ACOUSTICAL CHARACTERISTICS OF AIRCRAFT PANELS

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To Zhuren and Rödsol
It is not the strongest of species that survive, nor the most intelligent, but the one most responsive to change...

Charles Darwin
ABSTRACT

A deterministic approach based on a modal expansion and modal receptance method has been developed to evaluate the airborne sound insulation of aircraft panels with stringer and ring frame attachments. Furthermore, this method was extended to predict the noise radiation of stiffening panel subjected to TBL excitation. This approach integrates with the fast and accurate methods in evaluating the modal excitation terms and modal radiation efficiency. Based on these advantages, the effects of the curvature, overpressure, stringers, ring frames, hydrodynamic coincidence, composite structures and structural dissipation on the acoustical properties of a typical aircraft panel are able to be investigated efficiently.

Theoretic predictions were compared with laboratory measurements conducted on both model structures and aircraft panels. It was found that a small curvature may result in significant deterioration of the sound transmission loss at frequencies of interest. Unlike a flat uniform panel, the theoretical prediction for curved panels from the infinite model can not provide good agreement with the measurement close to and well below the ring frequency. However, in this frequency range, the finite model has been proved to be applicable.

For the large curved airplane panels studied here, it was found that the ring frames have little influence on sound transmission loss in the frequency range of interest. However the stringers may have considerable influence on sound transmission loss. The stringer improves this for a curved panel around the ring frequency, but it may result in a potential deterioration of the sound transmission loss above the ring frequency. In this study it is evident that the sound transmission loss of the composite skin attached with composite stringers is lower than that of the metallic panel attached with metallic stringers.

At frequencies higher than the corresponding ring frequency of the curved panel, both experiment and theoretical prediction reveal that the overpressure at the concave side tends to reduce the sound transmission loss at the rate of about 0.5dB /10000 Pa. While at lower frequencies, say well below the ring frequency,
the overpressure may increase or reduce sound transmission loss of a finite panel, depending on the shift of the resonant frequencies resulting from the overpressure.

For TBL excitation, numerical investigation reveals that the panel with the ring frames behaves more like a sub-panel between two frames. Below 500Hz, the ring frames slightly enhance the sound radiation while dramatically increasing it around 1.3kHz. The TBL forcing field excites the same vibration lever for the panel with and without ring frame attachments, but the modes excited for the panel with ring frames radiate more sound. Unlike the ring frames, the stringers increase sound radiation below 1kHz. Above 1kHz, the sub-panels between two bays respond independently and the stringer effects is therefore not obvious.

Key words: sound transmission loss, stiffener, stiffening, aircraft panel, cylindrical shell, turbulent boundary layer, TBL, noise, sound radiation
This thesis consists of the following papers

*Paper A*
Sound transmission through curved aircraft panels with stringers and ring frames
(Acceptance for publication in the Journal of Sound and Vibration)

*Paper B*
Influence of overpressure on sound transmission through curved panels
(Acceptance for publication in the Journal of Sound and Vibration)

*Paper C*
Noise radiation of aircraft panels subjected to boundary layer pressure fluctuations
(Part of work presented at the 13th International Congress on Sound and Vibration, 2006. The full version submitted to the Journal of Sound and Vibration)

*Paper D*
Influence of baffle size and curvature on sound radiated by vibration panels
(Presented at the 11th International Congress on Sound and Vibration, 2003)

*Paper E*
Paper E: Sound transmission through two concentric cylindrical shells connected by ring frames
(Part of work presented at the 10th International Congress on Sound and Vibration, 2002. The full version submitted to Journal of Sound and Vibration)

**Division of work between authors:**

The theoretical and experimental work presented in this thesis has been done by Bilong Liu under the supervision of Leping Feng and Anders Nillson.
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1 Introduction

The purpose of this research is to investigate the curvature, overpressure and flow influence on sound transmission through fuselage panels, within the scope of the EU project: Friendly Aircraft Cabin Environment (FACE), Contract No.: G4RD-CT2002-00764.

To set the scene for the work carried out a little background information first. The nature of the cooperation between many industrial partners, and academic institutions, and time constraints limited within the project, was such that delivery of aircraft panels for measurement arrived later than scheduled and necessary detailed information of aircraft panels was not supplied. On a positive note, though, after much re-scheduling most of time was spent judiciously in preparation in related technical areas. This included measurements on simple aluminium panels, a theoretical investigation of the baffle effect on sound transmission loss and the sound insulation properties of cylindrical shells.

Eventually, the aircraft panels arrived and the study progressed. Measurement data on vibro-acoustic properties of the aircraft panels were collected. A theoretical model based on a receptance method was developed. The influence of curvature, overpressure, stiff-ringers and panel finiteness on sound transmission loss were investigated and discussed. Conference papers and journal articles were written and herewith a completed thesis was accomplished.

A review of recent relevant literature in the area studies, preceded by a short description of the problem, is given below.

2 Effects of curvature and overpressure on sound transmission

Two features in sound transmission characteristics of cylindrical shells versus flat panels are apparent: these are the curvature of the walls and the constraint imposed on the sound field in the contained fluid. In a uniform flat plate,
small-amplitude flexural waves and in-plane longitudinal and shear waves are uncoupled and can propagate independently, the transverse displacements relating to sound radiation are produced predominantly by bending forces; whereas for cylinders the curvature of the shells couple the radial, axial, and tangential motions so that the equations of motion in these directions contain contributions from all three displacements and their derivatives. The corresponding transverse displacements of the shell are accounted for by a combination of membrane and bending forces. The interaction of membrane and bending forces leads to an important phenomenon of a shell: the ring frequency, where the wavelength of extensional waves in the shell wall is equal to the size of the circumference. At the ring frequency, the interaction of membrane and bending forces results in a theoretical zero value for the impedance of the shell. Above the ring frequency, the effects of bending stiffness in shells are predominant, and below that frequency, the effects of membrane force are significant. As a consequence, the sound insulation property of a shell structure is similar to that of a flat panel when the frequency is higher than twice the ring frequency, and is somewhat different from that of a flat panel when the frequency is around and below the ring frequency.

Research on sound transmission through fuselage structures are commonly based on a theoretical model of an infinite cylindrical shell, with and without stiffening ribs [1-11]. Smith [1] investigated the transmission of an acoustic wave through an infinite, homogeneous, isotropic cylinder, where the ratio of absorbed power to incident power is a measure of the transmission loss and is denoted by the absorption coefficient. To determine the absorption coefficient, the modal impedance of the shell and associates must be realised. The shell impedance can be determined by various shell theories, and the simplest one, for example, might be Donnell-Mushtari shell equations, reference [21]. For the acoustic impedance, inside the shell, some assumptions must be included due to the closed space environment. It is assumed that the walls are totally absorptive inside the shell such that only inward-traveling waves exist. This assumption is made in an obvious analogy for transmission loss for a flat plate. The inward-traveling wave solution in cylindrical coordinates is well known analytic...
solution, the Hankel function. An analytical expression for the acoustic impedance is straightforward.

Following a similar approach due to Smith [1], Koval [2-3] has investigated the sound transmission loss of an infinitely long, isotropic, thin cylindrical shell as a function of curvature, flow and pressurization effects. Numerical results show that two major dips dominate the description of sound transmission loss for a large diameter cylindrical shell. The lower dip occurs at the cylinder ring frequency and the other occurs at the critical frequency. Between the ring frequency and critical frequency, the sound transmission loss follows a mass-law, which is 5-6dB/octave. This mass-law behavior is consistent with the findings of Manning and Maidanik [12] who found that above the ring frequency the cylinder radiates like a flat panel and below the ring frequency, the sound transmission loss tend to be stiffness controlled, except where cylinder resonances are present. The cylinder resonances occur when the underlying wavelength and frequency match with a circumference mode. This resonance reduces the sound transmission loss of the cylinder. Compared with a flat plate, an interesting result arises, in that, the shell reduces sound transmission at lower frequencies; this phenomenon is supported by Bruderlin’s experiments in 1937, reference [13].

Koval [5] also investigated sound transmission loss through orthotropic cylindrical shells. Computational results showed that sound transmission loss appears to be sensitive to the ratio of the elasticity moduli for the orthotropic directions, especially in the region of the mass-law; increasing the ratio will enhance the sound transmission loss markedly. However, this result seemed controversial at the time and was later examined by Blaise et al. [9,10]. Here the authors concluded that there must be a numerical error in Koval’s results, and the orthotropic effect does not increase the sound transmission loss in the mass-controlled zone. The orthotropic ratio influence is particularly sensitive for frequencies below the ring frequency.

In addition to isotropic or orthotropic cylindrical shells, the laminated composite
cylindrical shell, with rings and stringers, are also of practical interest. Again, Koval [6-8] developed a model to analyse the influence of a laminated composite, including rings and stringers, on sound transmission through cylindrical shells. Numerical results indicated that a composite shell does not offer significant advantages over an aluminum shell. Such results were verified by measurements conducted at Marcus Wallenberg Laboratory (MWL), KTH, Stockholm. However, once again, the numerical conclusions on the influence of stringers and rings are a little contentious, since the main conclusions, that stiffeners have little effect on transmission loss below ring frequency, but improve the transmission loss markedly above ring frequency, do not follow the mass-law. Measurements conducted at MWL also indicated that stiffeners can only improve sound transmission loss below ring frequency, whilst almost no change above ring frequency has been observed.

Application of infinite length cylinder theory has limitations when the response and transmission through a finite length closed cylinder since the existence of diffraction of sound around the ends and the existence of a reverberant field within the closed volume of the cylinder. These phenomena affect the pressure field acting upon the inside of shell. White [14] took a totally statistical approach to predicate the sound transmission through a finite closed cylinder. Experimental measurements presented in reference [14] showed that the variation of sound transmission loss with angle of incidence of sound is much less sensitive than that of the infinite cylinder theories. The behaviour was attributed to the reverberant nature of the shell vibration field. The analysis of White was based upon power flow equations between multi-mode systems, as presented by Lyon and Maidanik for broad-band random vibration, [15]. The essence of this approach is to assume that the system is in equilibrium under a stationary random excitation of moderately small bandwidth. The equations for shell vibration energy state that net power received from the external acoustic field must be partly dissipated by mechanical losses in the shell and partly radiated to the enclosed fluid volume. In reference [14] the author represented the coupling factor $R_{\text{rad}}$, relating response of the shell to the energy of external pressure field. In addition the coupling factor, $R_{\text{int}}$, was introduced, which relates the acoustic
power radiated to the interior fluid to the shell vibration energy, by flat plate free-field radiation values, modified to account for the particular radiated space. It is felt, however, that a rigorous analysis of $R_{\text{int}}^{\text{rad}}$ could have been undertaken as it is not at all obvious that flat panel radiation is relevant. In addition to White’s work, Szechenyi [16-18] investigated the similar problem with more emphasis on boundary conditions. The analysis of Szechenyi showed that two major parameters affect the radiation efficiency. One is the ratio of frequency to critical frequency, $f/f_c$, which is in connection with the flat panel case, the other is the ratio of critical frequency to ring frequency, $f_c/f_r$. The significance of the values of $f_c/f_r$ is that if it is greater than unity, corresponding to the case of large-diameter, thin-walled shells, there is a range of frequency between $f_c$ and $f_r$ in which shell curvature effects on flexural wave disappear, and the cylinder radiates as a flat plate. Below, but close to, $f_r$ the radiation efficiency of the cylinder is much higher than that of the flat panel due to appearance of supersonic modes. Above $f_r$, the radiation efficiency falls and rises again as $f$ approaches $f_c$.

In the Szechenyi analysis [16-18], the free field radiation efficiency is assumed as an internal radiation efficiency. To avoid this deficiency, Fahy [19,20] took a rigorous approach to include the influence of internal cavity on radiation efficiency. The major conclusion from his work is that a nearly closed cylindrical shell exhibits the lower frequency limit phenomenon. The effect of this phenomenon reduces both broad-band response and radiation efficiency below this frequency to values substantially below those estimated from the diffuse field excitation and free field radiation calculations. Above this frequency these latter calculations may be applied to the case of excitation by sound in a contained fluid. The average radiation efficiency of a cylinder at frequencies given by $f < 0.8 f_r < f_c$ is proportional to the first power of the frequency, which is in contradiction to the assumptions of flat like behavior made in White [14] and Szechenyi [16-18]. Fahy [19,20] also pointed out that the experimental results for the cylinder and plates tend to the statistically estimated values rather than the results of detailed consideration of the coupling of individual mode pairs.
of an ideally coupled system. The possible reason for this might be attributed to the realistic system not behaving as perfect mode-to-mode couplings as an ideal coupled system, but as a rough average on the wide variations.

The influence of curvature on the sound radiation by vibrating panels was analytically investigated by Graham [21], where the modal impedance of a finite, curved rectangular panel in an infinite cylinder was considered. The asymptotic results showed that external modal impedance tends to the flat panel form in the limit $kR \to \infty$. Unfortunately, the internal mode impedance does not possess such a straightforward relation to the flat panel case due to the fundamentally different nature of the internal acoustic field. The effect of curvature on supersonic modes is negligible at sufficiently high frequencies, but not for certain subsonic modes, and subsequently it is not certain how sound transmission loss is affected. Recently, Liu [22] undertook an in-depth numerical study at the curvature effect on modal radiation efficiency.

Compared with curvature effects, the influence of internal pressurization has received little attention in the literature, see references [2-3, 23-24]. Generally speaking, internal pressurization results in three effects, viz. the out-of plane deformation of skins, the increase of in-plane membrane tensions, and the mismatch of the acoustic properties between internal and external fluid. The airplane skins are usually attached to extremely stiff stringers and frames, which prevent any large out-of plane deformation of the panels due to pressure difference at both sides. It is reasonable to assume that the resultant out-of plane deformation is negligible. The relation between the pressure difference and the in-plane tensions may then follow basic membrane theory. Hence the effects of the overpressure on sound transmission loss can be evaluated by including the in-plane tensions within the dynamic equation of the panel. Theoretical results based on infinite isotropic shell and plate models indicate that the increasing of in-plane tension results in kind of reduction of sound transmission loss, references [3, 23]. The mismatch of acoustics properties between internal and external medium can also be included in a theoretical model directly.
Although much theoretical work has been devoted to the sound transmission through cylindrical shells, there are few published measurement data and theoretical models for the problem of the sound transmission through curved, finite aircraft structures with stringer and ring frame attachments. From the viewpoint of manufacture and measurement, the sound insulation properties of finite panels are more relevant for study than that of the whole structure since only finite panels are possible for manufacture and for standard laboratory measurement. Moreover, aircraft skins are always stiffened by very strong ring frames, this situation is somehow more reasonable to treat the individual panel as responding independently to one another, or it seems more realistic to model the skin as a finite panel rather than an infinite cylindrical shell. Finite curved panels may behavior differently from that of infinite cylindrical shell, it is therefore necessary to make a comparison of the measurement and theoretical prediction for the flat and curved panels, with and without stiffener attachments.

3 The turbulent boundary layer induced noise

Regarding the aircraft cabin noise, the boundary layer induced noise is another critical issue and has received increasing attention recently [25-36]. The contribution of boundary layer induced noise is already significant in the current generation of aircraft, and is likely to become more important in the future as engine noise levels are to be further reduced. Measurements conducted on aircraft by Boeing showed that a typical pressure spectrum on an aircraft surface is resulting from the similar order contributions of jet noise and turbulence boundary layer noise below 800 Hz, but is dominated by the boundary layer pressures between 1 and 2 kHz [25-27]. Further measurements on aircraft conducted by Wilby and Gloyna [28-29] showed that jet noise is a more efficient exciter of vibration at lower frequencies, but above 500 Hz the situation is reversed, and the boundary layer induced response dominates.

There appears to be a large number of publications on the response of fuselage-like structure to various forms of excitation in the research literature. However, theoretical models directly concerned with the boundary layer noise problem are restricted to flat uniform panels without stringer attachments. An
earlier analytical model to predict TBL induced noise was made by Graham [30], where an analytical expression to evaluate the modal excitation terms was successfully developed and the time to calculate the excitation field was thereby significantly reduced. Another recent attempt to predict boundary layer induced noise was made by Han, who wished to do so by energy flow analysis [31-32]. The method is proved to be successful in predicating response of a flat isotropic panel subjected to TBL excitation, but did not satisfy accurate predictions for the noise radiated by the panel. The reason is rooted in the inaccuracy of this method in predicting the radiation efficiency of the panel. As far as an aircraft panel with ring frame and stringer attachments is concerned, two difficulties arise for this method. Firstly, there is no closed form expression for the structural impedance, and secondly, it is not a simple matter to estimate the radiation efficiency of the panel.

4 Receptance method and contributions of this work

The receptance method is a dynamic flexibility technique which is commonly used in the free vibration analysis of stiffened structures. Wilken and Soedel [37-38] considered an exact and approximate method for studying the modal characteristics of ring-stiffened cylinders with the aid of a receptance method. Lin [39] investigated the forced vibration properties of stiffened flat plates, with an application to ship structures. In this thesis, however, a deterministic approach based on modal expansion and modal receptance method was developed in evaluating random noise transmission through curved aircraft panels with stringer and ring frame attachments. Good agreements are achieved when compared with the experimental data for simple aluminum panels and aircraft panels collected by laboratory measurements. As a consequence, The influence of overpressure, curvature and stiffener on sound transmission through curved aircraft panel was investigated.

Furthermore, this method was extended to predict the noise radiation of stiffening panel subjected to TBL excitation. The Corcos [40] and Efimtsov [41] models were used to characterize the dynamic surface pressure cross-spectra. Closed-form solutions for the panel displacements, radiation and transmission
pressures were obtained. This approach integrates with the fast and accurate methods in evaluating the modal excitation terms and modal radiation efficiency [30, 42]. Based on these advantages, the effects of the stringers, ring frames, hydrodynamic coincidence and structural dissipation on the structural and acoustic response for a typical aircraft panel subjected to TBL excitation are able to be investigated in an efficient way.

5 Summary of the papers

Paper A: Sound transmission through curved aircraft panels with stringers and ring frames

Although much theoretical work has been devoted to the sound transmission through cylindrical shells, the literature records few test data and theoretical models regarding the sound transmission through curved, finite aircraft shell panels with stringer and ring frame attachments. Due to the fact that only finite panels are possible for manufacture and for standard laboratory measurement, the sound insulation properties of individual finite panels are more relevant for study than that of the whole structure from the viewpoint of manufacture and measurement. Moreover, aircraft skins are stiffened by very strong ring frames, hence the situation of treating the response of individual panels independently is reasonable, whence it seems more realistic to model the skin as a finite panel rather than an infinite cylindrical shell. Generally, finite curved panels behave differently to infinite cylindrical shells; it is necessary to make a comparison of the measurement and theoretical predictions for flat and curved panels, with and without stiffeners.

Therefore, a deterministic approach based on modal expansion and modal receptance methods has been developed in this article to evaluate the airborne sound insulation of curved aircraft panels with stringer and ring frame attachments. Experimental data for laboratory panels and aircraft panels have been collected by laboratory measurement. For the metallic panel, theoretical
predictions agree well with the test results in most frequency ranges of interest, see Fig.1. Both prediction and measurement indicated that the curvature reduces sound transmission loss near ring frequencies. The reason is caused by convergence of resonance frequencies of the panel led by the interaction of bending forces and membrane forces in the shell. The convergence not only increases the modal density of the curved panel around the ring frequency, but also increases the sound radiation efficiency of these modes by shifting them to a relatively higher frequency.

**Figure 1.** Left: the large metallic panel; Right: predicted and measured TL.

**Figure 2.** Left: the large metallic panel; Right: predicted and measured TL.
Figure 3. Comparison of the metallic panel (G) and the composite panel (H)

Figure 4. Predicted damping influence on TL for the metallic panel. The loss factor for the stringers is assumed as 1%
For a same weight composite panel, again, the prediction agrees well with the measurement except at very low frequencies, see Fig.2. The discrepancies between measured and predicted TL for Panel at rather lower frequency may result from the isotropic assumption in the calculation. For this Panel, the measured Young’s modulus shows there is a kind of orthotropic nature in the axial and circumferential direction, but in calculations, this effect is not included.

In comparing the metallic panel with the same weight composite panel, both measurement and prediction indicate that sound insulation properties of the composite panel is not as beneficial than that of the metallic panel in the frequency range, see Fig.3. Detailed numerical calculation revealed that the composite stringers attached to the composite panel may play a role in this reduction.

The influence of skin loss factor on sound transmission loss The numerical results reveal that increasing skin loss factor from 1% to 10% increases sound transmission loss about 1~2 dB below 500 Hz, Fig.4. In this frequency ranges, the sound transmission is dominant by resonance transmission due to modal convergence and higher radiation efficiency led by curvature. At frequencies above twice the corresponding ring frequency and but still well below the critical frequency, it is expected that the influence of skin loss factor is not significant because the sound transmission is dominated by force transmission.

Also, for large curved aircraft panels studied here, it was found that the ring frames have little influence on sound transmission loss in the frequency range of interest. The reason results from the sparsely-arranged ring frames in practical situation. Compared with the ring frames, the stringers may have significant influence on sound transmission loss. It is evident that the stringer will slightly improve sound transmission loss of a curved panel around the ring frequency, but it may result in potential deterioration of sound transmission loss above the ring frequency. It is of interest to note that the sound transmission loss of the composite skin panel attached with composite stringers is much lower than that of the metallic skin panel attached with metallic stringers. The relatively high cross-section of the stringer may be a reason for this behaviour.
**Paper B: Influence of overpressure on sound transmission through curved panels**

Much theoretical research related to the aeronautic industry work has been devoted to the sound transmission through the fuselage in aircraft, but there are few test data with reference to the overpressure influence on sound transmission. In this paper, the airborne sound transmission through curved, aircraft panels under the influence of overpressure at the concave side has been investigated. The measurement data has been collated under laboratory conditions, and the theoretical model including finite size panels and ring stiffeners has been developed.

Values for sound transmission losses from the metallic and composite panels, measured with and without overpressure, are shown in Fig.5 and Fig.6. It is evident that two frequency ranges can be classified to describe the overpressure effects. In the frequency range above 160 Hz, the overpressure reduces the sound transmission loss of the panel. It was found that the TL reduction was less than 1 dB in this frequency range for overpressures up to 8500 Pa. Below 160 Hz, however, the overpressure seems to increase the sound transmission loss by a few decibels. On comparison of Fig.5 with Fig.6, it may be concluded that the overpressure influence on the metallic and composite panels is roughly the same, indicating that the overpressure effects are not sensitive to the panel material.

The tendency for the overpressure to reduce sound transmission loss at relatively high frequencies can be predicted by an infinite shell model by including the increase of in-plane tension. Whilst the increase of sound transmission loss at lower frequencies is caused by the shift of resonances due to the combined influence of increasing in-panel tension and the finite-size of the panel. This has been explained partly through some assumptions within the theoretical model including a finite size panel and modelling of stiffeners of the panel.
Figure 5 Measured TL, with and without overpressure at the anechoic room side:
—— 0 Pa; ---○--- 8500 Pa; The large metallic panel, $f_R = 420\text{Hz}$.

Figure 6 Measured TL, with and without overpressure at the anechoic room side:—— 0 Pa; ---○--- 8500 Pa; The large composite panel, $f_R = 370\text{Hz}$. 
At frequencies higher than the ring frequency, both test and theoretical results reveal that the overpressure under laboratory conditions tends to reduce the sound transmission loss at the rate of about 0.5 dB /10000 Pa, where 80% of the reduction is results from the mismatch of air density, and 20% from the in-plane tension driven by the overpressure. While at low frequencies, below the associated ring frequency, the influence of the overpressure is dominated by the shift of the resonant frequencies due indirectly by the increased in-plane tension resulting from the combined influence of overpressure, finite panel size and stiffeners attached to the panel. These combined influences may increase or decrease sound transmission loss, depending on panel details and frequency range of observation.

**Paper C: Noise radiation of aircraft panels subjected to boundary layer pressure fluctuations**

A deterministic approach based on modal expansion and modal receptance method has been developed in predicting the noise radiation of stiffening panels subjected to turbulent boundary excitation. The Corcos and Efimtsov models were used to characterize the dynamic surface pressure cross-spectra. Closed-form solutions for the panel displacements, radiation and transmission pressures were obtained. The advantages of this approach are integrated with those efficient methods in evaluating the modal excitation terms and modal radiation efficiency.

For the panel studied here, numerical results reveal that the stiffeners have significant influences on TBL induced noise radiation. The panel with ring frames behaves more like a the sub-panel between two frames (see Fig.7, here case 2 represents a aircraft skin panel with size of $2.2m \times 1m$, reference case refer to a same panel but with size of $0.55m \times 1m$ and ring frames are equally spaced with a distance of $0.55m$). Below 500Hz, the ring frames slightly enhance the sound radiation while dramatically increasing it around 1.3kHz. The ring frames makes no change to the TBL excitation efficiency, but improve the sound
radiation efficiency by decreasing the axial modal. Unlike the ring frames, the stringers increase sound radiation below 1kHz. Above 1kHz, the sub-panels between two bays respond independently to one another and the stringer effect is therefore not evident.

The example also indicates that increasing the skin loss factor will reduce TBL induced noise radiation dramatically. The damping is effective in the whole frequency range, regardless of stringer attachments. The curvature increases the radiated sound significantly in the range of the ring frequency for the panel without stringer attachments, while having less effect on the panel with stringer attachments. The in-plane tension reinforces the radiated sound dramatically at low frequencies for the flat uniform panel, but has much less effect on the curved panel, with and without stringer attachments.

Figure 7 Predicted ring frame effects on averaged dimensionless sound power spectra: —○—, case 2 with ring frames; —★—, case 2; ————, reference case.
**Paper D: Influence of baffle size and curvature on sound radiated by vibration panels**

A fundamental problem in structural acoustics is the prediction of the sound radiated by a flat, rectangular panel set in an infinite baffle under some form of excitation, usually stochastic. The problem has thus been studied in some detail. However, practical situations, such as the measurement setup of sound transmission, always results in a finite baffle due to the finite size of the room. This is a controversial issue as the finite baffle alone may result in some influence on sound transmission. Moreover, many practical structures have a cylindrical geometry, and hereby it is of interest to see how curvature affects sound radiation. In this paper, three cases, viz. the flat and the curved panel in the wall of a semi-infinite rectangular room, and the curved panel in the cylindrical wall, are investigated. Modal radiation resistances are calculated for three cases in comparison with that of infinite baffle.

For the case of finite size panel in the middle of finite size wall, and if, roughly speaking, the area ratio of wall to panel is larger than 10:1, the discrepancies of modal radiation resistance from that of infinite baffle can be expected less than 2dB above 100Hz. Also one can conclude that the modal radiation resistances for the curved panel in finite flat baffle are similar to that of same size flat panel in the same baffle. However, for the case of cylinder baffle, the discrepancies from that of infinite flat baffle can be significant, which means that the infinite flat baffle model in prediction of sound transmission through a curved panel into a cylinder would miscalculate the sound power radiation of those subsonic modes and result in potential errors in the prediction of sound transmission loss.

**Paper E: Sound transmission through two concentric cylindrical shells connected by ring frames**

A mathematical model is developed in this paper to evaluate the airborne sound transmission through two concentric cylindrical shells connected by ring frames. For the shells studied here, numerical results show that many dips are found in the TL of the double-walled cylindrical shell. These dips are caused by the ring
frequency, mass-spring resonance, standing wave frequencies and uncertain resonances of circumference mode. Apart from that, above the ring frequency of the exterior shell, the TL of the double-walled cylindrical shell is similar to that of double-walled flat panel, while below the ring frequency, the double-walled shallow shell behaves similarly to that of single-walled cylindrical shell in most cases.

Numerical results also indicate that the absorption in the space between the shells has significant influence on the sound transmission loss. At relatively higher frequencies, increasing the absorption between two shells is an effective way to eliminate the dips on the TL curves and hereby dramatically improves the sound transmission loss. This, however, is not very efficient at relatively lower frequencies.

For the case studied, the ring frames, equally spaced with a distance of 0.55m, only show little influence below the ring frequencies of the cylindrical shells. In the frequency range calculated, the shell flexural wavelength is much shorter than 0.55m. Therefore, the sub-cylinders between two ring frames may respond more independently and the influence due to ring frame connections is not evident.

6 Recommendations for future work

Vibro-acoustic measurements conducted at MWL showed that the stringer itself may play a role on sound transmission. Such effects, however, are not covered in this thesis but are worthy for further investigation.

The influence of the cabin interior treatment on noise transmission is known to be significant. The extension of current model to include the influence of interior treatment on sound transmission would be of great interest, and the comparison of predicted and measured TBL induced noise, with and without interior treatment, would be an additional merit.
References


[39] T. Lin, Wave motion in finite coupled structures, with application to ship structures, Ph.D thesis, the University of Western Australia, 2005.


