MODAL RESPONSE OF CABINS AT LOW FREQUENCIES IN A RO-PAX VESSEL

Johan Augusto Bocanegra, Davide Borelli*, Tomaso Gaggero, Enrico Rizzuto and Corrado Schenone

Università degli Studi di Genova, Genova, Italy
e-mail: davide.borelli@unige.it

Onboard ship noise represents a complex issue due to the interaction of different contributions such as engines, propellers, HVAC systems, and several propagation pathways throughout the ship structure from these sources to the various occupied spaces. Resonances can occur and strongly affect the acoustical comfort into closed spaces, particularly into cabins used to rest by the crew or passengers. Four different cabin geometries from a real passenger vessel have been simulated using 3D FEM techniques in order to obtain the modal response of each enclosure at low frequencies. The density of the modal frequencies was obtained for each space. Some of those frequencies could cause annoyance and could be caused by the engines or the propellers of the ship. The presence of high acoustic pressure zones in sensible locations of the cabins is evident in all the considered geometries. This approach can represent a valuable tool at design or retrofitting stages to achieve the best possible comfort levels by adopting control measures depending on each cabin geometry.

Keywords: acoustic comfort, eigenmodes, port noise, ship noise, onboard noise.

1. Introduction

The interaction of several elements in a ship, such as motors, air conditioning, ventilation systems, and various propagation pathways from the sources to the occupied locations, makes onboard ship noise a very tangled issue. Noise from engines and other sources is mostly generated in machinery rooms, and acoustic energy and vibrations are transmitted throughout the ship's structure. The acoustical comfort of cabins used by the ship's crew or passengers is a critical problem and is also affected by possible resonances.

Previous research experimentally determined noise levels for passenger vessels [1]. Acoustical comfort in cabins has been the topic of previous investigations that showed, among other issues, the criticality of the modal behavior of the cabins [2-3]. The calculated eigenmodes showed, as expected, a sound concentration in the corners of the cabins where the head of people sleeping in the beds are placed [4]. The most important requirements given by the IMO for onboard noise in ships establish only dB(A) limits for accommodation spaces (cabins, mess rooms, recreation rooms) and other onboard spaces [5-6]. Other limits, inspired by the current normative framework, were developed within the SILENV project, and reviews on the topic can be found in [7-9]. It has to be underlined that the prescribed limits are often exceeded [10], and these limits in cabins are usually determined by a single-point measurement in the centre of the rooms, omitting the spatial distribution of noise levels within the cabin itself. Recently, acoustic cameras have been used in order to assess onboard noise [11].

In this work, the modal behaviour at low frequencies of different cabin typologies of a passenger's vessel is presented. The study was developed using numerical methods. The geometries under analysis were obtained from a real passenger ship (Ro-Pax vessel). They include irregular sections and inclined roofs. The three-dimensional space was recreated, including different items like furniture and beds present in the cabins.

2. Method

Four different typologies of passenger cabins of a Ro-Pax vessel were studied using the Finite Element Method. The cabins have complex geometries which are different from the box-shaped case usually used as a reference case in books or papers describing room modal analysis. All the cabins have fixed beds, additional beds, closets, and other furniture elements such as tables or sofas. Examples of the geometries are presented in Fig. 1. The acoustical behaviour of the cabins at low frequencies was the focus of the analysis, in particular the characterization of the normal modes.

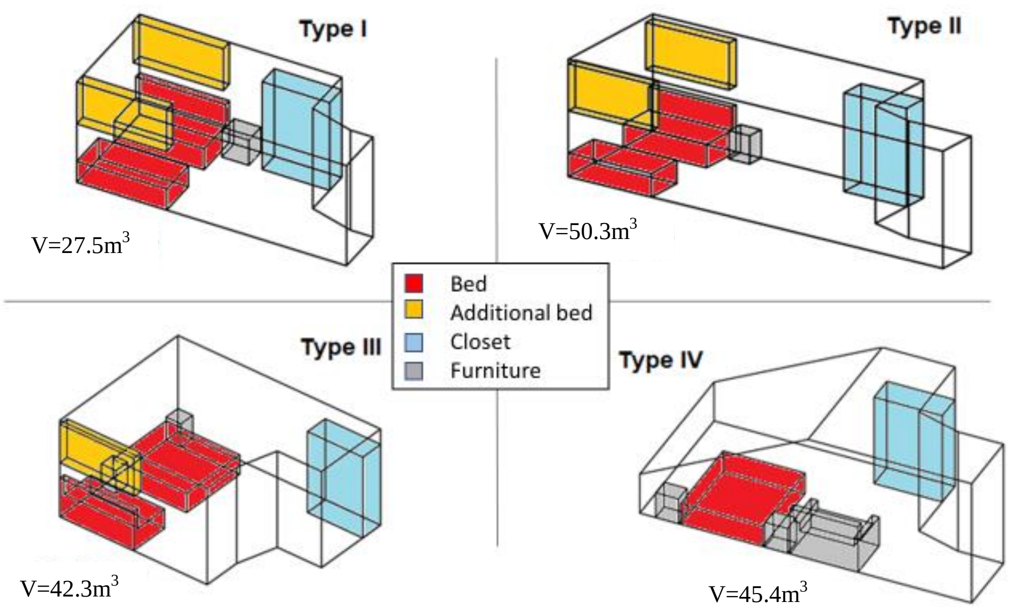

Figure 1: Geometry of the simulated cabins.

2.1 FEM modelling

Three-dimensional models were developed using COMSOL Multiphysics software. The normal modes were calculated using the finite element method. The mesh element size was selected to resolve the wavelength of the maximum frequency considered (200 Hz) using at least ten mesh elements. Second-order elements were considered in the models. All the walls were assumed as rigid boundaries. Standard conditions were considered for other parameters such as air density ρ_0=1.25 kg/m^3 and sound speed c_0=343 m/s.

3. Results

The modal analysis was performed to obtain the cabins' resonance frequencies, perform a modal classification, and study the modal distribution.

3.1 Modal classification

To classify the cabins, axial, longitudinal and Oblique modes were considered, in analogy to the modal classification of a rectangular (box-shaped) room (represented as an example in Fig. 2). Three numbers (n_x, n_y, n_z) were used to perform the classification; each number represents the number of pressure nodes along each axis.

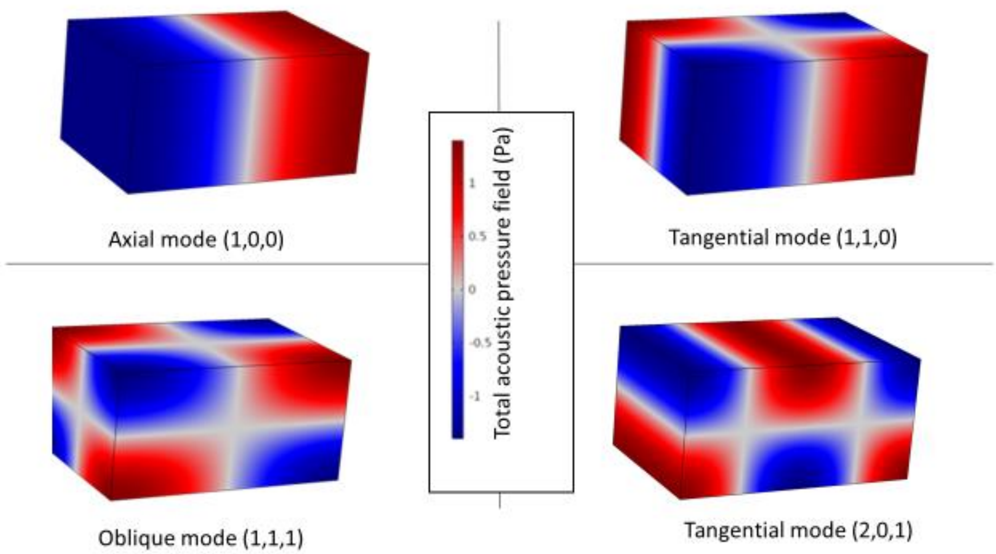

Figure 2: Modal classification examples - rectangular room.

The first normal modes of the four-cabin typologies are presented in Fig. 3. As it can be noted, the mode shape is nearly similar to the rectangular room mode (1,0,0) presented in Fig. 2, but the nodal shape changes according to the specific geometry. Of course, the modal eigenfrequency is associated with the length of the cabins, i.e., cabin Type II is the longest one and presents the lower eigenfrequency value.

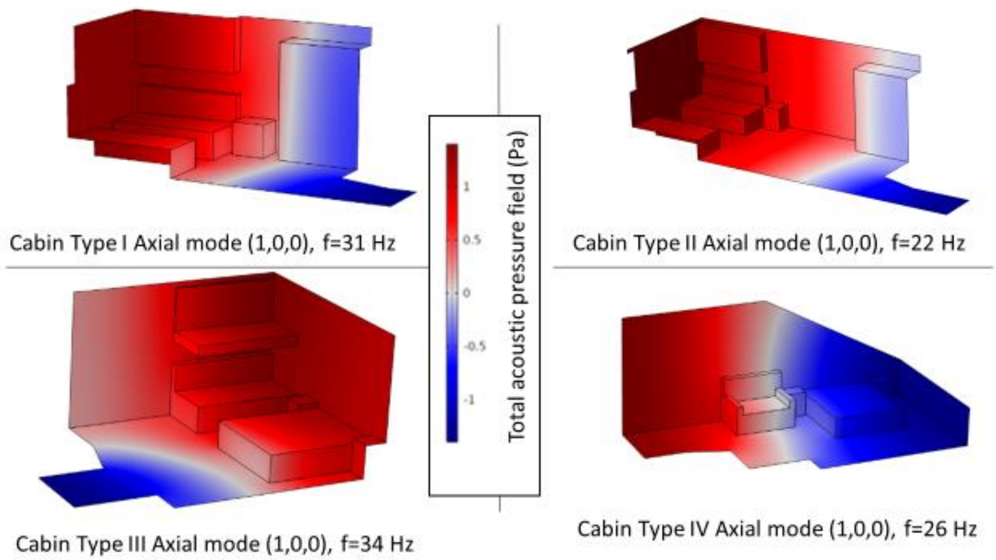

Figure 3: First normal mode of the different cabin typologies.

Figure 4 shows examples of normal modes with a high-pressure level at the corners (this negative issue is also visible for the additional beds). It can be noticed from the figure that the shape is complex, and the proposed modal classification using only the three indices is not always straightforward. The coupling between near modes or the specific geometry generates those complex patterns.

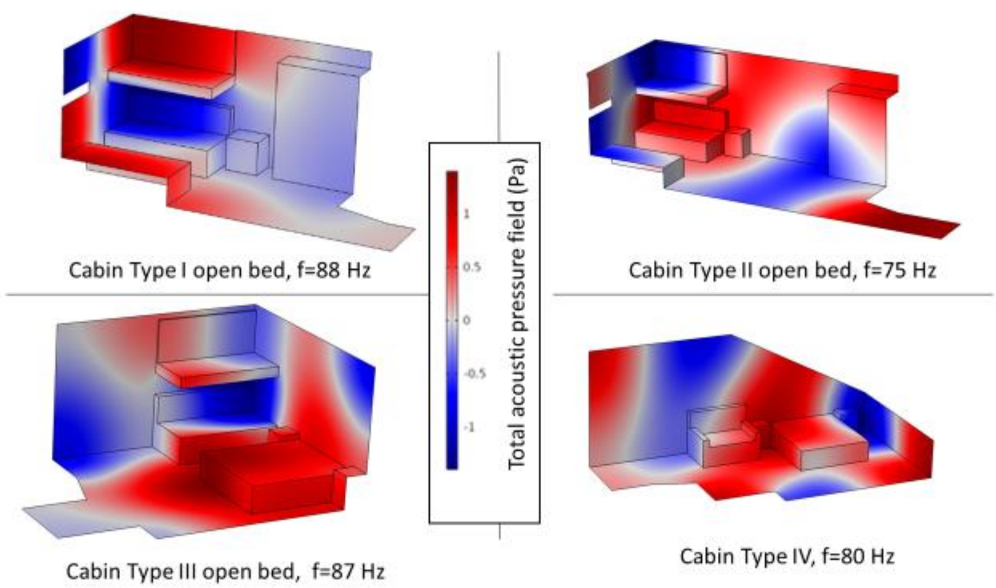

Figure 4: Normal modes with high pressure at the corners.

3.2 Modal density

Figure 5 presents the eigenfrequencies of the different modes below 200 Hz calculated for all the considered geometries. As it can be seen, only small differences are observed when the additional beds are open. The difference between the cabin typologies is sensible for the lower frequencies. The Schroeder frequency [12] calculated from the mean-free path of the sound rays (4V/S) is 213 Hz, 181 Hz, 178 Hz, and 185 Hz for each cabin type. Above this Schroeder frequency, the great density of nodes changes the behaviour of the enclosure from *normal dominated* to *diffuse dominated*, and the effect of the intensity distribution patterns of every single normal mode is negligible. This limit can be compared and confirmed with the simulations results that show more than 20 normal modes in the 111.4-140.3 third-octave band.

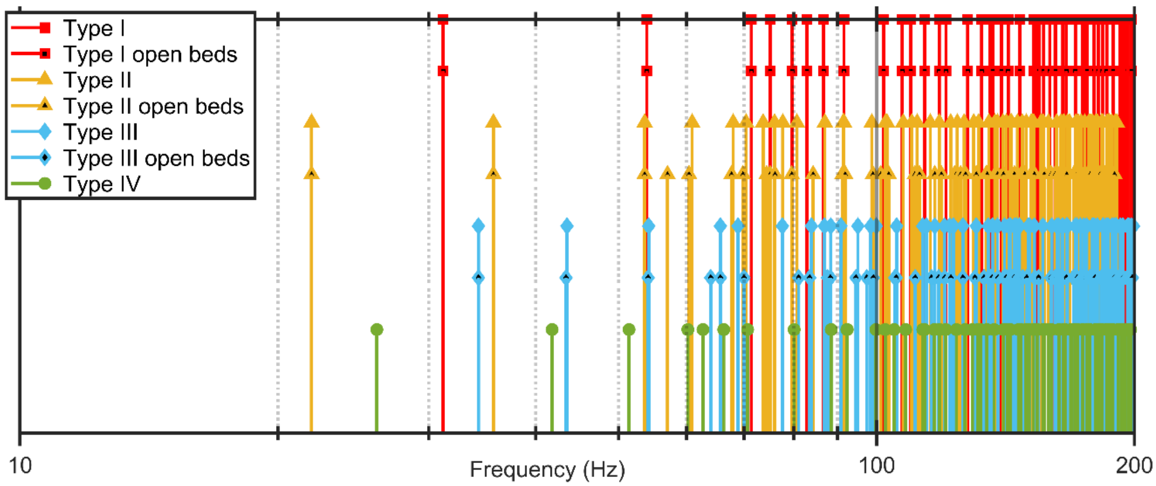

Figure 5: Mode distribution plot.

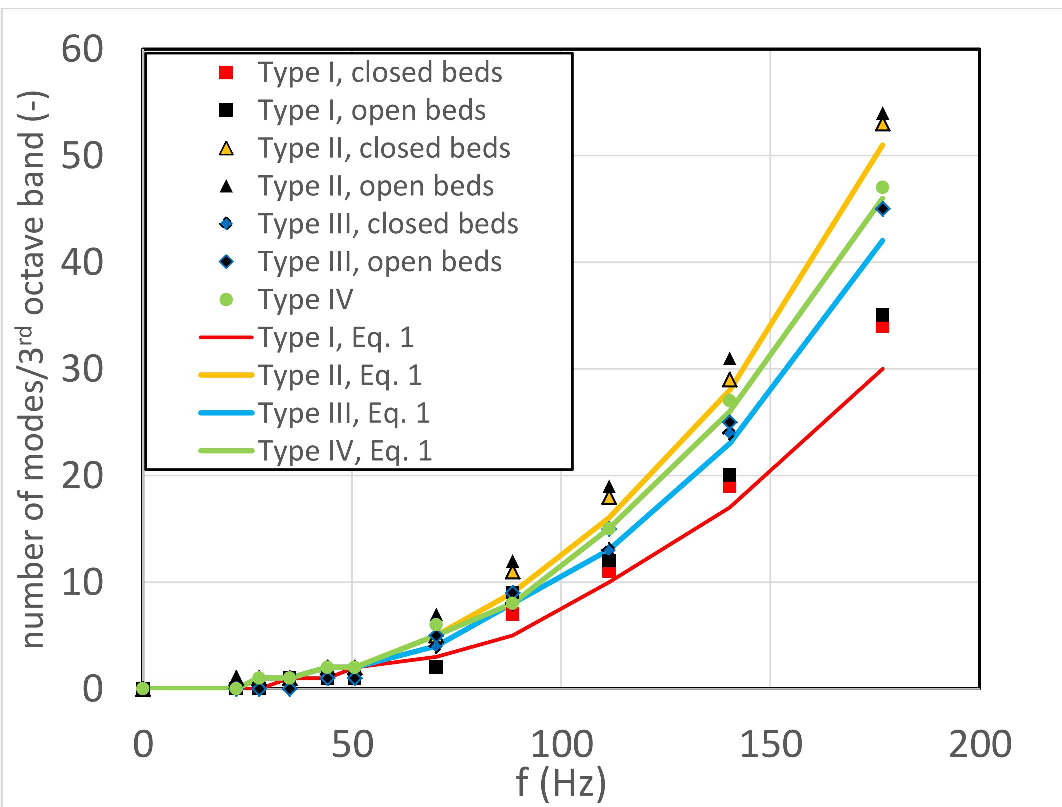

Figure 6: Number of normal modes per third-octave band.

The number of modes N in a room below a given frequency f can be approximately calculated [13] by means of Eq. (1) using some geometrical parameters, i.e. the room volume V (m^3), the surface area S (m^2) and the sum of the lengths of all edges in the room L (m):

$$N = \frac{4\pi f^3 V}{3c_0^3} + \frac{\pi f^2 S}{4c_0^2} + \frac{fL}{8c_0} \quad (1)$$

In Fig. 6 the results of the simulations are compared to the predictions of this formula. As can be seen, the formula correctly describes, as expected, the trend for all the cabins. Only small changes in the number of modes per third-octave band are observed when the additional beds are open, and the frequency limit of the modal behaviour can be determined by the simulations and the formula with small differences.

4. Conclusions

This work presented a modal analysis of four different Ro-pax vessel cabin typologies. The modal analysis was limited to the 1-200 Hz frequency range. The cabins differ in their geometry and elements present inside them, as beds and furniture.

- The normal modes, as expected, show differences if compared with the modes of a perfect box-shaped room, with more complex spatial patterns that fit each cabin geometry.
- The first modes are axial modes in all the geometries, but from 70 Hz complex modes were found.
- The calculated eigenmodes showed a sound concentration in the corners coinciding with the bed's location.
- Opening the additional beds changes the geometry of the cabin, affecting mainly the vertical mode shapes, and the effect in the associated eigenfrequencies seems negligible.
- Over the 111.4-140.3 Hz third-octave band, the modal density is high enough to consider a *diffuse behaviour*. This limit is near to the one calculated by analytical considerations.

The results of this study underline that for low frequencies, the spatial distribution of noise levels may impact acoustic comfort. It seems that the most feasible solution to avoid or reduce acoustic disturbance in passengers' cabins involves the furniture (especially beds) positioning in each space, avoiding for the lying position the placement of the occupant's head near the corners of the cabin, where it is feasible.

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