Basic Science
for Sustainable Marine Development

PROCEEDING
INTERNATIONAL SEMINAR 2015

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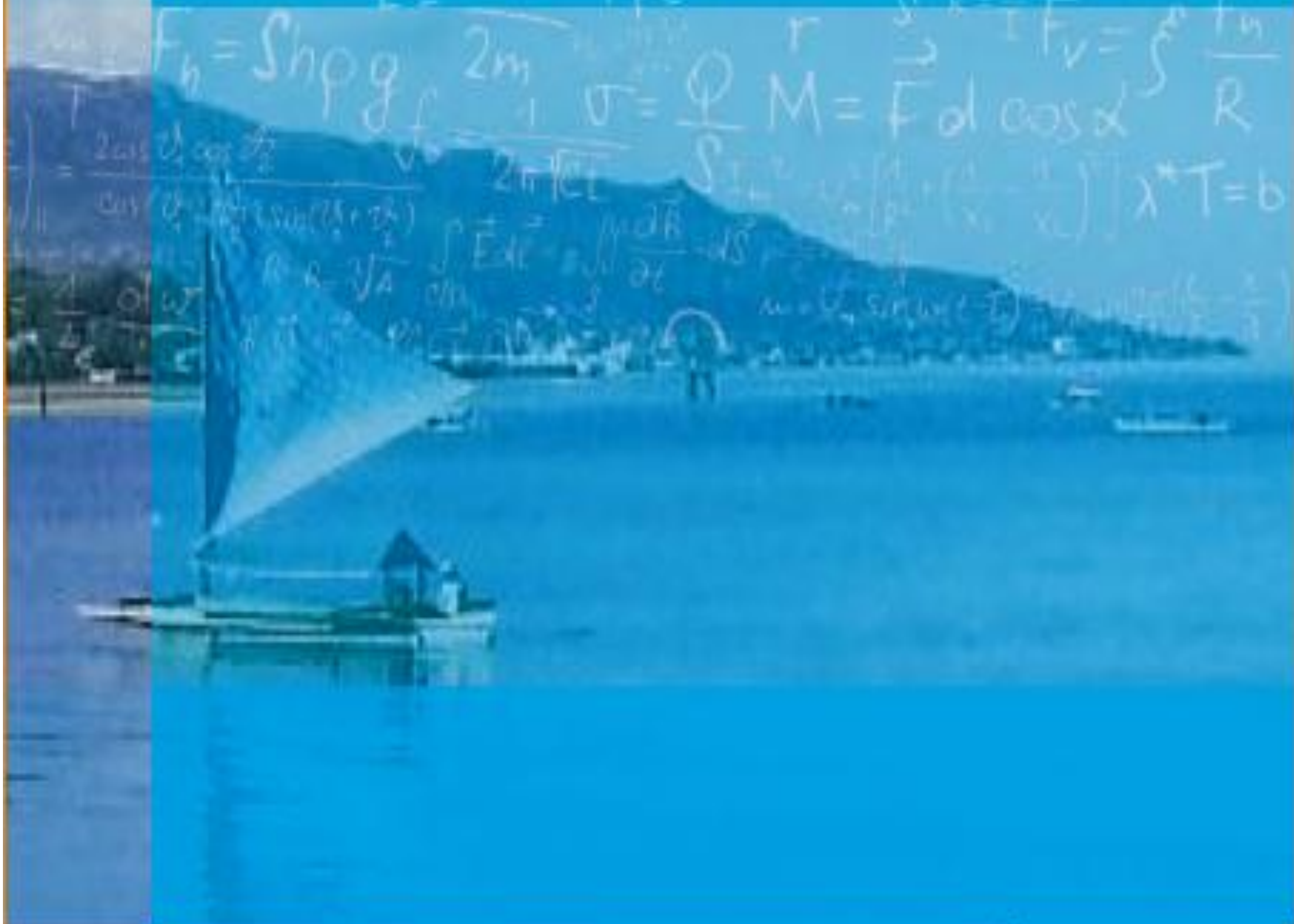

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Welcoming Address by The Organizing Committee

The honorable, the rector of Pattimura University

The honorable, the vice rector of academic affair, Pattimura University

The honorable, the vice rector of administration and financial affair, Pattimura University

The honorable, the vice rector of planning, cooperation and information affair, Pattimura University

The honorable, all the deans in Pattimura University

The honorable, the key note speakers and other guests.

We have to thank The Almighty God for the blessings that allow this International seminar can be held today. This is the first seminar about MIPA Science in which the Faculty of MIPA Pattimura University becomes the host. The seminar under the title Basic Science for Sustainable Marine Development will be carried out on 3 June 2015 at Rectorate Building, the second floor. There are 250 participants from lecturers, research institute, students, and also there are 34 papers will be presented.

This International seminar is supported by the amazing people who always give financial as well as moral supports. My special thanks refer to the rector of Pattimura University, Prof. Dr. Thomas Pentury, M.Si, and the Dean of MIPA Faculty, Prof. Dr. Pieter Kakissina, M. Si. I also would like to express my deepest gratitude to Dr. Kotaro Ichikawa, the director of CSEAS Kyoto University, Prof. Bohari M. Yamin, University of Kebangsaan Malaysia, Prof. Dr. Budi Nurani Ruchjana (Prisident of Indonesian Mathematical Society/Indo-MS), Dr. Ir. A. Syailatua, M.Sc (Director of LIPI Ambon), and Hendry Ishak Elim, PhD as the key note speakers. We expect that this international seminar can give valuable information and contribution especially in developing basic science for sustainable marine development in the future.

Last but not least, we realize that as human we have weaknesses in holding this seminar, but personally I believe that there are pearls behind this seminar. Thank you very much.

Chairman

Dr. Netty Siahaya, M.Si.

Opening Remarks
By Dean of Mathematic and Natural Science Faculty

I express my deepest gratitude to The Almighty God for every single blessing He provides us especially in the process of holding the seminar until publishing the proceeding of International Seminar in celebrating the 17th anniversary of MIPA Faculty, Pattimura University. The theme of the anniversary is under the title Basic Science for Sustainable Marine Development. The reason of choosing this theme is that Maluku is one of five areas in Techno Park Marine in Indonesia. Furthermore, it is expected that this development can be means where the process of innovation, it is the conversion of science and technology into economic value can be worthwhile for public welfare especially coastal communities.

Having the second big variety of biological resources in the world, Indonesia is rich of its marine flora and fauna. These potential resources can be treated as high value products that demand by international market. Basic science of MIPA plays important role in developing the management of sustainable marine biological resources.

The scientific articles in this proceeding are the results of research and they are analyzed scientifically. It is expected that this proceeding can be valuable information in terms of developing science and technology for public welfare, especially people in Maluku.

My special thanks refer to all researchers and reviewers for your brilliant ideas in completing and publishing this proceeding. I also would like to express my gratefulness to the dies committee-anniversary of MIPA Faculty for your creativity and hard working in finishing this proceeding, God Bless you all.

Dean of Mathematic and Natural Science Faculty

Prof. Dr. Pieter Kakisina, M.Si.

Contents

SIMULATION OF DYNAMIC MODEL TO ANALYZE SOUND ABSORBING CHARACTERISTICS OF POLYURETHANE FOAM

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Abstract

Noise is one of the problem that interfere the human health and activity. To solve these problem, the scientists have been developing many kind of soundproofing materials. Open-cell polyurethane foam has a great potential to applicated as an acoustic material because it has many advantages and benefits. Prediction problem of acoustic characteristics of the porous material has been developed by combining the Biot's theory with various non-acoustic estimation model. This research will be analyzed sound absorbing characteristics of polyurethane foam using the finite element method and a modified theoretical solutions. Dynamic model that used is based on Biot's poroelastic equations related to the solid skeleton and fluid displacements and then transformed into the Laplace domain. Analytical model that used is quadrilateral element model. And the approach that used to minimize the residual (error) is the Galerkin method. The results showed that the sound absorption coefficient is solved using the finite element method is closer to experimental results when compared with the modified theoretical solution.

Keywords: Biot, finite element method, modified theoretical solutions, polyurethane foam, sound absorption coefficient.

1. INTRODUCTION

With the rapid advancement of technology, development tools that used by humans is increasing. Most of the equipment generating noise causing unwanted noise. One way to prevent the propagation or radiation noise is to use acoustic materials to absorb the sound so noise can be reduced. Type of soundproofing materials can be classified into porous materials, resonators and panel (Lee, et al., 2003). In general, porous materials will absorb sound energy greater than the other types of materials, due to the presence of pores of the sound waves can enter the material.

In some recent research has tested and analyzed the acoustic properties of porous material. Sun, Chen and Feng have investigated the characteristics of the sound absorption of fibrous metal materials at high temperatures. In that study compared the sound absorption coefficient based on the theoretical results, Biot-Allard models and experimental results (Sun, et al., 2010). Furthermore, Fouladi, Job, and Nor have done numerical simulations using the software estimation WinFLAG™ for analyzing the characteristics of the absorption coefficient of coir fiber from coconut (Fouladi, et al., 2011). Kino, Nakano and Suzuki examined the acoustic properties of polyurethane foams based on some prediction models such as the acoustic properties of the revised Johnson-Allard model have been combined with the Biot's theory, Delany-Bazley model and Miki model (Kino, et al., 2012).

Because the polyurethane is a polymer that cheap, easily formed, can be created by people then the open cell polyurethane foam has been widely used as a sound absorption material in noise control engineering. Advantages of polyurethane foam as compared to other materials (rubber, metal, wood, and plastic) is that this material is elastic, portable, flexible in low temperatures, even its strength better than the rubber material. Therefore, polyurethane foam has a great potential to be applied as acoustic material, especially for noise reduction in narrow spaces such as housing and offices.

In this study carried out predictions of the sound absorption coefficient of the polyurethane foam based on the Biot's dynamic equations poroelastic that used to derive a theoretical solution of the dynamic stiffness. It also will apply the finite element method (FEM) to analyze the characteristics of sound absorption coefficient of the polyurethane foam. Interpolation method that used as a approach function is Lagrange polynomial interpolation (Steven, 2005). There are several approaches that can be used to minimize the error or the residue, among other Collocation method, weighted-residual methods, Galerkin's method and least squares method. Among the four approaches, Galerkin's and least squares method has a better accuracy rate (Mirzaei, 1941). Galerkin's method is forms a formulation to minimize the integral of the multiplication of basis functions as weighting functions to the residue. In the least squares method, the coefficients are determined by minimizing the integral of the square of the residual. Therefore, taking into account the difficulties in solving the dynamical equations of Biot poroelastic mathematically complete, then the Galerkin approach applied in this study to obtain results more efficiently.

2. THE GOVERNING EQUATIONS

Biot theory governing the deformation of a porous material can be written as:

$$N\nabla^2\boldsymbol{u} + \nabla[(A+N)e + Q\varepsilon] = \rho_{11}\ddot{\boldsymbol{u}} + \rho_{12}\ddot{\boldsymbol{U}} + b(\dot{\boldsymbol{u}} - \dot{\boldsymbol{U}}), \tag{1}$$

$$\nabla(\mathrm{Q}e + R\varepsilon) = \rho_{12}\ddot{\boldsymbol{u}} + \rho_{22}\ddot{\boldsymbol{U}} - b(\dot{\boldsymbol{u}} - \dot{\boldsymbol{U}})\,, \tag{2}$$

where N, A, Q, R are elastic constants, b is the dissipation coefficient, $\boldsymbol{u}$ is the average solid skeleton displacement vector, dan **U** is the average fluid displacement vector. Similarly, the solid dilatation e and the fluid dilatation ε untuk for small deformation are defined as $e = \boldsymbol{u}_{i,i}(i = x, y, z)$ dan $\varepsilon = \boldsymbol{U}_{i,i}(i = x, y, z)$. Here, $\boldsymbol{u}_i(i = x, y, z)$ are components of $\boldsymbol{u}$ dan $\boldsymbol{U}_i(i = x, y, z)$ are components of $\boldsymbol{U}$. The Laplacian is ∇^2 dan ∇ is the gradient. The quantities ρ_{11}, ρ_{12} and ρ_{22} are apparent mass densities, which take into account the fact that the relative fluid flow through the pores is not uniform. ρ_{11} represents the total effective mass of the solid moving in the fluid, ρ_{22} represents the total effective mass of that part of the fluid, and ρ_{12} represents a mass coupling parameter between the fluid and the solid. When there is no relative motion between the fluid and solid skeleton, it is found that $\rho = \rho_{11} + \rho_{22} + 2\rho_{12}$. Here, ρ denotes the total mass density of the fluid-saturated elastic foam. ρ can be expressed in terms of the mass density of solid (ρ_s) and the mass density of fluid (ρ_f), and the porosity (ϕ) as $\rho = (1-\phi)\rho_s + \phi\rho_f$ (Biot, 1956).

Modification of the theoretical solution to the one-dimensional problem of the dynamic stiffness is derived from the Biot's poroelasticity equations related to solid skeleton and fluida dilatational strain for polyurethane foam can be obtained by taking the divergence of equations (1) and (2) which yields

$$\nabla^2(Pe + Q\varepsilon) = \frac{\partial^2}{\partial t^2}(\rho_{11}e + \rho_{12}\varepsilon) + b\frac{\partial}{\partial t}(e - \varepsilon) \tag{3}$$

$$\nabla^2(Qe + R\varepsilon) = \frac{\partial^2}{\partial t^2}(\rho_{12}e + \rho_{22}\varepsilon) - b\frac{\partial}{\partial t}(e - \varepsilon) \tag{4}$$

where $P = A + 2N$.

In addition, the dynamic behavior of open cell polyurethane foam is subjected to a impulsive sound pressure on its the permeable upper surface investigated. According to Biot's poroelastic theory and Cartesian coordinates, the dynamic equations for the two-dimensional open cell polyurethane foam problems can be written as :

$$N\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)u_x+(A+N)\frac{\partial}{\partial x}\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)+Q\frac{\partial}{\partial x}\left(\frac{\partial U_x}{\partial x}+\frac{\partial U_y}{\partial y}\right)$$
$$=\frac{\partial^2}{\partial t^2}(\rho_{11}u_x+\rho_{12}U_x)+b\frac{\partial}{\partial t}(u_x-U_x) \qquad (5)$$

$$N\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)u_y+(A+N)\frac{\partial}{\partial y}\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)+Q\frac{\partial}{\partial y}\left(\frac{\partial U_x}{\partial x}+\frac{\partial U_y}{\partial y}\right)$$
$$=\frac{\partial^2}{\partial t^2}(\rho_{11}u_y+\rho_{12}U_y)+b\frac{\partial}{\partial t}(u_y-U_y) \qquad (6)$$

$$\frac{\partial}{\partial x}\left[Q\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)+R\left(\frac{\partial U_x}{\partial x}+\frac{\partial U_y}{\partial y}\right)\right]=\frac{\partial^2}{\partial t^2}(\rho_{12}u_x+\rho_{22}U_x)-b\frac{\partial}{\partial t}(u_x-U_x) \qquad (7)$$

$$\frac{\partial}{\partial y}\left[Q\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)+R\left(\frac{\partial U_x}{\partial x}+\frac{\partial U_y}{\partial y}\right)\right]=\frac{\partial^2}{\partial t^2}(\rho_{12}u_y+\rho_{22}U_y)-b\frac{\partial}{\partial t}(u_y-U_y) \qquad (8)$$

where u_x, u_y, U_x and U_y are displacement components of the solid skeleton and the fluid, respectively (Tsay, et al., 2006).

3. MATERIAL PROPERTIES OF OPEN-CELL POLYURETHANE FOAM

For frequency response function calculations, the elastic constants N, A, Q, R; dissipation coefficient b, and apparent mass densites ρ_{11}, ρ_{12}, ρ_{22} can be connected to the foam constituents, ie, porosity ϕ, tortuosity α, pore cross-sectional shape correction factor c, and direct current flow resistivity σ_0. The typical material properties of the open cell polyurethane foam are discussed in detail as follows:

Porosity is the ratio of the total volume of fluida V_f in the interconnected pores to the total volume of foam material V_T. Porosity can be estimated from the equation $\phi=1-(\rho_s/\rho_m)$, where ρ_s and ρ_m are the densities of the porous medium and the raw material, respectively. The assumed density of polyurethane was 1200 kg m^{-3} (Kino, et al., 2012). Turtuosity α is generally used to describe diffusion in porous media. If there is no reliable data available for α_∞, it can be assumed to be 1. The coupling apparent mass (ρ_{12}) can be represented as $\rho_{12}=-\phi\rho_f(\alpha_\infty-1)$. The total effective mass densities for the solid

(ρ_{22}), and the effective mass densities of fluid (ρ_{22}), respectively defined as $\rho_{11} = (1-\phi)\rho_s - \rho_{12}$ and $\rho_{22} = \phi\rho_f - \rho_{12}$.

According to the Biot's theory, bulk modulus of air (fluid) K_f in the pores of polyurethane foam can be written as:

$$K_f = \frac{p_{amb}\,\gamma}{\gamma - (\gamma-1)F(B^2\omega)} \tag{9}$$

where

$$F(B^2\omega) = \left[1 + \frac{\sigma_0\phi}{iB^2\omega\rho_f}G_c(Bm)\right]^{-1} \tag{10}$$

$$G_c(m) = \frac{-m}{4}\sqrt{-i}\;\frac{J_1(m\sqrt{-i})}{J_0(m\sqrt{-i})}\Big/\left[1 - \frac{2}{n\sqrt{-i}}\frac{J_1(m\sqrt{-i})}{J_0(m\sqrt{-i})}\right] \tag{11}$$

In equation (11), m is equal to $m = c\left(\frac{8\omega\alpha_\infty\rho_f}{\sigma_0\phi}\right)^{1/2}$. p_{amb} is the ambient mean pressure, B is the square root of Prandtl number, and $\gamma = c_p/c_v$ where c_v and c_p are specific heats per unit mass at constant volume and pressure, respectively. J_0 dan J_1 are Bessel functions of first kind of order zero and one (Allarad, et all., 2009).

Because the cross section shape correction factor of the foam is circle ($c = 1$), considered tortuosity ($\alpha_\infty = 1$) then the bulk modulus of air in the equation (10) can be reformulated as:

$$K_f = \frac{p_{amb}\,\gamma}{\gamma - (\gamma-1)\left[1 - \frac{2}{Bm_{r_0}}\frac{J_1(Bm_{r_0})}{J_0(Bm_{r_0})}\right]} \tag{12}$$

where $m_{r_0} = c\left(\frac{-8i\omega\alpha_\infty\rho_f}{\sigma_0\phi}\right)^{1/2}$.

In the DC flow ($\omega = 0$), the flow resistivity yields $\sigma_0 = (8c\mu\alpha_\infty)/\phi r_0^2)$ where μ is the viscosity of fluid (air), r_0 is the radius of the pore, and c is a cross section shape correction factor. By comparison, dissipation coefficient (b) defined in the dynamic poroelastic theory is given by:

$$b = \frac{-\sigma_0}{4}\phi^2\left\{\frac{[m_{r_0}J_1(m_{r_0})]/J_0(m_{r_0})]}{1 - [2J_1(m_{r_0})]/[m_{r_0}J_0(m_{r_0})]}\right\} \tag{13}$$

For the elastic coefficient of P, N, Q, and R can be determined by combinations of porosity ϕ, the shear modulus of solid skeleton N, the bulk modulus of solid skeleton K_b, the bulk modulus of the fluid K_f, which is simply written as:

$$P = \frac{(1-\phi)^2}{\phi} K_f + K_b + \frac{4}{3} N \tag{14}$$

$$Q = (1-\phi) K_f \tag{15}$$

$$R = \phi K_f \tag{16}$$

For the fluid (air) saturated ope-cell foam, N, K_b, and K_f are complex coefficients, and K_b can be evaluated by $K_b = \frac{2N(1+v)}{3(1-2v)}$ where v is the Poisson's ratio (Allarad, et all., 2009).

Table 1. Measured and estimated (*) of material properties of polyurethane foam.

Sampel / material properties	Polyurethane foam 1	Polyurethane foam 2	Polyurethane foam 3	Polyurethane foam 4
Porosity (ϕ)*	0,97	0,97	0,97	0,97
Turtuosity (α_∞)*	1,0	1,0	1,0	1,0
Shear modulus (N)* ($N.m^{-2}$)	175(1+0.2i)	175(1+0.2i)	175(1+0.2i)	175(1+0.2i)
Flow resistivity (σ_0)* ($Ns.m^{-4}$)	6700	6700	6700	6700
Poisson coefficient (v)	0.35	0.35	0.35	0.35
Density (ρ_s) ($kg.m^{-3}$)	40	40	40	40
Thickness h (m)	0,0095	0,012	0,015	0,0175
Shape factor c	1,0	1,0	1,0	1,0

4. THEORETICAL SOLUTIONS OF DYNAMIC STIFFNESS

By study before, we have results for $\bar{\boldsymbol{u}}$ and $\bar{\boldsymbol{U}}$ at $z = h$ as:

$$\bar{\boldsymbol{u}}|_{z=h} = \frac{-p_0 \begin{Bmatrix} \Delta_{11}\delta_1[(1-\phi)(\bar{Q}+\bar{R}\bar{C}_3) - \phi(\bar{P}+\bar{Q}\bar{C}_3)]tanh(\delta_1 h) \\ +\Delta_{13}\delta_2[\phi(\bar{P}+\bar{Q}\bar{C}_1) - (1-\phi)(\bar{Q}+\bar{R}\bar{C}_1)]tanh(\delta_2 h) \end{Bmatrix}}{(\bar{P}\bar{R}-\bar{Q}^2)(\bar{C}_3-\bar{C}_1)} \tag{17}$$

and

$$\overline{\boldsymbol{U}}|_{z=h} = \frac{-p_0 \begin{Bmatrix} \Delta_{31}\delta_1[(1-\phi)(\bar{Q}+\bar{R}\bar{C}_3) - \phi(\bar{P}+\bar{Q}\bar{C}_3)]tanh(\delta_1 h) \\ +\Delta_{33}\delta_2[\phi(\bar{P}+\bar{Q}\bar{C}_1) - (1-\phi)(\bar{Q}+\bar{R}\bar{C}_1)]tanh(\delta_2 h) \end{Bmatrix}}{(\bar{P}\bar{R}-\bar{Q}^2)(\bar{C}_3-\bar{C}_1)} \tag{18}$$

With subtitution displacement results, equation (17) and (18), the Laplace transformed dynamic stiffness ($\bar{K}$) on the surface of polyurethane foam with a permeable upper surface is derived as:

$$\begin{aligned} \bar{K}(s) &= \frac{-p_0}{(1-\phi)\bar{\boldsymbol{u}}|_{z=h} + \phi\overline{\boldsymbol{U}}|_{z=h}} \\ &= \frac{(\bar{P}\bar{R}-\bar{Q}^2)(C_3-C_1)}{\begin{Bmatrix} [(1-\phi)\Delta_{11}+\phi\Delta_{31}][(1-\phi)(\bar{Q}+\bar{R}\,C_3) - \phi(\bar{P}+\bar{Q}\,C_3)]\delta_1\,tanh(\delta_1 h) \\ +[(1-\phi)\Delta_{13}+\phi\Delta_{33}][\phi(\bar{P}+\bar{Q}\,C_1) - (1-\phi)(\bar{Q}+\bar{R}\,C_1)]\delta_2\,tanh(\delta_2 h \end{Bmatrix}} \end{aligned} \tag{19}$$

Equation (19) is the dynamic stiffness equation that used to predict the sound absorption coefficient as a benchmark solution sound absorption coefficient is solved using the finite element method (Leleury, 2012).

5. FINITE ELEMENT MODEL

The basic concept underlying the finite element method is a discretization principle. In general, the discretization can be interpreted as an attempt to divide the system of the problem to be solved (the object) into parts smaller. The parts are smaller, hereinafter referred to as finite element are connected by nodes that are used by these elements and the boundary of the object. Associated with a local coordinate system (ξ,η), the four node quadrilateral element is defined with reference to the Cartesian coordinate system (x,y) can then be transformed into quadrilateral elements as shown in Figure 2. After transformation of the coordinate system of the point $P(x,y)$ is then expressed as $P(\xi,\ \eta)$. Basis functions of a node point in the interpolation on the finite element has specific properties, which have value one at the node point and has a value of zero at the point of the other nodes in the same element. According to the local coordinates defined, the basis functions for the four-node quadrilateral element can be written as:

$$\varphi_1(\xi,\eta) = \tfrac{1}{4}(1-\xi)(1-\ \eta) \qquad \varphi_2(\xi,\eta) = \tfrac{1}{4}(1+\xi)(1-\ \eta)$$
$$\varphi_3(\xi,\eta) = \tfrac{1}{4}(1+\xi)(1+\ \eta) \qquad \varphi_4(\xi,\eta) = \tfrac{1}{4}(1-\xi)(1+\ \eta)$$

such that $u = \varphi_1(\xi,\eta)u_1 + \varphi_2(\xi,\eta)u_2 + \varphi_3(\xi,\eta)u_3 + \varphi_4(\xi,\eta)u_4$

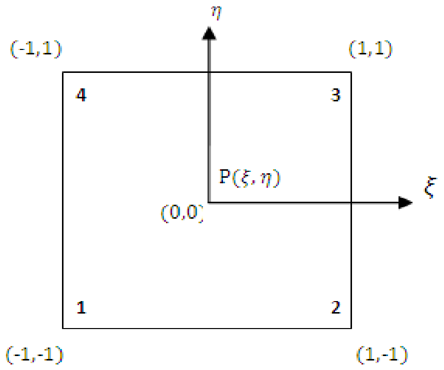

Figure 2. Four node rectangular element in ξ and η space

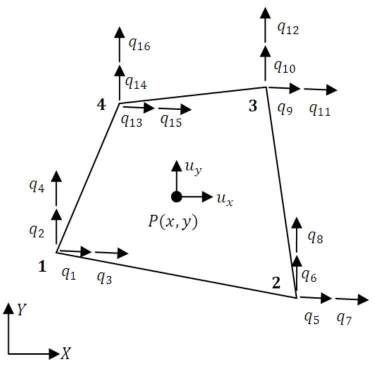

Figure 3. Rectangular element which have plane strains

Figure 3 shows the node quadrilateral element of a foam experiencing plane strain. These elements are referenced to a Cartesian coordinate system and the nodes have been arbitrarily numbered in the counterclockwise direction. If two components of the displacement of solid skeleton and fluid at each node are defined, the quadrilateral element will have 16 degrees of freedom, given by the column vector of displacement $\{q\} = [q_1, q_1, \dots, q_{16}]^T$. Coordinates of the point $P(x, y)$ is an arbitrary point within an element. With the use of the column vector of displacements $\{q\}$ and interpolation functions defined, solid skeleton and fluid displacement components can be written as:

$$\{u\} = [\varphi]\{q\} \tag{20}$$

where $\{u\} = [\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y]^T$, $[\varphi]$ is the basis function matrix. The basis function for the quadrilateral element can be written as

$$[\varphi] = \begin{bmatrix} [\varphi]_1 \\ [\varphi]_2 \\ [\varphi]_3 \\ [\varphi]_4 \end{bmatrix} = \begin{bmatrix} \varphi_1 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 & \varphi_3 & 0 & 0 & 0 & \varphi_4 & 0 & 0 & 0 \\ 0 & \varphi_1 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 & \varphi_3 & 0 & 0 & 0 & \varphi_4 & 0 & 0 \\ 0 & 0 & \varphi_1 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 & \varphi_3 & 0 & 0 & 0 & \varphi_4 & 0 \\ 0 & 0 & 0 & \varphi_1 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 & \varphi_3 & 0 & 0 & 0 & \varphi_4 \end{bmatrix}$$

Taking of the Laplace transform with respect to time variable t of equation (5) to equation (8) and then by using the initial condition, yields

$$\begin{aligned} &R_1(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y) \\ &\quad = N\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\bar{u}_x + (A+N)\frac{\partial}{\partial x}\left(\frac{\partial \bar{u}_x}{\partial x} + \frac{\partial \bar{u}_y}{\partial y}\right) + Q\frac{\partial}{\partial x}\left(\frac{\partial \bar{U}_x}{\partial x} + \frac{\partial \bar{U}_y}{\partial y}\right) \\ &\qquad - s^2(\rho_{11}\bar{u}_x + \rho_{12}\bar{U}_x) - bs(\bar{u}_x - \bar{U}_x) = 0 \end{aligned} \tag{21}$$

$$R_2(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y)$$

$$= N\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\bar{u}_y + (A+N)\frac{\partial}{\partial y}\left(\frac{\partial \bar{u}_x}{\partial x}+\frac{\partial \bar{u}_y}{\partial y}\right) + Q\frac{\partial}{\partial y}\left(\frac{\partial \bar{U}_x}{\partial x}+\frac{\partial \bar{U}_y}{\partial y}\right)$$

$$-s^2\left(\rho_{11}\bar{u}_y + \rho_{12}\bar{U}_y\right) - bs\left(\bar{u}_y - \bar{U}_y\right) = 0 \tag{22}$$

$$R_3\left(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y\right)$$

$$= \frac{\partial}{\partial x}\left[Q\left(\frac{\partial \bar{u}_x}{\partial x}+\frac{\partial \bar{u}_y}{\partial y}\right) + R\left(\frac{\partial \bar{U}_x}{\partial x}+\frac{\partial \bar{U}_y}{\partial y}\right)\right] - s^2(\rho_{12}\bar{u}_x + \rho_{22}\bar{U}_x) + bs(\bar{u}_x - \bar{U}_x) = 0 \tag{23}$$

$$R_4\left(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y\right)$$

$$= \frac{\partial}{\partial y}\left[Q\left(\frac{\partial \bar{u}_x}{\partial x}+\frac{\partial \bar{u}_y}{\partial y}\right) + R\left(\frac{\partial \bar{U}_x}{\partial x}+\frac{\partial \bar{U}_y}{\partial y}\right)\right] - s^2\left(\rho_{12}\bar{u}_y + \rho_{22}\bar{U}_y\right) + bs\left(\bar{u}_y - \bar{U}_y\right) = 0 \tag{24}$$

where $\bar{u}_x$, $\bar{u}_y$, $\bar{U}_x$ and $\bar{U}_y$ are Lapacle transformed of u_x, u_y, U_x dan U_y, respectively. s is the Laplace transform parameter. Furthermore, equation (21) until equation (24) are the equation residual. The key idea in Galerkin finite element method is the choice of weighting functions which are orthogonal to the equations residual that forms a formulation to minimize the integral of the multiplication of basis functions as weighting functions with residues (Hunter, 2003). Thus, we can write the equations governing the behavior of an element as

$$\sum_{e=1}^{n}\int_{A_e}\left\{\begin{matrix}[\varphi]_1^T R_1\left(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y\right) + [\varphi]_2^T R_2\left(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y\right) \\ +[\varphi]_3^T R_3\left(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y\right) + [\varphi]_4^T R_4\left(\bar{u}_x, \bar{u}_y, \bar{U}_x, \bar{U}_y\right)\end{matrix}\right\} dA = 0 \tag{25}$$

If we integrate equation (25) for each sub-summery is partially derived form the following matrix:

$$\sum_{e=1}^{n}\int_{A_e}\left\{\begin{matrix}(A+2N)\dfrac{\partial[\varphi]_1^T}{\partial x} + (A+N)\dfrac{\partial[\varphi]_2^T}{\partial y} + Q\left(\dfrac{\partial[\varphi]_3^T}{\partial x}+\dfrac{\partial[\varphi]_4^T}{\partial y}\right) \\ N\dfrac{\partial[\varphi]_1^T}{\partial y} \\ N\dfrac{\partial[\varphi]_2^T}{\partial x} \\ (A+N)\dfrac{\partial[\varphi]_1^T}{\partial x} + (A+2N)\dfrac{\partial[\varphi]_2^T}{\partial y} + Q\left(\dfrac{\partial[\varphi]_3^T}{\partial x}+\dfrac{\partial[\varphi]_4^T}{\partial y}\right) \\ Q\left(\dfrac{\partial[\varphi]_1^T}{\partial x}+\dfrac{\partial[\varphi]_2^T}{\partial y}\right) + R\left(\dfrac{\partial[\varphi]_3^T}{\partial x}+\dfrac{\partial[\varphi]_4^T}{\partial y}\right) \\ 0 \\ 0 \\ Q\left(\dfrac{\partial[\varphi]_1^T}{\partial x}+\dfrac{\partial[\varphi]_2^T}{\partial y}\right) + R\left(\dfrac{\partial[\varphi]_3^T}{\partial x}+\dfrac{\partial[\varphi]_4^T}{\partial y}\right)\end{matrix}\right\}^T \left\{\begin{matrix}\dfrac{\partial \bar{u}_x}{\partial x} \\ \dfrac{\partial \bar{u}_x}{\partial y} \\ \dfrac{\partial \bar{u}_y}{\partial x} \\ \dfrac{\partial \bar{u}_y}{\partial y} \\ \dfrac{\partial \bar{U}_x}{\partial x} \\ \dfrac{\partial \bar{U}_x}{\partial y} \\ \dfrac{\partial \bar{U}_y}{\partial x} \\ \dfrac{\partial \bar{U}_y}{\partial y}\end{matrix}\right\} dA$$

$$+\sum_{e=1}^{n}\int_{A_e}[[\varphi]_1^T,[\varphi]_2^T,[\varphi]_3^T,[\varphi]_4^T]\begin{Bmatrix} s^2(\rho_{11}\bar{u}_x+\rho_{12}\bar{U}_x)+bs(\bar{u}_x-\bar{U}_x)\\ s^2(\rho_{11}\bar{u}_y+\rho_{12}\bar{U}_y)+bs(\bar{u}_y-\bar{U}_y)\\ s^2(\rho_{12}\bar{u}_x+\rho_{22}\bar{U}_x)-bs(\bar{u}_x-\bar{U}_x)\\ s^2(\rho_{12}\bar{u}_y+\rho_{22}\bar{U}_y)-bs(\bar{u}_y-\bar{U}_y)\end{Bmatrix}dA$$

$$-\sum_{e=1}^{n}\int_{l_e}[[\varphi]_1^T,[\varphi]_2^T,[\varphi]_3^T,[\varphi]_4^T]\begin{Bmatrix}\bar{\sigma}_{xx}l_x+\bar{\tau}_{xy}l_y\\ \bar{\tau}_{xy}l_x+\bar{\sigma}_{yy}l_y\\ \bar{\sigma}l_x\\ \bar{\sigma}l_y\end{Bmatrix}dl \;=\; 0 \qquad (26)$$

where $\bar{\sigma}_{xx}$, $\bar{\sigma}_{yy}$, $\bar{\tau}_{xy}$ and $\bar{\sigma}$ are the Laplace transform of σ_{xx} , σ_{yy} , τ_{xy} and σ, respectively. Furthermore σ_{xx} , σ_{yy} dan τ_{xy} are stresses acting on the solid skeleton of the foam and σ s the stress of the fluid in the foam. By subtituting equations (19) and equation (20) into equation (26) and rearranging terms gives

$$\sum_{e=1}^{n}\{\,[K^{(e)}]\,\{q\}-\ \{F^{(e)}\}\}\ =0 \qquad (27)$$

where $[K^{(e)}]$ is the stiffness coefficient matrix for the element and $\{F^{(e)}\}$ may be viewed as the loading vector which contains boundary conditions. Taking into account the size of the width (k) and thickness (h) of samples of polyurethane foam that used as sound absorption material in this research, the width of the foam divided into 40 sections and the thickness of the foam divided into 4 sections. Thus, there are 205 nodes and 160 quadrilateral elements. Therefore, we can be written that:

$$x=\frac{k}{40}.\xi\Rightarrow\frac{dx}{d\xi}=\frac{k}{40}\ \Rightarrow\frac{d\xi}{dx}=\frac{40}{k}$$

$$y=\frac{h}{4}.\eta\Rightarrow\frac{dy}{d\eta}=\frac{h}{4}\ \Rightarrow\frac{d\eta}{dy}=\frac{4}{h}$$

The quality of the soundproofing material derermined by A_0 (sound absorption coefficient). If A_0 is 0, meaning no sound is absorbed. If A_0 is 1, meaning that 100% of the sound that comes absorbed by the material. Before calculating the acoustic impedance, reflection coefficient, and the sound absorption coefficient, then the dynamic stiffness determined in the first. The Laplace transformed dynamic stiffness on the top surface of the foam $\bar{K}(s)$ can be defined as:

$$\bar{K}(s)=-p_0/[(1-\phi)\bar{\boldsymbol{u}}+\phi\bar{\boldsymbol{U}}\,] \qquad (28)$$

Once it is calculated, the Laplace transformed surface acoustic impedance $\bar{Z}$, reflection coefficient R_0, and the sound absorption coefficient A_0 for normal incidence case can be defined as:

$$\bar{Z}(s) = \frac{-p_0}{(1-\phi)s\bar{\boldsymbol{u}} + \phi s\,\bar{\boldsymbol{U}}} = \frac{\bar{K}(s)}{s} \tag{29}$$

$$R_0 = \frac{\bar{Z} - Z_{air}}{\bar{Z} + Z_{air}} = \frac{\bar{K}(s)/s - Z_{air}}{\bar{K}(s)/s + Z_{air}} \tag{30}$$

$$A_0 = 1 - |R_0|^{\,2} \tag{31}$$

where Z_{air} is the characteristic impedance of air. Frequency response functions of K, Z, R_0, and A_0 can then be rapidly resulted by replacing the Laplace transform parameter s by $i\omega$, where ω is the radial frequency (Tsay, et al., 2005).

5. NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS

Polyurethane foam can be analyzed by discretizing it with finite element as shown in Figure 4. The individual element equations would then be assembled to form the equations for the foam. After manipulation, the Laplace transformed finite element equations for the foam will have the form as

$$[K]^*\,\{q\}^* = \{F\}^* \tag{32}$$

where $[K]^*$ is the global stiffness matrix, $\{q\}^*$ is the global displacement vector, dan $\{F\}^*$ is the global loading vector.

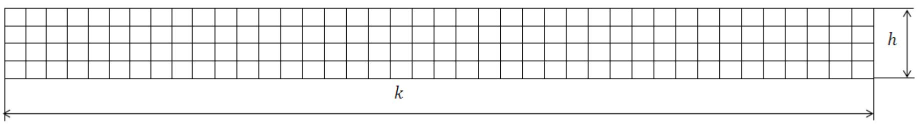

Figure 4. A quadrilateral element model of polyurethane foam with width k dan thickness h.

Because there are 205 nodes, the number of degrees of freedom $\{q\}^*$ be 820 which represents the displacement component of solid skeleton and fluid, and size of the matrix $[K]^*$ will be 820 x 820. Next, we set boundary conditions in which the lower and side surfaces is presumed to be fixed on a rigid and impermeable plane. Hence, the Laplace transformed solid skeleton and fluid displacements ($\bar{u}_x$, $\bar{u}_y$, $\bar{U}_x$, dan $\bar{U}_y$) must be zero on this face, i.e

$$\boldsymbol{u}(x,0) = \boldsymbol{U}(x,0) = 0$$

$$\boldsymbol{u}(0,y) = \boldsymbol{U}(0,y) = 0$$

$$\boldsymbol{u}(k,y) = \boldsymbol{U}(k,y) = 0$$

The boundary conditions of the top surface after laplace transform can be written as $\bar{\sigma}_f = \phi p$ and $\bar{\sigma}_s = (1-\phi)p$, ie $\boldsymbol{u}(x,h) = \bar{\sigma}_s$ and $\boldsymbol{U}(x,h) = \bar{\sigma}_f$.

Figure 5 - 8 shows a graph of the sound absorption coefficient of each sample of polyurethane foam using a quadrilateral element model and theoretical solutions compared with experimental data. The simulation results show that the sound absorption coefficient of the polyurethane foam is solved using the finite element method is closer to the experimental results when compared with the theoretical solution. Even for the polyurethane foam samples 1, 2, and 4 (Figure 5, 6 and 8) shows that the sound absorption coefficient using the FEM has the shape of the curve is more similar to the curvature of the sound absorption coefficient of the experimental results.

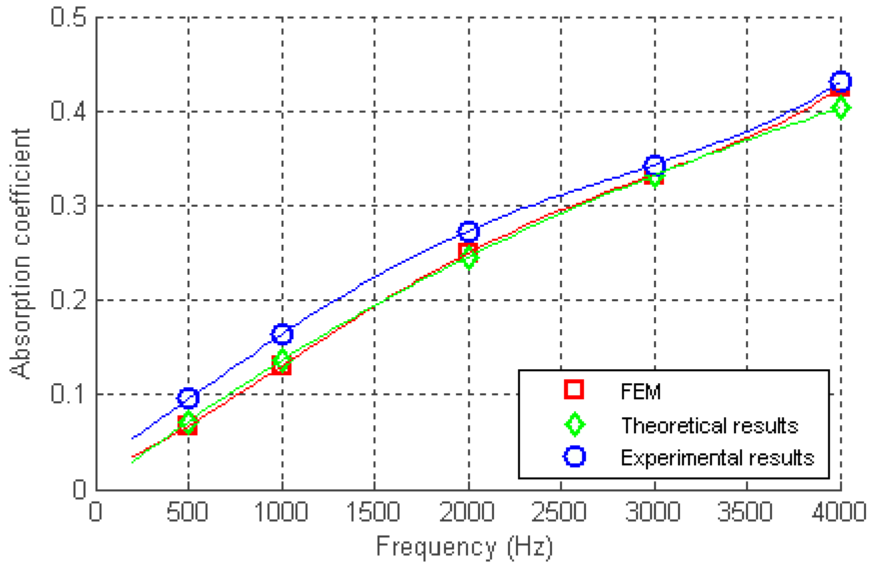

Figure 5. Comparison of absorption coefficients of polyurethane foam 1 (h = 0.95 cm).

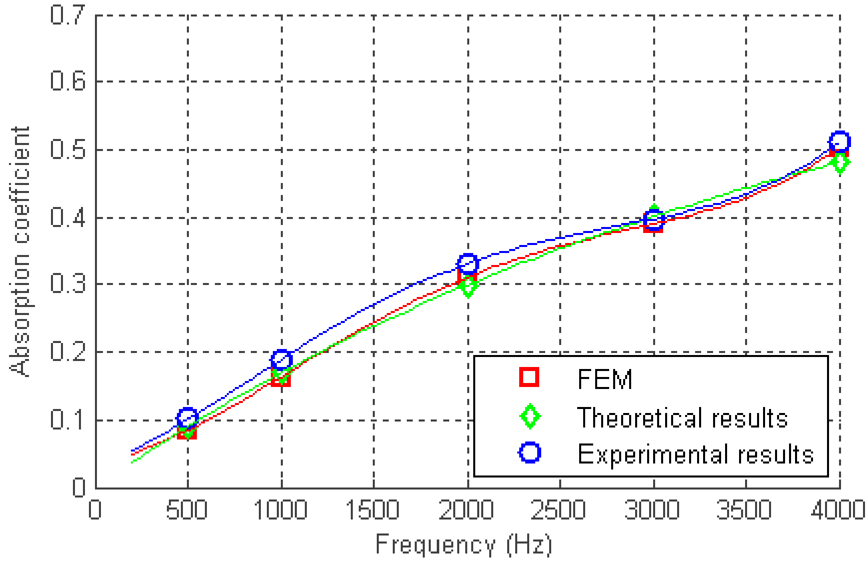

Figure 6. Comparison of absorption coefficients of polyurethane foam 2 (h = 1.20 cm).

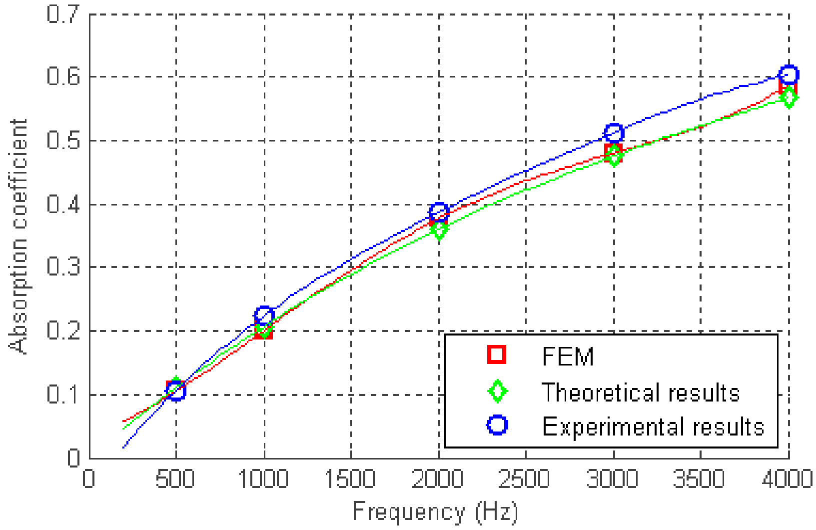

Figure 7. Comparison of absorption coefficients of polyurethane foam 3 (h = 1.50 cm).

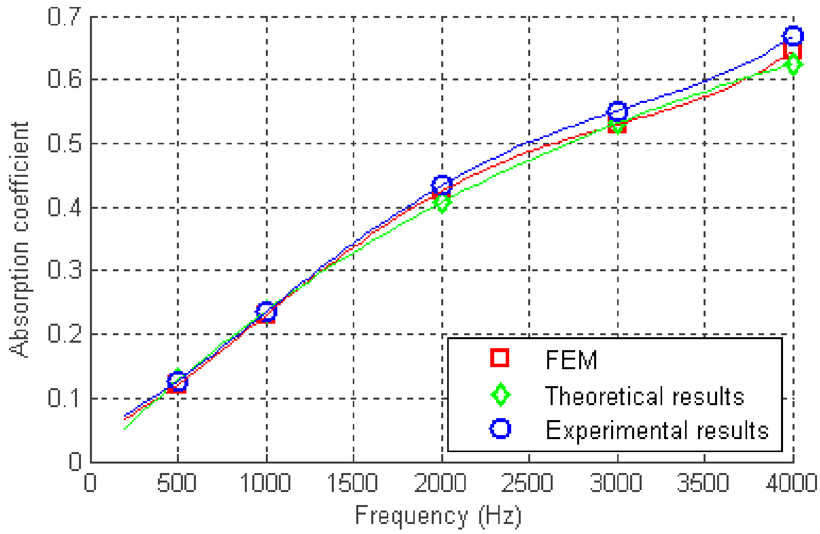

Figure 8. Comparison of absorption coefficients of polyurethane foam 4 (h = 1.75 cm).

Polyurethane foam 1 - 4 of thickness of 0.95 cm, 1.20 cm, 1.50 cm and 1.75 cm are used for investigating the influence of the thickness on the sound absorption coefficient of the polyurethane foam. Based on Figure 9 and 10 show that the change of the foam thickness will directly alter value of absorption coefficient of the polyurethane foam. For a sample thickness of polyurethane foam that used in this research and also to sound frequencies between 500 Hz to 4000 Hz is based on the experimental and predicted results showed when the polyurethane foam thickness increasing, the absorption coefficient will be larger.

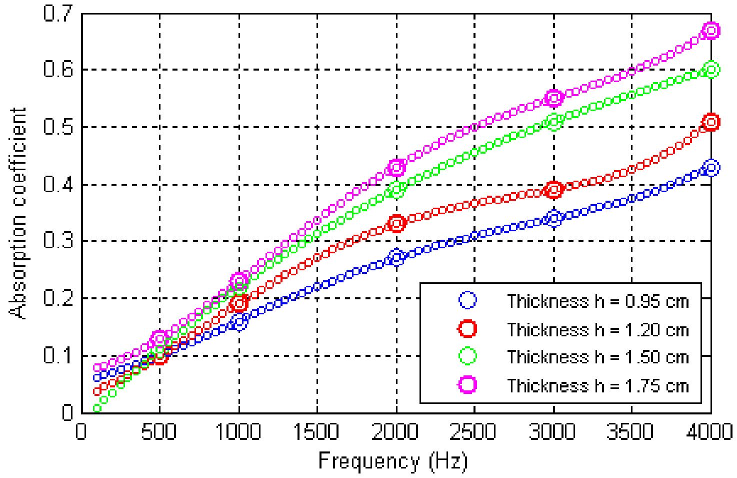

Figure 9. Comparison measurements of sound absorption coefficient of the polyurethane foam for different thicknesses.

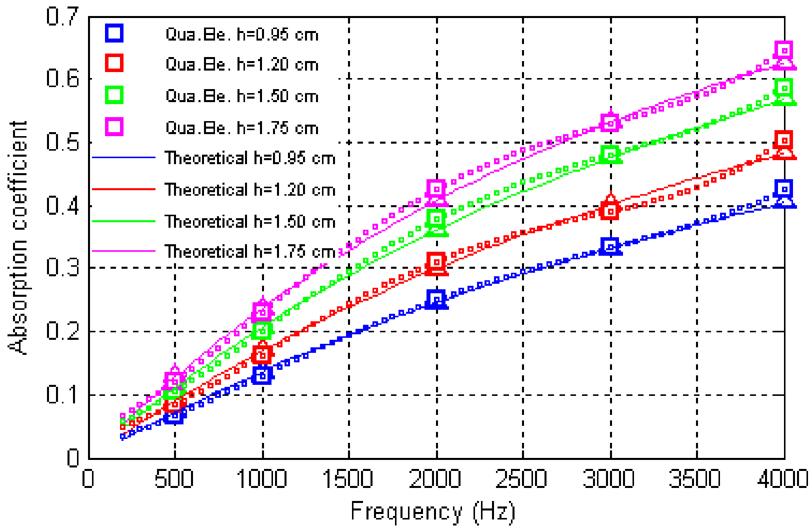

Figure 10. Comparison of sound absorption coefficient of the polyurethane foam for different thicknesses using element model and theoretical solutions.

The results also showed that polyurethane foam is best used as an acoustic material, which is as sound dampening material because it can absorb sound, especially at high frequencies.

6. CONCLUSION

Based on the description and discussion of results that have been exposed to it can be concluded that the sound absorption coefficient of the polyurethane foam is solved using the finite element method is closer to the experimental results compared with the modified theoretical solutions. In addition, polyurethane foam is also excellent used as soundproofing material because it can absorb sound, especially at high frequencies. If the polyurethane foam thickness increasing then the absorption coefficient will be larger, especially at a frequency of 500 Hz to 4000 Hz.

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