Vibro-Acoustic simulation of structure-borne induced radiation of ship windows

Bernard Van Antwerpen, Diego d'Udekem [1], Christof Weißenborn [2]

[1] Free Field Technologies SA, Belgium, Email: bernard.vanantwerpen@fft.be

[2] Germanischer Lloyd, Germany, Email: christof.weissenborn@gl-group.com

Introduction

In a ship cabin, the large windows seem to represent a weak point in terms of acoustic transmission from the exterior shell to the cabin. Due to increased comfort requirements, there is an emerging need to predict the behaviour of those components prior to their final design, construction and assembly on board.

In this framework, numerical methods offer a good platform for predicting the acoustic radiation and structural vibration of such windows and comparing the performance of different windows system designs. For instance, it allows predicting the radiation efficiency, which represents a key point in reducing the global sound pressure level within the cabin. This paper presents a vibro-acoustic study performed with the finite/infinite element code ACTRAN. The radiation efficiency of one window configuration is estimated. The focus is placed on the determination of the most sensitive system parameters.

In this paper, the mathematical background of the simulation method is first briefly introduced. The numerical results are then compared to a set of full scale experimental measurements for validation.

Germanischer Lloyd, Hamburg, cooperated with FFT to validate the approach, proving it's suitability. It must be stated that the distribution of the structure-borne noise in the ships structure and the specific peculiarities of ship window systems are the key issues this application.

Finite element code

The main focus of this paper being related to the modeling of large ship windows, the vibro-acoustic model is briefly described. More details on the implementation can be found in the ACTRAN User's manual [1]. Basically the modeling strategy relies on usual elasto-acoustic approximations and the selection of a finite element approach. In the present case, a solid displacement- fluid velocity potential (u-φ) formulation is selected since it enables the unified treatment of various material models (visco-elastic, poro-elastic and acoustic materials) and preserves the symmetry of the resulting FE model. In a harmonic context (ω is the circular frequency), the set of discrete equations related to an elasto-acoustic model appears as:

$$\begin{bmatrix} K_s - \omega^2 M_s & i\omega C_{sa} \\ i\omega C_{sa}^T & K_a - \omega^2 M_a \end{bmatrix} \begin{pmatrix} U \\ \Phi \end{pmatrix} = \begin{pmatrix} F_s \\ F_a \end{pmatrix} \quad (1)$$

where Ks and Ms are the structural stiffness and mass matrices, Ka and Ma are the acoustic 'stiffness' and 'mass' matrices, C_{sa} is the coupling matrix while U, Φ, F_s and F_a denote the nodal displacement and potential vectors and the nodal structural and acoustic load vectors, respectively.

The input/output relation of the elasto-acoustic model can be written as:

$$y(\omega) = H(\omega) * x(\omega) \quad (2)$$

where

$$x = \begin{pmatrix} F_s \\ F_a \end{pmatrix} \quad (3)$$

and

$$y = \begin{pmatrix} U \\ \Phi \end{pmatrix} \quad (4)$$

while the receptance matrix H is defined as:

$$H = \begin{bmatrix} K_s - \omega^2 M_s & i\omega C_{sa} \\ i\omega C_{sa}^T & K_a - \omega^2 M_a \end{bmatrix}^{-1} \quad (5)$$

Finite element model

Overall model

Large ship windows are made of a complex window pane clamped and glued on the surrounding ship vessel (A typical view of such windows can be seen in Figure 1). As the main focus of this paper is the FE-representation and study of different window designs, only the near surrounding structural environment is modelled. Indeed, identical windows can be placed at multiple locations throughout the ship vessel having thus a different structural environment and excitation, which is not studied furthermore in this paper.

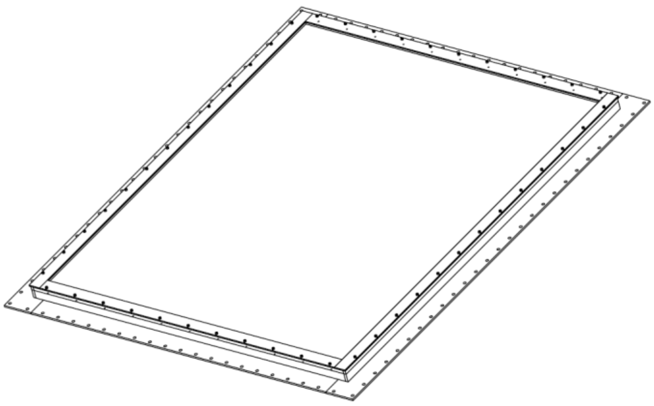

Figure 1: Typical view of a mounted large ship window

Window pane

The window pane is made of different layers of laminated glass. Each laminate is made of glass and PVB layers, which are modelled using visco-elastic shell elements. Between the two laminated layers, an Argon layer provides an additional insulation. This Argon layer is modelled using a visco-thermal acoustic elements representation, which allows to model the acoustic transmission and to calculate both viscous and thermal losses due to the reduced thickness of this layer.

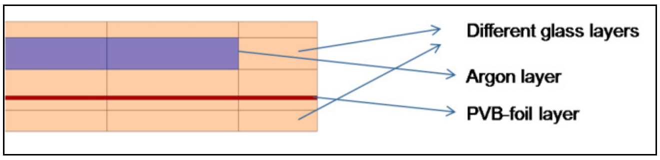

Figure 2: Layer setup of the window pane

Visco-thermal elements

These elements allow accounting for the dissipation mechanisms related to the acoustic propagation in narrow section ducts. Their finite element formulation is based on a reduced wave equation taking into account both viscous and thermal losses. Basically these effects can be described by resorting to the Navier-Stokes equation. The main drawback of such an approach is its complexity since the related model involves several unknown fields (pressure, velocity, density and temperature). The reduction of the Navier-Stokes equation to a particular wave equation involving only the acoustic pressure is however possible if the acoustic wavelength is significantly larger that the characteristic dimension (the thickness of the Argon layer) and the boundary layer thickness is small with respect to the acoustic wavelength. The related model is precisely the 'reduced frequency' model developed by Beltman ([2],[3]). The major consequence of this model is the reduction of the pressure along the thickness of the layer.

The Navier-Stokes equations can be simplified into a reduced wave equation:

$$\Delta_p p + k^2\Gamma^2 p = -ikC\Gamma^2 S \tag{6}$$

In which the propagation constant Γ includes both viscous and thermal effects:

$$\Gamma = \Gamma(s, \sigma, \gamma, cross-\mathrm{sec}tion) \tag{7}$$

$$\sigma = \sqrt{\frac{\mu C_p}{\lambda}} \qquad \gamma = \frac{C_p}{C_v} \tag{8}$$

where μ represent the viscosity, λ the thermal conductivity, C_p the specific heat coefficient at constant pressure and C_v the specific heat coefficient at constant volume.

Frame and surrounding structure

The different frames are made of steel, and are structurally coupling the window pane to the vessel. They are rigidly coupled to the surrounding vessel structure through the use of compatible meshes, are glued to the window pane.

The glue is modeled using visco-elastic properties.

The surrounding vessel is only partially modeled. Indeed, as the stiffness of both the vessel panels and the window panes are similar, it cannot be assumed to be rigid. Partially modeling the surrounding panel allows taking into account the impedance of the surrounding structure without modeling the global structure. This method also has the advantage that convergence is always obtained by increasing the size of the surrounding panel. The surrounding panel is simply supported at its extremities, which is a standard type of boundary condition.

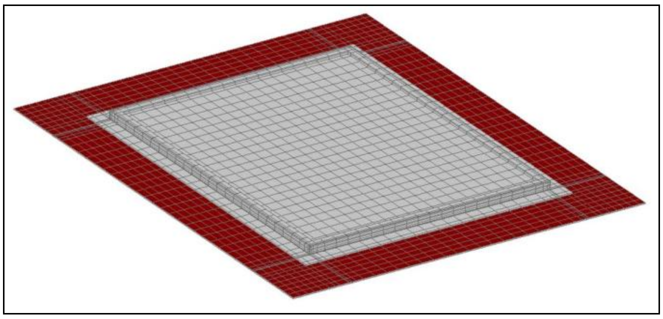

Figure 3: Visualisation of the exterior panels

Structure-borne excitation

In order to investigate the effect of unknown broadband structure-borne excitations a possible strategy is to make use of “rain-on-the-roof like” excitations. These allow the modelling of spatially perfectly uncorrelated broadband sources by statistically independent point forces.

Two types of excitations are thus usable. A rain-on-the-roof method is applied by computing different solutions using randomly placed point loads on the surrounding structure. The different computations can be performed at once using a multiple right-hand-side. The other method consists in using a delta-correlated stochastic excitation, which has a clear advantage of needing only one computation in order to converge. This excitation type is used in the context of broadband structure-borne excitation on the contour of the window frame, as visible on Figure 4.

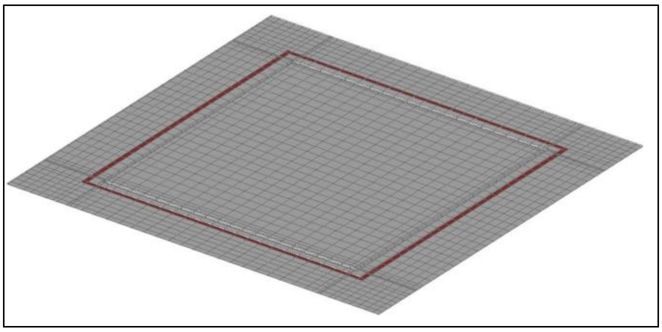

Figure 4: Location of the broadband structure-borne excitation

Free-field radiation

In order to compute the performance in sound transmission of the window, the free-field radiation of the window pane must be insured. This latest being placed in a plane of a rigid baffle and radiating in a half-space, adapted boundary elements such as Rayleigh boundary elements can be used for this purpose. The acoustic material is then supposed to be homogenous.

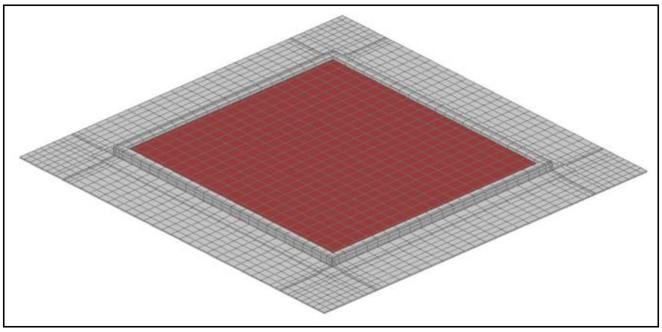

Figure 5: Rayleigh boundary elements placed on the window pane to establish the acoustic radiation

Vibro-acoustic behaviour of the ship window

The computed values are compared to full scale experimental results for validation. The experimental set-up can be seen in Figure 6. The ship window is mounted on a reduced mock-up, which is excited by different shakers for creating the broadband structure-borne excitation.

Several simplifications and assumptions are made in the numerical approach, the exact structure of the experimental mock-up (including the inner cavity) is not taken into account. It must also be stated that the experimental mock-up is placed above the ground, which influences the measurement of the radiated sound. All these assumptions do certainly influence the vibro-acoustic behaviour of the window, more specifically at lower frequencies.

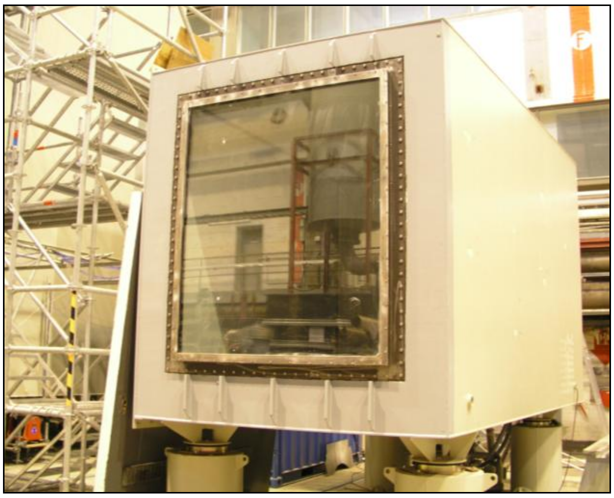

Figure 6: View of the experimental mock-up

The experimental data are measured using 9 sound intensity probes nearfield the outer window pane for the radiated sound and a laser vibrometer for the mean velocity values of the window pane.

In the numerical set-up, the radiated power is automatically computed by integration of the radiated intensity over the structure surface. There is therefore no approximation performed.

In order to compare properly the experimental values with the numerical values, the radiation efficiency values are computed. As this radiation efficiency is independent of the absolute level of structural power injected within the system, this indicator allows to compare the behaviour without the influence of the shaker.

The radiation efficiency is computed using following formula:

$$10\log_{10}(\sigma) = 10\log_{10}\left(\frac{W}{\rho c S \bar{v}^2}\right) \qquad (9)$$

where W represents the radiated sound power, ρc the characteristic impedance of air, S the surface area of the window pane and v² the mean quadratic velocity of the vibrating surface.

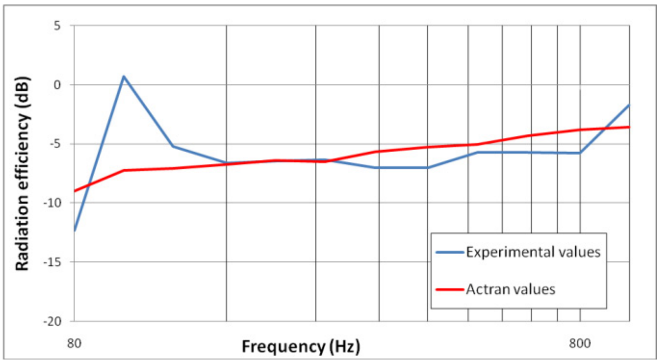

Figure 7: Measurement/computation comparison on the radiation efficiency

Taken into account the major differences between experimental and numerical set-up (for example the structural boundary conditions and the measurement conditions of the radiated power), the correlation between the measurements and the simulation is acceptable. . The general trend of the radiation efficiency is correctly captured within the numerical values. The difference at lower frequencies can objectively be explained by the major difference in structural boundary condition (as we do not model the real mock-up).

Conclusions

A finite element method for predicting the acoustic radiation and structural vibration of large ship windows has been presented and compared to experimental results. The vibro-acoustic behaviour of these windows can be simulated in standard structural conditions, which allow analyzing large ship windows independently of their position within the ship structure. The described method takes into account complex effects, such as the visco-thermal losses within the Argon layer, a broadband structure-borne excitation, the structure-fluid coupling or the effect of complex frame structures.

The described method allows predicting the influence of different construction designs in standard conditions in terms of radiation efficiency. This value is a key point in terms of noise transmission reduction aboard of a ship, as broadband structural excitations are omnipresent along the ship's vessel. However, to predict the overall sound pressure level inside a ship's cabin, the specific knowledge of the vessels structure and its dynamic behaviour is of vital impact.

References

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