Faculty of Mechanical Engineering

MATCHING PLATE DESIGN TECHNIQUE FOR PZT TYPE LAMB WAVE TRANSDUCERS

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DECLARATION

I declare that this thesis entitled "Matching Plate Design Technique for PZT Type Lamb Wave Transducers" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……………………………

Name : ……………………………

Date : ……………………………

APPROVAL

I hereby declare that I have read this thesis and in my own opinion, this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature	:	………………………………………
Supervisor Name	:	………………………………………
Date	:	……………………………………….

DEDICATION

To my beloved mother and father, siblings, and wife

ABSTRACT

Piezoelectric transducers are widely used in defect inspections on large structures. The non-destructive inspections are typically performed on metal structures but can be applied on non-metal structures such as concretes and carbon fibre reinforced polymers. Mismatch of acoustic impedance between piezoelectric element and medium in inspections reduces the amount of ultrasonic energy emitted from the element. This ultrasonic energy reduction is due to the reflection that occurs at the interface caused by the difference in the acoustic impedance values. In addition, the signal attenuation also shortens the monitoring distance in structural health monitoring and leads to an inconsistent wave ringing or unwanted signal in the measurements. Thus, a study on the matching plate in the piezoelectric transducer is conducted to reduce the mismatch of acoustic impedance between the piezoelectric element and medium of the wave propagation. In order to achieve higher transmission of ultrasonic energy into the propagating medium, single layer and multilayer matching plates are placed between the active piezoelectric element and medium of the wave propagation. Two different design techniques were performed to obtain a single layer matching plate by using quarter wavelength and group velocity dispersion techniques. Evaluations on the quarter wavelength and group velocity dispersion techniques were carried out on single layer matching plates using a developed model in ABAQUS. The evaluations on matching plates of aluminium, brass, copper, and acrylic were performed at different thicknesses that obtained from both techniques. Assessments on time waveforms, Fast Fourier Transforms, and visualizations of the transmitted waves into the propagating medium have been made to measure the performance of the matching plates. The results indicate good transmission waves into the propagating medium from the single layer matching plates which are designed from the behaviour of the group velocity dispersion curves. The group velocity dispersion curves which are used as the guideline in selection of the suitable matching layer for the wave transmission have been applied into matching plate designs for two, three and four layers of multilayer matching plates. The simulation results are also compared to the results from single layer matching plates which are designed from the dispersion curve technique. The results show high transmission of ultrasonic energy for the matching plates with small dispersions in group velocities. At the end, the study indicates feasibility development of matching plates based on the properties of the plotted dispersion curves.

ABSTRAK

Transduser piezoelektrik digunakan secara meluas dalam pemeriksaan kecacatan pada struktur yang besar. Ujian tanpa musnah biasanya dilakukan pada struktur logam, walaubagaimanapun ia juga digunakan pada struktur bukan logam seperti konkrit dan polimer yang diperkuat dengan gentian karbon. Perbezaan impedans akustik di antara bahagian piezoelektrik dan medium dalam pemeriksaan boleh mengurangkan pemindahan tenaga ultrasonik yang dihasilkan dari bahagian piezoeletrik. Pengurangan tenaga ultrasonik ini adalah disebabkan oleh pantulan akibat daripada perbezaan nilai impedans akustik yang berlaku pada permukaan pemisah tersebut. Di samping itu, penggunaan isyarat yang lemah ini juga akan mengakibatkan jarak pemantauan yang terhad dalam pengawasan kesihatan struktur dan menyumbang kepada deringan gelombang yang tidak konsisten atau isyarat yang tidak diingini dalam pengukuran. Oleh itu, satu kajian pada plat padanan dalam transduser piezoelektrik telah dijalankan untuk mengurangkan ketidak padanan impedans akustik di antara bahagian piezoelektrik dan medium perambatan gelombang. Untuk mencapai pemindahan tenaga ultrasonik yang lebih tinggi ke dalam medium perambatan, plat padanan tunggal dan plat padanan berbilang lapisan diletakkan di antara bahagian piezoelektrik aktif dan medium perambatan gelombang. Dua teknik berbeza telah digunakan untuk merekabentuk plat padanan tunggal dengan menggunakan teknik seperempat panjang gelombang dan teknik penyebaran halaju kelompok. Kajian mengenai seperempat panjang gelombang dan teknik penyebaran halaju kelompok dijalankan pada plat padanan tunggal menggunakan model yang dibangunkan dalam ABAQUS. Kajian pada plat padanan tunggal daripada aluminium, tembaga, kuprum, dan akrilik telah dijalankan pada ketebalan-ketebalan yang diperolehi daripada kedua-dua teknik tersebut. Penelitian terhadap gelombang masa, Tranformasi Fourier Cepat, dan visualisasi gelombang yang dipindahkan ke medium perambatan telah dibuat untuk menilai prestasi plat-plat padanan tersebut. Plat padanan tunggal yang direka berdasarkan ciri-ciri lengkung penyebaran halaju kelompok menunjukkan pemindahan gelombang yang lebih baik daripada plat padanan tunggal ke medium perambatan. Lengkung penyebaran halaju kelompok yang digunakan sebagai panduan untuk pemilihan plat padanan yang sesuai untuk penghantaran gelombang telah juga digunakan untuk menghasilkan plat padanan berbilang lapisan dengan menggunakan dua, tiga dan empat lapisan padanan. Keputusan daripada simulasi tersebut juga dibandingkan dengan keputusan daripada plat padanan tunggal yang direka dari teknik lengkung penyebaran. Keputusanya menunjukkan pemindahan tenaga ultrasonik yang tinggi untuk padanan yang direka berdasarkan ciri-ciri penyebaran yang kecil dalam halaju kelompok. Di akhir kajian ini, keputusan yang diperolehi menunjukkan kebolehlaksanaan untuk membangunkan plat padanan berdasarkan ciri-ciri lengkung penyebaran yang diusulkan.

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LIST OF ABBREVIATIONS AND SYMBOLS

SHM	-	Structural Health Monitoring
NDE	-	Non-Destructive Evaluation
NDT	-	Non-Destructive Testing
EMATs	-	Electromagnetic Acoustic Transducers
MEMS	-	Micro-Electro-Mechanical Systems
PVDF	-	Polyvinylidene Fluoride
MSs	-	Magnetostrictive Sensors
PZT	-	Lead Zirconium Titanate
IDTs	-	Inter Digital Transducers
FEM	-	Finite Element Method
FFT	-	Fast Fourier Transform
BEM	-	Boundary Element Method
SAFE	-	Semi Analytical Finite Element Method
UT	-	Ultrasonic Transducer
I_c	-	Mesh Size
$\lambda_{\min}$	-	Shortest Wavelength
t_c	-	Calculation Time
l	-	Distance Between Excitation & Inspection Point
C_{min}	-	Minimum Speed of Wave Propagation in Aluminium Plate

C_l	-	Longitudinal wave velocity
C_t	-	Shear wave velocity
c_p	-	Phase Velocity
c_g	-	Group Velocity
Z_M	-	Acoustic Impedances for Matching Plate
Z_{PZT}	-	Acoustic Impedances for Piezoelectric Element
Z_L	-	Acoustic Impedances for Loading
ρ	-	Density
c	-	Acoustic Velocity
ω	-	Angular Frequency
k	-	Wave Number
f	-	Frequency
d	-	Thickness
u, f	-	Vectors
K	-	Set of Matrix
$\mathbf{M}^{uu}$	-	Mechanical Mass Matrix
$\mathbf{C}^{uu}$	-	Mechanical Damping Matrix
$\mathbf{K}^{uu}$	-	Mechanical Stiffness Matrix
$\mathbf{K}^{\phi\phi}$	-	Dielectric Stiffness Matrix
$\mathbf{K}^{u\phi}$	-	Piezoelectric Coupling Matrix
$\mathbf{F}$	-	Nodal Vector of External Forces
$\mathbf{Q}$	-	Nodal Vector of Electric Charges
$\mathbf{d}$	-	Vector of Mechanical Displacements
$\boldsymbol{\phi}$	-	Vector of Electric Potentials

LIST OF PUBLICATIONS

Ilham, H.M., Salim, M.N., Jenal, R.B., and Hayashi, T., 2016. Guided Wave Matching Layer Using a Quarter of Wavelength Technique. *Applied Mechanics and Materials*, 833, pp.59–68.

H. S. Ilham, M. N. Salim, A. F. Ab Ghani, 2017. Effect of Weight Ratios in Backing Material on Lamb Wave Excitation in PZT Transducers. *Proceedings of Mechanical Engineering Research Day 2017*, pp.366-367.

CHAPTER 1

INTRODUCTION

1.1 Guided Wave Inspection

Guided wave inspection technique is widely used in many areas of structural health monitoring (SHM). Its ability to perform inspections on a large structure from a single point turned it to become an attractive solution for plate-like structure such as storage tanks, pressure vessels, aircraft components, and large structures in civil engineering.

The early studies in guided waves have been conducted by Rayleigh, Lamb, Love, and Stoneley (Victorov, 1967). They are the pioneer researchers in the guided wave studies. In Lamb wave propagations, several researchers including Victorov (1967), Graff (1975), Achenbach (1984), Royer and Dieulesaint (1999), and Rose (2014) had extended their studies in advanced device developments and inspection techniques. Worlton (1961) was among the first to realize the advantages of Lamb and Rayleigh waves over conventional ultrasonic bulk waves for Non-Destructive Evaluation (NDE). Then, Victorov (1967) conducted the studies on the application of these waves into ultrasonic testing. Rose and Barshinger (1998), and Krautkramer and Krautkramer (1983) reported on portable guided wave ultrasonic devices for inspection of steam generator turbines, aging aircraft structures and moulded parts in manufacturing plants. Large areas of inspections and fast structure screening had been demonstrated from these studies.

The distinctive characteristic of guided wave is it can travel along the media which are guided by the geometric boundaries of the structures. Since the wave is guided by the geometric boundaries of the structures, behaviours of the wave are strongly influenced by the geometries of the structures (Redwood, 1960).

There are several methods to excite guided waves in structures. The waves can be generated from piezoelectric type transducers, Electromagnetic Acoustic Transducers (EMATs), Magnetostrictive Sensors (MSs), laser or Micro-Electro-Mechanical Systems (MEMS). The most common method is using an angled beam piezoelectric transducer as shown in Figure 1.1. Difference in acoustic impedance between the wedge material and the medium of wave propagation causes wave refraction into the structure. The wave will bounce back and forth inside the structure which is called as a waveguide. The phenomenon of wave interference and mode conversion at the boundaries form different wave structures in pipes, plates, and rails (Rose, 2014).

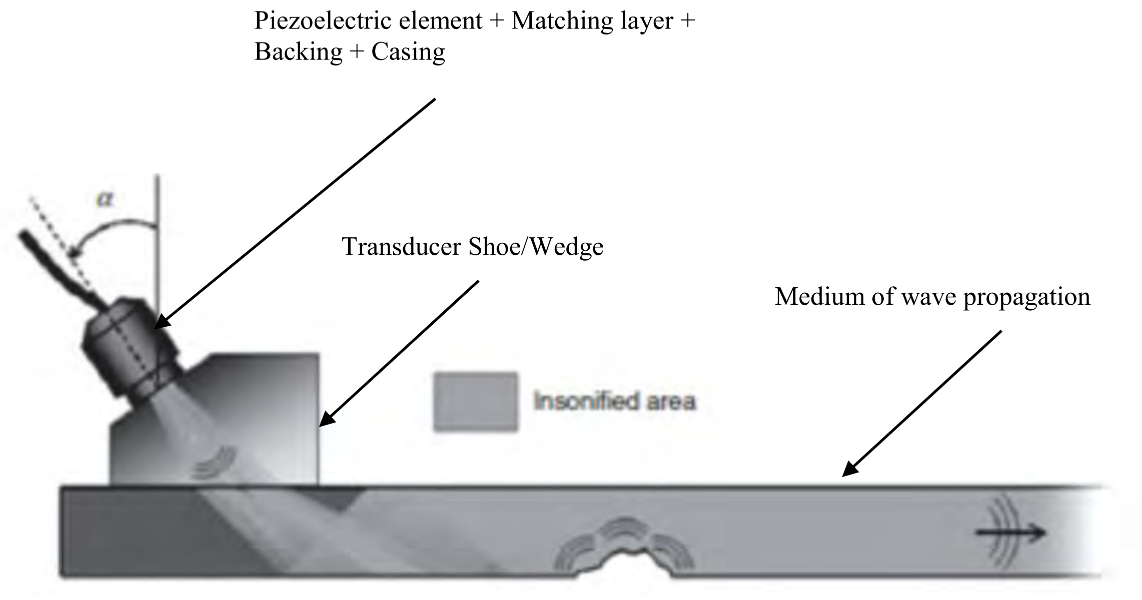

Figure 1.1: Guided Wave Inspection with Angled Beam Transducer (Rose, 2014)