ACOUSTIC CHARACTERISTICS OF DEFORMABLE ORIGAMI STRUCTURES FOR MULTI-PURPOSE HALL

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DEDICATION

To the Love of My Life:

My Mother
Kamariah Che' Ku

My Father
Muarat Abdullah

My Siblings
Rosenita Muarat, Mohd Nasri Muarat, Md Nasir Muarat, Mohd Nasharuddin Muarat, Mohd Idham Muarat, Mohd Amir Hidayat Muarat

My Future Soulmate, Insya Allah
Airi Ali

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ABSTRACT

In the multi-purpose hall, variable acoustic elements are required to vary the acoustics of the space tailored to the intended use. The variable acoustics elements are normally achieved by the variable absorption, variable volume and active acoustic system and have been successfully implemented in many halls. However, there is a necessity to explore other innovative variable acoustic elements in order to improve knowledge in this field. In the engineering field, the origami-inspired structures that are made up by folding a flat sheet of material to three-dimensional structures have been an increasing topic of interest among researchers in various applications. The applications range from sandwich structures to mechanical metamaterials and the interest is due to the intriguing characteristics that possessed by the origami-inspired structures. For that reason, this research proposed deformable origami structure as an element that can vary the acoustic condition. To realize the research ideas, comprehensive experimental works were carried out to investigate the feasibility of origami structure as variable acoustic element. Two types of origami patterns namely Triangular and Miura origami fabricated using three different materials (i.e. paperboard, felt and ethylene-vinyl acetate foam material) were investigated in this study. The origami structures were characterized by the absorption coefficient through sound absorption tests in a 1:5 scaled reverberation chamber. The 1:5 scaled reverberation chamber is compiled to ISO 354 (2003) which qualified the chamber to conduct sound absorption measurement. The origami structures were tested in a reverberation chamber by varying the height of the structure to simulate origami deformation using the perimeter-to-area (P/A) ratio method. The result shows that the origami structure has the ability to change the sound absorption characteristic by changing the height of the structure. However, the choice of material used to construct the origami structure has a significant influence on the effectiveness and the frequency range in which the absorption coefficient is altered. The study also shows that the size of the sample plays a critical role in the determination of the absorption coefficient as it introduces the edge effect to the test result. A case study performed in this study also indicated that the utilization of deformable origami structure can vary the acoustics of a space.

ABSTRAK

Di dalam dewan pelbagai guna, elemen akustik boleh ubah diperlukan untuk mengubah keadaan akustik yang bersesuaian dengan tujuan pengunaan. Elemen akustik boleh ubah kebiasaannya dapat dicapai melalui serapan boleh ubah, isipadu boleh ubah dan sistem akustik aktif dan telah berjaya dilaksanakan di dalam banyak dewan. Namun, terdapat keperluan bagi meneroka elemen akustik boleh ubah inovatif yang lain bagi menambahbaik pengetahuan dalam bidang ini. Di dalam bidang kejuruteraan, struktur berinspirasikan origami yang dibuat dengan melipat kepingan bahan rata kepada struktur tiga dimensi telah menjadi topik yang menarik minat yang semakin berkembang di kalangan pengkaji-pengkaji di dalam pelbagai bidang. Bidang ini meliputi struktur lapisan sehingga ke bahan meta mekanikal dan minat dipengaruhi oleh ciri-ciri menarik yang dimiliki oleh struktur yang berinspirasikan origami. Oleh kerana itu, kajian ini mencadangkan struktur origami yang berubah bentuk sebagai elemen yang dapat mengubah keadaan akustik. Bagi merealisasikan idea kajian ini, ujikaji yang menyeluruh telah dijalankan bagi menyelidiki kebolehlaksanaan struktur origami sebagai elemen akustik boleh ubah. Dua jenis corak origami iaitu Segitiga dan Miura dibuat dengan menggunakan tiga jenis bahan yang berbeza (iaitu bahan papan kertas, laken dan busa etilena-vinil asetat) telah diselidiki dalam kajian ini. Struktur origami telah dicirikan oleh pekali serapan melalui ujian serapan bunyi di dalam ruang gema berskala 1:5. Ruang gema berskala 1:5 ini menepati keperluan ISO 354 (2003) yang melayakkan ruang tersebut digunakan bagi pengukuran serapan bunyi. Struktur origami telah diuji di dalam ruang gema dengan mengubah ketinggian struktur bagi mensimulasi perubahan bentuk origami dengan menggunakan cara nisbah perimeter kepada luas (*P/A*). Keputusan ujian menunjukkan struktur origami mempunyai kebolehan untuk mengubah ciri serapan bunyi dengan menukar ketinggian struktur. Namun, pemilihan bahan yang digunakan untuk membina struktur origami mempunyai pengaruh yang ketara ke atas keberkesanan dan julat frekuensi pekali serapan yang dapat diubah. Kajian juga menunjukkan saiz sampel memainkan peranan yang kritikal dalam penentuan pekali serapan sambil mengenengahkan kesan bucu terhadap keputusan ujian. Satu kajian kes yang dilaksanakan dalam kajian ini juga menunjukkan penggunaan struktur origami yang berubah bentuk dapat mengubah keadaan akustik sesuatu ruang.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACS	-	Acoustical Control System
ASTM	-	American Society for Testing and Materials
CARMEN	-	Contrôle Actif de la Réverbération par Mur virtuel à Effet Naturel
EVA	-	Ethylene-vinyl acetate
IR	-	Impulse Response
ISO	-	International Organization for Standardization
LabVIEW	-	Laboratory Virtual Instrument Engineering Workbench
LARES	-	Lexicon Acoustic Reinforcement and Enhancement System
MCR	-	Multichannel Amplification of Reverberation
MDF		Medium-density fibreboard
MLS	-	Maximum Length Sequence
NI	-	National Instruments
PVC	-	Polyvinyl Chloride
RT		Reverberation Time
SIAP	-	System for Improved Acoustic Performance
UTM	-	Universiti Teknologi Malaysia
VRAS	-	Variable Room Acoustic System

LIST OF SYMBOLS

a	-	Side length of parallelogram for Miura origami
A	-	Total sound absorption at room boundaries
A_1	-	Equivalent sound absorption area of empty reverberation chamber
A_2	-	Equivalent sound absorption area of reverberation chamber with the presence of specimen
A_m	-	Material area
b	-	Side length of parallelogram for Miura origami
b_n	-	Air absorption discrepancy
c	-	Speed of sound
c_1	-	Speed of sound for empty reverberation chamber
c_2	-	Speed of sound for reverberation chamber with the presence of specimen
E	-	Ratio of perimeter-to-area
f	-	Frequency
f_{min}	-	Minimum frequency
f'	-	Scale model frequency
f_{ro}	-	Oxygen relaxation frequency
f_{rN}	-	Nitrogen relaxation frequency
h	-	Height of Triangular and Miura origami
h	-	Molar concentration water vapour
$H_n(t)$	-	Time dependent amplification factor
h_r	-	Relative humidity
I_{max}	-	Longest straight line fit in the reverberation chamber
K	-	Scale factor
ℓ	-	Length of Miura origami
l	-	Full-scale length
l'	-	Scale model length
L	-	Total length of Triangular and Miura origami
$2\ \ell$	-	Length of Miura origami

m	-	Number of Miura unit in x-axis
m	-	Full scale power air attenuation coefficient
m'	-	Scale model power air attenuation coefficient
$M1$	-	Microphone at position 1
$M2$	-	Microphone at position 2
$M3$	-	Microphone at position 3
n	-	Number of Triangular units
n	-	Number of Miura unit in y-axis
p	-	Atmospheric pressure
p	-	p-value
P_{atm}	-	Atmospheric pressure
p_r	-	Reference atmospheric pressure
p_{sat}	-	Saturated vapour pressure
P/A	-	Ratio of perimeter-to-area
RT	-	Reverberation time
RT_{20}	-	Reverberation time of 20 dB decay level
RT_{60}	-	Reverberation time of 60 dB decay level
RT_0	-	Reverberation time of empty reverberation chamber
RT_1	-	Reverberation time of empty reverberation chamber
RT_2	-	Reverberation time of reverberation chamber with the presence of specimen
R^2	-	Coefficient of determination
RH	-	Relative humidity
$RH1$	-	Relative humidity sensor at position 1
$RH2$	-	Relative humidity sensor at position 1
S	-	Surface area at room boundaries
S	-	Surface area covered by specimen in reverberation chamber
S_i	-	Surface area at i^{th} surface in room
S_s	-	Surface area of specimen
s	-	Side length of Triangular origami
$2s$	-	Width of a Miura unit
$S1$	-	Speaker at position 1
$S2$	-	Speaker at position 1

SE	-	Standard error of estimate or standard error of regression
t	-	Thickness of origami material
T	-	Full-scale time
T'	-	Scale model time
T	-	Temperature
T1	-	Temperature sensor at position 1
T2	-	Temperature sensor at position 1
T_0	-	Reference temperature
T_{01}	-	Triple-point isotherm temperature
v	-	Length of Miura unit
V	-	Volume of room or reverberation chamber
w	-	Inner width of Triangular unit
wt	-	Outer width of Triangular unit
W	-	Total width of Triangular and Miura origami structure
α	-	Sound absorption coefficient
α'	-	Scale model absorption coefficient
α_i	-	Sound absorption coefficient of i^{th} surface material
α_0	-	Average sound absorption coefficient of empty reverberation chamber
α_S	-	Sound absorption coefficient of specimen
α_∞	-	Sound absorption coefficient of infinite sample size
β	-	Slope of regression line
λ	-	Full-scale wavelength
λ'	-	Scale model wavelength
θ	-	Angle between the side length of Triangular origami
θ	-	Angle between facets and *x-y* plane of Miura origami structure
γ	-	Acute angle of Miura unit
∞	-	Infinity

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The use of a hall for more than one purpose is far from new but the conscious design to accommodate more than one acoustic type of performance is relatively recent. It has become increasingly apparent that for economic reasons, a hall dedicated to just one single use are often unrealistic especially in large cities where a degree of flexibility in use is now becoming the norm (Barron, 2009).

In the case of multi-purpose hall, variable acoustics elements are normally included in order to vary the acoustic of the space tailored to the intended use so that the acoustic quality for each use can be maximized. The most common variable acoustics approaches are variable volume and variable absorption (Barron, 2009; Poletti, 2010; Newell, 2012; Long, 2014). Through the variable volume, the acoustic of space is commonly varied by the moveable ceilings and coupled spaces. Meanwhile, the variable absorption is commonly realized by the adjustable curtains, adjustable draperies and moveable panels. Among these two variables acoustics, variable absorption approach is simpler compared to the variable volume which in practice is difficult to be accommodated. The change of acoustic by the variable volume approach has the advantage that it does not affect the sound level compared to the variable absorption which reduces the sound level.

Alternatively, the acoustic of space also can be varied by the active acoustics system (Barron, 2009; Poletti, 2010). Through the active system, a wider range of acoustic variation can be achieved in medium and large halls which is difficult to be achieved by the passive variable acoustics (i.e. variable volume and variable absorption). However, the acoustic enhancement by the active system has an issue regarding the unnatural sound (Barron, 2009; Poletti, 2010). Due to that, the physical variable acoustics elements are more advantageous and preferable since the change of acoustic is realized in a natural way.

As a conclusion, even though there are some limitations and drawbacks, the existing variable acoustics methods are well known and have shown to successfully vary the acoustic in many halls. However, this research study purposely not to solve the existing limitations and drawbacks but to explore other variable acoustics elements in order to acquire knowledge in this area. For this reason, this study proposes deformable origami structure as a candidate that could be used as potential variable absorption element.

1.2 Application of Origami Structure

Origami is the ancient art of Japanese paper folding that can transform a flat sheet of paper into a three-dimensional structure. The most common origami fold pattern that has gained much attention in the literature is Miura-ori. Miura-ori is named after Koryo Miura, a Japanese Engineer who first introduced this type of fold pattern to engineering applications. Koryo Miura studied the folding mechanism of Miura-ori and applied it in the design of solar panels for use in space (Miura, 1985; Nishiyama, 2012). As a result, the solar panels designed by Koryo Miura can be folded in a compact form during rocket launch and deploys to a large size once it reaches into space. The solar panels successfully flew in 1995.

To date, Miura-ori has remained the most commonly studied fold pattern and has inspired in various engineering applications. For example, Miura-ori has inspired in the development of sandwich core structures in aircraft design (Heimbs, 2009; Fischer *et al*, 2009; Heimbs *et al*, 2010; Hähnel *et al*, 2011; Heimbs, 2013). The core structures based on Miura-ori have shown to provide higher weight-specific bending stiffness compared to the conventional honeycomb core. Besides, the ability of Miura-ori structure to absorb energy during deformation and distribute the impact forces throughout the structure has inspired in the design of energy absorption (Tolman *et al*, 2014; Ma *et al*, 2018) as well as the design of sound barrier (Yu *et al*, 2019). Furthermore, the auxetic behaviour possesses by Miura-ori structure when undergoing deformation also has attracted many studies in the design of mechanical metamaterial (Schenk and Guest, 2013; Lv *et al*, 2014; Eidini and Paulino, 2015; Zhou *et al*, 2016; Kamrava *et al*, 2017).

From above, it can be seen that origami has given sources of inspirations and the research related to origami has become diverse with time. Therefore, it would be very interesting if the origami structure could be studied and explored in other areas such as variable acoustics for hall.

1.3 Deformable Origami Structure

Figure 1.1 shows an example of Miura-ori folded from standard printing paper. The fold pattern of Miura-ori allows the structure to expand and contract in all directions. Interestingly, the in-plane deformation behaviour of Miura-ori structure is auxetic meaning it exhibits negative Poisson's ratio, as demonstrated in Figure 1.2 (Schenk and Guest, 2010). From the figure, when the Miura-ori structure is stretched in one direction, the structure also expands in the orthogonal in-plane direction. As a result, the geometrical characteristics of the Miura-ori also changing along with the deformation of the structure. The geometry of Miura-ori is well defined and presented in Schenk and Guest (2013).

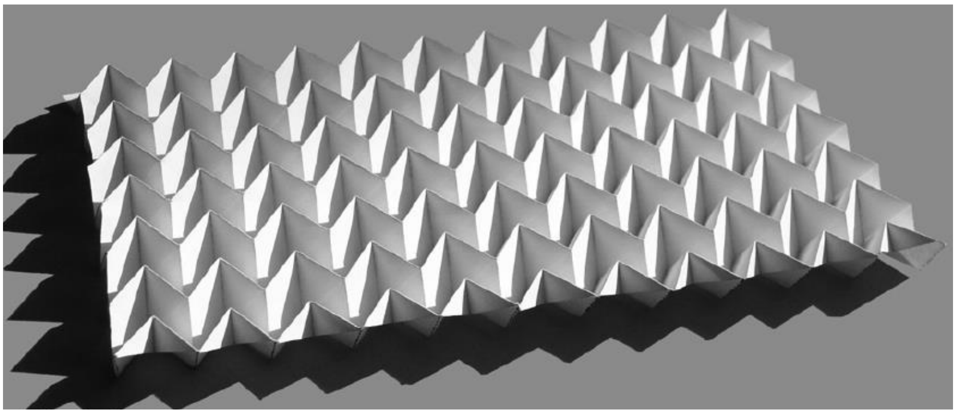

Figure 1.1 Example of Miura-ori structure adapted from Schenk and Guest (2010)

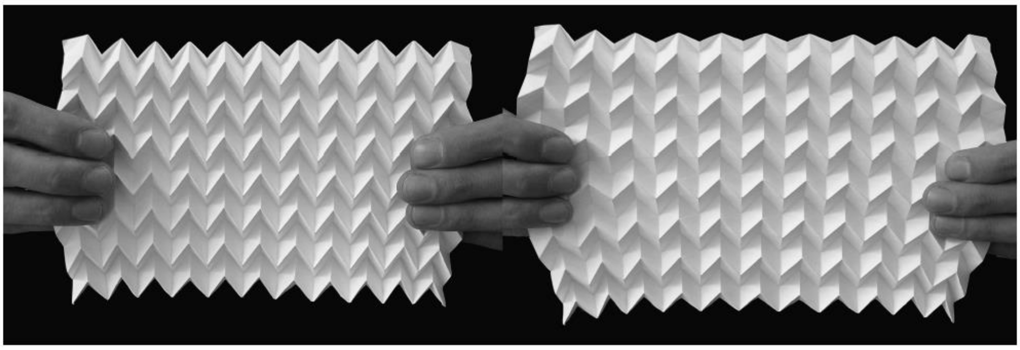

Figure 1.2 Example of in-plane deformation of Miura-ori structure demonstrated by Schenk and Guest (2010)

The ability of Miura-ori to deform and its attractive feature has inspired the author to study its absorption characteristics. This is because, if such origami structure could provide variable absorption characteristics by deforming its structure to the desired configuration, then the findings from this study could assist in the design of variable absorption element in the future.

1.4 Problem statement

The passive variable acoustics methods such as the variable volume and variable absorption methods have successfully been implemented in many halls and can provide significant variation of acoustic change. The active system on the other hand can provide a wider range of acoustic change compared to passive variable acoustics but the use of active system is less preferred to be used in the halls due to factor of unnatural sound. Due to that, passive variable acoustics methods are commonly found in most halls (Barron, 2009; Poletti, 2010). However, the adjustment of the physical variable absorption element (i.e. adjustable curtains or adjustable panels) is not conducted in a controllable way. This could be an advantage if the variable absorption element could be adjusted in a more controllable manner depending on the required acoustic performance of the hall. The idea of using deformable origami structure as variable absorption element could be potentially studied but to date, no one has tested and examined the potential application of the deformable origami structure in any depth. There is lack of literature and methodology related to the research of deformable origami structure as variable sound absorber and this forms the basis of the research work. The deformable origami structure may become a potential candidate that could be designed as one of the variable sound absorption elements but requires proper fundamental research studies in order to provide a comprehensive understanding on the acoustic characteristics of the origami structure and its relationship with the deformation of the origami structure. The identification of suitable origami structure to be used in the study is necessary since origami comes in various patterns. Meticulous methodology to confidently characterize the acoustic characteristics of the origami structure is vital in order to ensure the results obtained in this study are reliable. The study of the effect of different pattern and different material on acoustic characteristics will enlighten the fundamental understanding that would assist in designing origami structure as a viable variable absorption element.

1.5 Research Objective

The aim of this research is to investigate the feasibility of the deformable origami structure whether it can provide variable acoustic characteristics through the deformation of its structure.

To achieve the above aim, the following objectives have been identified:

(1) To establish a meticulous methodology for assessing the acoustic characteristics of the deformable origami structure.

(2) To characterize the acoustic characteristics of the deformable origami structure based on the experiment in a scale model reverberation chamber.

(3) To evaluate and present the relationship between the acoustic characteristics and origami deformation.

1.6 Research Scopes

The scopes of this study can be summarized as

(1) The origami structure shall has folding pattern that can be practically implemented, able to provide in-plane deformation and possible to be folded from different material into a three-dimensional structure without the need of machining.

(2) The adopted methodology shall be based on established International Standard guidelines and published works by other researchers.

(3) Scaled test rig is used to conduct the experimental works.

1.7 Significance of the Study

To date, there is no research investigating the feasibility of deformable origami structures as the variable acoustic element. In order to utilize the features offered by the origami structure, the acoustic characteristics related to physical deformation of the origami structure has to be investigated. Therefore, a comprehensive study should be conducted to assess and compare the performance of origami structure as an acoustic element. Once the acoustics characteristic has been identified, this will enable ones to design a control strategy that can actively alter the sound behaviour in a room or space using the variation provided by the origami geometry. Hence, this research provides the foundation on the design, analysis and evaluation of the origami structure capability in acoustic field which is significant in predicting the performance and efficacy when this structure is utilized in multi-purpose hall. A structured study emphasizing the influence of origami mechanic to sound property is important to realize origami as an option to sound quality control method.

1.8 Thesis Outline

This thesis contains six chapters including this chapter. In Chapter 2, there are two parts of literature reviews. The first part provides a literature review explaining the basic concept of acoustics in space and examples of the existing variable acoustics found in halls. Since deformable origami structures have not yet been studied as a variable acoustic element, the accurate measurement method for the acoustic characterization is crucial in this study. Therefore, the second part of the literature review focuses on the measurement method. In this part, the issues associated with the sound absorption measurement are discussed and the related research works are reviewed.

Chapter 3 explains the methodology used to conduct the research. In this chapter, the research flowchart is explained at the beginning of the chapter followed by the introduction of two types of origami patterns used throughout the study. The characteristics of the deformation of each of the origami pattern along with the geometries are described in this chapter. Test configurations, acoustic characterization method, construction of origami sample and the measurement procedures are also described in this chapter.

Chapter 4 describes the test facility developed for this study. This includes the explanations on the design and construction of a 1:5 scale reverberation chamber model as well as the measurement system developed using LabVIEW platform. The verification and validation on the developed software and the scaled reverberation chamber are also reported in this chapter.

Chapter 5 presents the findings obtained in this study. In this chapter, the analysis procedure for the data obtained from the experiment is explained at the beginning of the chapter followed by the discussion on the results from the analyses.

Chapter 6 is the last chapter that concludes the research findings. Recommendation and suggestion to advance the research work are stated in this chapter.

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