3D FREQUENCY SELECTIVE SURFACES FOR STRUCTURAL HEALTH MONITORING SYSTEM

by

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Specially dedicated to my beloved parents, brothers, lecturers and friends

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LIST OF SYMBOLS

C	Capacitance
°	Degree
L	Inductance
$\tan\delta$	Loss Tangent
Ω	Ohm
Π	Phi
%	Percentages
f_r	Resonant Frequency
c	Speed of Light
θ	Theta
Δ	Variance
λ	Wavelength

LIST OF ABBREVIATIONS

AE	Acoustic Emission
ADC	Analog Digital Converter
CST	Computer Simulation Technology
dB	Decibel
ENA	Economic Network Analyzer
FSS	Frequency Selective Surfaces
GHz	Giga Hertz
GPS	Global Positioning System
MEMS	Micro Electro Mechanical System
MHz	Mega Hertz
mm	Millimeter
OFS	Optic Fiber Sensor
PDMS	Polydimethylsiloxane
PEC	Perfect Electric Conductor
RF	Radio Frequency
RFID	Radio Frequency Identification
RCS	Radio Cross Section
SHM	Structural Health Monitoring

3D	Three Dimensional
2D	Two Dimensional
TE	Transverse Electric
TM	Transverse Magnetic
THz	Tera Hertz
WSN	Wireless Sensor Network
WPAN	Wireless Personal Area Network

3D Frekuensi Permukaan Terpilih untuk sistem Pemantauan Struktur Kesihatan

ABSTRAK

Kerja-kerja penyelidikan dalam penulisan ini menekankan kepada kajian keupayaan 3D Frekuensi Terpilih Permukaan untuk bertindak sebagai sensor dalam pemantauan struktur bangunan. Sejenis tiga dimensi yang baru (3D) Frekuensi Terpilih Permukaan (FSS) yang pasif boleh digunakan dalam Pemantauan Struktur Kesihatan (SHM) dibentangkan. Bentuk persegi FSS dipilih dalam kajian ini dimana ia mampu untuk mengawal sensitiviti sambutan frekuensi. Selain itu, FSSs ini diubahsuai dalam bentuk 3D untuk menampilkan prestasi yang baik berbanding FSSs dan sensor konvensional. Lebih khusus lagi, cadangan 3D FSS dapat mengawal sensitiviti $|S_{21}|$ sama ada dalam TE atau gelombang kejadian sudut TM. Dalam penyelidikan ini, ciri-ciri sudut tuju dinilai untuk aplikasi SHM dengan mendapatkan jawapan sudut sehingga 80 darjah. Kelakuan salunan gelombang TE-kejadian sudut menunjukkan ia sensitif terhadap sudut tuju dan sesuai untuk digunakan bagi memantau sebarang kecondongan bangunan dan kerosakan. Ini adalah disebabkan oleh perubahan unsur-unsur panjang konduktor. Sementara itu, gelombang TM-kejadian sudut didapati tidak sensitive (frekuensi beroperasi tidak beranjak) terhadap sudut kejadian itu. Terdapat beberapa pembaharuan diperolehi di dalam thesis ini dimana telah diperkenalkan 3D FSS memberi kelebihan tambahan untuk melaksanakan sebagai sensor pasif dan persamaan untuk berkaitan antara sambutan frekuensi dan sudut kejadian diperolehi.

3D Frequency Selective Surfaces for Structural Health Monitoring system

ABSTRACT

The research work in this dissertation mainly highlighted to the study of capability 3D Frequency Selective Surfaces to act as a sensor in structure monitoring. A new type of three-dimensional (3D) Frequency Selective Surfaces (FSS) applied for passive sensing in Structural Health Monitoring (SHM) is presented. Square shape FSS are chosen in this research which it able to govern the sensitivity of frequency response. Moreover, these FSSs are modified in a 3D form to feature enhanced performance compared to conventional FSSs and sensors. More specifically, the proposed 3D FSS is able to control its sensitivity $|S_{21}|$ in either TE or TM incident waves. In this research, incident angle characteristics are evaluated for SHM application to obtain angular responses of up to 80 degrees. The resonant behavior of the TE-incident wave is shown to be sensitive towards the incident angle and is suitable to be used for monitoring any building tilting and damages. This is due to the significant 3D length hanges of the conductor elements. Meanwhile, the TM-incident wave is found to be insensitive (frequency operation not shifting) towards the incident angle. There have some novelty have been introduced in this work such 3D FSS give an extra advantage to perform as a passive sensor and equation for relation between frequency response and incident angle are derived.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Following the tragic earthquake in Sabah, there are concerns that the earthquake could also hit others place such as national capital and most residents global city of Malaysia which is Kuala Lumpur. According to a geologist, Kuala Lumpur is located near the epicenters of the ancient fault line zone and most of our buildings are unfortunately not designed for it. Therefore, structural health monitoring (SHM) technologies for civil structures are becoming important. It is used to monitor structural changes such as tension and stress.

Structural Health Monitoring (SHM) is defined as an integrated procedure for the detection and characterization of damage to the structure or building. The systems are installed on bridges, building and highways in order to improve the capacity of damage detection. Over the past decade, the field of Structural Health Monitoring (SHM) has begun to attract the interest of researchers.

Several effective sensors such as electromechanical impedance (Bhalla & Soh, 2004), scattering of guided waves (Clarke, Cawley, Wilcox, & Croxford, 2009), acoustic emissions (Lovejoy, 2008), and optical techniques have been developed.

However the existing sensors require an input power supply. When the sensor has detected a change in the tension or pressure on a building, it is necessary to transfer information to the data acquisition system where is located at the base station away from the structure to be monitored (Lovejoy, 2008), (Dhital, Chia, & Lee, 2010) . The necessary connection of sensors by wires for power and data transmission makes the SHM system complex and difficult to maintain. The whole structure sometimes needs to be redesigned to accommodate the connections among these sensor networks. Therefore, it will increase the cost of manufacture. Figure 1.1 depicts two comparison in cost installation sensor network which is wired and wireless for SHM. Wired sensor network facing some lack in installation where it need more huge number of equipment, therefore the costing whole system will increasing. In this section common sensor types and their advantages and disadvantages will be discussed.

Regarding to SHM system, wireless sensors for Structural Health Monitoring (SHM) are an emerging new technology that promises to overcome many disadvantages pertinent to conventional, wired sensors. Active wireless sensors network is one of the methods where it is used a combination system of RF communication module, microprocessor, sensing module and battery. It can broadcast the sensing signal up to 100 meter range hence give early indicator for society. Moreover, passive sensors have been developed for tracking abnormalities building structure without pertinent to power supply on itself. Example of passive sensors consist such RFID and FSS. Basically, previous FSS was behave as redirecting signal, filtering, reflective and absorbing of electromagnetic waves (Y. S. Lee, Malek & Wee, 2013), (Sung, Sowerby, Neve & Williamson, 2006). Here, in this research will introduce the modification and novelty towards Frequency Selective Surfaces (FSS) characteristics.

Various types of sensors have been developed previously to monitor and detect the building structure performance. The impressive sensors with several techniques have been developed by researchers to maintain and upgrading the systems for SHM. Figure 1.1 illustrated the summary proposed sensors with the techniques and features in SHM system.

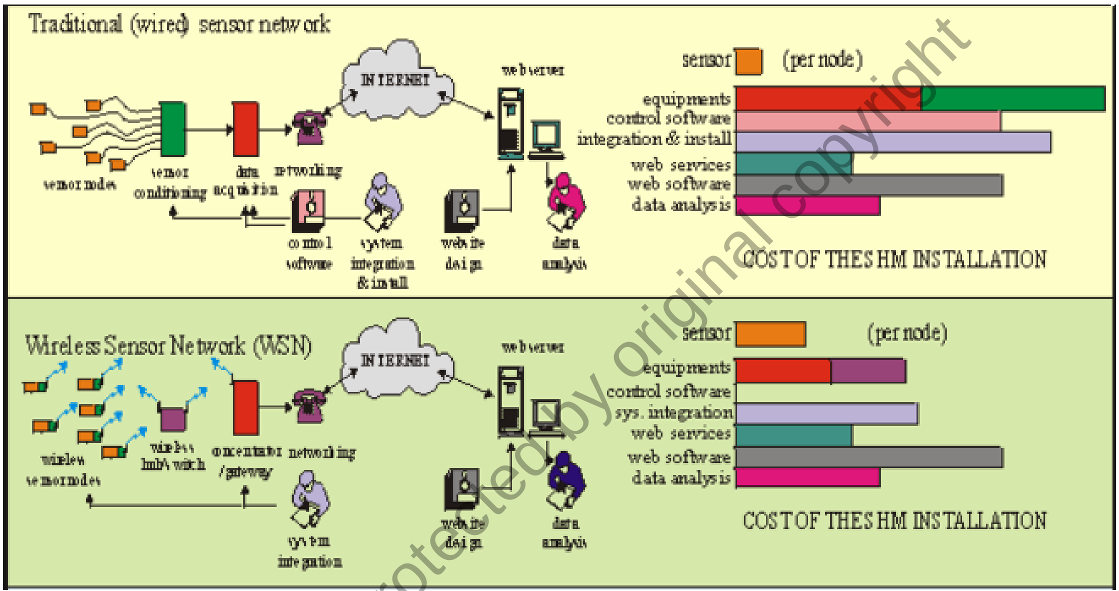

Figure 1.1: Differentiation sensor network in SHM system (F. Bastianini & Markus Kruger, 2012)

1.2 Problem Statement

Recently, passive FSS was applied in SHM application. The 2D FSS sensors were bonded to the surfaces of existing structures for the detection and monitoring of strain and buckling displacement due to loading (Pieper, Donnell, Abdelkarim & A. ElGawady, 2016) and also using a combination of Microelectromechanical system (MEMS) (Pavia, Otter, Lucyszyn & Ribeiro, 2016). Strain changes were detected by the re-radiated electromagnetic wave from the cross dipole FSS elements. Two polarizations (horizontal and vertical) were used to determine structural abnormalities using the FSS. However, this system is limited to detect changes in building behavior on horizontal direction only. This is due to the insignificant electromagnetic wave variation from the vertical detection frequency shifting (sensitivity). 2D FSS also lack of sensitivity in term of shifting in frequency response when the FSS is tilted or bending. For example, Frequency response of a sensitive FSS would proportionally vary toward the incident angle change. In this case, variation in FSS performance due to different signal incident angles is highly desirable.

Previously, a wired SHM sensor is used to monitor the structures changes (D. Wang, Chen & Wang, 2015). However, wired SHM have a limitations in term to cover large area where hundreds of sensor is required (S. Yang, 2014), (H. S. Kim & Kim, 2011). It is also prone to have a wired connection problem where the cable will be easily damage and difficult to be repaired. Therefore, passive wireless SHM sensor network is the alternative method to reduce the network connecting problems.

1.3 Motivation

In order to overcome the conventional 2D FSS limitation, this research designed the square FSS with a third-dimensional (3D) geometry as a passive sensor for SHM. In order to improve the sensitivity incidence angle changes characteristic, 3D square FSS is proposed. The 3D square FSS consists of vertically arranged unit elements of a certain height. It is been reported that 3D square FSS introduce an additional design parameter that extending the potential functionality of the structure beyond conventional FSS. A 3D square FSS array resonator element was demonstrated offering great flexibility in terms of controlling the frequency response. Furthermore, the extra dimension (3D) offers greater flexibility, freedom in the design and extra control frequency response characteristic (Rowe, As-Saber, Azemi & Ghorbani, 2015). The electromagnetic wave characteristic of 3D FSS will change by incidence angle change due to structural bending or structural failure. The changes feature is used as a sensing function.

1.4 Objectives

The main aim of this research is to design and analyze the possibility of introducing the Structural Health Monitoring using 3D FSS. The main objective of the study includes:

i. To design passive wireless 3D FSS sensor for structural monitoring system.

ii. To enhance the capability of 2D FSS towards 3D FSS in term of sensitivity frequency shifting for monitoring structural changes.

ii. To evaluate the performance of SHM 3D Frequency Selective Surface as passive sensor.

1.5 Research Scope

The scope of this research consists of several stages to achieve the objectives of this project. The stages are divided into three phase as follows:

Phase 1: 3D Frequency Selective Surface development and procedure.

The 3D FSS consist of a three-dimensional periodic array of square resonators. In order to stabilize FSS response for both TE and TM incidence angles from 0 to 80 degrees at the same frequency, the height cross-sectional dimension of the 3D square FSS element will be elevated.

Phase 2: Electromagnetic characteristic change of FSS is investigated through experimental.

To verify the independent incident angle response of the 3D Square FSS, a prototype is fabricated by using periodic arraying aluminum materials. Different bending condition illustrate building strain will be studied.

Phase 3: Validated the system comparing with simulation and measurement result.

It is believed wireless SHM sensor using 3D Square FSS is system cost effective, able to record acceleration of building in high rate data with high sensitivity and send the data wirelessly. The 3D Square FSS substrate will be validated using free space measurement setup. Measured and simulated results will be compared.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is discussed the literature review of this research about conventional Frequency Selective Surfaces and summary previous sensors in Structural Health Monitoring systems. FSS are obtained in SHM application to act as a passive sensor where has been reviewed the conventional 2D FSS with a limitation of sensitivity sensing. Basically, conventional FSS characteristic behave such filter, transmit and reflect the electromagnetic wave. Therefore, this thesis emphasized about the behavior of passive FSS was modified their characteristic as a sensor compare to conventional FSS. In addition, these review also emphasis on the sensing sensitivity towards abnormalities building structure. Several main factors of FSS are reviewed in this chapter such as FSS application, type of FSS, characteristic, incident angles and review 3D FSS. For the SHM factors, the review about type of sensors and problem faced in current sensors are also summarized. These all factors are the fundamental knowledge that required realizing an ideal sensor by using FSS in SHM application. Importance parts required to examine in how FSS behave a sensor is incident angle. In

SHM applications, FSS behave a sensor by analyzed the incident angle to monitoring any structure mobility.

2.1.1 Frequency Selective Surfaces review

Frequency Selective Surfaces are composed by periodic array that behave effectively as a filter to electromagnetic energy. The surface of FSS is assembled by an array or aperture metallic patterns periodically in 2-Dimensional patterns (Munk, 2000). FSS can act in various types of filters that were classified to low pass, high pass, band stop and band pass by depending on their material and element shapes as indicate in Figure 2.1. Different geometry elements also distinguish the frequency response of FSS. Recently, there are have various elements shape have been develop such as circle (Bharti, Singh, & Jyoti, 2012), (Shukor et al., 2014), (Bharti, Singh, Jha, & Jyoti, 2013) square (Jha, Singh, & Jyoti, 2012), (Li et al., 2011) , cross dipole (Kiani, Olsson, Karlsson, Esselle, & Nilsson, 2011), (Chen, Chen, Wang, Gu, & Shi, 2013), fractal geometries (Ratnaratorn, Mahatthanajatuphat, & Akkaraekthalin, 2014), (Panwar, Puthucheri, Singh, & Roorkee, 2015) and hexagon (Lu, Shen, & Yan, 2011), (S. F. Zheng, Yin, Zheng, Liu, & Sun, 2011).

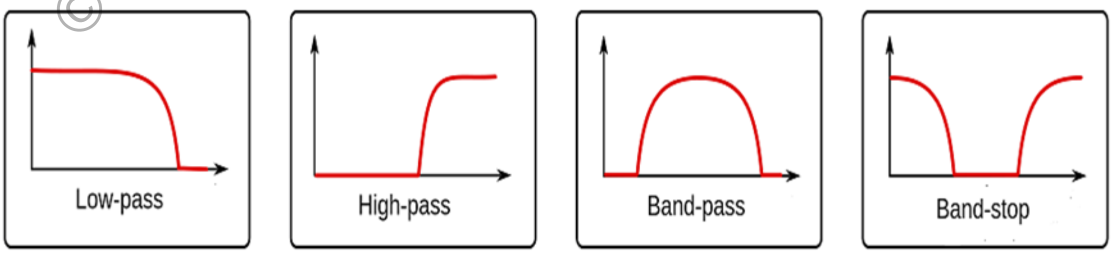

Figure 2.1: Classification of FSS filter response.

2.1.2 FSS application

Frequency Selective Surfaces application are wide variety and also ranging exceed electromagnetic spectrum. Recently, FSS have been contributed significantly toward advancing modern communications system which they are design to reflect and transmit the electromagnetic waves through an FSS (Zhang, Yang, Li, & Wu, 2010), (D'Assunção, Fontgalland, Baudrand, Titaouine, & Neto, 2009), (Li et al., 2011). There have various type of application has been applied using FSS to overcome the existing problem and enhances performance. The numerous application have been applied such as reflector antenna (Lin, Li, Zheng, & Zen, 2009) which covers for reflecting elements, electromagnetic shielding against interference (Yogesh Ranga, Matekovits, Esselle, & Weily, 2011) bandwidth and efficiency antenna arrays (Y. Ranga, Matekovits, Esselle, & Weily, 2011a) and also antenna radomes (Vnlapalli, 2009).

As indicated in Figure 2.2, only operating frequency is allowed to enter through the radomes, while other frequency band specular reflected by radomes. Antenna radomes basically behave as a shield for unwanted signal travelling towards them to reduce backscattering radar cross section (RCS). To reduce the radar cross section, band pass radomes will reflect the signal wave outside frequency response range while allowing the signal wave in operating frequency at various angles (Costa F & Monorchio, 2012). This radomes application using FSS has been contributed and deployed widely for military uses such as aircraft, ships and missiles.