Transmission loss modelling of double wall structures using hybrid simulation

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Introduction

The major part of the acoustic mid-frequency power flow into cabins of aircraft, trains or cars is transmitted via double wall systems. Especially the double wall effect is a typical example for hybrid theory because of the deterministic nature of the double wall resonance. In hybrid theory implementations deterministic subsystems are modelled using the finite element method (FEM) or deterministic analytical models like the transfer matrix approach. In the higher frequency range first subsystems start to become dynamically complex and can therefore be modelled as random subsystems using statistical energy analysis (SEA). This paper deals with a hybrid modelling approach applied to typical double wall structures as they occur in the environment of civil aircrafts.

Motivation

In Figure 1 a typical aircraft section is shown, denoting several possible double wall configurations. The most representative part of these double walls is the sidewall window part, which is nearest to the passenger and directly hit for example by jet noise.

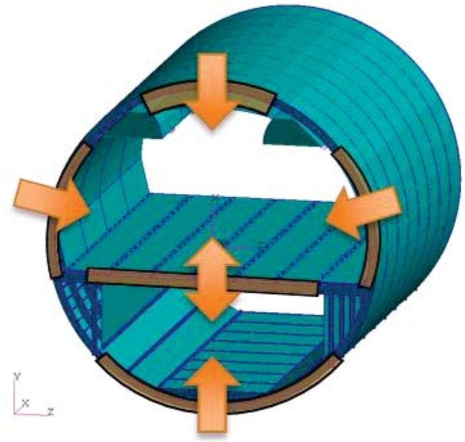

Figure 1: Typical aircraft section with several examples for double walls

Theory

In hybrid FEM/SEA theory as described in [1]and [2] both domains of simulation are extended by additional terms that accounts for connection to the other domain respectively. In Figure 2 the fuselage sidewall as typical FEM subsystem and the discrete equation of motion is shown. If this deterministic system is coupled to several random subsystems as shown in Figure 3 the stiffness matrix $\mathbf{D_d}$ and the external force $\mathbf{f}$ is extended by two additional terms:

1. The free field radiation stiffness accounting for the radiation into the SEA subsystems
2. The reverberant load accounting for the excitation of the FEM systems to the reverberant field in the SEA subsystems

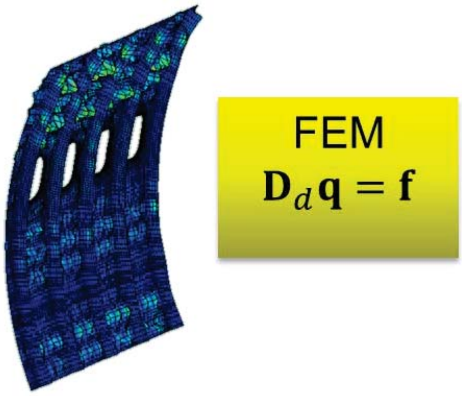

Figure 2: Full deterministic system (FEM) and corresponding equation of motion

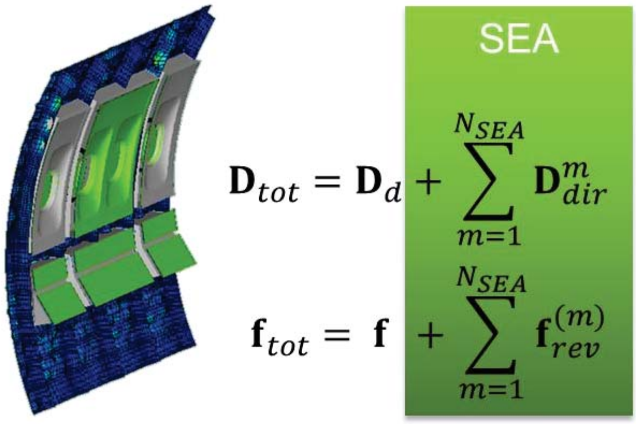

Figure 3: FEM subsystem extended by statistical subsystems and additional expressions for the stiffness matrix and load

The free field radiation stiffness can for example be determined by the boundary element method or by simplified assumptions for radiation into the free field. Because of the random nature of the reverberant load, it must be expressed by an ensemble cross correlations. This load is according to [2] also determined by the free field radiation stiffness $\boldsymbol{D}^{(m)}_{dir}$

$$\langle \mathbf{f}\mathbf{f}^H_{rev}\rangle = \frac{4E_m}{\pi\omega n_m} Im\{D^{(m)}_{dir}\} \qquad (1)$$

If the equations from Figure 3 are cross correlated the response at the degrees of freedom of the FEM systems can be calculated using the following expression:

$$\langle \boldsymbol{q}\boldsymbol{q}^H\rangle = \boldsymbol{D}^{-1}_{tot}\left(\boldsymbol{S}^{ext}_{ff} + \sum\nolimits_m \frac{4E_m}{\pi\omega n_m} Im\{\boldsymbol{D}^m_{dir}\}\right)\boldsymbol{D}^{-\mathrm{H}}_{tot} \qquad (2)$$

The random part of the simulation is deals with using the power balance matrix that is normally used in SEA:

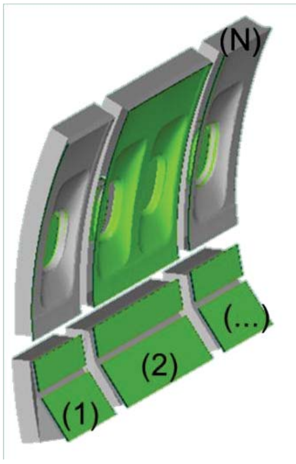

Figure 4: SEA subsystems in our double wall example

There is no formal difference between the classical SEA power balance and the hybrid SEA equation. The difference is hidden in the coupling factor as given in equation (3).

$$\begin{bmatrix} M_1 + h_{tot,1} & \cdots & -h_{1N_{SEA}} \\ \vdots & \ddots & \vdots \\ -h_{N_{SEA}1} & \cdots & M_{N_{SEA}} + h_{tot,N} - h_{NN} \end{bmatrix} \begin{Bmatrix} \frac{E_1}{n_1} \\ \vdots \\ \frac{E_N}{n_N} \end{Bmatrix} = \begin{Bmatrix} P^1_{in,0} \\ \vdots \\ P^N_{in,0} \end{Bmatrix}$$

$$h_{nm} = \frac{2}{\pi} \sum_{jk} Im\left\{D^{(m)}_{dir,jk}\right\} \left(\mathbf{D}^{-1}_{tot} Im\left\{D^{(n)}_{dir,jk}\right\} \mathbf{D}^{-H}_{tot}\right)_{jk} \quad (3)$$

The double wall formulation

In principle double walls are not representative for SEA simulation because there are several non resonant paths that violates the SEA assumptions [3]. However, they are required to describe the physics of the double wall. Some of the non resonant paths (for example the mass law) are automatically included in the hybrid theory by equation (3) but the double wall effect of the radiation of the FE subsystem fuselage wall into the cabin cavity must be considered using a transfer matrix approach.

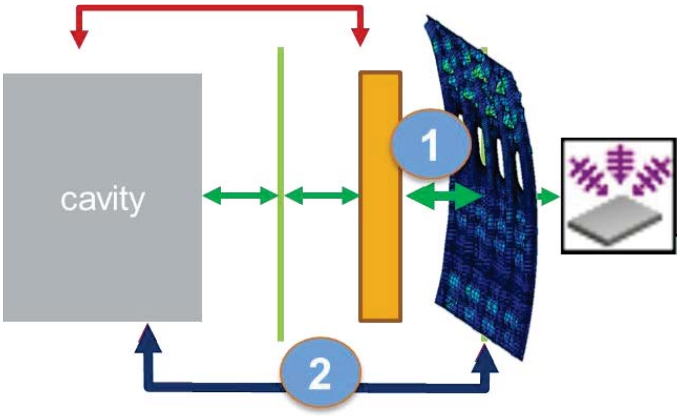

Figure 5: Resonant (green) and non-resonant (red/blue) paths of the hybrid double wall system.

Modelling strategy

In order to set up a modelling strategy one must identify the dynamic complexity of the included subsystems as shown in Figure 6

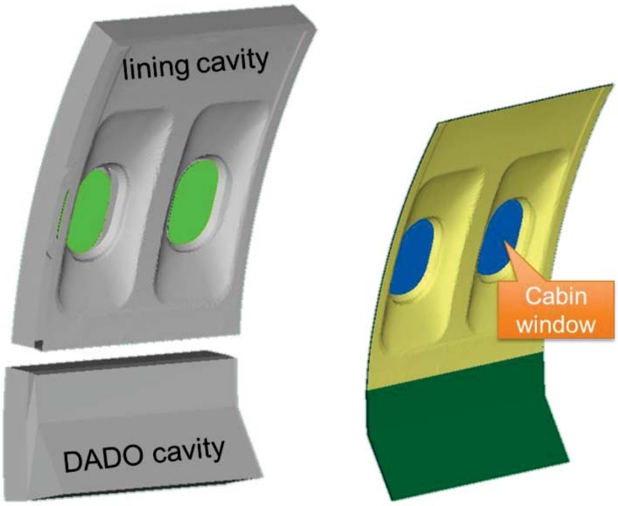

Figure 6: Air cavities and the lining panels oft the double wall configuration

The dynamical complexity can be estimated using the modes in band of the included subsystems. If we look into the modes in band of the plates (Figure 7) and the cavities (Figure 8) one can see that SEA modeling of these subsystems make sense starting from 400 Hz. Before 400 Hz the systems shall only be considered by their deterministic behavior using FEM or a transfer matric approach. Here, we use the transfer matrix approach.

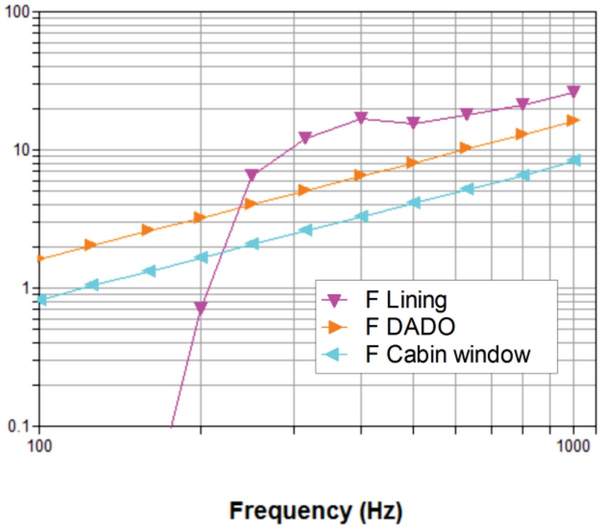

Figure 7: Modes in band of lining panels and the acrylic window.

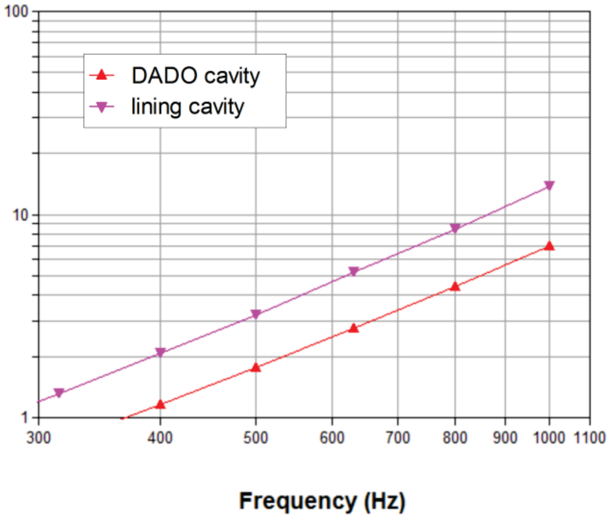

Figure 8: Modes in band of the DW cavities

Strategy for the mid frequency range

From these considerations the following modelling strategy is derived. In the frequency range 100-400 Hz only the FE part is modelled using the transfer matrix representation for cavities and lining (Figure 9). For the higher part (400-1000 Hz) additional SEA subsystems will be connected to the FE part as shown in Figure 10.

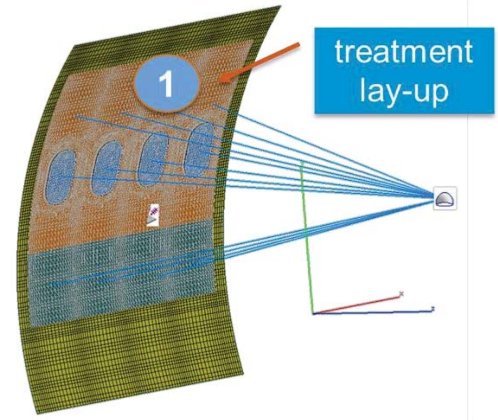

Figure 9: FEM sidewall plus transfer matrix at 100-400 Hz

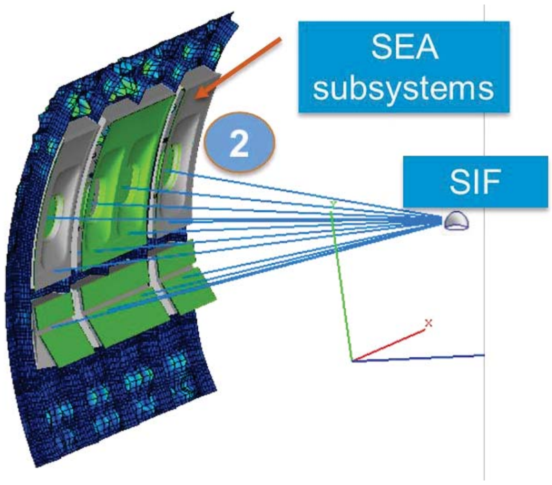

Figure 10: System here with additional SEA part from 400-1000 Hz

As described in [3] the cavities are filled with glass wool, i.e. the damping is determined by the propagation damping in the material. Thus the material is modeled using the properties derived from the equivalent fluid model of light glass wool. That means that we have to consider a different density and speed of sound in the SEA cavities.

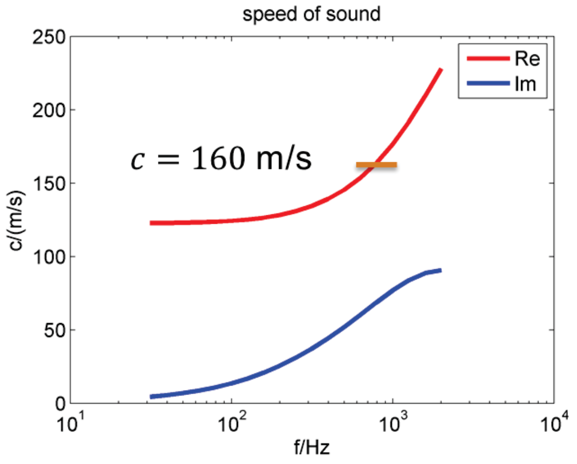

Figure 11: Complex speed of sound of glass wool

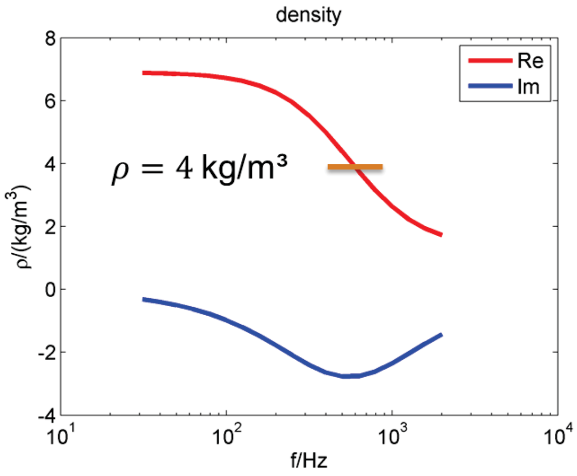

Figure 12: Complex density of glass wool

In the lay-up of the transfer matrix model the glass wool properties are automatically considered because the equivalent fluid model is included in the formulation of the software. The window cavity is a simple layer of air plus the thin inner window.

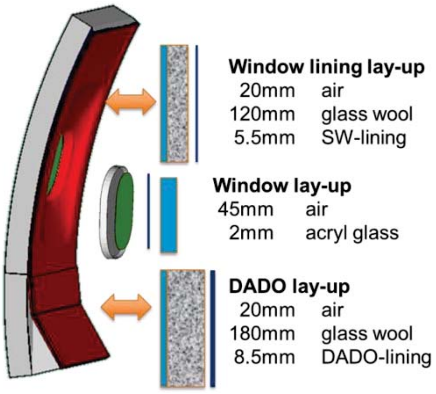

Figure 13: Lay-ups of the single components of the double wall

Results

The hybrid modelling is compared to two reference results (1) Experimental results from tests in a twin chamber arrangement and (2) a full FEM solution using an in-house tool Hy-TL for the diffuse sound field excitation. The results including the single wall simulation are shown in Figure 14. One can see that the hybrid approach using only the lay-up is not sufficient for the high frequency regime. If the SEA subsystems are included they coincide well with the Hy-TL full FEM solution. Unfortunately there is an issue with the test results. Actually it is supposed that the lower part of the panel in the tests were not perfectly isolated which leads to bad high frequency results. However, this must be further investigated.

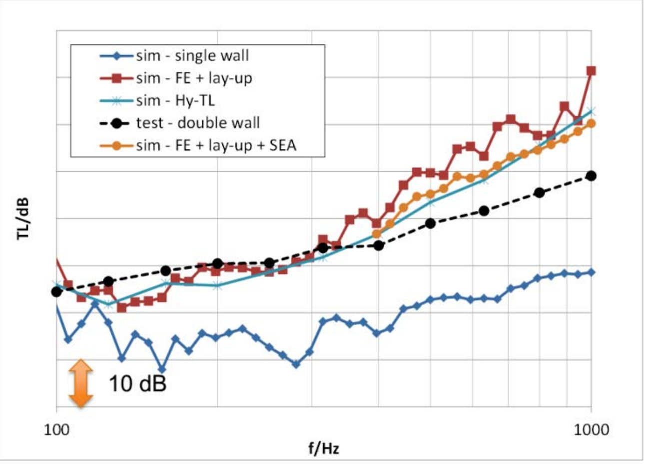

Figure 14: Transmission loss results from the different approaches

The purpose of all simulation is to improve the technical systems. Therefore we investigate the power flow into the cabin. In Figure 15 one can see that the major contributions are from the window lining and the windows itself. If this holds simple absorption in the window cavity might help. In the tests several detailed quantities were taken which might be used in order to verify this assumption.

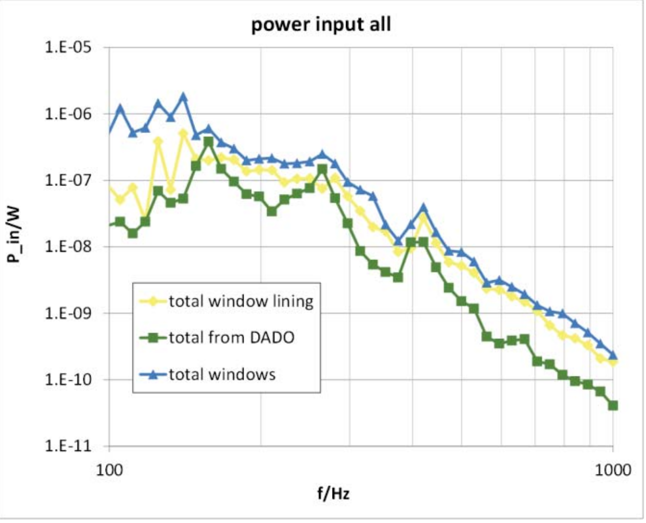

Figure 15: Power input from the subsystems

Conclusions

Hybrid modelling of double walls provides reliable results compared to full FEM (Hy-TL) simulations. In terms of computational expense there is a slight improvement in calculation time of about 60%. If this transmission loss is used in a full aircraft model if may be implemented by an insertion loss for all window panels in order to avoid repetitive calculation of the double wall in the global SEA model. For practical double wall implementation some points are still pending, i.e. the automatic consideration of propagation damping of fully filled glass wool cavities.

This method provides means for a detailed comparison to tests at sub component level and can also be used to derive the response to turbulent boundary layer excitation. For higher frequencies a full SEA model will be used. In the lower frequency range a practical implementation of all required material models is also still pending, for example an equivalent fluid model in reliable structural FE solvers.

References

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