Improvement of Sound Absorption of Honeycomb Panels

Pan, J. (1) , Guo, J. (2) , and Ayres, C. (3)

(1) School of Mechanical Engineering, The University of Western Australia, Crawley, WA
(2) WorkSafe, Western Australia
(3) Ayers Composite Panels, Western Australia

ABSTRACT

Honeycomb panels are commonly used in ship, aircraft and building industries because of their lightweight, high-stiffness and non-combustibility properties. However, they provide very little absorption to sound approaching to them. This paper reports a significant improvement of the sound absorption in a broad frequency range when one of the surface sheets of honeycomb panels is micro-perforated. Acoustical analysis and test have been used to select the panel parameters for achieving the optimal sound absorption performance of the perforated honeycomb panels. One practical outcome of this study is a new type of micro-perforated honeycomb panels, and their successful test results for noise reduction in ship building industry is also presented.

INTRODUCTION

A honeycomb panel consists of honeycomb core, adhesive, and facing sheets. Facing sheets are adhesively bonded to the honeycomb core.

Honeycomb panels are commonly used in many applications including trains, ships, airplanes and buildings as internal walls, ceilings and partitions due to their properties of light-weight and high stiffness normal to the panel plane. However, traditional honeycomb panels provide very little absorption to sound approaching to them. As a result in order to reduce the sound pressure level or reverberation time in the space enclosed by the honeycomb panels, extra sound absorptive materials (such as polymer foams) have to be used to cover some panels. Effective sound absorption of low/middle frequency noise requires the use of sound absorptive layers of significant thickness, weight and cost.

This paper presents experimental evidence and theoretical analysis to demonstrate that sound absorption of traditional honeycomb panels can be significantly increased through optimal perforation at one of the surface sheets. Application of the acoustically treated honeycomb panels (micro-perforated honeycomb panels) to noise control in ship building industry is briefly described.

ANALYSIS OF PERFORATED PANEL ABSORBER

To improve the sound absorption of traditional honeycomb panels, one of the surface sheets of the panels are perforated. The design of the perforation rate and the core size is critical in order to achieve the maximum value in the sound absorption coefficients and the widest frequency bandwidth of absorption. Based on the theory of Helmholtz panel absorber [Morse and Ingard 1968, Kinsler et al 1982], the normal sound absorption coefficient of the perforated panel sound absorber can be obtained as

$$\alpha = \frac{4(R_s / \sigma)\rho_o c_o}{(R_s / \sigma + \rho_o c_o)^2 + (X_s / \sigma)^2} \tag{1}$$

where σ is the perforation ratio and $\rho_o c_o$ is the specific acoustic impedance of plane waves in air. R_s and X_s are respectively the real and imaginary parts of the specific acoustic impedance of one of the Helmholtz absorbers which make up the panel sound absorber. If a honeycomb panel is perforated on one of its surfaces, the perforation hole (assuming each core cavity only has one hole) and its core cavity are modelled as a Helmholtz absorber. The specific acoustical impedance of the absorber can be expressed as [Maa 1998]:

$$R_s = \frac{8\eta t}{a^2}\sqrt{1+\frac{|Ka|^2}{32}} + R_{sR} \tag{2}$$

$$X_s = \omega\rho_o t[1+\frac{1}{\sqrt{9+\frac{|Ka|^2}{2}}}] - \frac{\rho_o c_o^2 \sigma}{\omega D} + X_{sR} \tag{3}$$

where t, a and D are respectively the thickness of the perforated sheet, radius of the hole and depth of the honeycomb core. η is the shear viscous coefficient of air and

$$K = (1-j)\sqrt{\frac{\rho_o \omega}{2\eta}} . \tag{4}$$

$R_{sR} + jX_{sR}$ corresponds to the radiation impedance of the moving air in the hole, which is modelled as a vibrating piston on a rigid baffle [Kinsler et al 1982].

Solving

$$X_s(\omega) = 0 \tag{5}$$

for ω, the frequency for peak sound absorption coefficient can be determined. At the low frequencies and when a is sufficiently large, X_{sR} describes the effect of added mass.

For this case, an analytical expression of resonance frequency exists:

$$f_H = \frac{c_o}{2\pi}\sqrt{\frac{\sigma}{t_e D}} \quad (6)$$

where t_e is the equivalent thickness of the perforated sheet. For general cases and at the resonance frequency determined from Equation (5), the absorber has a peak sound absorption coefficient of

$$\alpha_p = \frac{4(R_s/\sigma)\rho_o c_o}{(R_s/\sigma + \rho_o c_o)^2}. \quad (7)$$

which leads to the necessary condition for maximum achievable peak sound absorption coefficient ($\alpha_{p\max} = 1$):

$$\frac{R_s}{\sigma\rho_o c_o} = 1. \quad (8)$$

Searching system parameters σ, a, D and t which satisfy condition (8) composes a nonlinear optimization problem. However, some insight could be gained by fixing two parameters, such as D and t, and investigating the effect of changing σ and a on the objectives of optimization. For honeycomb panels, the cross section area S_H of the core cavity, which is a hexagon, is usually fixed by manufactures. Thus σ is related to radius of the perforation hole a by

$$\sigma = \frac{a^2\pi}{S_H}. \quad (9)$$

Figure 1 shows the relationship between $\frac{R_s}{\sigma\rho_o c_o}$ and perforation radius. For this figure, we have used ½ inch core size (defined as L in Figure 5), $0.3mm$ sheet thickness and $D = 19mm$. The curve in Figure 1 demonstrates that the selection of the perforation radius is critical for achieving the maximum sound absorption. With the commonly used honeycomb parameters ($D \sim 5mm - 50mm$, $t \sim 0.3mm - 0.8mm$ and ½ inch core size), the diameter of the perforation hole must be within one millimetre range so that maximum sound absorption can be achieved. The frequency range of the maximum sound absorption can be designed by selecting suitable D and t and Equation (6) is used as an approximate estimation of the resonance frequency. This consideration of optimal design of honeycomb parameters has led to the concept development of optimal designed micro-perforated honeycomb panels which will be discussed in detail in the rest of this paper.

The sound absorption coefficients of three micro-perforated honeycomb panels; with parameters D and core size identical those used in Figure 1 and $t = 0.3mm$, are shown in Figure 2. Clearly if the panel with parameters satisfying condition (8) has the largest peak sound absorption coefficient. For this case, the optimal perforation radius is $a = 0.36mm$ and corresponding perforation ratio is $\sigma = 0.39\%$.

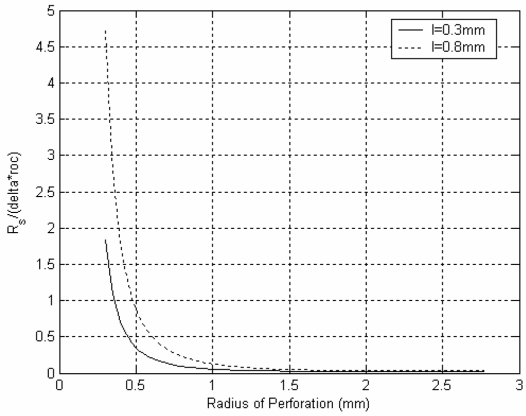

Figure 1 $R_s/(\sigma\rho_o c_o)$ as a function of the perforation radius a and at the absorber's resonance frequency ($D = 19mm$, and ½ inch core size).

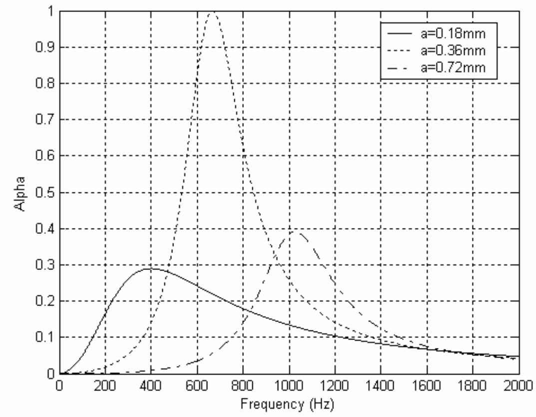

Figure 2 Predicted sound absorption coefficient of perforated honeycomb panels ($D = 19mm$, $t = 0.3mm$ and ½ inch core size).

Similar sound absorption feature is observed for $t = 0.8mm$ in Figure 3, that maximum peak absorption occurs at the optimal value of $a = 0.48mm$ based on the dotted curve in Figure 1. For this case the corresponding perforation ratio is $\sigma = 0.69\%$

It is worth noting that if the parameters D, t and core size are fixed, slightly reducing the perforation radius from the optimal value will decrease the peak frequency and the peak sound absorption coefficient. This could be an option when reduction of lower frequency noise is important and changing of other parameters is not practical.

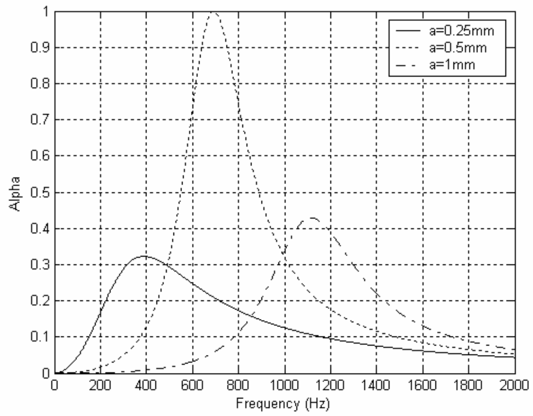

Figure 3 Predicted sound absorption coefficient of perforated honeycomb panels ($D = 19mm$, $t = 0.8mm$ and ½ inch core size).

EXPERIMENTAL RESULTS

Measured sound absorption coefficient

The sound absorption coefficients of samples of micro-perforated panels are measured in an impedance tube using the standing-wave ratio method. The panel's parameters are $D = 19mm$, $t = 0.3mm$ and ½ inch core size of $L = 12.7mm$. The perforation pattern of the surface sheet of the panel is a parallelogram with pitch of $P = 7mm$, orientation angle $\phi = 60^{\circ}$ and perforation radius $a = 0.4mm$. Typical measured sound absorption coefficient curves are shown in Figure 4. Compared with the sound absorption coefficient of traditional non-perforated honeycomb panels ($\alpha < 0.05$), micro-perforated honeycomb panels provide significant sound absorption over a broad frequency range.

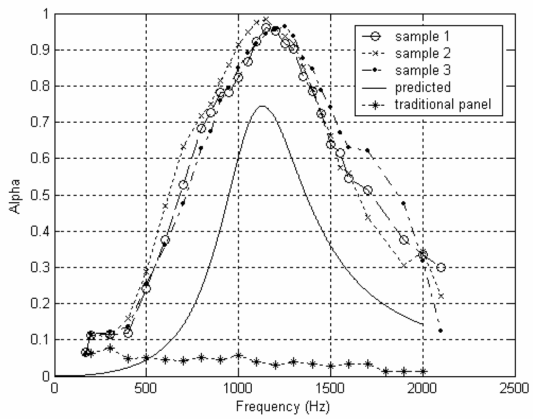

Figure 4 Measured sound absorption coefficient of three micro-perforated honeycomb panel samples ($D = 19mm$, $t = 0.3mm$, ½ inch core size, $a = 0.4mm$, $P = 7mm$ and $\phi = 60^{\circ}$). Dashed curve is predicted using Equations (1), (2), (3) and (13).

Using the panel's parameters, the average number of holes per core cavity is determined by:

$$\overline{N} = \frac{S_H}{S_P} \tag{10}$$

where S_H is the cross section area (Hexagon) of the core

$$S_H = \frac{3}{4} L^2 \sin 60^{\circ} \tag{11}$$

and S_P is the parallogram area that each perforation hole occupies

$$S_P = P^2 \sin 60^{\circ} . \tag{12}$$

The sound absorption coefficient and specific acoustic impedance can be calculated by Equations (1), (2) and (3), except that the perforation ratio is replaced by

$$\sigma = \overline{N} \frac{a^2 \pi}{S_H} . \tag{13}$$

The predicted sound absorption coefficient is also shown in Figure 4. Compared with the predicted result, the measured sound absorption coefficient has shown a much higher peak sound absorption and broader frequency range of absorption, where the frequency range may be defined as the frequency difference between the upper and lower frequencies corresponding to the half coefficient points from the peak in the $\alpha \sim f$ curves.

It should be noted that $R_s /(\sigma \rho_o c_o) = 0.3316$ for this case, which is much less than the optimal value. The main reasons for selecting the high perforation ratio in this design are:

(1) Glue used underneath the perforation sheet may block some holes, which decreases the perforation ratio and increases $R_s /(\sigma \rho_o c_o)$.

(2) Glue gathered at the edges of the perforation holes may increase the specific acoustic resistance through reducing the perforation radius and direct increase the viscous friction between moving air particles.

In addition, an increase in frequency bandwidth of sound absorption is expected because of the fluctuation of number of holes per cavity. Such fluctuation is due to the geometrical difference between the hexagon gride of the core cavities and the parallelogram gride of the perforation, and to irregularity of the core size and blockage of the holes by the glue due to manufacturing process.

In the following analysis, we intend to identify the most sensitive effect which contributed to the improvement of the peak sound absorption and frequency bandwidth of the measured absorption.

Analysis of experimental results

<u>Statistical description of perforation ratio fluctuation</u>

Given the hexagon cross section of the core, parallelogram pattern of the perforation and their sizes, the number of holes that each core cavity has may vary from 1 to 4 as illustrated in Figure 5, where the core size and pitch of the parallelogram are also defined.

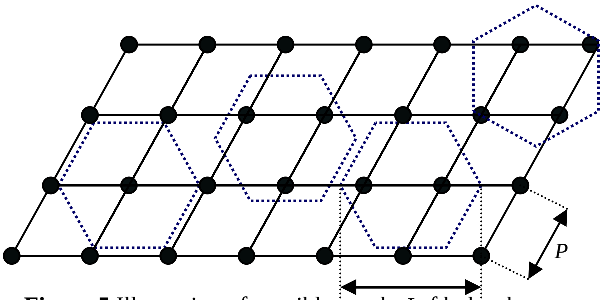

Figure 5 Illustration of possible number of holes that one core cavity could have in the micro-perforated honeycomb panels. The relative sizes of the hexagon and parallelogram grids correspond to the sample parameters used in the experiment.

Dependent upon the relative layout between the hexagon and parallelogram grides, and possible irregularity of the core size, the number of holes per core cavity may fluctuate and so the perforation ratio will fluctuate. As a result, the amount of sound absorption and peak frequency of individual core cavity also fluctuate from its averaged value determined by the averaged number of holes per cavity (Equation (10)). The analysis of Helmholtz absorber in the previous section has to be extended to accommodate the fluctuation of perforation ratio and its contribution to the overall sound absorption coefficient of the panel.

A distribution function $P(n)$ is defined to describe the percentage of total number of core cavities in the panel as a function of number of holes per core cavity:

$$P(n) = P_o e^{-\frac{(n-\overline{N})}{\tau}} \tag{14}$$

where $\overline{N}$ is the averaged number of holes per core cavity determined by Equation (10),

$$P_o = \frac{2}{\sqrt{\tau\pi}\left[1 + erf\left(\frac{\overline{N}}{\sqrt{\tau}}\right)\right]} \tag{15}$$

is a normalization factor and τ describes the level of the fluctuation.

For core cavities with n number of holes, the corresponding sound absorption coefficient $\alpha(n)$ and specific acoustic impedance can be calculated by Equations (1), (2) and (3), except that the perforation ratio is replaced by

$$\sigma = n\frac{a^2\pi}{S_H}. \tag{15}$$

Thus the overall sound absorption coefficient of the micro-perforated honeycomb panels is expressed as

$$\overline{\alpha} = \int_0^\infty \alpha(n)P(n)dn. \tag{16}$$

Figure 6 shows the results of predicted overall sound absorption coefficients for two different levels of fluctuation in perforation ratio. These results suggest that although increasing the fluctuation in perforation ratio increases the absorption frequency bandwidth, there is a significant reduction in the peak sound absorption coefficient. As the fluctuation neither affects the average number of holes per core cavity nor the specific acoustic resistance of the holes, the frequency corresponding to the peak sound absorption remains unchanged.

Thus, we conclude that the fluctuation of perforation ratio due to irregular core size and relative layout between the core and perforation grids is not the main reason for the increased peak and frequency bandwidth in the overall sound absorption as increased fluctuation always decreases the peak sound absorption.

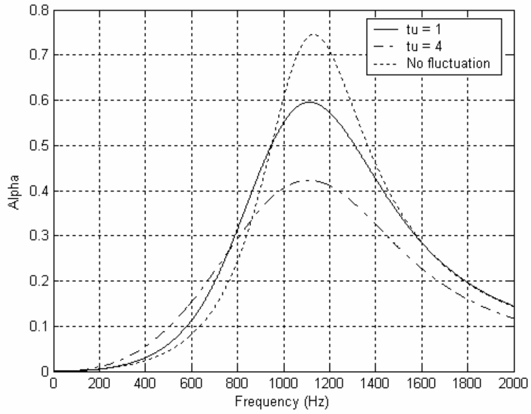

Figure 6 Effect of fluctuation of perforation ratio on the overall sound absorption of micro-perforated honeycomb panels.

Effect of glue

The effect of glue behind the perforated sheet on the sound absorption is through partial blockage of the holes. The blockage may provide a fluctuation of perforation ratio as well. However it will not present as a major reason for the increase in the peak sound absorption and frequency bandwidth. The blockage also provides an increase in the specific acoustic resistance of the hole through reduced perforation radius and an increase in viscous friction between the moving air particles and holes. In Equation (2), the shear viscous coefficient $\eta = 15.6\times10^{-6}\rho_o$ is due to the frictional loss when vibrating air particles pass the holes with rigid surfaces. When glue material is presented around the edges of the holes, the resistance in Equation (2) needs to be modified as:

$$R_s = \frac{8(\eta+\eta_g)t}{a_g^2}\sqrt{1+\frac{|Ka_g|^2}{32}} + R_{sR} \tag{17}$$

where η_g and a_g are respectively the contribution of the glue to the shear viscous loss and reduced perforation radius. The predicted sound absorption coefficient of the micro-perforated panels including glue induced viscous loss is presented in Figure 7, which shows an excellent agreement with the measured result when we chose $\eta_g = 5\eta$ and $a_g = a$. Thus we conclude that the improved sound absorption properties of the micro-perforated honeycomb panels may due to the increase of specific acoustic resistance by the glue material around the perforation holes.

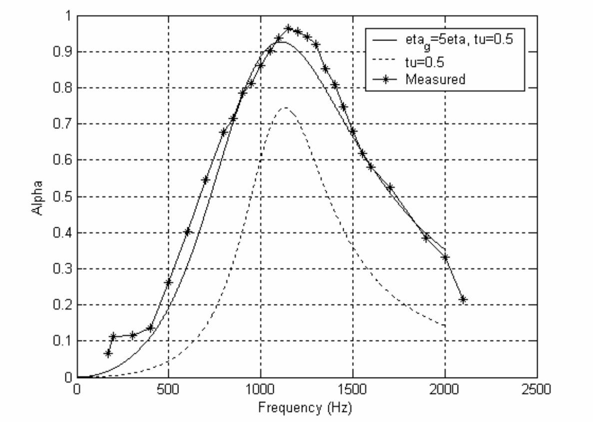

Figure 7 Measured and predicted sound absorption coefficient of micro-perforated honeycomb panels. In the prediction, the effect of glue on the viscous loss is included (solid curve, and $\eta_g = 5\eta$ and $a_g = a$).

<u>Effect of punched holes on the side-walls of core cavity</u>

To provide a uniform thermo expansion of the air in each core cell during the manufacturing process, the thin walls of each core cell are punched and left with tiny holes of approximately $0.1 \sim 0.2mm$ in diameter. Figure 8 illustrates the sound pressures in two adjacent core cells and the punched hole between them.

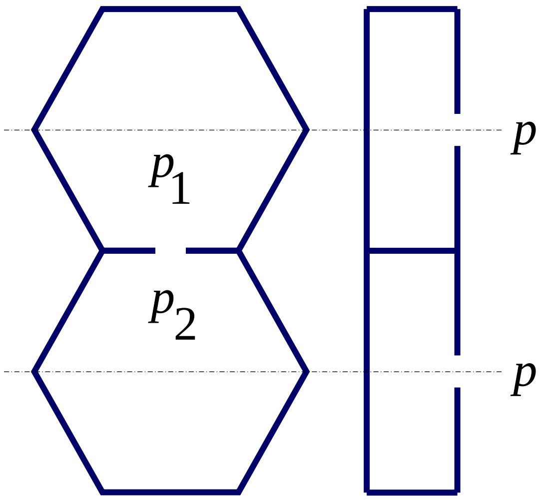

Figure 8 Illustration of the effect of coupling of sound pressures in two adjacent core cavities through one punched hole.

Qualitatively, the effect of the specific impedance of the punched hole on the sound absorption of each core cavity may be modelled by coupled Helmholtz absorbers. When the sound pressures in the adjacent cavities are not identical due to system parameter fluctuation, such effect can be significant. For this case, the specific acoustical resistance of the punched hole may affect the effective specific acoustic impedances of the perforation holes through the coupling effect, and therefore the overall sound absorption coefficient of the panel. However quantitative analysis of the effect of punched holes on the sound absorption of micro-perforated honeycomb panels is beyond the scope of this paper.

APPLICATION OF MICRO-PERFORATED HONEYCOMB PANELS

Noise reduction in an enclosure

Micro-perforated honeycomb panel has been tested to demonstrate its potential in reducing the averaged sound pressure level in an enclosure. A wooden chamber with an opening of $800 \times 1730mm^2$ was used for the test. A micro-perforated honeycomb panel, with dimensions of $1250 \times 1850 \times 50mm^3$, was fitted to the chamber's opening. The panel was sealed on the opening to avoid acoustic leakage and the perforation surface faces the interior of the chamber. The resultant sound pressure level in the chamber is compared with that when the panel turned its un-perforated surface towards the chamber's interior. For both cases, the white noise from the loudspeakers inside of the chamber remains unchanged. The reduction level of the noise in the chamber is shown in Figure 9. About 6 dB noise reduction is achieved in the frequency range between 300Hz to 1000Hz.

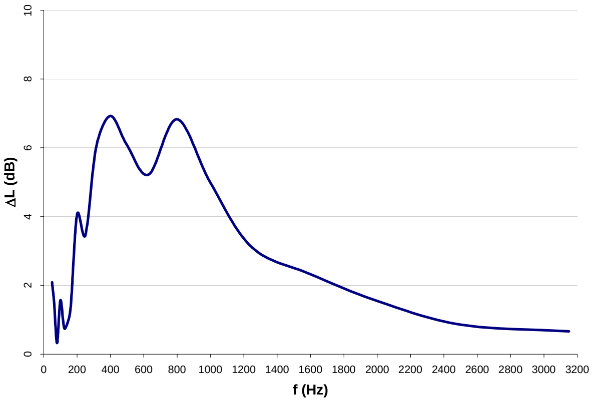

Figure 9 Noise reduction level (ΔL) in the chamber when a micro-perforated honeycomb panel is used to replace one side-wall.

Noise reduction in a 13.7m Crew Launch

The noise measurements were conducted in two identical 13.7m Crew Launch vehicles, which are made of aluminium and powered by two water jets. The rpm of the engine during the sound measurements was 2630 +/-10. There is no difference between the first Crew Launch (Crew Launch#1) and the second (Crew Launch#2), except that the 10mm honeycomb panels used in the passenger area of Crew Launch#2 are replaced by Ayres Acoustical Honeycomb Panels. The perforated surface of the acoustic honeycomb panel faces towards the noise source (opposite to the passenger area as shown in Figure 10).

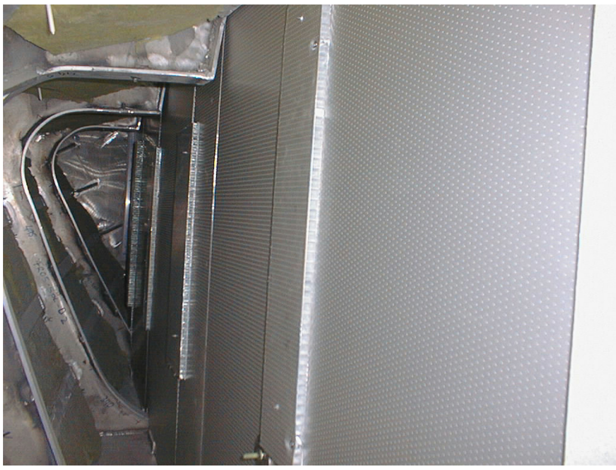

Figure 10 Micro-perforated honeycomb panels installed in a 13.7m crew launch #2.

The honeycomb panels are used as trim panels in the passenger area of Crew Launch#2, which covers two sides and the front bulkhead. The percentage of the coverage of the surface area in the passenger area by the acoustic honeycomb panels is approximately 40%.

The noise levels were measured at 6 locations (as shown in Figure 11) in the boats. Locations 1-4 are within the passenger room area and those 5-6 are located in the bridge area. The measurement result is summarised in Table 1. Clearly with the treatment of micro-perforated honeycomb panels, the overall noise level within the passenger area and in the bridge area is reduced.

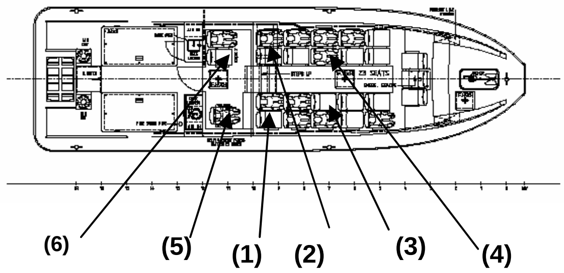

Figure 10 13.7m Crew Launch and locations of sound pressure measurement.

Table 1. Measured sound pressure level in two Crew Launches with and without the treatment of micro-perforated honeycomb panels (MPHP).

Location	1	2	3	4	5	6	Average
No MPHP (dBA)	82	84	85	85	86	86	85
With MPHP (dBA)	82	81	80	83	83	82	82

CONCLUSIONS

The analysis and experimental work on the sound absorption by perforated panel sound absorbers has led successfully to the development of micro-perforated honeycomb panels. The sound absorption properties are unique and remarkable, for panels with such low weight/stiffness ratio. The panel parameters can be adjusted to absorb noise with different types of frequency spectrum. The application of full size micro-perforated panels for noise reduction in a laboratory chamber and in one Crew Launch vehicle has demonstrated the potential of this type of acoustical panel in marine, transportation and building industries.

This paper also revealed, through the comparison of predicted and measured sound absorption coefficients of the panel samples, that micro-perforated honeycomb panels have a much higher specific acoustical resistance than what can be predicted by the existing theory on micro-perforation. This property may due to the effect of glue close to the perforation holes or/and to the side holes which are on the core for the purpose of uniform thermo expansion. Research is required to provide a quantitative understanding of such an increase in acoustical resistance so that it can be used for the design of future micro-perforated honeycomb panels.

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