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MODELING METHODS FOR VIBRO-ACOUSTIC ANALYSIS OF COMMERCIAL AIRCRAFTS

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Abstract

This paper describes an ongoing program of work concerned with the development of improved methods for modelling the vibro-acoustic response of commercial aircraft structures at mid and high frequencies. The study is focused on the noise and vibration transmission in an actual section of a 737 Boeing aircraft, including trimmed sidewalls, stowage bins, and connected floor structure. Six transmission problems have been identified and two of them are presented in this paper: the transmission of vibrational energy into the stowage bins via the stowage bin tie rods, and the transmission of vibrational energy between the sidewall and floor panels through the floor beams. The different modelling approaches make use of the recently developed Hybrid FE-SEA method and general periodic SEA subsystem. In all test cases, the numerical predictions are compared with test and good agreement is observed.

1. INTRODUCTION

The transmission of noise and vibration in aerospace structures often involves a combination of “air-borne” transmission through acoustic fluids and/or “structure-borne” transmission through structural components. In order to guide design changes that minimize the noise and vibration, it is useful to be able to predict and quantify the various sound transmission paths. This can prove difficult as the system may require many degrees of freedom to describe the response and is sensitive to variations in manufacturing processes, material variability and environmental conditions. These problems become increasingly severe as the frequency of interest increases due to the reduction in wavelength of the system deformations. Therefore, standard deterministic approaches to structural-acoustic dynamics such as finite elements (FE) and boundary elements (BEM) are confined to low frequencies.

The Statistical Energy Analysis (SEA) method overcomes the above difficulties by the use of space and frequency averaged quantities such as energy [1]. This allows the modelling of some components of a system and the power exchanged between those components. SEA is now a proven method for creating an efficient “system level” model of the various transmission paths in a vibro-acoustic system. Two areas for improving the accuracy of SEA for aerospace structures have been identified and addressed recently: (i) the need to compute coupling loss factors between SEA subsystems connected at complex junctions, and (ii) the need to model complex ribbed panels as SEA subsystem. While modern SEA codes contain a large library of different subsystems and junctions, applications are sometimes encountered where a standard formulation doesn't exist for a given type of construction. In some instances it is possible to estimate the subsystem properties from test or local FE models; however, generic algorithms that can include an arbitrarily complicated geometry are desirable.

In this paper a recently developed Hybrid method is used which provides a rigorous way to couple FE and SEA components of a system [2,3,4,5]. The Hybrid method enables the introduction of FE details into a standard SEA analysis, and this is typically performed at complex junctions to capture the physics of the transmission. FE can also be introduced to described complex loaded components and obtain a more accurate estimation of the power input into the rest of the structure described with SEA.

The second development reported in this paper is the periodic SEA subsystem, based on the use of periodic structure theory [6,7]. A finite element model is created of a unit cell and analytical expressions are used to obtain the SEA properties of a larger panel comprised of a large number of such cells. The approach provides an efficient and accurate way to model arbitrarily complex sections in SEA that are difficult to model using traditional formulations.

Two application cases are presented that make use of those recent extensions to SEA.

2. STRUCTURE-BORNE TRANSMISSION OF STOWAGE BIN TIE RODS

This section describes the process for building a model of structure-borne noise transmission from a fuselage attachment point to the stowage bin through a connecting frame.

2.1 Description of the Structure

The bin, frame and connecting tie rods shown in Fig. 1 are included in the analysis that targets the frequency range from 50 to 1600 Hz. The overall dimensions of the bin and frame are of the order of 65”×20”. The frame is of rectangular shape and made of connected aluminium beams with different cross sections. Small add-on brackets are used to attach the several rods and the bin. The bin whose door has been removed is made of four curved or corrugated panels: the bottom part is made of a honeycomb sandwich, while both sides and the top panels are in aluminium. There are four connections between the bin and the frame.

Fig. 1: *Left: Stowage bin assembly connected to the fuselage section through a rectangular frame and some tie rods. Right: Test setup for bin-frame-tie rod assembly.*

An approximate analysis of the dynamic properties of each component shows that: (i) the tie rod and frame are stiff structures that are not expected to have too many modes in the frequency range of interest, so that SEA might not be accurate for those; (ii) Alternatively, the bin panels have enough modes to be adequately described by SEA. It is thus decided to build a Hybrid model where the frames and tie rods are described with FE, and the bin with SEA.

2.2 SEA Model of the Bin

The bin is made of two side panels, a door panel, and a top and bottom panels. All four panels are descried using singly-curved shell SEA subsystems in the software package *VA One* [8]. The model is shown in Fig. 2, and it comprises four five line junctions and six point junctions. The structure was tested in isolation for intermediate validation and to measure the damping loss factors (using the decay rate method [1]).

2.3 FE Model of the Frame and Tie Rod

As shown in Fig. 1, the frame structure connecting the bin to the fuselage is made of beams and several small add-on brackets used to connect the beams together or to the tie rods and bin. The tie rod that was driven in the tests is attached in the middle of the *Z*-section beam via a bracket. All frame components are made of aluminium.

An FE model of the frame was built based on simple geometrical measurements and weighting (see Fig. 2). The FE model is made of independent components described with CQUAD4 and CTRIA3 elements and connected via CRIGD1 elements (rigid elements from COSMIC Nastran). The tie rod and screws in the four brackets connecting to the bin where described with CBAR. The complete model comprises 3783 nodes.

2.4 Hybrid FE-SEA Model of the Assembly

The frame and bin were assembled and suspended with elastic strings from two tie rods, as shown in Fig. 1. It can be seen that there are two connections per side beam: the connection with the yellow bracket is with the side panel only, while the other one is with the side and bottom panels. The assembly was tested using an impact hammer and 14 accelerometers. As the ultimate goal is to measure the transmission from the tip of the tie rod to the bin, impact test were performed with loading the rod tip.

The Hybrid model of complete assembly is made of the SEA model of the bin and the FE model of the frame. As shown in Fig. 2, those are connected through four Hybrid point junctions representing the actual physical connections between the bin and the frame. The dark arrow shows the location and direction of the excitation at the end of the tie rod.

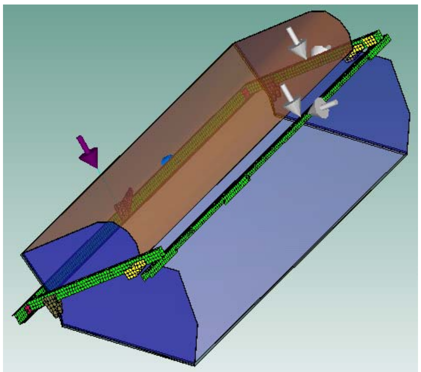

Fig. 2: *Hybrid FE-SEA model of the bin-frame-tie rod assembly in VA One.*

2.5 Predictions versus Tests

For the loading in the axial directions at the tip of the tie rod, the measured and predicted RMS velocity responses at a point of the frame are shown in Fig. 3. The responses are averaged over the 1/3rd octave bands from 50 to 1600 Hz. The energy response of the four panels of the bin is also shown. The Hybrid model predicts the band-averaged energy or RMS velocity response of the frame and bin within about 5 dB over most of the frequency range.

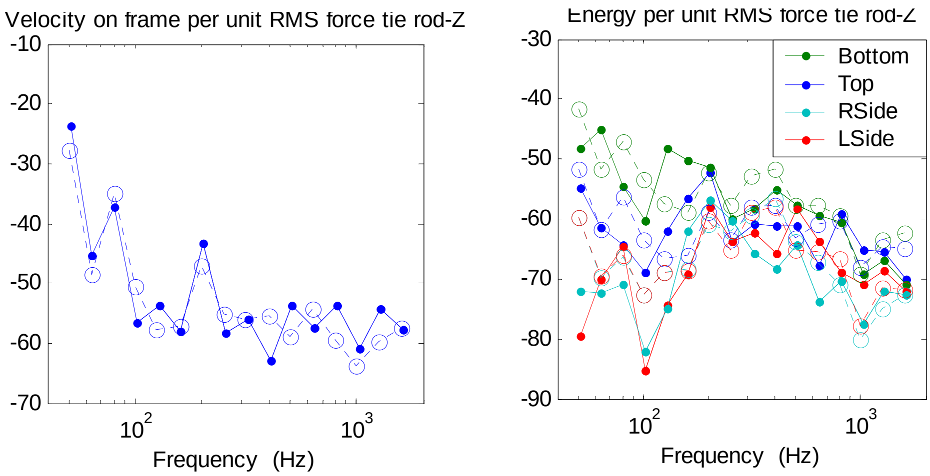

Fig. 3: *Experimental (solid) and predicted (dotted) response, when loading at the end of the tie rod. Left: RMS velocity response at a point of the frame; Right: energy responses of the four panels of the bin.*

3. STRUCTURE-BORNE TRANSMISSION BETWEEN SIDEWALL AND FLOOR PANELS

This section is concerned with the noise transmission between sidewall and floor panels of an aircraft. Those panels exhibit a high modal density and are connected through some complicated and stiff beams, so that neither FE nor SEA alone are very well suited for the analysis. As a mean to enhance SEA models, the Hybrid FE-SEA method is used to couple FE and SEA descriptions of the various components.

3.1 Description of the Structure

The sidewall and floor panels were extracted from the Boeing 737 section (see Fig. 4). The sidewall panels above and below the floor are 63” wide and respectively 16.5” and 24” high: they are made of similar skin-stringer-frame arrangement, with two stringers and three frames. The floor is split in two unequal panels made of honeycomb sandwich, with dimensions 51.75”×17.5” and 11”×16.25”.

Fig. 4: *Sidewall and floor panels connected through some beams, and details of the frames.*

The sidewall and floor panels are connected through three stiff *I*-section beams. A plate with holes next to the skin connects the beams with the floor and skin. The seat track is parallel to the skin and connects the beams and the floor. The floor panels are directly connected to the beams, along the edges of the panels.

The structure was suspended from two beams with elastic strings, and tested using an impact hammer and 14 accelerometers. The impact locations were scattered on the bottom sidewall panel (7 points), the top sidewall panel (7 points), the floor panel (4 points), and on the top of each *I*-section beam. The acceleration response was measured at 5 points on each sidewall panel and 4 points on the floor panel.

3.2 SEA Model of the Floor Panels

The two floor panels in the fuselage section have different area, but are made of the same sandwich material with honeycomb aramid core and two identical fiberglass faces with thickness 0.02”. An SEA model of each floor panel was built using the sandwich formulation in *VA One* [8]. The standard fiberglass material properties available in *VA One* where used for the faces, and the effective material properties of a honeycomb construction were obtained from the cell size and foil thickness, and the assumed material properties of the foil.

3.3 SEA Models of the Ribbed Skin Panels

This section describes the process for building a Statistical Energy Analysis (SEA) model of the dynamic response of the sidewall panels of the aircraft fuselage section. It can sometime prove difficult to model complex ribbed structures with SEA, and a new periodic theory developed to enhance the SEA models is used here.

An FE model of a single periodic cell was created as shown in Fig. 5, and was used to compute the modal density, power input from point forces, and velocity response per unit energy (using the algorithms described in [6,7]). The FE model is made of 1856 CQUAD4 shell elements and comprises 1941 nodes.

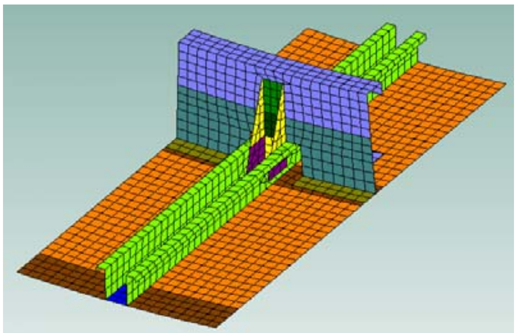

Fig. 5: *FE model of a single cell of the sidewall panel used in the periodic SEA subsystem formulation.*

The periodic formulation for the SEA subsystem was validated against tests on a simpler structure comprising the skin and stringer. The modes in band of a simply stiffened panel were computed using the periodic theory and the standard *VA One* ribbed panel formulation, and then compared to test data obtained on the panel in isolation (no frames). The agreement in Fig. 6 is satisfactory in the frequency range below 600 Hz where the experimental data are reliable (above 600 Hz, phase mismatch made the drive point impedance measurements inaccurate). Both the ribbed panel and the periodic formulations give good results, but the periodic section does not predict bands with no modes while the ribbed formulation predicts zero modes in the bands centred at 64 and 128 Hz.

The predicted distribution of RMS velocity per unit energy of the panel is shown on the right for the band centred at 1600 Hz. It can be seen that the response of the structure is not homogeneous at this frequency, as scatter of the response goes to more than 12 dB.

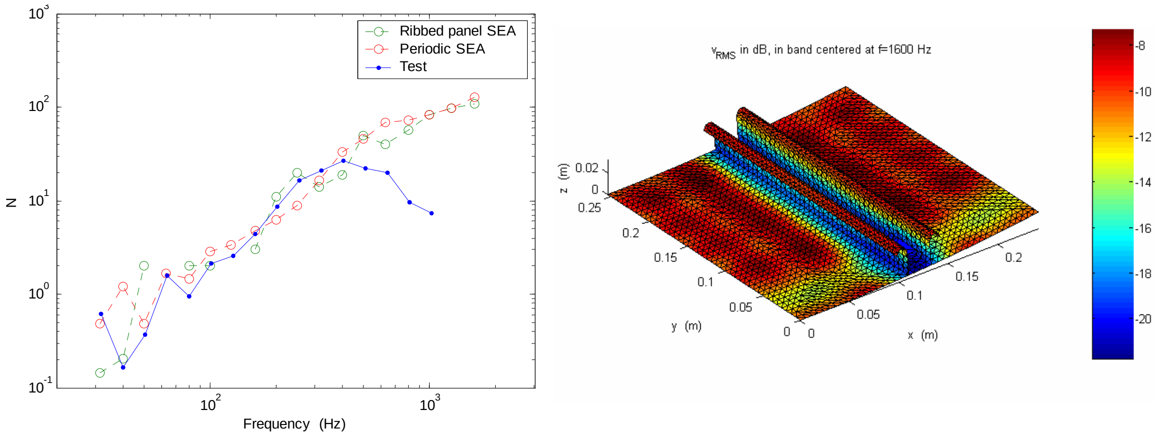

Fig. 6: *Left: Modes in third octave bands from 32 to 1600 Hz. The experimental data above 600 Hz are not reliable. Right: Distribution of RMS velocity over the periodic cell, per unit energy of the panel at 1600 Hz.*

3.4 FE Model of the Floor Beams

The sidewall and floor panels are connected through stiff beam components, and it was decided to model those with FE. Three stiff beams below the floor have a *I*-section 5.5” high and 1.875” wide, with wall thickness between 0.08” and 1/8”. The beams have holes and reinforcements. The rail track is 63” long, with an *I* section (1” high, 1.75” wide) and the rail on the top of it. It is bolted to the floor. The component between the floor and the sidewalls is a corrugated plate with holes, with width varying from 5.4” to 7”, and thickness about 0.033”.

The FE model shown in Fig. 7 was built with all connections assumed perfect. It is made of CQUAD4 finite elements, and contains 6874 nodes. Standard aluminium properties were used. The *VA One* inbuilt FE solver was used to extract 426 modes below 2700 Hz.

3.5 Hybrid FE-SEA Model of the Assembly

The Hybrid model of the complete assembly is made of the SEA model of the sidewall and floor panels and the FE model of the beams (see Fig. 7). There are thus four SEA subsystems and one FE subsystem, connected through Hybrid line junctions.

As a reference, a full SEA model of the sidewall and floor panels assembly was built in *VA One* (see Fig. 7). The sidewall and the floor panels were kept identical to the ones in the Hybrid model. A lot of details have been removed from the floor beams to keep one flat plate per *I*-section beam; a flat plate connects the skin and the floor (with thickness equal to the averaged value for this part), and a flat plate describes the seat track. A quick look at the number of modes in band for each SEA subsystem indicates that almost all subsystem may be correctly described with SEA above 800 Hz.

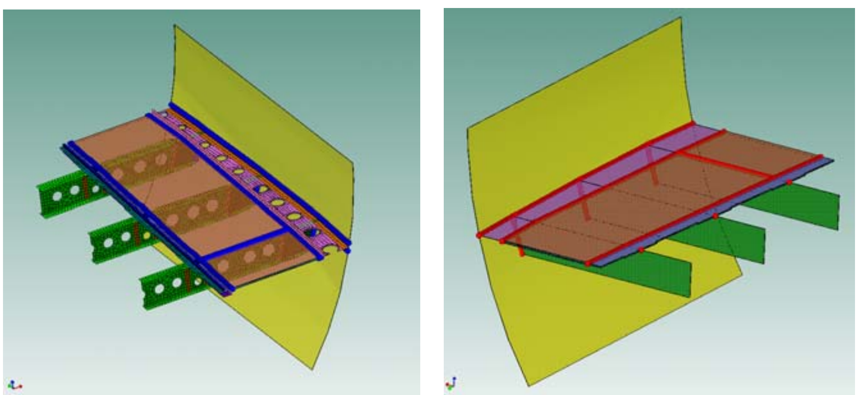

Fig. 7: *Left: Hybrid FE-SEA model of the sidewall and floor panels assembly in VA One. The Hybrid line junctions are shown in blue. Right: SEA model of sidewall and floor panel assembly.*

3.6 Models Predictions versus Tests

For "rain-on-the-roof" loading of the top sidewall panel, the measured and predicted mean square velocity responses of the panels are shown in Fig. 8. The same test data are present in both figures, but the predictions come successively from the Hybrid and the pure SEA models.

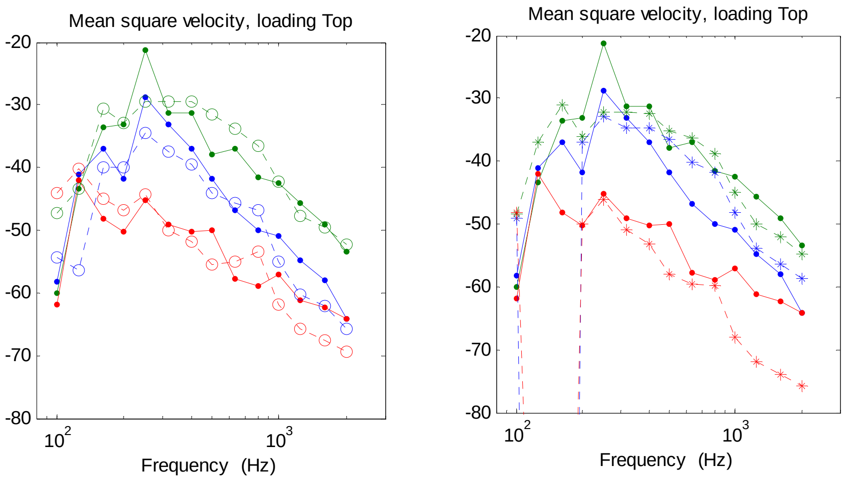

Fig. 8: *Mean square velocity response of the sidewall and floor panels to "rain-on-the-roof" loading of the top panel. Experimental (solid) and predicted by Hybrid (dotted on the left) and by SEA (dotted on the right).*

The agreement between tests and Hybrid predictions is fairly satisfactory (within 5 dB and right trends) apart from the lowest frequencies where discrepancies can be seen. This may be due to the limited number of modes in the panels below 200 Hz. The SEA prediction is fairly good as well, although it seems that the transmission to and from the floor is systematically under-estimated. It can also be seen that the ribbed panel formulation predicts some bands with no resonant modes, and this explain the missing data on the pure SEA prediction below 200 Hz. The periodic formulation for the ribbed panel does not predict such "stop bands".

For the forces applied on the *I*-section beams below the floor, the measured and predicted mean square velocity responses of the panels are shown in Fig. 9.

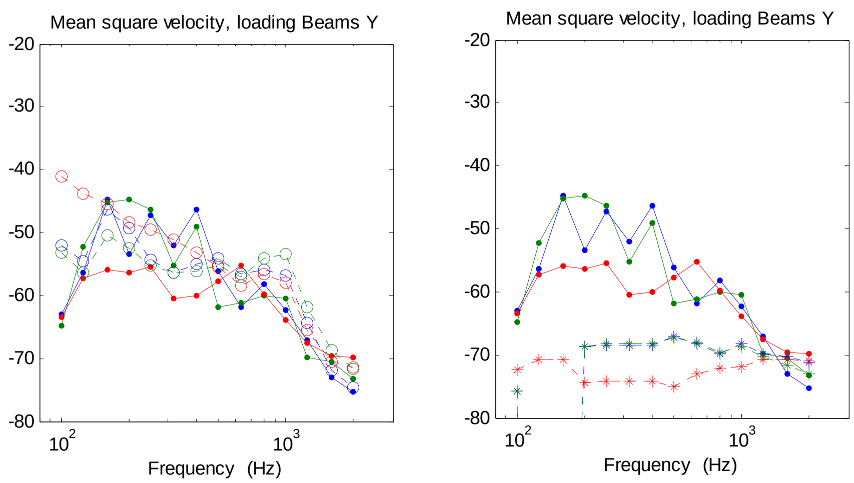

Fig. 9: *Mean square velocity response of the sidewall and floor panels to a unit point force applied on the floor beams. Experimental (solid) and predicted by Hybrid (dotted on the left,) and by SEA (dotted on the right).*

Here again, the agreement between tests and Hybrid predictions is satisfactory above 200 Hz. The SEA predictions are not good, as the SEA model of the *I*-section beam is not able to capture the right power input into the system. It can be checked that the number of modes of the beams in the flexure becomes adequate at around 800 Hz (more than 3 modes per frequency band). This is where the SEA prediction becomes accurate on the left of Fig. 9.

Overall, some of the limitations of the Hybrid model may be due to the rough FE description of the beams (partly due to the lack of exact information, and real updating), and to the models assumption that the sidewall and floor panels carry a diffuse field. The first limitation is likely to become more significant as frequency increases while the second one is more present at low frequencies (below 200 Hz). The second limitation also applies to the SEA model with a larger frequency span as stiffer components are described with SEA.

Considering the complexity of the structure, the available amount of information, and the absence of any forms of updating/tuning, those results are fairly satisfactory. In particular, they show that an SEA model a structure-borne transmission can be improved by the use of

- the Hybrid method that allows to better capture the power input into stiff components and the transmission through stiff and/or complicated parts,
- the periodic SEA subsystem description for the sidewall ribbed panels, where accurate SEA characteristics can be obtained for complicated geometries with fair robustness with regard to the perfect periodicity.

4. CONCLUSIONS

This paper has discussed the application of the Hybrid FE-SEA method and the periodic SEA subsystems to various structural-borne transmission problems. The examples demonstrate that the new methods can provide improvement to existing SEA models. For the problems considered, the methods are typically several orders of magnitude faster than a purely deterministic analysis, although they are more demanding than pure SEA. The methods are well suited to the analysis and design of structural-acoustic systems of practical interest.

ACKNOWLEDGMENTS

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