The Prediction of Structure-borne Noise Transmission in Ships Using Statistical Energy Analysis

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ABSTRACT: This paper is concerned with the transmission of noise and vibration in ship structures, and in particular, naval ship structures. The first part of the paper presents a review of different methods for ship noise prediction. It then introduces the method of Statistical Energy Analysis (SEA) for the investigation of ship noise and vibration in the high frequency regions. Previous studies have shown that SEA is a useful tool for the analysis of vibration transmission in structures which consist mainly of plate elements. However, naval ship structures often involve more complex elements such as shells and beam stiffened plates. In the second part of the paper, two types of structure which are considered to be characteristic of naval ship constructions are identified. They are: a cylindrical shell coupled to an end plate; and a plate with periodic stiffeners coupled at right angles to a uniform plate. The Coupling Loss Factors (CLFs) of these two structures are evaluated, using travelling wave analysis, for SEA studies. Results from an experimental program confirm the validity of the formulation of CLFs.

1. INTRODUCTION

The study of noise and vibration in ships has received considerable attention in the past few decades as a result of stringent ship noise legislation introduced by many countries [1]. Such legislation aims to provide a safe and comfortable working environment for crew members by specifying a maximum allowable sound pressure level in various ship compartments. The ability for the designer to predict noise level in ship compartments at the design stage is therefore highly desirable and several empirical and analytical studies on ship noise prediction have been reported (see, for example, references [2]-[7]).

Naval surface ships and submarines require additional noise and vibration control measures to minimise the risk of detection and the interference with on-board equipment (for example, sonar and weapon systems). Furthermore, the extensive use of periodically stiffened plates and shells in naval ships increases the structural complexity for noise and vibration analysis. It has long been recognised [8] that vibration waves in a periodic structure can only propagate in certain frequency bands (pass bands) and this phenomenon has a significant effect on vibration transmission. Due to the complexity of naval ship structures and the high frequency range of interest (up to 20 kHz for torpedo homing devices), a deterministic analysis of all the resonant modes of vibration is usually impractical. A powerful tool for predicting the high frequency response of complex systems is Statistical Energy Analysis (SEA) which deals with the time-averaged and frequency-averaged (octave or 1/3 octave) flow of vibrational energy between elements of a complex system [9].

In this paper, a number of methods used for the study of noise transmission in ship structures are reviewed. In particular, recent developments in SEA modelling of complex structures characteristic of naval ships are discussed.

2. REVIEW OF SHIP NOISE PREDICTION METHODS

Due to the complexity of ship structures, it is clear that a rigorous analysis based on the 'classical' approach (for example, wave theory) is impractical. Nilsson ([4] and [10]) presented a simplified analytical method based on a grillage model which was made up of two parallel hull frames and the associated plate elements. He considered that the frames would act as wave guides for the transmission of vibration from the hull to the superstructure. The plate elements used in Nilsson's analysis were assumed to be uniform and this approach may not be suitable for the analysis of structures with horizontal stringers between the frames that are typical of naval ship structures. A further restriction of this method is that it is essentially a two-dimensional model and is not readily applicable to the general analysis of vibration transmission in ships.

The Finite Element Method (FEM) may be used to model the response of complex structures. However, in the frequency range of interest for structure-borne noise studies (i.e., up to the several kHz range), the number of elements required is generally too large for the practical analysis of a substantial part of a ship's structure, even with the help of modern computer technology and software packages. Furthermore, at high frequencies where the wavelength is much smaller than the overall dimensions of the structure, FEM would become very sensitive to the system parameters and may lead to incorrect prediction of the structural response. Hence FEM is normally restricted to the vibration analysis of ship structures at low frequencies.

A number of empirical studies (see, for example, references [2], [5] and [11]) have been reported for ship noise predictions. These studies were mainly based on measurements and data taken on board merchant ships. In general, empirical methods are valuable tools in the analysis of a generic type of ship, especially at the design stage where limited information is available. These methods become less attractive in situations where a detailed analysis is required on different types of ships (for example, naval surface ships and submarines).

Statistical Energy Analysis (SEA) is a framework of study for the forced response of systems, and is based on the power balance between individual elements of a system [9]. It provides a basis for the prediction of average vibration and noise levels in complex structures, particularly at high frequencies.

Sawley [12] demonstrated that SEA can be used successfully to investigate the noise transmission paths of a motor vessel. Ødegaard Jensen [3] studied the distribution of vibratory power in a 1:5 scale ship section and also investigated the effects of damping on vibration transmission. Good agreement between calculated and measured results was obtained for the lightly damped case but the agreement was poor for the heavily damped case and Jensen attributed the discrepancy to the effect of in-plane waves acting as flanking transmission paths for the vibratory power.

Other authors ([7], [13] and [14]) also reported on the application of SEA to the study of vibration transmission in ships. A more detailed treatment of this subject was given by Plunt [6] where he investigated the rear section of a cargo ship and found reasonable agreement with experimental results.

A common feature of the SEA studies reviewed so far is that the ship structures were modelled as an assembly of plate elements subjected to bending waves except for Plunt [6] where longitudinal waves were also considered.

Tratch [15] investigated the transmission of vibration in a 1:2.5 scale model of the machinery foundation of a ship bottom structure using SEA. He also modelled the structure as plate elements but considered all the possible wave types generated at the junction (i.e., bending, longitudinal and shear). Good agreement between calculated and experimental results was reported.

Naval ship structures often make use of shell elements coupled to various types of plate element (for example, a submarine hull/bulkhead coupled structure). The transmission of vibration through coupled cylinder/plate structures has been investigated by a number of researchers. Hwang and Pi [16] conducted an experimental investigation on a cylindrical shell welded onto a base plate and concluded that the SEA method was not capable of reaching any intelligent prediction of the coupling loss factor due to the strong interaction at the cylinder/plate interface. Blakemore et al. [17] studied a number of flange-connected cylindrical shells and found considerable discrepancy between measurement and SEA predictions. They attributed the discrepancy to internal acoustic coupling, non-equipartition of energy between modes in a cylindrical shell element and low modal overlap. Pollard [18] also investigated experimentally two cylinder/plate structures (one with a long thin cylinder and the other with a short squat cylinder) and found conflicting results although the short cylinder showed good agreement between the theoretical and experimental results. Recently, Schlesinger [19] presented a theoretical analysis of the transmission of vibration through a cylinder/plate coupled structure based on an arbitrary distribution of the wave energies in the radial, circumferential and longitudinal directions. The theory is supported by a limited amount of experimental data but further work is needed to show that this method satisfies the reciprocity requirement of SEA. Thus the study of cylinder/plate coupled structures using SEA has been less successful compared with plate/plate structures and further research effort is required to address this shortcoming.

Another type of structure often used in naval engineering constructions is a plate or shell element reinforced with periodic stiffeners. The application of conventional SEA through successive elements of this type of structure can significantly overestimate the transmission loss (see, for example, reference [17]). This is a matter of concern and has been the subject of criticism [20]. Clearly, the band pass nature of a periodic structure has to be considered in SEA modelling since it has a strong influence on the transmission of vibratory power.

Keane and Price [21] applied the theory of periodic structures to enhance a one-dimensional SEA model. They investigated a point spring coupled, multi-modal system and compared the results obtained from 'exact' modal analysis with the normal and enhanced SEA model. A significant improvement in results was obtained by using the enhanced SEA model rather than the normal model. However, the model studied by these authors was made up of highly idealised one-dimensional elements and therefore the analysis may not be readily applicable to ship structures such as hull plates and bulkheads. Langley [22] also studied the modal characteristics of periodic structures and derived modal density expressions for one- and two-dimensional structures. He further studied the forced response of a damped one-dimensional periodic structure based on vibratory energy flow and compared the effect of material damping with the effect of damping caused by structural irregularity on vibration attenuation [23]. On the subject of 'near' periodic structures, Langley [24] investigated the wave transmission through a randomly disordered one-dimensional periodic structure and discussed the occurrence of frequencies of perfect transmission.

From the preceding discussion, it can be concluded that SEA is a useful tool for the prediction of vibration transmission through complex built-up structures, especially in situations where the structure can be modelled as an assembly of plate elements. However, a number of areas have to be addressed before this method can be applied successfully to naval ship structures. Notably, the SEA modelling of cylinder/plate structures and coupled periodic structures. The following section outlines some of the recent research activities in SEA modelling conducted in the Aeronautical and Maritime Research Laboratory, Defence Science and Technology Organisation, as part of an effort to control the acoustic signatures of naval vessels.

3. STATISTICAL ENERGY ANALYSIS

In this method, a complex system is considered to be an ensemble average of a set of physically similar systems. The system is then sub-divided into a number of inter-connecting subsystems, usually at locations where the coupling between subsystems may be considered as 'weak' (for example, at structural discontinuities where incident waves are substantially reflected). The subsystems are then modelled as SEA elements, each consisting of a group of resonant modes of the same nature. For example, a uniform plate under bending and in-plane motions may be modelled as two SEA subsystems representing the resonant modes associated with these two types of motion respectively. The mean energy of the subsystems may be related to the input power by SEA parameters, known as modal densities, internal loss factors and coupling loss factors (CLFs), to form a set of linear, power balance equations. Solution of the power balance equations leads to the mean energy level (and hence the response) of the individual elements. The fundamental equations of SEA, as well as the basic theory and assumptions concerning the interaction between multi-mode subsystems, are given by Lyon [9]. In addition, review papers on this subject have been presented by Hodges and Woodhouse [25] and Fahy ([20] and [26]).

3.1 Cylinder/plate Coupled Structure

A number of researchers have modelled a ship structure as coupled plate elements and derived the CLFs on the assumption that the wave field in each plate element is diffuse ([6] and [15]). The concept of a diffuse wave field poses no difficulty for the modelling of isotropic elements like uniform flat plates but is less clear from an SEA point of view for non-isotropic elements like curved plates and cylinders. Langley [27] pointed out that the assumption of a diffuse wave field is equivalent to the equipartition of energy amongst the resonant modes for an isotropic element. He then derived the CLFs for structural junctions between curved plates based on the modal concept of equipartition of energy. The present authors have extended the modal concept to consider the modelling of submarine structures which consist of cylindrical elements.

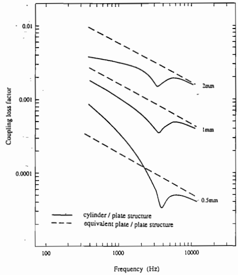

Figure 1. Coupling loss factors of three cylinder / plate structures with different shell thicknesses. The coupling loss factors of their equivalent plate / plate structure are also shown for comparison.

They derived the CLF between a cylindrical shell and an end plate ([28] and [29]) using travelling wave analysis. The derivation consists of the evaluation of transmission efficiency for the cylinder/plate junction (defined as the ratio between the transmitted wave power and the incident wave power) by considering the appropriate boundary conditions (i.e., the compatibility of displacements and the equilibrium of forces and moments at the junction). The transmission efficiency is then related to the CLF between the cylinder and plate elements based on the assumption of equipartition of energy amongst all the resonant modes of the cylinder. In the present study, the plate is assumed to have a hole cut out to accept the cylinder. This arrangement enables the results to be compared with those of an equivalent plate/plate structure in order to confirm the validity of the present formulation of CLF at high frequencies where the cylinder behaves as a flat plate. The equivalent plate/plate structure consists of two flat plates coupled at right angles to each other with the coupling line length equal to that of the cylinder/plate structure. The areas and thicknesses of the flat plates are equal to those of their respective elements of the cylinder/plate structure.

Calculations were performed to evaluate the CLFs of three steel cylinders each coupled to a 2 mm thick steel end plate. The shell thicknesses of the three cylinders are 0.5, 1.0 and 2.0 mm respectively. The length and mean diameter of all cylinders are 0.8 m and 0.45 m respectively. Figure 1 shows the CLFs of the three cylinder/plate structures. The CLFs of their corresponding equivalent plate/plate structure based on a diffuse bending wave field are also plotted in the figure for comparison. It can be seen from Figure 1 that all of the cylinder/plate structures show a dip in the CLF at around the

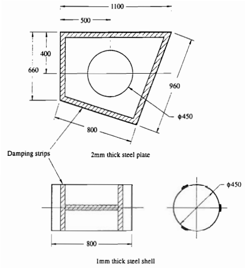

Figure 2. Cylinder and plate elements.

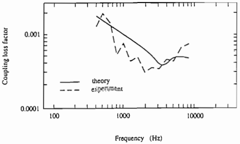

Figure 3. Coupling loss factor of cylinder / plate structure.

ring frequency of 3730 Hz, presumably caused by the increase in modal density of the cylinder around the ring frequency region. Thereafter, the CLFs asymptote to the values of their equivalent plate/plate structures as the frequency increases. This finding is consistent with the well established fact that the response of a cylinder may be approximated by a flat plate at high frequencies. Below the ring frequency, the response of a cylinder is dominated by the membrane effects and as a result, the CLFs of the cylinder/plate structures differ considerably from their equivalent plate/plate structures.

Experiments were conducted to measure the CLF of an example cylinder/plate structure to confirm the validity of the theoretical model [29]. The test structure (see Figure 2) consisted of a thin steel cylinder of 1 mm thickness and 0.45 m diameter coupled to a steel end plate of 2 mm thickness. It can be seen in Figure 3 that the experimental results are fairly well predicted by the theory. The dip in CLF which is predicted in the theoretical analysis can be observed in the experimental data. It occurs at a frequency of around 2500 Hz compared with a predicted value of 3730 Hz which corresponds to the ring frequency of the cylinder. The experimental data also show some discrepancy with the predicted CLF above a frequency 6300 Hz. An attempt to conduct further tests (above 8000 Hz) to confirm the convergence of the experimental results to the theoretical CLF of a plate/plate structure was hampered by the limitation in sampling rate of the data acquisition system. However, further examination of the results reveals that the discrepancy is consistent with previous work on the experimental investigation of CLF (see, for example, references [30] and [31]) and may be partially attributed to the random nature of the experiment and the assumptions involved in the analysis (for example, the equipartition of energy amongst circumferential modes).

3.2 Coupled Periodic Structure

Periodic structures are used extensively in naval ship constructions where relatively lightweight uniform plates or shells are reinforced by the attachment of stiffeners at regular intervals. It is well known [8] that a periodic structure freely transmits vibration waves in certain frequency bands (pass bands) and attenuates waves in other frequency bands (stop bands). This band pass nature has a strong influence on the transmission of noise and vibration through naval ship structures.

The SEA modelling of one-dimensional periodic structures has been considered by Keane and Price [21] by using a probability density function to model the band pass nature of the periodic structure. However, as mentioned earlier in Section 2, this approach is not readily applicable to ship structures since it is based on highly idealised one-dimensional elements. In the present study, the emphasis is focused on the application of wave transmission analysis to evaluate the CLF of coupled periodic structures which consist of two-dimensional elements (such as plates with periodic stiffeners). To this end, the authors have applied the standard travelling wave analysis procedure to evaluate the CLF, with the proviso that wave transmission is not permitted in the attenuation zones [32]. This approach allows the salient characteristic of a two-dimensional periodic structure (i.e., the existence of propagation and attenuation zones) to be incorporated into the standard CLF formulation.

A steel structure which consists of a plate with periodic stiffeners coupled at right angles to a uniform plate (see in Figure 4) is considered here as an example. The coupling line length of the structure is 0.7 m. Both plates are rectangular in shape with overall dimensions of 0.7 m × 1 m and 0.7 m × 1.2 m for the uniform plate and the plate with periodic stiffeners respectively. The thickness of both plates is 2 mm and the stiffeners are 6 mm × 14 mm rectangular sections spaced at 100 mm apart.

The CLF between the uniform plate and the plate with periodic stiffeners was calculated according to the procedures outlined in reference [32]. Experiments were also conducted on this example structure to measure the CLF. Figure 5 shows a comparison between the theoretical and experimental

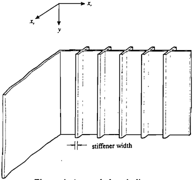

Figure 4. A coupled periodic structure.

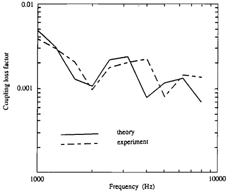

Figure 5. Coupling loss factor between a uniform plate and a plate with periodic stiffeners.

results. The results are in very good agreement in the low frequency bands. At higher frequencies, the theoretical results appear to have shifted by one-third of an octave compared with the experimental data. The apparent shift in frequency may have been caused by the assumptions and simplifications involved in the theoretical analysis. For example, in the analysis of the wave transmission properties of the plate with periodic stiffeners, it is assumed that the boundary conditions can be applied on the plate/stiffener centreline. However, the plate/stiffener attachment point is in fact offset from the stiffener centreline by an amount equal to half the stiffener width and this has an effect on the accuracy of the theoretical model, especially at high frequencies where the cross sectional dimensions of the stiffener are not negligible compared with the bending wavelength. Also, the offset of the attachment point from the stiffener centreline means that the bending wave will travel in the plate elements a distance (in the x_r-direction, see Figure 4) equal to the stiffener spacing minus the stiffener width rather than the stiffener spacing as used in the theoretical model. Overall, the experimental results for the present example are reasonably well predicted by the theoretical model.

4. CONCLUSIONS

Following a review of different methods applicable to the investigation of ship noise, it is concluded that SEA is a useful tool for the high frequency noise and vibration analysis of ship structures. The SEA method has been further developed by the authors, using travelling wave analysis, for naval ship applications and the theoretical values of CLFs of two example structures have been presented here. Experimental results for both structures show good agreement with theoretical predictions and it is therefore suggested that the present formulation of CLFs using travelling wave analysis may be used for SEA studies of structures characteristic of naval ships. However, mention must be made of a number of areas that require further study before the method of SEA can be applied successfully to more realistic naval ship structures. For example, in the analysis of coupled periodic structures, the present work has only considered bending waves to simplify the analysis. In reality, the stiffeners of ship structures are often offset to one side of the plate and thus generate in-plane waves which may have a significant effect on vibration transmission. Also, the coupling between other types of periodic structures typical of naval ship constructions such as ring stiffened cylindrical shells requires further investigation. Finally, the effect of fluid loading on SEA elements has to be considered in the analysis of ship noise.

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