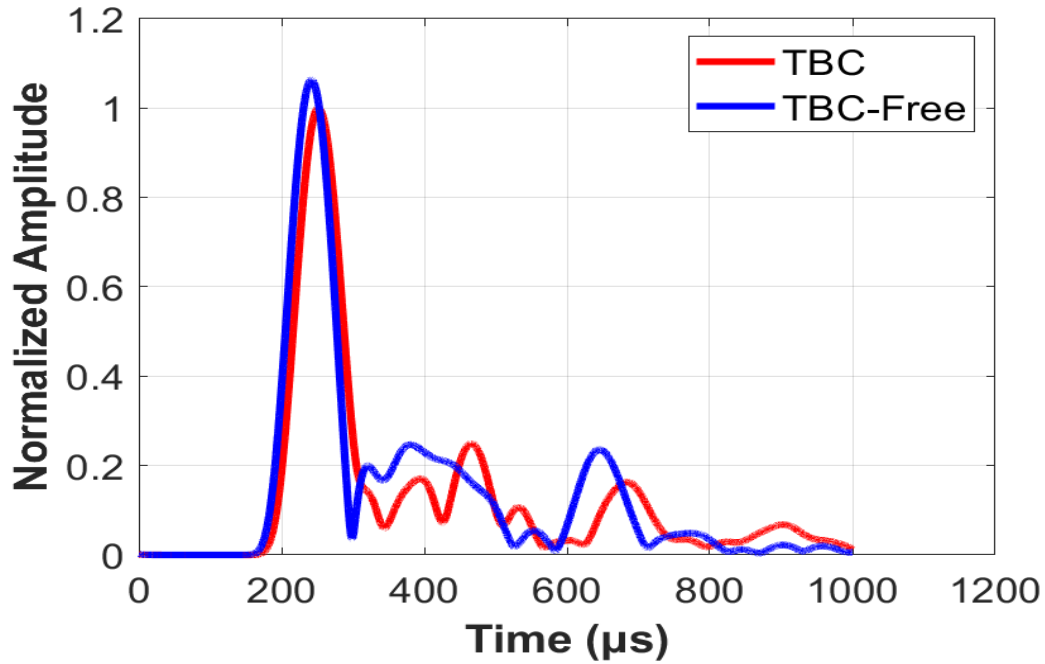
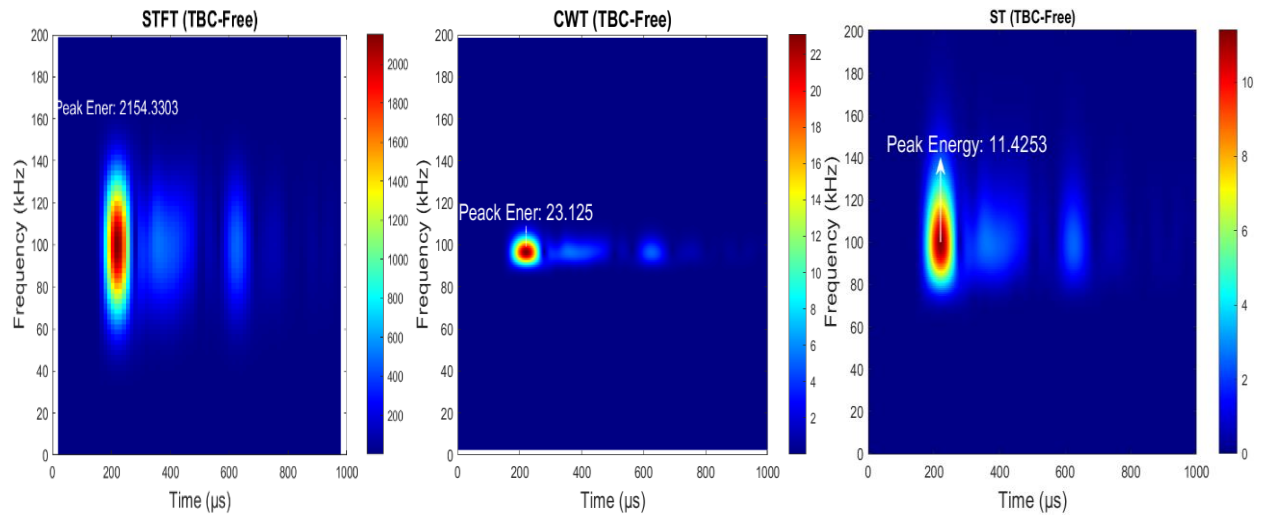
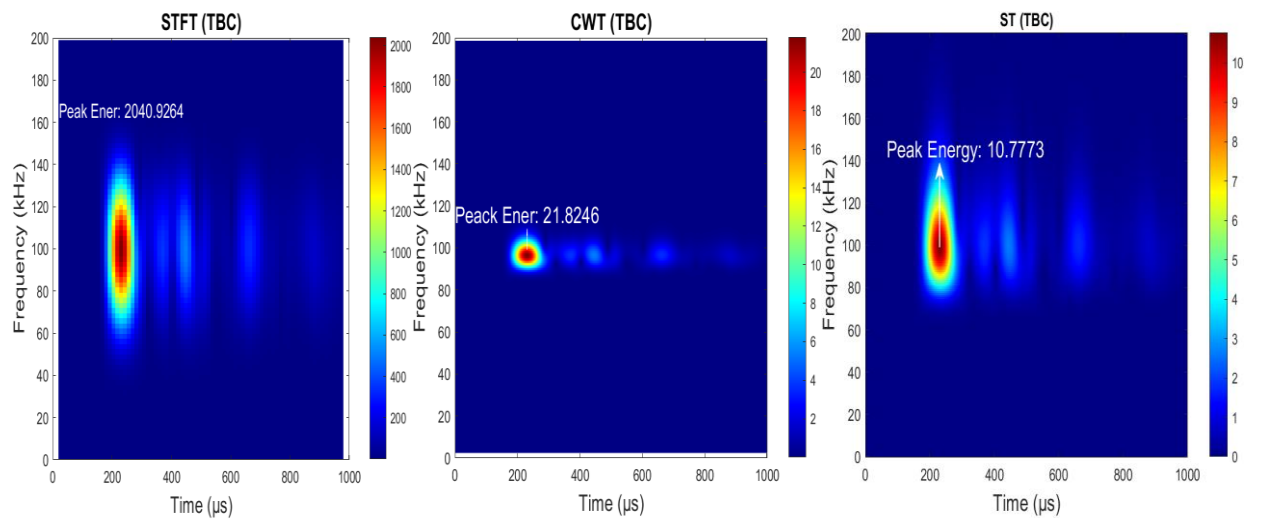


Fig. 59. Normalized Hilbert Waveform with Bandpass Filtered Envelope relative to the Coated plate obtained from the simulation.

To evaluate the impact of TBC on signal behavior, TFRs are applied to the received signals with and without TBC using STFT, CWT, and S-Transform. The TFRs shown in Fig. 60 reveal that higher energy regions are concentrated around 100 kHz, matching the transducer frequency. While the TFRs for both TBC-coated and uncoated signals exhibit similar time-frequency patterns, significant differences in energy levels are observed at corresponding points. These variations in energy, highlighted in Fig. 60, allow for distinguishing between signals with and without TBC based on the energy discrepancies in the TFR.



(a) TFRs of signals of Pure IN738 Plate



(b) TFRs of signals of IN738 Coated Plate

Fig. 60. TFRs for signals for (a) Pure IN738, (b) IN738+TBC Plates

6.4 Validation

To assess the reliability of the numerical results, experimental measurements conducted on the turbine blade were compared with the outputs of the two-dimensional finite element model developed using COMSOL Multiphysics. Given that the numerical model employs a simplified representation of the actual blade geometry and boundary conditions, the validation emphasizes qualitative agreement rather than strict quantitative matching. The comparison aims to verify that the simulation captures the essential characteristics of wave propagation observed experimentally.

6.4.1 Plate with Varying Thickness Model

Figure 33.a presents the experimental A-scan signals for a healthy turbine blade and a blade containing a crack, while Fig. 49.a shows the corresponding numerical simulation results for a healthy plate, a plate with a void, and a plate with a notch. The notch in the simulation is intended to represent the crack observed in the experimental specimen. In both the experimental and simulation results, the presence of a defect leads to a noticeable reduction in the amplitude of the direct wave compared to the healthy case. Additionally, a second dominant peak is observed after the initial arrival in the cracked or notched cases, which is attributed to reflections or scattering caused by the presence of the defect. The qualitative similarity between the experimental and simulated results confirms that the developed numerical model is capable of capturing the essential features of defect-induced wave scattering and energy dissipation.

The TFRs from the simulation (Fig. 50) show energy concentration around 100 kHz and significant attenuation due to defects, consistent with experimental observations (Fig. 39). Although the simulated energy loss (~50%) is higher than the experimental reduction (~35%), this difference is reasonable given the simplified tapered plate geometry used in the model. The absence of complex blade curvature in the simulation likely led to stronger scattering and higher energy dissipation. Overall, the simulation captures the key trends in energy attenuation and scattering behavior, validating the reliability of the numerical model.

6.4.2 Airfoil Cross-Section Model

Figure 33.a shows the experimental A-scan signals obtained from a healthy turbine blade and a blade with a crack, while Fig. 55.a presents the corresponding simulated results for a healthy airfoil cross-section and airfoils with a void and a notch. The notch in the simulation serves as an idealized representation of the crack present in the experimental blade. Both experimental and simulated results consistently show that the presence of a defect causes a reduction in the amplitude of the direct wave when compared to the healthy condition. Additionally, secondary peaks and signal distortions are observed following the initial wave arrival in both the experimental and numerical cases, indicating wave scattering and reflections induced by the defects. While slight differences in timing and waveform shape are expected due to geometrical simplifications in the simulation, the overall trends between the experimental and simulation data are in good qualitative agreement. These results further confirm that the finite element model successfully captures the main features of guided wave behavior in more realistic geometries such as the turbine blade cross-section.

The TFRs obtained from the Airfoil Cross-Section simulation (Fig. 56) show energy concentration near 100 kHz, in agreement with the experimental blade results (Fig. 39). Defective models exhibit reduced energy levels compared to the healthy case, following the same trend observed experimentally. Although the simulated energy dissipation (~21%) is somewhat lower than the experimental reduction (~35%), this difference is reasonable given the simplified closer geometry in the model to the real blade, resulting in less scattering. The milder energy loss in the simulation is likely due to smoother wave interactions and less complex scattering compared to the actual cracked blade. Overall, the simulation captures the key features of defect-induced energy attenuation, confirming its effectiveness for predictive modelling.

6.4.3 IN738 Plate with and without TBC

The influence of the TBC layer on guided wave behavior was assessed by comparing signals from an IN738 plate with and without coating. As shown in the experimental (Fig. 30) and simulation results (Fig. 59), the addition of TBC led to a slight delay in wave arrival time and a noticeable reduction in signal amplitude.

The TFRs from both the experiment (Fig. 35) and simulation (Fig. 60) consistently show energy concentration around 100 kHz, aligned with the transducer frequency. Although the time-frequency structures are similar for TBC-coated and uncoated cases, both results highlight notable differences in energy levels. The coated samples exhibit reduced peak energy and broader dissipation due to the damping effect of the TBC. These consistent energy variations between experiment and simulation confirm the model's ability to accurately capture the influence of TBC on guided wave propagation. Overall, the observed delay in arrival time, the reduction in signal amplitude, and the differences in energy distribution are attributed to the viscoelastic properties of the TBC, which introduce additional damping and promote energy dissipation during wave propagation. The numerical results show strong qualitative agreement with the experimental observations and align well with trends reported in the literature, reinforcing the reliability of the simulation approach in capturing the effects of TBC on guided wave behavior.

6.5 Conclusion Remarks

Three distinct 2D simulations for the air-coupled system were developed to investigate the behavior of air-coupled guided waves in (1) a plate with varying thickness, (2) a cross-sectional airfoil, and (3) an IN738 plate with and without TBC.

A set of defects were introduced into the plate and airfoil to study their impact on guided wave behavior and to validate experimental results. The findings showed that defects led to energy dissipation, resulting in a reduction of signal amplitude compared to the defect-free case. Additionally, the defects caused a second dominant peak to appear after the direct signal arrival. The simulations and experimental results showed good agreement.

A comparison of IN738 plate with and without TBC revealed that the addition of TBC caused a slight delay in signal arrival and a decrease in amplitude. This effect is attributed to the viscoelastic properties of the coating, which dissipate energy from the Lamb waves as they propagate. The results demonstrated good agreement between the simulations, experimental findings, and literature.

CHAPTER 7

CONCLUSIONS AND FUTUR WORK

7.1 Conclusions

7.1.1 Turbine Blade Failures

Turbine blade failures can result from coating removal, erosion, corrosion, and fatigue, with TBC removal being the most prevalent. Abrasive particles cause erosion and damage to the blade's leading and trailing edges, while hot corrosion at the blade tip leads to material loss and reduced thickness. Fatigue failures often originate from cracks, with LCF involving early crack formation and gradual propagation, while HCF is influenced by additional damage types such as FOD, thermal fatigue, and LCF interactions. The failure progression begins with TBC removal, leading to erosion, material oxidation, and crack formation, which can culminate in thermal fatigue, blade fragmentation, and secondary failures like FOD or downstream component damage. Severe TBC loss (>50%) and fatigues necessitate interim inspections, potentially impacting turbine operation and availability. Moreover, the current inspection and maintenance practices had been discussed, which include using borescope cameras for internal damage detection without removing the turbine casing, though they may miss unseen areas. When the casing is open, visual inspection is commonly performed to identify visible damage like cracks or erosion but may fail to detect internal or microscopic issues. Advanced NDT methods, such as ultrasonic, radiographic, and eddy current testing, can identify surface and internal damages but require specialized training and equipment. The most thorough approach, strip-down inspection, involves disassembling and inspecting each blade individually but is highly time-consuming and costly. Additionally, gas turbine blades are typically repaired at mid-lifespan, involving cleaning to remove dirt and deposits, reapplying protective coatings to combat corrosion and erosion, and repairing or replacing damaged blades as needed.

7.1.2 BHM Techniques

A comprehensive review of the most relevant NDT and SHM techniques for gas turbines was conducted, offering a detailed comparison of various turbine blade monitoring methods. The analysis highlights the distinct advantages and limitations of these techniques in terms of monitored parameters, fault detection capabilities, and implementation challenges. Blade Tip Timing effectively identifies rubbing and cracks by measuring tip clearance and time of arrival; however, its application is hindered by the need for complex sensor installations and casing modifications, resulting in high costs. Vibrational monitoring, though effective for detecting rubbing and cracks, lacks the sensitivity required to identify minor defects and is associated with significant expenses. Temperature monitoring excels in the early detection of faults such as TBC loss, fatigue, corrosion, and erosion, though the selection of appropriate sensors presents a notable challenge.

Acoustic Emission techniques enable crack detection but face limitations due to signal attenuation, operational constraints in high-temperature environments, and elevated costs. Similarly, Ultrasound methods, including linear and non-linear techniques, offer precise crack detection when used within hybrid systems but are difficult to deploy in operational settings. Pressure-based techniques monitor casing pressure to detect rubbing and cracks, but operational implementation remains complex. Meanwhile, performance monitoring, which evaluates parameters like efficiency, pressure ratios, and flow rates, addresses all types of failure modes but necessitates extensive sensor networks and significant computational resources.

In conclusion, while each technique has distinct advantages and drawbacks, their applicability is contingent upon operational requirements, the type of fault being addressed, and practical feasibility. A hybrid strategy that integrates multiple monitoring methods could offer a more robust and comprehensive solution for the maintenance and fault detection of turbine blades.

7.1.3 TBC Effects on Air-Coupled Guided Waves

The influence of TBC on air-coupled guided wave propagation was investigated using the DC calculator. Dispersion curves and through-thickness displacement profiles were generated for 1.41 mm IN738 plates, both with and without TBC, to analyze the effect of TBC on wave behavior. The group velocity curves showed that the addition of TBC caused notable changes in wave mode characteristics, with modes in pure IN738 (A0 and S0) transforming into B0 and B1, and A1 and S1 into B2 and B3, respectively. The B1 mode, unlike the A0 mode in pure IN738, did not approach the Rayleigh wave speed at high frequency-thickness values. Furthermore, the application of TBC reduced the prominence of B2 and B3 modes, making them less discernible in the time domain.

Through-thickness displacement profiles at maximum energy velocity revealed that at lower frequency-thickness values, B0 and B1 resembled their single-material counterparts, exhibiting strong out-of-plane and in-plane motion, respectively. Higher-order modes, such as B2, showed increased sensitivity to surface defects due to significant displacement within the YSZ top coat, attributed to its lower Young's modulus. However, modes like B5, B7, and B9 exhibited reduced displacement and sensitivity to defects, leading to lower signal amplitudes. Overall, TBC altered wave propagation by modifying group velocity characteristics and reducing the detectability of higher modes.

An experimental study was conducted to evaluate a fully non-contact method using air-coupled transducers for guided wave excitation and sensing, aimed at examining the effects of TBC removal on turbine blades. The findings demonstrated notable distinctions in the received signals between coated and uncoated blades. The uncoated blade exhibited higher peak energy, reflecting more efficient wave transmission and reduced attenuation compared to the coated blade, where the presence of TBC resulted in increased energy dissipation and scattering. These results were derived through advanced signal processing techniques, including normalized Hilbert waveforms with bandpass-filtered envelopes, as well as time-frequency analysis methods such as STFT, CWT, and S-Transform. Moreover, feature extraction tools like EFC, ETC,

and DMR-EDC effectively characterized amplitude variation patterns across TBC-free and TBC-coated conditions.

A 2D simulation was conducted to examine the behavior of air-coupled guided waves in an IN738 plate, both with and without TBC. The findings indicated that the presence of TBC led to a minor delay in signal arrival and a reduction in signal amplitude. This phenomenon is attributed to the viscoelastic characteristics of the coating, which attenuate the energy of the Lamb waves during propagation. The simulation results were found to align well with experimental observations.

7.1.4 Crack Effects on Air-Coupled Guided Waves

An experimental investigation was carried out to assess a fully non-contact approach using air-coupled transducers for the excitation and detection of guided waves, with the goal of studying the impact of material loss due to FOD on turbine blades. The results revealed distinct differences between the signals from healthy and cracked blades. The cracked blade exhibited a second prominent peak after the arrival of the direct signal and showed a decrease in peak energy compared to the healthy blade, which was attributed to energy attenuation caused by scattering and dispersion. These observations were made possible through advanced signal processing techniques, including normalized Hilbert waveforms, bandpass-filtered envelopes, and time-frequency methods such as STFT, CWT and ST. Furthermore, feature extraction methods like EFC, ETC, and DMR-EDC effectively captured the amplitude variation patterns across both defect-free and defective conditions.

Two separate 2D simulations for the air-coupled system were developed to explore the behavior of air-coupled guided waves in (1) a plate with varying thickness and (2) a cross-sectional airfoil. A series of defects were introduced into both the plate and the airfoil to examine their effects on the guided wave propagation and to validate the experimental observations. The results revealed that the presence of defects caused energy dissipation, leading to a reduction in signal amplitude compared to the defect-free scenario. Moreover, the defects induced a second dominant peak to appear after the arrival of the direct signal. Both the simulation and experimental results showed good consistency.

Overall, these findings underline the potential of air-coupled guided waves for applications in NDT and SHM, offering quantifiable metrics for defect detection and assessment in coated, uncoated, healthy and defected turbine blades. These findings provide valuable insights for monitoring structural integrity, optimizing wave propagation, and understanding the implications of coatings and cracks on blade performance.

7.2 Future Work

There is significant potential for further research in this field, particularly in the following areas:

7.2.1 Environmental Factors

Gas turbines operate under extreme conditions of high temperatures and high pressures, which present significant challenges for the implementation of air-coupled guided wave systems. Understanding how these environmental factors influence the transmission of guided waves is crucial for ensuring the reliability and accuracy of non-contact inspection techniques in turbine applications. Factors such as temperature variations can alter the material properties of both the turbine blade and the air, potentially affecting wave speed, attenuation, and dispersion. High pressure environments may also impact the behavior of guided waves, including their interaction with defects. Therefore, studying the effects of these environmental conditions on wave propagation would provide valuable insights for optimizing air-coupled systems and improving the precision of damage detection in turbines operating under such conditions.

7.2.2 Sensors Optimization and Installation

Optimizing the design, performance, and installation of sensors is essential for improving the effectiveness of air-coupled guided wave systems in turbine blade inspection. This research emphasizes the benefits of using a non-contact sensing system, which simplifies the challenges posed by environmental factors that can affect the sensor body and its wiring connections. By eliminating direct physical contact with the turbine blade, a non-contact system reduces the risk of sensor damage from harsh conditions such as high

temperatures, pressure, and vibrations. It also alleviates the complexity associated with installing and maintaining wiring, providing a more robust and reliable solution for long-term monitoring in demanding environments. However, the complex geometry of turbine blades presents challenges in obtaining useful signals with a single transmitter and receiver. To address this, phased array air-coupled transducers could offer a promising alternative for effective wave excitation and sensing. The propagation of a single-mode Lamb wave in variable thickness blades can be modeled as the wave traveling through a series of short, constant-thickness elements with varying thickness. The partial output response of one element can serve as the input excitation for the next element in the propagation direction, enabling more accurate wave propagation analysis. Therefore, investigating the installation possibilities of phased array air-coupled transducers and examining their improvements in relation to wave propagation would offer valuable insights for optimizing air-coupled systems and enhancing the accuracy of damage detection in turbine blades.

7.2.3 Advanced Defect Characterization

Developing a deeper understanding of the interaction between air-coupled guided waves and more complex types of defects, such as microstructural flaws or those induced by operating conditions like temperature variations or fatigue, could significantly enhance the detection and diagnosis of turbine blade damage. By creating artificial cracks using advanced machining techniques, we can simulate various defect types and study their impact on wave propagation in detail. This approach would help to better understand how these defects affect the signal response and improve the accuracy of damage detection. Additionally, the development of machine learning models, such as neural networks, could play a pivotal role in connecting the observed wave behavior to specific types of cracks. By training these models with experimental data on wave responses from different defect scenarios, a neural network could potentially classify and quantify defects based on their unique wave signatures. This could lead to more precise and automated defect detection systems, enabling early identification of damage and contributing to more efficient maintenance and monitoring of turbine blades.

7.2.4 Simulation Models

The 2D FEM used in this study produced results that closely aligned with the experimental findings. While efforts have been made to extend the 2D model into a 3D model, this work is still ongoing and was not included in this research due to the need for advanced systems and processing capabilities.

References

- [1] S. Gupta, Optimization of Gas Turbine Blades Under Manufacturing Uncertainties, *Journal of Purdue Undergraduate Research* 8 (2018) 75–76. <https://doi.org/10.5703/1288284316742>.
- [2] D.C. de Oliveira, J.R. Pinheiro Vaz, M. de O. E Silva, E.B.S. de Abreu, M.A. Barros Galhardo, L.F. de Araújo, TMSmall steam turbine operating at low pressure for generating electricity in the Amazon, *Revista Materia* 28 (2023). <https://doi.org/10.1590/1517-7076-RMAT-2023-0059>.
- [3] J. Kamenik, I. Voutchkov, D.J.J. Toal, A.J. Keane, L. Högner, M. Meyer, R. Bates, Robust Turbine Blade Optimization in the Face of Real Geometric Variations, *J Propuls Power* 34 (2018) 1479–1493. <https://doi.org/10.2514/1.B37091>.
- [4] M. Perrut, P. Caron, M. Thomas, A. Couret, High temperature materials for aerospace applications : Ni-based superalloys and γ -TiAl alloys, *C R Phys* 19 (2018). <https://doi.org/10.1016/j.crhy.2018.10.002>.
- [5] H.S. Mali, D.R. Unune, Machinability of Nickel-Based Superalloys: An Overview, in: *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2017. <https://doi.org/10.1016/b978-0-12-803581-8.09817-9>.
- [6] Ikuhiro INAGAKI, Yoshihisa SHIRAI, Tsutomu TAKECHI, Nozomu ARIYASU, Application and Features of Titanium for the Aerospace Industry, *NIPPON STEEL & SUMITOMO METAL* 106 (2014) 22–27.
- [7] T.S. Chowdhury, F.T. Mohsin, M.M. Tonni, M.N.H. Mita, M.M. Ehsan, A critical review on gas turbine cooling performance and failure analysis of turbine blades, *International Journal of Thermofluids* 18 (2023). <https://doi.org/10.1016/j.ijft.2023.100329>.
- [8] R. Dewangan, J. Patel, J. Dubey, P. Kumar Sen, S. Kumar Bohidar, C. Author, GAS TURBINES BLADES-A CRITICAL REVIEW OF FAILURE ON FIRST AND SECOND STAGES, *International Journal of Mechanical Engineering and Robotics Research* 4 (2015) 216–223.
- [9] H.M. Tawancy, A.I. Mohammad, L.M. Al-Hadhrami, H. Dafalla, F.K. Alyousf, On the performance and failure mechanism of thermal barrier coating systems used in gas turbine blade applications: Influence of bond coat/superalloy combination, *Eng Fail Anal* 57 (2015) 1–20. <https://doi.org/10.1016/j.engfailanal.2015.07.023>.
- [10] I.H. Shin, D.K. Lee, Y.S. Kim, J.M. Koo, C.S. Seok, T.W. Lee, Assessment of the characteristic of thermal barrier coating applied to gas turbine blade by thermo-gradient mechanical fatigue test, in: *Procedia Eng*, Elsevier Ltd, 2013: pp. 210–213. <https://doi.org/10.1016/j.proeng.2013.03.244>.
- [11] S. Rani, A.K. Agrawal, V. Rastogi, Failure analysis of a first stage IN738 gas turbine blade tip cracking in a thermal power plant, *Case Stud Eng Fail Anal* 8 (2017) 1–10. <https://doi.org/10.1016/j.csefa.2016.11.002>.

- [12] Y. Ji, C. Ma, B. Ge, S. Zang, Conjugate heat transfer investigation on the cooling performance of air cooled turbine blade with thermal barrier coating, *Journal of Thermal Science* 25 (2016) 325–335. <https://doi.org/10.1007/s11630-016-0867-6>.
- [13] M. Bogdan, J. Błachnio, A. Kułaszka, D. Zasada, Investigation of the relationship between degradation of the coating of gas turbine blades and its surface color, *Materials* 14 (2021). <https://doi.org/10.3390/ma14247843>.
- [14] A.A. Pauzi, N. Berahim, S. Husin, Degradation of Gas Turbine Blades for a Thermal Power Plant, in: *MATEC Web of Conferences*, 2016: pp. 1–4. <https://doi.org/10.1051/conf/20160002matec543>.
- [15] G. Sridhar, D. M, D. Mathew, G. H, CFD Analysis of A Thermal Barrier Coated Turbine Blade, *International Journal of Scientific and Research Publications (IJSRP)* 9 (2019) p9011. <https://doi.org/10.29322/ij srp.9.06.2019.p9011>.
- [16] V. Bonu, H.C. Barshilia, High-Temperature Solid Particle Erosion of Aerospace Components: Its Mitigation Using Advanced Nanostructured Coating Technologies, *Coatings* 12 (2022). <https://doi.org/10.3390/coatings12121979>.
- [17] B. Swain, P. Mallick, S. Patel, R. Roshan, S.S. Mohapatra, S. Bhuyan, M. Priyadarshini, B. Behera, S. Samal, A. Behera, Failure analysis and materials development of gas turbine blades, in: *Mater Today Proc*, Elsevier Ltd, 2020: pp. 5143–5146. <https://doi.org/10.1016/j.matpr.2020.02.859>.
- [18] M.J. Presby, N. Kedir, L.J. Sanchez, C. Gong, D.C. Faucett, S.R. Choi, G.N. Morscher, *EROSION BEHAVIOR IN A GAS TURBINE GRADE OXIDE/OXIDE CERAMIC MATRIX COMPOSITE*, 2019.
- [19] F.R. Martínez, M.T. Velázquez, J.A. Francis, A.A.R. Martínez, I.C. Mariscal, J.A.O. Herrera, G. Polupan, Theoretical and Numerical Analysis of the Mechanical Erosion in Steam Turbine Blades. Part II, *Energy Power Eng* 03 (2011) 238–245. <https://doi.org/10.4236/epe.2011.33030>.
- [20] L. Fathyunes, M.A. Mohtadi-Bonab, A Review on the Corrosion and Fatigue Failure of Gas Turbines, *Metals (Basel)* 13 (2023). <https://doi.org/10.3390/met13040701>.
- [21] R.M. Mitrović, D.B. Momčilović, I.D. Atanasovska, Determination of critical size of corrosion pit on mechanical elements in hydro power plants, *Applied Engineering Letters* 3 (2018) 1–5. <https://doi.org/10.18485/aeletters.2018.3.1.1>.
- [22] J. Molloy, P.E.O. Quintero, Combustion Turbine Compressor Condition Assessment, n.d. www.mmengineering.com.
- [23] M. Rajabinezhad, A. Bahrami, M. Mousavinia, S.J. Seyedi, P. Taheri, Corrosion-fatigue failure of gas-turbine blades in an oil and gas production plant, *Materials* 13 (2020). <https://doi.org/10.3390/ma13040900>.

- [24] D. Ziegler, M. Puccinelli, B. Bergallo, A. Picasso, Investigation of turbine blade failure in a thermal power plant, *Case Stud Eng Fail Anal* 1 (2013) 192–199.
<https://doi.org/10.1016/j.csefa.2013.07.002>.
- [25] K. Yonezawa, G. Nakai, M. Takayasu, K. Sugiyama, K. Sugita, S. Umezawa, S. Ohmori, Influence of blade corrosion on aerodynamic characteristics of a gas turbine, *Energy* 230 (2021).
<https://doi.org/10.1016/j.energy.2021.120665>.
- [26] R. Bannazadeh, M. Riahi, M. Aieneravaie, Failure Analysis of a Gas Turbine Blade Made of Inconel 738LC Super Alloy, *Amirkabir Journal of Mechanical Engineering Amirkabir J. Mech. Eng* 50 (2018) 35–38. <https://doi.org/10.22060/mej.2016.773>.
- [27] S. Asadikouhanjani, M. Torfeh, R. Ghorbanf, Failure Analysis of a Heavy Duty Gas Turbine Blade*, *Strength of Materials* 46 (2014) 608–612. <https://doi.org/10.1007/s11223-014-9589-8>.
- [28] V.N. Bhushana Rao, I.N. Kumar, K.B. Prasad, Failure analysis of gas turbine blades in a gas turbine engine used for marine applications, *International Journal of Engineering, Science and Technology* 6 (2014) 43–48. <https://doi.org/10.4314/ijest.v6i1.5>.
- [29] K. Prasad, B.A. Prasad, M. Anandarao, Material Optimization and Dynamic Approach for performance criteria in application to Gas Turbine Blade to overcome resonance, *Int J Sci Eng Res* 8 (2017). <http://www.ijser.org>.
- [30] J.F. Yang, L.L. Chen, W. Bin Liu, The failure cause and fault tree analysis to the blade of flue gas turbine, in: *Applied Mechanics and Materials*, 2013: pp. 403–407.
<https://doi.org/10.4028/www.scientific.net/AMM.378.403>.
- [31] S.P. Zhu, P. Yue, Z.Y. Yu, Q. Wang, A combined high and low cycle fatigue model for life prediction of turbine blades, *Materials* 10 (2017). <https://doi.org/10.3390/ma10070698>.
- [32] L. Bansal, V. Kumar Rathi, K. Mudafale, A Review on Gas Turbine Blade Failure and Preventive Techniques, *International Journal of Engineering Research and General Science* 6 (n.d.).
www.ijergs.org.
- [33] D.T. Vo, T.D. Mai, B. Kim, J.S. Jung, J. Ryu, Numerical investigation of crack initiation in high-pressure gas turbine blade subjected to thermal-fluid-mechanical low-cycle fatigue, *Int J Heat Mass Transf* 202 (2023). <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123748>.
- [34] C. Chen, X. Yan, X. Zhang, Y. Zhang, M. Gui, M. Tao, Effect of aluminized coating on combined low and high cycle fatigue life of turbine blade at elevated temperature, *J Eng Gas Turbine Power* 141 (2019). <https://doi.org/10.1115/1.4041252>.
- [35] A. V. Savikovskii, A.N. Gordeev, A.A. Michailov, O. V. Antonova, A.S. Semenov, Numerical Aspects of the J-Integral Estimation for Thermomechanical Loading, in: 2023: pp. 157–175.
https://doi.org/10.1007/978-3-031-37246-9_12.

- [36] Y. Kang, S. Cao, T. Gao, Z. You, Development and validation of a rotating blade-casing rubbing model by considering the blade deformation and abradable coating, *J Sound Vib* 563 (2023). <https://doi.org/10.1016/j.jsv.2023.117853>.
- [37] T. Tang, Y. Wang, S. Wang, S. He, Z.Y. Chen, M. Zhang, Rubbing characteristics of a rotating blade with cracks, *J Sound Vib* 567 (2023). <https://doi.org/10.1016/j.jsv.2023.117927>.
- [38] T. Tang, Y. Wang, Z. Chen, S. Wang, M. Zhang, Study on rubbing characteristics of blade-casing model considering transverse cracks, *J Sound Vib* 567 (2023). <https://doi.org/10.1016/j.jsv.2023.117928>.
- [39] J.H. Macdonald, An Investigation of the Damage Mechanisms Occurring During Compressor Blade Rubbing, 2020. <https://doi.org/10.26174/thesis.lboro.12241880.v1>.
- [40] M. Mohammadian, D. Akbari, M. Farahani, P. Faraji Kalajahi, Nondestructive inspection of gas turbine blades by active thermography using different fluids, *Proc Inst Mech Eng B J Eng Manuf* 236 (2022) 1553–1563. <https://doi.org/10.1177/09544054221078384>.
- [41] Gas Turbine Blade Inspection with NDT-RAM, n.d.
- [42] R. Przysowa, M. Chalimoniuk, D. Grzelka-Gajek, R. Shakalo, A. Karpenko, CT Inspection of Cooled Turbine Blades, *Journal of KONBiN* 50 (2020) 307–331. <https://doi.org/10.2478/jok-2020-0064>.
- [43] I. Alfred, M. Nicolaus, J. Hermsdorf, S. Kaierle, K. Möhwald, H.J. Maier, V. Wesling, Advanced high pressure turbine blade repair technologies, in: *Procedia CIRP*, Elsevier B.V., 2018: pp. 214–217. <https://doi.org/10.1016/j.procir.2018.08.097>.
- [44] M. Adamowicz, G. Zywicka, Advanced gas turbines health monitoring systems, *Diagnostyka* 19 (2018) 77–87. <https://doi.org/10.29354/diag/89730>.
- [45] F. Mevissen, M. Meo, A review of NDT/structural health monitoring techniques for hot gas components in gas turbines, *Sensors (Switzerland)* 19 (2019). <https://doi.org/10.3390/s19030711>.
- [46] A.M. Abdelrhman, L.M. Hee, M.S. Leong, S. Al-Obaidi, Condition monitoring of blade in turbomachinery: A review, *Advances in Mechanical Engineering* 2014 (2014). <https://doi.org/10.1155/2014/210717>.
- [47] M. Zielinski, G. Ziller, Noncontact vibration measurements on compressor rotor blades, *Meas Sci Technol* 11 (2000) 847–856. <https://doi.org/10.1088/0957-0233/11/7/301>.
- [48] Z. Wang, Z. Yang, S. Wu, H. Li, S. Tian, X. Chen, An Improved Multiple Signal Classification for Nonuniform Sampling in Blade Tip Timing, *IEEE Trans Instrum Meas* 69 (2020) 7941–7952. <https://doi.org/10.1109/TIM.2020.2980912>.

- [49] H. Li, S. Tian, Z. Yang, S. Wu, X. Chen, Phase-offset-based synchronous resonance identification method for blade tip timing signal, *Measurement (Lond)* 218 (2023). <https://doi.org/10.1016/j.measurement.2023.113166>.
- [50] J. Cao, Z. Yang, R. Sun, G. Teng, X. Chen, OPR-free single probe blade tip timing for monitoring rotating blade, *Int J Mech Sci* 247 (2023). <https://doi.org/10.1016/j.ijmecsci.2023.108174>.
- [51] S. REN, X. XIANG, Q. ZHAO, W. WANG, W. ZHAO, C. ZHAN, Multi-probe linear fitting and time of arrival linear correction method to analyze blade vibration based on blade tip timing without once-per-revolution, *Chinese Journal of Aeronautics* 36 (2023) 290–310. <https://doi.org/10.1016/j.cja.2022.06.006>.
- [52] J. Cao, S. Tian, Z. Yang, G. Teng, H. Li, R. Jin, R. Yan, X. Chen, Blade Tip Timing Signal Filtering Method Based on Sampling Aliasing Frequency Map, *IEEE Trans Instrum Meas* 71 (2022) 1–12. <https://doi.org/10.1109/TIM.2022.3156979>.
- [53] L. Zhang, Q. Wang, X. Li, Vibration Parameters Identification of Rotating Blades Based on Blade Tip-Timing Sensor Waveforms, *Applied Sciences (Switzerland)* 13 (2023). <https://doi.org/10.3390/app13105920>.
- [54] C. Fan, Y. Wu, P. Russhard, A. Wang, An Improved Blade Tip-timing Method for Vibration Measurement of Rotating Blades During Transient Operating Conditions, *Journal of Vibration Engineering and Technologies* 8 (2020) 859–868. <https://doi.org/10.1007/s42417-019-00195-0>.
- [55] J.W. Zhang, K.Q. Ding, G. Chen, High-Precision Extraction Method for Blade Tip-Timing Signal with Eddy Current Sensor, *International Journal of Rotating Machinery* 2020 (2020). <https://doi.org/10.1155/2020/8882858>.
- [56] T. Tocci, L. Capponi, G. Rossi, R. Marsili, M. Marrazzo, State-Space Model for Arrival Time Simulations and Methodology for Offline Blade Tip-Timing Software Characterization, *Sensors* 23 (2023). <https://doi.org/10.3390/s23052600>.
- [57] Z. Fan, H. Li, J. Dong, X. Zhao, D. Wei, Q. Zhou, Blade Vibration Difference-Based Identification of Blade Vibration Parameters: A Novel Blade Tip Timing Method, *J Sound Vib* 512 (2021). <https://doi.org/10.1016/j.jsv.2021.116402>.
- [58] J. Zhang, F. Duan, G. Niu, J. Jiang, J. Li, A blade tip timing method based on a microwave sensor, *Sensors (Switzerland)* 17 (2017). <https://doi.org/10.3390/s17051097>.
- [59] H. Ma, F. Yin, X. Tai, D. Wang, B. Wen, Vibration response analysis caused by rubbing between rotating blade and casing, *Journal of Mechanical Science and Technology* 30 (2016) 1983–1995. <https://doi.org/10.1007/s12206-016-0404-2>.

- [60] N. Wang, C. Liu, D. Jiang, K. Behdinan, Casing vibration response prediction of dual-rotor-blade-casing system with blade-casing rubbing, *Mech Syst Signal Process* 118 (2019) 61–77. <https://doi.org/10.1016/j.ymssp.2018.08.029>.
- [61] K. Feng, Y. Xiao, Z. Li, Z. Jiang, F. Gu, Gas turbine blade fracturing fault diagnosis based on broadband casing vibration, *Measurement (Lond)* 214 (2023). <https://doi.org/10.1016/j.measurement.2023.112718>.
- [62] Y. Xiao, K. Feng, Z. Li, F. Gu, Z. Jiang, Gas Turbine Blade Passing Frequency Reconstruction and Its Application for Blade Fracturing Fault Diagnosis, in: 2023: pp. 1006–1017. https://doi.org/10.1007/978-3-031-26193-0_88.
- [63] T. Ando, Pulsation and vibration measurement on stator side for turbocharger turbine blade vibration monitoring, *International Journal of Turbomachinery, Propulsion and Power* 5 (2020). <https://doi.org/10.3390/IJTPP5020011>.
- [64] C.R. Soto-Ocampo, J.M. Mera, J.D. Cano-Moreno, J.L. Garcia-Bernardo, Low-cost, high-frequency, data acquisition system for condition monitoring of rotating machinery through vibration analysis-case study, *Sensors (Switzerland)* 20 (2020) 1–19. <https://doi.org/10.3390/s20123493>.
- [65] D. Li, C. Feng, K. Daniel, S. Gao, L. Chen, Z. Kang, Turbine blade temperature error as measured with an optical pyrometer under different wavelengths and blade TBC thickness, *Appl Opt* 58 (2019) 1626. <https://doi.org/10.1364/AO.58.001626>.
- [66] B.E. Jaeger, S. Schmid, C.U. Grosse, A. Gögelein, F. Elischberger, Infrared Thermal Imaging-Based Turbine Blade Crack Classification Using Deep Learning, *J Nondestr Eval* 41 (2022). <https://doi.org/10.1007/s10921-022-00907-9>.
- [67] E. DeShong, B. Peters, K. Paynabar, N. Gebraeel, K.A. Thole, R.A. Berdanier, Applying Infrared Thermography as a Method for Online Monitoring of Turbine Blade Coolant Flow, *J Turbomach* 144 (2022). <https://doi.org/10.1115/1.4054814>.
- [68] J.G. Sun, N. Tao, Thermal property measurement for thermal barrier coatings using pulsed thermal imaging - Multilayer analysis method, in: *AIP Conf Proc*, American Institute of Physics Inc., 2016. <https://doi.org/10.1063/1.4940564>.
- [69] S. Gao, C. Feng, L. Wang, D. Li, Multi-spectral temperature measurement method for gas turbine blade, *Opt Rev* 23 (2016) 17–25. <https://doi.org/10.1007/s10043-015-0155-9>.
- [70] C. Falsetti, M. Sisti, P.F. Beard, Infrared thermography and calibration techniques for gas turbine applications: A review, *Infrared Phys Technol* 113 (2021). <https://doi.org/10.1016/j.infrared.2020.103574>.

- [71] D. Ketui, F. Chi, G. Shan, Single wavelength and ratio pyrometry reflection errors in temperature measurement of gas turbine blade, *Measurement (Lond)* 86 (2016) 133–140. <https://doi.org/10.1016/j.measurement.2016.02.054>.
- [72] T.P. Jenkins, C.F. Hess, S.W. Allison, J.I. Eldridge, Measurements of turbine blade temperature in an operating aero engine using thermographic phosphors, *Meas Sci Technol* 31 (2020). <https://doi.org/10.1088/1361-6501/ab4c20>.
- [73] Z. Zhang, G. Yang, K. Hu, Prediction of fatigue crack growth in gas turbine engine blades using acoustic emission, *Sensors (Switzerland)* 18 (2018). <https://doi.org/10.3390/s18051321>.
- [74] S. Shahkar, K. Khorasani, Gas Turbine Condition Monitoring Using Acoustic Emission Signals, *J Nondestruct Eval Diagn Progn Eng Syst* 2 (2019). <https://doi.org/10.1115/1.4044232>.
- [75] H. Jo, Y. Kim, D. Jo, Acoustically monitoring defects on rotating turbine blades, *Journal of Mechanical Science and Technology* 34 (2020) 1913–1923. <https://doi.org/10.1007/s12206-020-0413-z>.
- [76] M.S. Nashed, J.A. Steel, R.L. Reuben, The use of acoustic emission for the condition assessment of gas turbines: Acoustic emission generation from normal running, *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 228 (2014) 286–308. <https://doi.org/10.1177/0954408913502167>.
- [77] M.S. Nashed, J. Renno, M.S. Mohamed, R.L. Reuben, Gas turbine failure classification using acoustic emissions with wavelet analysis and deep learning, *Expert Syst Appl* 232 (2023). <https://doi.org/10.1016/j.eswa.2023.120684>.
- [78] F. Mevissen, M. Meo, A nonlinear ultrasonic modulation method for crack detection in turbine blades, *Aerospace* 7 (2020). <https://doi.org/10.3390/AEROSPACE7060072>.
- [79] E. Rau, J. Bamberg, J. Burchards, P. Berwig, W. Voelkl, High resolution crack detection on turbine blade roots by the use of eddy current and ultrasonic Rayleigh waves, 2016. <http://creativecommons.org/licenses/by-nd/3.0/>.
- [80] LI SHITAO; WANG YI; CAI HONGSHENG; JIN FENG; YANG XU; ZHANG WUNENG, Method for detecting ultrasonic guided wave of turbine blades, CN104535648A, 2015. <https://worldwide.espacenet.com/patent/search/family/052851218/publication/CN104535648A?q=pn%3DCN104535648A> (accessed December 30, 2023).
- [81] C.J.L. Lane, A.K. Dunhill, B.W. Drinkwater, P.D. Wilcox, The development of a 2D ultrasonic array system for the in situ inspection of single crystal turbine blades, in: 2012: pp. 865–872. <https://doi.org/10.1063/1.4716315>.
- [82] K.W. Lopes, C.G. Gonzalez-Bueno, D.J. Inman, D.D. Bueno, On the symmetric damage detection with flexural waves using circular piezoelectric transducers, in: P. Fromme, Z. Su (Eds.), *Health*

- Monitoring of Structural and Biological Systems XVII, SPIE, 2023: p. 16.
<https://doi.org/10.1117/12.2657300>.
- [83] M.K. Kim, Y.-K. An, H. Sohn, Piezoelectric transducers, in: *Sensor Technologies for Civil Infrastructures*, Elsevier, 2022: pp. 77–111. <https://doi.org/10.1016/B978-0-08-102696-0.00004-X>.
 - [84] Z. Fang, C. Gao, J. He, J. Lin, Graphene doped flexible piezoelectric transducers for guided wave application, in: *12th International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE 2022)*, Institution of Engineering and Technology, 2022: pp. 1009–1013. <https://doi.org/10.1049/icp.2022.3003>.
 - [85] E. Guerra-Bravo, A. Baltazar, Excitation of torsional guided waves with flexible PZT transducers in water-filled pipes, *Measurement* 216 (2023) 112903.
<https://doi.org/10.1016/j.measurement.2023.112903>.
 - [86] F. Mevissen, M. Meo, Ultrasonically stimulated thermography for crack detection of turbine blades, *Infrared Phys Technol* 122 (2022). <https://doi.org/10.1016/j.infrared.2022.104061>.
 - [87] Y. Jia, R.M. Zhang, W. Zhang, G.F. Jin, J.F. Liu, G. Tian, Z.W. Yang, Rapid Detection of Cracks in Turbine Blades Using Ultrasonic Infrared Thermography, in: *IOP Conf Ser Mater Sci Eng*, Institute of Physics Publishing, 2018. <https://doi.org/10.1088/1757-899X/389/1/012023>.
 - [88] Y. Seo, D. Kim, N.A. Hall, High-Temperature Piezoelectric Pressure Sensors for Hypersonic Flow Measurements, in: *2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII (TRANSDUCERS & EUROSENSORS XXXIII)*, IEEE, 2019: pp. 2110–2113. <https://doi.org/10.1109/TRANSDUCERS.2019.8808755>.
 - [89] C. Jiang, X. Liu, F. Yu, S. Zhang, H. Fang, X. Cheng, X. Zhao, High-temperature Vibration Sensor Based on $\text{Ba}_2\text{TiSi}_2\text{O}_8$ Piezoelectric Crystal With Ultra-Stable Sensing Performance up to 650 °C, *IEEE Transactions on Industrial Electronics* 68 (2021) 12850–12859.
<https://doi.org/10.1109/TIE.2020.3044792>.
 - [90] S. Bouchy, R.J. Zednik, P. Belanger, Ultrasonic Transducers for In-Service Inspection and Continuous Monitoring in High-Temperature Environments, *Sensors* 23 (2023).
<https://doi.org/10.3390/s23073520>.
 - [91] M.H. Amini, A.N. Sinclair, T.W. Coyle, A New High-Temperature Ultrasonic Transducer for Continuous Inspection, *IEEE Trans Ultrason Ferroelectr Freq Control* 63 (2016) 448–455.
<https://doi.org/10.1109/TUFFC.2016.2519348>.
 - [92] L. Yule, B. Zaghari, N. Harris, M. Hill, Surface temperature condition monitoring methods for aerospace turbomachinery: Exploring the use of ultrasonic guided waves, *Meas Sci Technol* 32 (2021). <https://doi.org/10.1088/1361-6501/abda96>.

- [93] J. Cox, P. Anusonti-Inthra, Turbine engine rotor blade fault diagnostics through casing pressure and vibration sensors, in: J Phys Conf Ser, Institute of Physics Publishing, 2014.
<https://doi.org/10.1088/1742-6596/548/1/012066>.
- [94] J. Ratz, G.L. Forbes, R.B. Randall, Post print of conference paper presented at MFPT 2013 and ISA's 59th International Instrumentation Symposium GAS TURBINE BLADE NATURAL FREQUENCY MEASUREMENT USING EXTERNAL CASING VIBRATIONS, 2013.
- [95] G.L. Forbes, R.B. Randall, Estimation of turbine blade natural frequencies from casing pressure and vibration measurements, Mech Syst Signal Process 36 (2013) 549–561.
<https://doi.org/10.1016/j.ymssp.2012.11.006>.
- [96] H. Hanachi, C. Mechefske, J. Liu, A. Banerjee, Y. Chen, Performance-Based Gas Turbine Health Monitoring, Diagnostics, and Prognostics: A Survey, IEEE Trans Reliab 67 (2018) 1340–1363.
<https://doi.org/10.1109/TR.2018.2822702>.
- [97] M. Tahan, E. Tsoutsanis, M. Muhammad, Z.A. Abdul Karim, Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines: A review, Appl Energy 198 (2017) 122–144. <https://doi.org/10.1016/j.apenergy.2017.04.048>.
- [98] V. Panov, GAS TURBINE PERFORMANCE DIAGNOSTICS AND FAULT ISOLATION BASED ON MULTIDIMENSIONAL COMPLEX HEALTH VECTOR SPACE, n.d. www.euroturbo.eu.
- [99] F. Ciampa, S.G. Pickering, G. Scarselli, M. Meo, Nonlinear imaging of damage in composite structures using sparse ultrasonic sensor arrays, Struct Control Health Monit 24 (2017) e1911.
<https://doi.org/10.1002/stc.1911>.
- [100] B. Yilmaz, A. Asokkumar, E. Jasiūnienė, R.J. Kažys, Air-Coupled, Contact, and Immersion Ultrasonic Non-Destructive Testing: Comparison for Bonding Quality Evaluation, Applied Sciences 10 (2020) 6757. <https://doi.org/10.3390/app10196757>.
- [101] H. Zhang, S. Li, J. Wang, Y. Ma, J. Sun, S. Liu, Z. Wang, X. Huang, X. Rui, Air-coupled capacitive micromachined transducer array for non-contact Lamb wave detection, Sens Actuators A Phys 355 (2023) 114315. <https://doi.org/10.1016/j.sna.2023.114315>.
- [102] H. Cho, C.J. Lissenden, Structural health monitoring of fatigue crack growth in plate structures with ultrasonic guided waves, Struct Health Monit 11 (2012) 393–404.
<https://doi.org/10.1177/1475921711430439>.
- [103] K. Luo, L. Chen, W. Liang, Structural health monitoring of carbon fiber reinforced polymer composite laminates for offshore wind turbine blades based on dual maximum correlation coefficient method, Renew Energy 201 (2022) 1163–1175.
<https://doi.org/10.1016/j.renene.2022.11.063>.

- [104] M. Harb, F. Yuan, Barely visible impact damage imaging using non-contact air-coupled transducer/laser Doppler vibrometer system, *Struct Health Monit* 16 (2017) 663–673. <https://doi.org/10.1177/1475921716678921>.
- [105] H. Zhang, S. Li, J. Wang, Y. Ma, J. Sun, Z. Wang, Capacitive Micromachined Ultrasonic Transducer Array for Air-coupled Lamb Wave Detection of Plate Structure, in: 2022 IEEE International Ultrasonics Symposium (IUS), IEEE, 2022: pp. 1–4. <https://doi.org/10.1109/IUS54386.2022.9957309>.
- [106] Z. Ma, L. Yu, Lamb wave defect detection and evaluation using a fully non-contact laser system, n.d.
- [107] N.P. Kishore, P.G. Sowjanya, A. Professor, EXPERIMENTAL STUDY OF LAMB WAVES USING ACOUSTO-ULTRASONIC TECHNIQUE, *JETIR*, 2020. www.jetir.org.
- [108] A. Sedaghati, F. Honarvar, A.N. Sinclair, Lamb wave-based experimental and numerical studies for detection and sizing of corrosion damage in metallic plates, *Proc Inst Mech Eng C J Mech Eng Sci* 233 (2019) 2107–2120. <https://doi.org/10.1177/0954406218781965>.
- [109] M. Bharati, L. Rana, R. Gupta, A. Sharma, P.K. Jha, M. Tomar, Simulation and Fabrication of Higher-Mode Lamb Wave Acoustic Devices for Sensing Applications, *Physica Status Solidi (a)* 220 (2023). <https://doi.org/10.1002/pssa.202200760>.
- [110] C.N. Sathyanarayana, S. Raja, P. Durai Arun, M. Mahesh, B.R. Aparna, Lamb Wave Propagation and Low Velocity Impact Damage Identification in Carbon Fiber Reinforced Plastic (CFRP) Laminates, in: 2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon), IEEE, 2022: pp. 1–8. <https://doi.org/10.1109/MysuruCon55714.2022.9972408>.
- [111] C. He, Y. Wang, Y. Lu, Y. Liu, B. Wu, Design and Fabrication of Air-Based 1-3 Piezoelectric Composite Transducer for Air-Coupled Ultrasonic Applications, *J Sens* 2016 (2016) 1–11. <https://doi.org/10.1155/2016/4982616>.
- [112] Q. Wu, Q. Chen, G. Lian, X. Wang, X. Song, X. Zhang, Investigation of an air-coupled transducer with a closed-cell material matching strategy and an optimization design considering the electrical input impedance, *Ultrasonics* 115 (2021) 106477. <https://doi.org/10.1016/j.ultras.2021.106477>.
- [113] J. Zhou, J. Bai, Y. Liu, Fabrication and Modeling of Matching System for Air-Coupled Transducer, *Micromachines (Basel)* 13 (2022) 781. <https://doi.org/10.3390/mi13050781>.
- [114] B. Park, H. Sohn, C.-M. Yeum, T.C. Truong, Laser ultrasonic imaging and damage detection for a rotating structure, *Struct Health Monit* 12 (2013) 494–506. <https://doi.org/10.1177/1475921713507100>.

- [115] Z. Li, A.M. Lomonosov, C. Ni, B. Han, Z. Shen, Selective generation of Lamb modes by a moving continuous-wave laser, *Opt Lett* 43 (2018) 78. <https://doi.org/10.1364/OL.43.000078>.
- [116] F. Bruno, J. Laurent, P. Jehanno, D. Royer, C. Prada, Laser beam shaping for enhanced Zero-Group Velocity Lamb modes generation, *J Acoust Soc Am* 140 (2016) 2829–2838. <https://doi.org/10.1121/1.4965291>.
- [117] L. Ambrozinski, J. Spytek, J. Mrowka, L.J. Pieczonka, Multi-resolution non-contact laser-sensing damage detection technique for composite laminates, *J Acoust Soc Am* 153 (2023) A75–A75. <https://doi.org/10.1121/10.0018213>.
- [118] S. Wang, J. Echeverry, L. Trevisi, K. Prather, L. Xiang, Y. Liu, Ultrahigh Resolution Pulsed Laser-Induced Photoacoustic Detection of Multi-Scale Damage in CFRP Composites, *Applied Sciences* 10 (2020) 2106. <https://doi.org/10.3390/app10062106>.
- [119] Z. Wu, S.Y. Chong, M.D. Todd, Laser ultrasonic imaging of wavefield spatial gradients for damage detection, *Struct Health Monit* 20 (2021) 960–977. <https://doi.org/10.1177/1475921720951336>.
- [120] N. Hosoya, R. Umino, A. Kanda, I. Kajiwarra, A. Yoshinaga, Lamb wave generation using nanosecond laser ablation to detect damage, *Journal of Vibration and Control* 24 (2018) 5842–5853. <https://doi.org/10.1177/1077546316687904>.
- [121] T. Kang, S.-J. Han, S. Moon, S. Han, J.Y. Jeon, G. Park, Lamb-wave sparse-frequency interdigital-transducer-based scanning laser Doppler vibrometry for quantitative depth-wise visualization of defects in plates, *NDT & E International* 107 (2019) 102137. <https://doi.org/10.1016/j.ndteint.2019.102137>.
- [122] P. Kudela, T. Wandowski, P. Malinowski, W. Ostachowicz, Application of scanning laser Doppler vibrometry for delamination detection in composite structures, *Opt Lasers Eng* 99 (2017) 46–57. <https://doi.org/10.1016/j.optlaseng.2016.10.022>.
- [123] T. Kang, M. Yoon, S. Han, K.-M. Kim, B. Koo, Selection of optimal exciting frequency and Lamb wave mode for detecting wall-thinning in plates using scanning laser Doppler vibrometer, *Measurement* 200 (2022) 111676. <https://doi.org/10.1016/j.measurement.2022.111676>.
- [124] M.A. Faki, S.K. Singh, S. Mustapha, P. Malinowski, Damage Localization in 3D-Printed Plates with Different Infill Densities, in: 2022 49th Annual Review of Progress in Quantitative Nondestructive Evaluation, American Society of Mechanical Engineers, 2023. <https://doi.org/10.1115/QNDE2022-95348>.
- [125] J. Segers, S. Hedayatrasa, G. Poelman, W. Van Paepegem, M. Kersemans, Nonlinear local wave-direction estimation for in-sight and out-of-sight damage localization in composite plates, *NDT & E International* 119 (2021) 102412. <https://doi.org/10.1016/j.ndteint.2021.102412>.

- [126] Z. Ma, L. Yu, Lamb wave defect detection and evaluation using a fully non-contact laser system, in: P. Fromme, Z. Su (Eds.), *Health Monitoring of Structural and Biological Systems XIII*, SPIE, 2019: p. 69. <https://doi.org/10.1117/12.2514048>.
- [127] Z. Tian, S. Howden, Z. Ma, W. Xiao, L. Yu, Pulsed laser-scanning laser Doppler vibrometer (PL-SLDV) phased arrays for damage detection in aluminum plates, *Mech Syst Signal Process* 121 (2019) 158–170. <https://doi.org/10.1016/j.ymssp.2018.11.016>.
- [128] E. Compton, A. Campbell, P.-K. Sun, L. Yu, Excitation and sensing of Lamb waves in very thin metals and nuclear cladding material using fully non-contact PL-SLDV system, in: P. Fromme, Z. Su (Eds.), *Health Monitoring of Structural and Biological Systems XVI*, SPIE, 2022: p. 3. <https://doi.org/10.1117/12.2612634>.
- [129] M. Masmoudi, M. Castaings, Three-dimensional hybrid model for predicting air-coupled generation of guided waves in composite material plates, *Ultrasonics* 52 (2012) 81–92. <https://doi.org/10.1016/j.ultras.2011.06.014>.
- [130] R. Kazys, A. Vilpisauskas, J. Sestoke, Application of Air-Coupled Ultrasonic Arrays for Excitation of a Slow Antisymmetric Lamb Wave, *Sensors* 18 (2018) 2636. <https://doi.org/10.3390/s18082636>.
- [131] M.S. Harb, F.G. Yuan, A rapid, fully non-contact, hybrid system for generating Lamb wave dispersion curves, *Ultrasonics* 61 (2015) 62–70. <https://doi.org/10.1016/j.ultras.2015.03.006>.
- [132] A. Dyrwal, M. Meo, F. Ciampa, Nonlinear air-coupled thermosonics for fatigue micro-damage detection and localisation, *NDT & E International* 97 (2018) 59–67. <https://doi.org/10.1016/j.ndteint.2018.03.012>.
- [133] G. Fan, H. Zhang, H. Zhang, W. Zhu, X. Chai, Lamb Wave Local Wavenumber Approach for Characterizing Flat Bottom Defects in an Isotropic Thin Plate, *Applied Sciences* 8 (2018) 1600. <https://doi.org/10.3390/app8091600>.
- [134] D. Mindykowski, T. Wandowski, M. Radzienski, F. Piotr, P. Fiborek, Optimal slope angles of the air-coupled transducer from viewpoint of the effective Lamb waves propagation in different materials, *E-Journal of Nondestructive Testing* 27 (2022). <https://doi.org/10.58286/27328>.
- [135] M.S. Harb, F.-G. Yuan, Damage imaging using non-contact air-coupled transducer/laser Doppler vibrometer system, *Struct Health Monit* 15 (2016) 193–203. <https://doi.org/10.1177/1475921716636336>.
- [136] L. Bustamante, N. Jeyaparakash, C.-H. Yang, Hybrid laser and air-coupled ultrasonic defect detection of aluminium and CFRP plates by means of Lamb mode, *Results Phys* 19 (2020) 103438. <https://doi.org/10.1016/j.rinp.2020.103438>.

- [137] X. Jiang, J. Wang, Y. Zhang, S. Jiang, Defect Detection in Solid Timber Panels Using Air-Coupled Ultrasonic Imaging Techniques, *Applied Sciences* 14 (2024) 434. <https://doi.org/10.3390/app14010434>.
- [138] A. Römmeler, R. Furrer, U. Sennhauser, B. Lübke, J. Wermelinger, A. de Agostini, J. Dual, P. Zolliker, J. Neuenschwander, Air coupled ultrasonic defect detection in polymer pipes, *NDT & E International* 102 (2019) 244–253. <https://doi.org/10.1016/j.ndteint.2018.12.004>.
- [139] B. Wang, W. Shi, B. Zhao, X. Tian, J. Tan, Detecting delamination defects in CFRP plates using nonlinear defect index of air-coupled Lamb waves and adaptively weighted imaging algorithm, *Mech Syst Signal Process* 208 (2024) 111023. <https://doi.org/10.1016/j.ymssp.2023.111023>.
- [140] A. Asokkumar, E. Jasiūnienė, R. Raišutis, R.J. Kažys, Comparison of Ultrasonic Non-Contact Air-Coupled Techniques for Characterization of Impact-Type Defects in Pultruded GFRP Composites, *Materials* 14 (2021) 1058. <https://doi.org/10.3390/ma14051058>.
- [141] Lukasz Ambrozinski, Tadeusz Stepinski, Tadeusz Uhl, Bogdan Piwakowski, Application of Air-Coupled Ultrasonic Transducers for Damage Assessment of Composite Panels, 6th European Workshop on Structural Health Monitoring (EWSHM 2012), July 3 -6, 2012 in Dresden, Germany. (2013).
- [142] E. Moreno, R. Giacchetta, R. Gonzalez, D. Sanchez, O. Sanchez, A. Torre, G. Cosarinsky, W. Coelho, Ultrasonic Non-Contact Air-Coupled Technique For Assessment Of Sandwich Composites Plates Using Antisymmetric Lamb Waves, (2023). <https://doi.org/10.20944/preprints202309.0791.v1>.
- [143] T. Wandowski, P. Kudela, M. Radzienski, Low-frequency air-coupled transducer based damage detection in composite materials, *J Phys Conf Ser* 2692 (2024) 012026. <https://doi.org/10.1088/1742-6596/2692/1/012026>.
- [144] Y. Li, C. He, Y. Lyu, G. Song, B. Wu, Crack detection in monocrystalline silicon solar cells using air-coupled ultrasonic lamb waves, *NDT & E International* 102 (2019) 129–136. <https://doi.org/10.1016/j.ndteint.2018.11.020>.
- [145] D. Reichle, Y. Bernhardt, P. Thieleke, M. Kreutzbruck, In-line flaw detection of pultruded profiles by air-coupled ultrasound, in: 2020: p. 020046. <https://doi.org/10.1063/5.0028344>.
- [146] J.-W. Park, K.-H. Im, D.K. Hsu, J.-A. Jung, I.-Y. Yang, Pitch-catch ultrasonic study on unidirectional CFRP composite laminates using Rayleigh wave transducers, *Journal of Mechanical Science and Technology* 26 (2012) 2147–2150. <https://doi.org/10.1007/s12206-012-0533-1>.
- [147] K. Huang, Q. Li, K. Zhu, B. Chen, X. Qian, X. Wang, X. Li, A Through-Transmission Ultrasonic Method for the Detection of Ferrite Tile Defects, *Applied Sciences* 13 (2023) 11172. <https://doi.org/10.3390/app132011172>.

- [148] T. Reindl, Y. Bernhardt, K.-U. Kohn, M. Kreutzbruck, Phased-Array Approach to Air-coupled Ultrasound with Resonant Defect Excitation, *Research and Review Journal of Nondestructive Testing* 1 (2023). <https://doi.org/10.58286/28087>.
- [149] B. Han, C. Jiang, A.M. Omer, K.O. Hamad, T. Shao, L. He, X. Ding, H. Zhang, J. Fu, J. Meng, Y. Duan, A generic time-frequency analysis-based signal processing and imaging approach for air-coupled ultrasonic testing, *NDT & E International* 144 (2024) 103101. <https://doi.org/10.1016/j.ndteint.2024.103101>.
- [150] F. Laub, C. Haugwitz, G. Allevato, J. Seiler, R. Findeisen, M. Kupnik, Non-Contact Lamb Wave Defect Detection Based Solely on Air-Coupled Ultrasonic Phased Arrays, in: *2023 IEEE SENSORS*, IEEE, 2023: pp. 1–4. <https://doi.org/10.1109/SENSORS56945.2023.10324898>.
- [151] J.L. Rose, *Ultrasonic Guided Waves in Solid Media*, Cambridge University Press, 2014. <https://doi.org/10.1017/CBO9781107273610>.
- [152] Armin hurber, *The Dispersion Calculator*, (2018). <https://www.dlr.de/en/zlp/about-us/the-institute/site-augsburg/dispersion-calculator-an-open-source-software-for-the-calculation-of-dispersion-curves-and-mode-shapes-of-guided-waves> (accessed September 29, 2024).
- [153] H. Huang, F. Zhu, J. Zhu, B. Wang, Z. Qian, A general approach for dispersion relations in multilayered structures with an arbitrary number of piezoelectric layers and elastic layers, *Acta Mech* 231 (2020) 489–502. <https://doi.org/10.1007/s00707-019-02540-6>.
- [154] Q. Gao, Y.H. Zhang, Stable and Accurate Computation of Dispersion Relations for Layered Waveguides, Semi-Infinite Spaces and Infinite Spaces, *J Vib Acoust* 141 (2019). <https://doi.org/10.1115/1.4042708>.
- [155] M. Asif, R. Nawaz, R. Ibrahim Nuruddeen, Dispersion of an inhomogeneous sandwich plate having imperfect interfaces and supported by the Pasternak foundation, *Smart Mater Struct* 32 (2023) 125002. <https://doi.org/10.1088/1361-665X/ad04b6>.
- [156] L. Yule, N. Harris, M. Hill, B. Zaghari, Temperature Monitoring of Through-Thickness Temperature Gradients in Thermal Barrier Coatings Using Ultrasonic Guided Waves, *J Nondestr Eval* 43 (2024) 22. <https://doi.org/10.1007/s10921-023-01038-5>.
- [157] S. Zhang, Z. Ma, L. Lin, W. Feng, Comprehensive Analysis for the Effect of Thermal Barrier Coating Porosity on Ultrasonic Longitudinal Wave Velocity, in: 2020: pp. 349–357. https://doi.org/10.1007/978-981-33-6378-6_26.
- [158] N. Tassini, K. Lambrinou, I. Mircea, M. Bartsch, S. Patsias, O. Van der Biest, Study of the amplitude-dependent mechanical behaviour of yttria-stabilised zirconia thermal barrier coatings, *J Eur Ceram Soc* 27 (2007) 1487–1491. <https://doi.org/10.1016/j.jeurceramsoc.2006.05.041>.

- [159] P.-C. Ostiguy, N. Quaegebeur, P. Masson, Non-destructive evaluation of coating thickness using guided waves, *NDT & E International* 76 (2015) 17–25.
<https://doi.org/10.1016/j.ndteint.2015.08.004>.
- [160] M. Mehrabi, M. Hossein Soorgee, H. Habibi, V. Kappatos, An experimental technique for evaluating viscoelastic damping using ultrasonic guided waves, *Ultrasonics* 123 (2022) 106707.
<https://doi.org/10.1016/j.ultras.2022.106707>.
- [161] C. Xu, Q. Wang, G. Gao, M. Deng, Lamb wave based damage imaging in variable thickness plates, *Mech Syst Signal Process* 223 (2025) 111926. <https://doi.org/10.1016/j.ymssp.2024.111926>.
- [162] Ping Wang, Jinghuai Gao, Zhiguo Wang, Time-Frequency Analysis of Seismic Data Using Synchrosqueezing Transform, *IEEE Geoscience and Remote Sensing Letters* 11 (2014) 2042–2044.
<https://doi.org/10.1109/LGRS.2014.2317578>.
- [163] C. Mateo, J.A. Talavera, Bridging the gap between the short-time Fourier transform (STFT), wavelets, the constant-Q transform and multi-resolution STFT, *Signal Image Video Process* 14 (2020) 1535–1543. <https://doi.org/10.1007/s11760-020-01701-8>.
- [164] J. Venkata Suman, Y. Sumabindu, J. Beatrice Seventline, Performance Analysis of Time Frequency Resolution Techniques for Non-Stationary Signals, *Indian J Sci Technol* 8 (2015).
<https://doi.org/10.17485/ijst/2015/v8i23/71530>.
- [165] L.D. Ha, K.J. Kim, S.J. Kwon, B. Chang, S. Hwang, Time-Resolved Electrochemical Impedance Spectroscopy of Stochastic Nanoparticle Collision: Short Time Fourier Transform versus Continuous Wavelet Transform, *Small* 19 (2023). <https://doi.org/10.1002/smll.202302158>.
- [166] B. Murali Krishna, M. Srinivas, S. Raja Gopal, G. L. P. Ashok, Time Frequency analysis of Non-Stationary signals by Differential frequency window S –Transform, *International Journal of Engineering & Technology* 7 (2018) 878. <https://doi.org/10.14419/ijet.v7i2.7.11086>.
- [167] D. Li, J. Dong, K. Peng, A Novel Adaptive STFT-SFA Based Fault Detection Method for Nonstationary Processes, *IEEE Sens J* 23 (2023) 10748–10757.
<https://doi.org/10.1109/JSEN.2023.3264994>.
- [168] Z. Cui, G. Yu, W. Tian, S-Transform based time–frequency analysis tool with application to detection of bearing fault, *J Phys Conf Ser* 2352 (2022) 012004. <https://doi.org/10.1088/1742-6596/2352/1/012004>.
- [169] J. Long, H. Wang, D. Zha, P. Li, H. Xie, L. Mao, Applications of fractional lower order S transform time frequency filtering algorithm to machine fault diagnosis, *PLoS One* 12 (2017) e0175202.
<https://doi.org/10.1371/journal.pone.0175202>.

- [170] B. Li, P.-L. Zhang, S.-B. Liang, Y.-T. Zhang, H.-B. Fan, Feature extraction for engine fault diagnosis utilizing the generalized S-transform and non-negative tensor factorization, *Proc Inst Mech Eng C J Mech Eng Sci* 225 (2011) 1936–1949. <https://doi.org/10.1177/0954406211403360>.
- [171] G.G. Santos, T.S. Menezes, J.C.M. Vieira, P.H.A. Barra, An S-Transform based approach for fault detection and classification in power distribution systems, in: 2019 IEEE Power & Energy Society General Meeting (PESGM), IEEE, 2019: pp. 1–5. <https://doi.org/10.1109/PESGM40551.2019.8973961>.
- [172] D. Li, A. Ukil, K. Satpathi, Y.M. Yeap, Improved S Transform-Based Fault Detection Method in Voltage Source Converter Interfaced DC System, *IEEE Transactions on Industrial Electronics* 68 (2021) 5024–5035. <https://doi.org/10.1109/TIE.2020.2988193>.
- [173] B. Han, C. Jiang, A.M. Omer, K.O. Hamad, T. Shao, L. He, X. Ding, H. Zhang, J. Fu, J. Meng, Y. Duan, A generic time-frequency analysis-based signal processing and imaging approach for air-coupled ultrasonic testing, *NDT & E International* 144 (2024) 103101. <https://doi.org/10.1016/j.ndteint.2024.103101>.
- [174] R. V Nandish, E. Madhu, S. Paul Vizhian, S. Ramachandra, Dynamic Vibration Analysis of Ti-Alloy Gas Turbine Blade Rotating at High Speed After Grind-Out Repair of Foreign Object Damage, *International Journal of Mechanical Engineering and Technology (IJMET)* 8 (2017) 202–211. <http://www.iaeme.com/IJMET/index.asp202http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=4http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=4http://www.iaeme.com/IJMET/index.asp203>.
- [175] L. Chen, B. Li, L. Zhang, Z. Shang, 3D positioning of defects for gas turbine blades based on digital radiographic projective imaging, *NDT & E International* 133 (2023) 102751. <https://doi.org/10.1016/j.ndteint.2022.102751>.
- [176] Wave Optics Module User's Guide, 1998. www.comsol.com/blogs.
- [177] J.R. Lilly, G. Capodaglio, D. Engwirda, R.L. Higdon, M.R. Petersen, Local time-stepping for the shallow water equations using CFL optimized forward-backward Runge-Kutta schemes, *J Comput Phys* 520 (2025) 113511. <https://doi.org/10.1016/j.jcp.2024.113511>.
- [178] G. Yue, X. Cui, K. Zhang, Z. Wang, D. An, Guided Wave Propagation for Monitoring the Rail Base, *Math Probl Eng* 2020 (2020) 1–11. <https://doi.org/10.1155/2020/4756574>.

Vitae

Name Awad Abdallah Almomani

Nationality: Jordan

Date of Birth: May 16, 1990

Email: awad.almomani@gmail.com

Address: Building# 201, Hamza bin Abdulmutalib Street, Al Qusur, Dhahran 34247, Saudi Arabia.

Academic Background:

- Received Bachelor of Science in Mechanical Engineering from Jordan University of Science and Technology, 2012, Irbid, Jordan.
- Joined the Department of Mechanical Engineering at King Fahad University of Petroleum and Minerals, Dhahran, Saudi Arabia, as a part-time student.

Professional Experience: Working at Siemens Energy while pursuing a Master of Science degree.