論文の内容の要旨

Experimental Method for Improvement of Structural Vibrations Analysis at High Frequencies

(高周波域の構造振動の実験的予測手法に関する研究)

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Excessive vibration levels in structures need to be controlled in order to reduce noise emissions, avoiding fatigue failure and increasing accuracy of high precision devices. It is therefore necessary to analyze the vibration levels in structures in order to understand the transmission path and determine the measures required to control them. There are a number of methods to carry out vibration analysis of structures. Arguably, the most popular method in the low frequencies is the Finite Element Method. The analysis of high frequencies is commonly done using the Statistical Energy Analysis (SEA) or Experimental Statistical Energy Analysis (ESEA) methods. While these methods give accurate results for many types of structures, they have important limitations, especially in the mid frequency range.

This research proposes a novel method for structural analysis in the high frequency ranges named Experimental Wave Intensity Analysis (EWIA). The formulation of the EWIA method is based on the Wave Intensity Analysis (WIA) method, which is an extension of the SEA method for non-diffuse energy fields. Therefore, this research can be divided into two sections: the first section investigates the WIA formulation in depth. The reason is that the WIA method shows an important potential for practical application. However, since it was proposed, there has been very little work regarding this method and the literature available is very scarce, what makes the method difficult to understand for non-experts. The second section proposes the EWIA method as and extension of the WIA method for its application to complex systems and its expansion into the mid frequency ranges.

EWIA is an extension of the WIA method that uses experimental data to describe more accurately the structures under analysis. A simplified experimental procedure is also proposed, since acquiring the EWIA experimental data, wave intensity measurements, can be very cumbersome. This procedure consists in using ESEA experimental models (internal and coupling loss factors) obtained through the power injection method instead of wave intensity measurements. Then, semi-experimental transmission coefficients required to describe the coupling between the different subsystems of the structure are estimated from those experimental coupling loss factors at each boundary and frequency band. The characteristics of the EWIA formulation and its stability have also been analysed and compared with the WIA, SEA and ESEA methods.

The WIA and EWIA methods were applied to a to a simple two-plate system (Fig. 1) in order to

validate the latter. Then, the EWIA method was applied to a complex system consisting in a dash-and-floor substructure of the body-in-white of a car (Fig. 2). Figure 3 shows he subdivision of the model into subsystems. The results confirmed that the WIA method could improve SEA results for the case of plate systems tested in the research of this thesis. However, It was found that the stability of the method, evaluated by the sensitivity of the coupling matrix to the operation of matrix inversion, could have important influence on the energy predictions at specific frequencies. The sensitivity is more apparent in the case of using measured internal loss factors (and theoretical transmission coefficients). On the other hand, the SEA method showed to be much more stable and no problems were found when using the same experimental internal loss factors, as shown by the low condition number in Fig. 4.

The reason for the sensitivity of the WIA method is the great difference between the values of the elements in its coupling matrix. The elements associated to the diffuse energy fields have, in general, much lower values than those associated to the non-diffuse energy fields. This difference can be importantly increased when using experimental internal loss factors due to their variability. Since the SEA coupling matrix includes only the elements of the WIA coupling matrix associated to the diffuse energy field, the SEA method is not affected by the variability of the internal loss factors as much as the WIA method.

It was reported by Langley and Bercin that the WIA method can improve energy predictions in systems where, due to its configurations, the energy field is not highly diffuse, for example, a row of connected plates, which promotes energy transmission in its longitudinal axis more than in the transversal axis. For the case of box structures, which configuration promotes a diffuse energy field, Bercin finds that WIA does not present important improvements in the energy predictions in comparison to SEA and based the explanation of the results solely on the type of energy field, diffuse or non-diffuse. However, this thesis shows that also in the case of structures with multiple connections that, in principle, can be considered diffuse (for the same reasons as the box structure tested by Bercin), the WIA method can achieve improvement in the energy predictions. This improvement can be explained based on the effect of the energy filtering effect and the non-direct coupling loss factors rather than using a diffuse or non-diffuse energy field explanation. The reason for the improvements is that, the energy filtering effect and non-directly coupling loss factors occur at every connected boundary, no matter the configuration of the system. Since SEA formulation does not take into account the energy filtering effect and the associated non-direct coupling loss factors, the method introduces errors in the energy prediction at each boundary. If two subsystems are separated by a number of boundaries, the error at each boundary is accumulated so that the miss-prediction increases with distance, as found by Langley and Bercin.

For systems with multiple connections in different directions such as a box like structure, the energy filtering effect does not promote non-diffuse energy fields. However, the energy filtering is present at every boundary and, also in this case, the SEA method will introduce errors at each boundary. This conclusion is more apparent in large structures with multiple connections. In this structures the energy field could, in principle, be considered diffuse but the energy filtered at each boundary between the excited subsystem and a subsystem located several boundaries far from it will become significant, and the WIA method will predict more accurately the energy levels of those subsystems than SEA.

It was also found that the application of WIA to complex systems is greatly limited. The reason is that the experimental data required by WIA for its application in complex structures becomes very difficult to acquire. The main reasons are: location of the devices on the structure for both contact and non-contact methods (like optical methods or accelerometer measurements, respectively). That problem is especially true in contact methods where sets of five to sixteen transducers are required to measure the corresponding intensity vectors. Contact methods also present weight problems, since those sets of transducers become relatively heavy and affect the measurements. Moreover, these methods also present contact problems since in very irregular surfaces the perfect contact of every transducer of every set used is not guaranteed.

Then, It was proved that the proposed simplified EWIA is a valid method for estimation of vibration energy in complex structures for which the WIA method is not accurate. By using ESEA data (coupling and internal loss factors) rather than intensity measurements, the EWIA method is greatly simplified and all the measuring problems presented above are overcome. EWIA estimates the energy transmitted by combining experimental measurements of coupling loss factors and theoretical distributions of the transmission coefficients. While the theoretical distribution at boundaries of real systems could be far from those of real transmission coefficients, this simplification allows the EWIA method to take into account, in some extent, the energy filtering effect neglected by the ESEA method and thus, ESEA results are improved while using exactly the same experimental data.

The use of theoretical distribution of the transmitted energy can also be justified by the fact that structural intensity is greatly dependent on factors such as system conditions, loading location and so on. Therefore, the intensity field measured in one set of experiments and its corresponding distribution of transmitted energy could greatly differ from the next set of experiments. Thus, the statistical average of those sets might not be representative of any of them (the variance may be very large). For this reason, the average of measured intensity data might become just a coarse approximation and, in that case, the approximation using theoretical distributions could also be defended. Figure 5 shows an example of energy the energy distributions given by WIA (theoretical) and EWIA of a subsystem in the dash-floor structure.

EWIA can improve WIA results, as shown in Fig. 6. This is the case especially for complex structures where theoretical data greatly differs from experimental measurements. The reason for the improvements is that, while EWIA uses same distribution of the transmitted energies as WIA, in ESEA, those energies are correlated with experimental data (internal and coupling loss factors). Therefore, the energy filtered at each boundary and the non-direct coupling loss factors represent a better approximation than those estimated by WIA using fully theoretical models.

However, the very important factor of EWIA is the possibility of improvement of ESEA energy predictions since ESEA is valid for complex structures. EWIA can improve ESEA results while using exactly the same experimental data. The reason is that EWIA can estimate the energy filtered at each boundary of the subsystem and can also define the relationship between non-directly connected subsystems through the estimated non-direct coupling loss factors, as shown in Fig. 7.

Since the energy filtering effect is accumulative as the energy wave crosses successive boundaries, the EWIA and ESEA results for the excited subsystem should be very similar. However, for the other subsystems in the structure, the EWIA method will improve the ESEA energy predictions. It should be noticed that the improvement does not depend solely on the distance between the subsystem calculated and the excited subsystem but also on the value of the coupling loss factor between subsystems. The reason is that, in EWIA, the coupling loss factors determine not only the amount of energy transmitted, as is the case of ESEA, but also the amount of energy filtered. Therefore, even for directly connected subsystems, if the amount energy filtered is important at the connecting boundary, the EWIA method would be expected to give better energy estimations than the SEA method.

The EWIA method incorporates a new variable named C*nst* (Fig. 8). This variable is a proportionality constant that related the experimental and theoretical models of a given structure. In a more simplistic way, the *Cnst* constant can be thought as a scaling factor applied to the theoretical transmission coefficient. This scaling factor ensures that, assuming a theoretical distribution of the energy at a given boundary, the amount of energy transmitted matches the energy measured in the experiments, which is determined by the experimental coupling loss factors, form with *Cnst* is derived. For this reason, EWIA can improve WIA predictions since it ensures that the energy transmitted is same as in the real structure. For the same reason, EWIA can improve ESEA predictions, because having the same amount of energy transmitted, EWIA defines its dependency with the angle of transmission by applying theoretical transmission coefficients.

The *Cnst* constant can be applied into the EWIA formulation in different ways. While these are equivalent, it was found on the results that important variations could result on the energy predictions depending on the way *Cnst* is applied. That difference can be justified by considering the accumulative behavior of the energy filtering effect and the dependency of *Cnst* on the experimental coupling loss factors. Therefore, if *Cnst* is applied in a given coupling direction of transmission at each boundary between the subsystems of a structure, its value at each boundary will depend on the coupling loss factor in that direction. Consequently, the total energy filtered will depend on the combination of those *Cnst* values. On the other hand, If the direction selected to apply *Cnst* is the opposite, its value at each boundary will depend on the coupling loss factor in the opposite direction and, given the variability of experimental data for the two coupling directions of any given boundary, the total amount of energy filtered could greatly differ from that calculated above.

In conclusion, it is shown that EWIA is an efficient method for improving ESEA predictions while using the same experimental ESEA procedures. Therefore, EWIA does not require complex experimental procedures and the level of simplicity is similar to ESEA. Moreover, predictions of existing ESEA models can be improved using the available ESEA data with no additional manipulation.

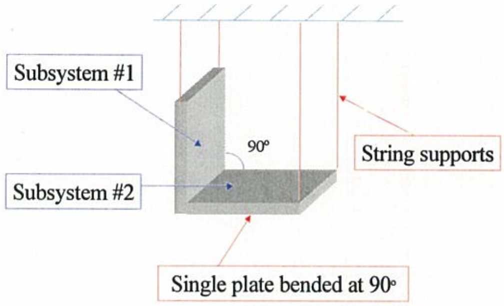

Figure 1: Illustration of simply supported L-plate system

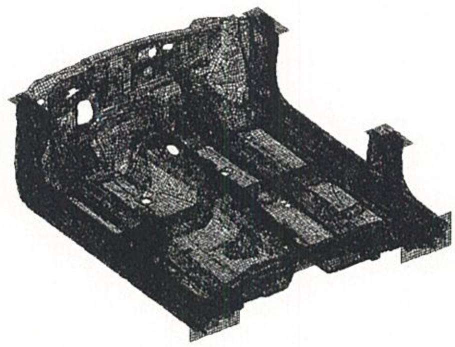

Figure 2: Dash-Floor model from body in white of a car

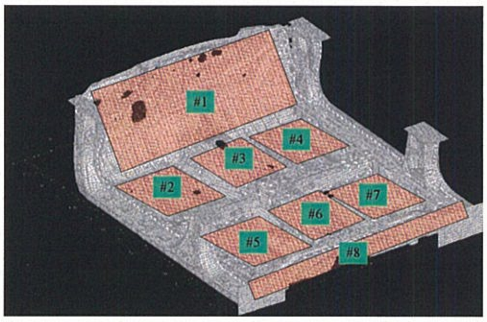

Figure 3: Subdivision of dash-floor model into subsystems

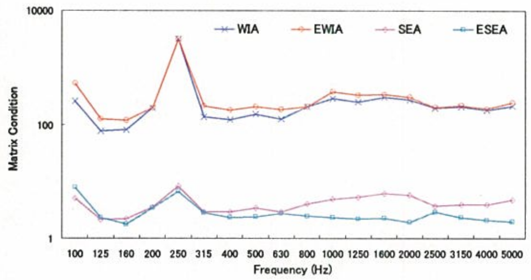

Figure 4: Comparison of matrix condition between EWIA, ESEA and SEA and WIA using experimental internal loss factors for the L-shape system

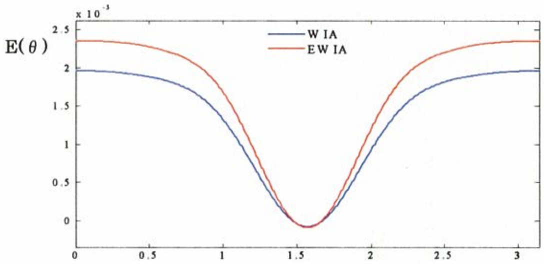

Figure 5: Comparison between the energy functions of WIA and EWIA model of a two-plate system at 2500 Hz using three Fourier components. Subsystem 2

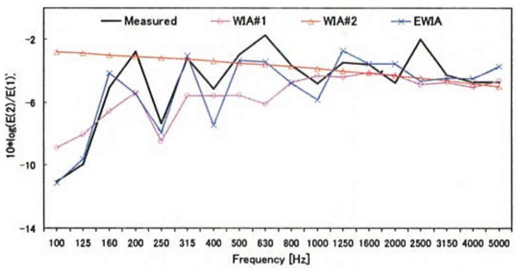

Figure 6: Comparison of measured energy, WIA using experimental ILF (WIA#1) and WIA using constant ILF(WIA#2) and EWIA for L-plate structure

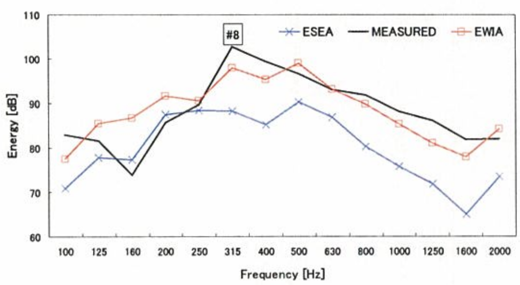

Figure 7: Energy prediction comparisons between measured energies, ESEA and EWIA predictions for Subsystem 8

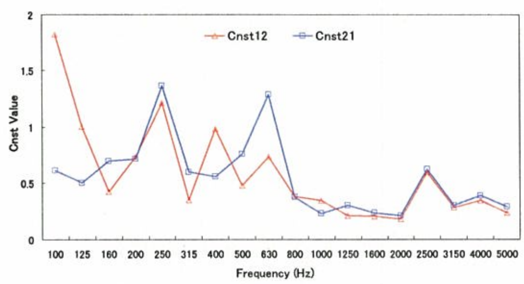

Figure 8: EWIA proportionality constant, *Cnst,* oin both coupling directions L-shape structure
Cnst 12: coupling from Subsystem 1 to Subsystem 2
Cnst 21: coupling from Subsystem 2 to Subsystem 1