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ACOUSTICAL BEHAVIOUR OF A PASSENGER CABIN OF A RO-PAX VESSEL

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Noise on board Ro-Pax vessels is an increasingly important evaluation factor for ferries and cruise vessels. The available normative framework, albeit well established and developed in the form of Comfort Classes, is based on dB(A) limits for the different spaces on board and is mainly applied on a voluntary basis. In the present study, an acoustical analysis of a typical passenger cabin in a Ro-Pax vessel has been carried out in order to provide an effective and comprehensive picture of the sound distribution inside the cabin volume. A comparison between the measured noise levels and the proposed limits has been carried out, in order to identify the presence of critical areas inside the cabin in respect to acoustic comfort. A finite element model of the cabin has been finally developed, aimed at obtaining the eigenmodes of the cabin, in order to analyse the sound intensity pattern for every associated eigenfrequency.
Keywords: room acoustics; ship cabin noise; ship noise comfort; room eigenmodes.

1. Introduction

The annoyance due to noise pollution on board ships is a very sensitive issue for passengers and plays an important role especially in the design of pleasure crafts, passenger ships and ferries. Current standards are still based on dB(A) limits, and are formulated in terms of voluntary class notations (generally termed Comfort Classes: CC) [1-3]. In general, the procedure for assessing compliance to the limits requires measurements carried out with a sound level meter placed in the centre of the cabin. This methodology, in force for decades, appears to be quite outdated in these days, also taking into account the recent technological advances and the simplicity in recording spectral measurements in 1/1 or 1/3 octaves.

It is well known that sound energy tends to concentrate in the corners of a room [4], and these are the places where, in a narrow space like the cabin of a ship, beds and in particular pillows are positioned. Typical double-walled elements (i.e. windows, doors, partitions, etc.), usually adopted on board ships due to their high damping effect at medium and high frequencies, experience excitation of cavity resonances (or eigenresonances) due to low-frequency noise. The mass-spring resonance mechanism damps medium and high frequencies, which is a positive aspect and would justify the use of a conventional single-number weighting, but may anyway lead to a noticeable amplification of certain low frequencies, resulting in an uncomfortable situation for the occupant [5-6]. Moreover, the perception of eigenresonances is most noticeable in rooms in which at least one dimension is smaller than about 5 m, which is the case of most passenger cabins in Ro-Pax featuring smaller dimensions in either directions.

For this reason, in this study a measurement campaign was carried out in a typical passenger cabin of a Ro-Pax vessel, in order to evaluate the differences in sound pressure levels in different points of the cabin itself.

2. Measurements campaign and methodology description

The measurement campaign was carried out in steady navigation conditions and calm sea conditions; the instrumentation used for the survey was composed by an IEC 61672 Class 1 compliant sound level metre equipped with a random incidence microphone. The microphone was calibrated with an IEC 60942 Class 1 compliant calibrator.

Spectra in one third octave band were measured in the cabin, in order to better analyse and evaluate the effects of the spatial differences of sound distribution. The main sources of noise in ship cabins during navigation and manoeuvres are the structure-borne noise due to main engines at lower frequencies and the HVAC duct outlet nozzle at higher frequencies (see e.g. [7-11]).

Measurements were taken in seven different spots, indicated with letters from A to G in figure 1, reporting the sketch of the cabin analyzed.

In Table 1 the results of the measurements are reported in terms of dB(A) levels. According to the current standards, the reference measure that is intended to fully describe the acoustical behaviour of the cabin (and that should be compared with current dB(A) limits) was taken in a position that approximately represents the centre of the cabin (position C) with the microphone placed at a height of 1.5 m. As it can be noted, the reference position features the overall lowest level compared to the other measurement points. This, of course, is not generalizable, as the results are highly dependent on the specific features of the cabin, but raises the problem of the sensitivity of the result with regard to the measuring position.

This can be particularly important for both legal aspects, when contractual noise limits are to be fulfilled, and comfort aspects, since a cabin which is apparently compliant with the standards and the comfort classes could nevertheless be felt noisy from the occupant's point of view [12].

As a matter of fact, the shipping company for which this work was carried out has a policy regarding the use of questionnaires in order to check the customer satisfaction. From the data analysis it was found that in several cabins where the CC limit values were not exceeded, occupants reported anyway an uncomfortable situation in terms of noise pollution.

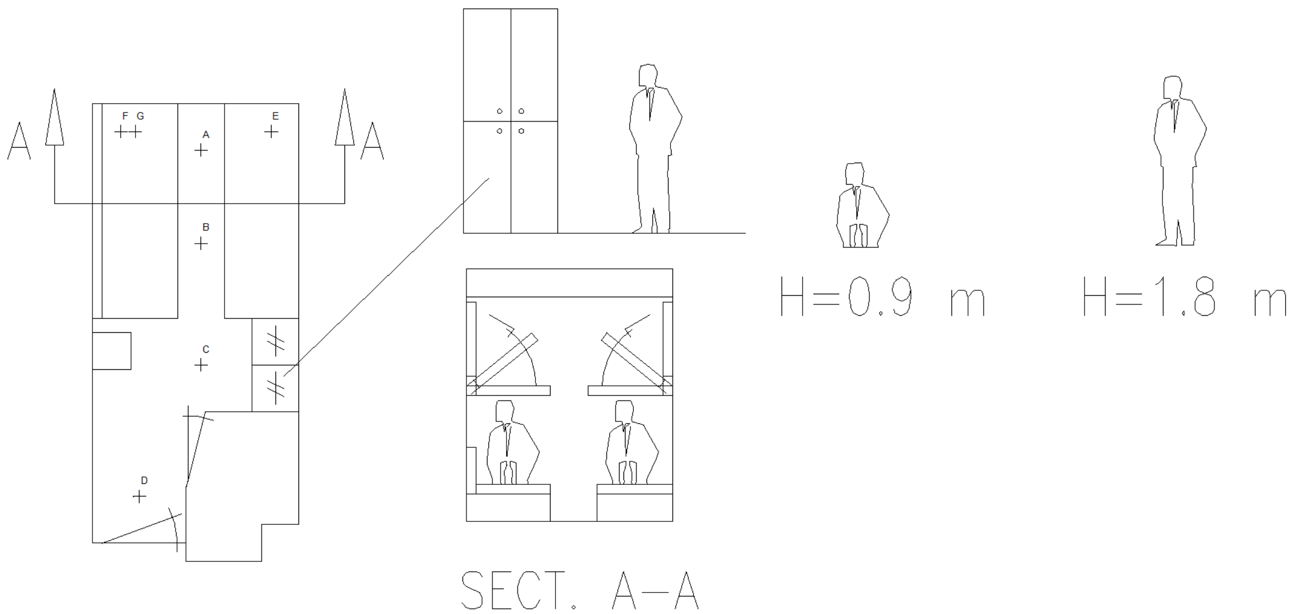


Figure 1: Cabin sketch with measurement positions.

Table 1: dB(A) levels measured in the positions shown in Figure 1 (in bold the row regarding the standard reference position).

Point	x [cm]	y [cm]	z [cm]	Level [dB(A)]	Difference with reference position [dB(A)]
A	116.0	441.0	50.0	40.9	1.3
B	116.0	348.0	50.0	40.6	1
C	116.0	217.5	50.0	41.8	2.2
D	50.0	69.5	50.0	41.3	1.7
D	50.0	69.5	190.0	40.4	0.8
A	116.0	441.0	190.0	40.4	0.8
B	116.0	348.0	190.0	40.5	0.9
C	116.0	217.5	190.0	40.4	0.8
E	191.0	461.0	210.0	41.7	2.1
F	30.0	461.0	210.0	42.3	2.7
G	45.5	461.0	70.0	40.0	0.4
E	191.0	461.0	70.0	41.1	1.5
E (with pillow)	191.0	461.0	70.0	39.9	0.3
C_{ref}	**116.0**	**217.5**	**150.0**	**39.6**	-

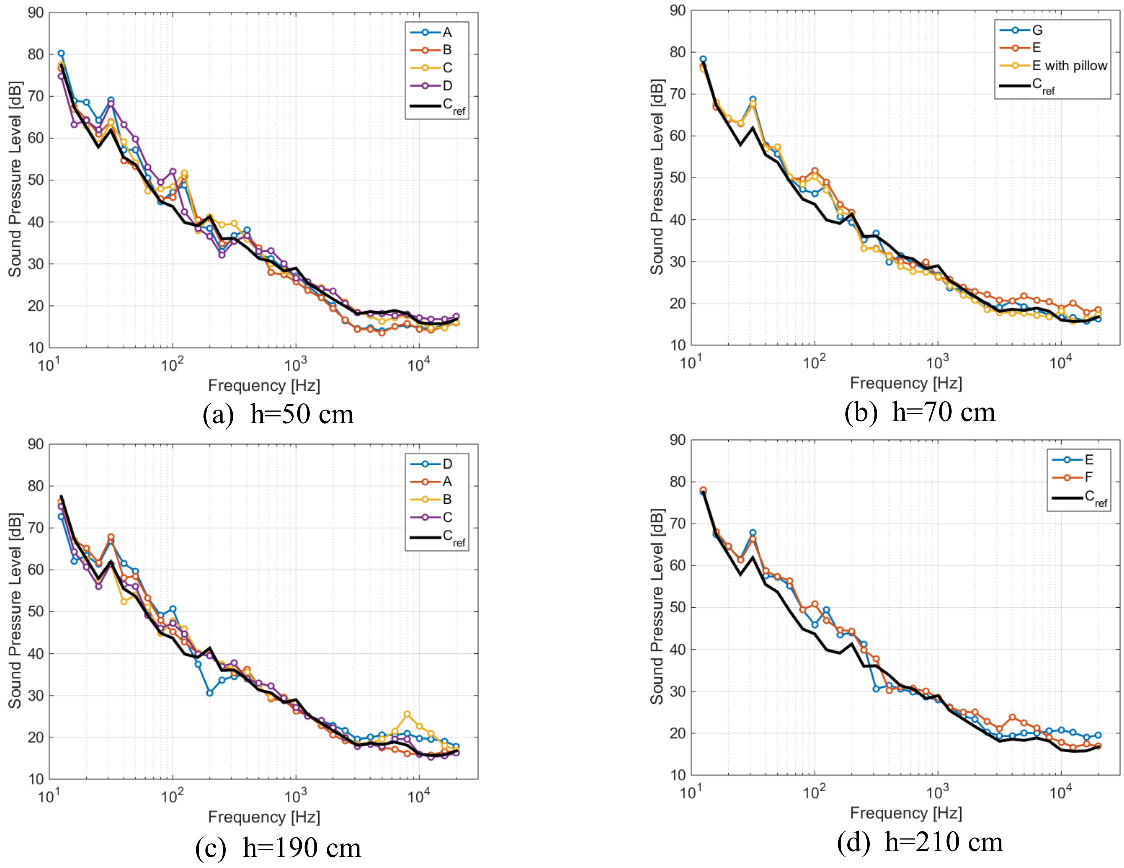
This led the shipowner to decide for a further detailed investigation about the possible reasons of this occurrence, in order to find appropriate solutions and to avoid further complaints and bad publicity. From the analysis of Table 1 it can also be noted that the highest level difference of 2.7 dB(A) is found in correspondence of point F at a height of 2.1 meters. The lowest values are in correspondence of points E and G, corresponding to the pillow positions on the two cabin beds. In position E, the absence of the pillow led to an increase of 1.2 dB(A) if compared with the measurement carried out with it. Further analyses will be discussed here after taking into account the spectral components of the sound, in order to underline the need for a deeper evaluation procedure than the dB(A) based standard one.

3. Analysis and discussion

The 1/3 octave band spectra of the measurements are reported in Figure 2, grouped for different microphone heights. Analysing the shapes of the different spectra it is possible to note the difference in the frequency contents at the different points within the cabin and to draw some observations. It is interesting to note that, comparing to the reference measurement:

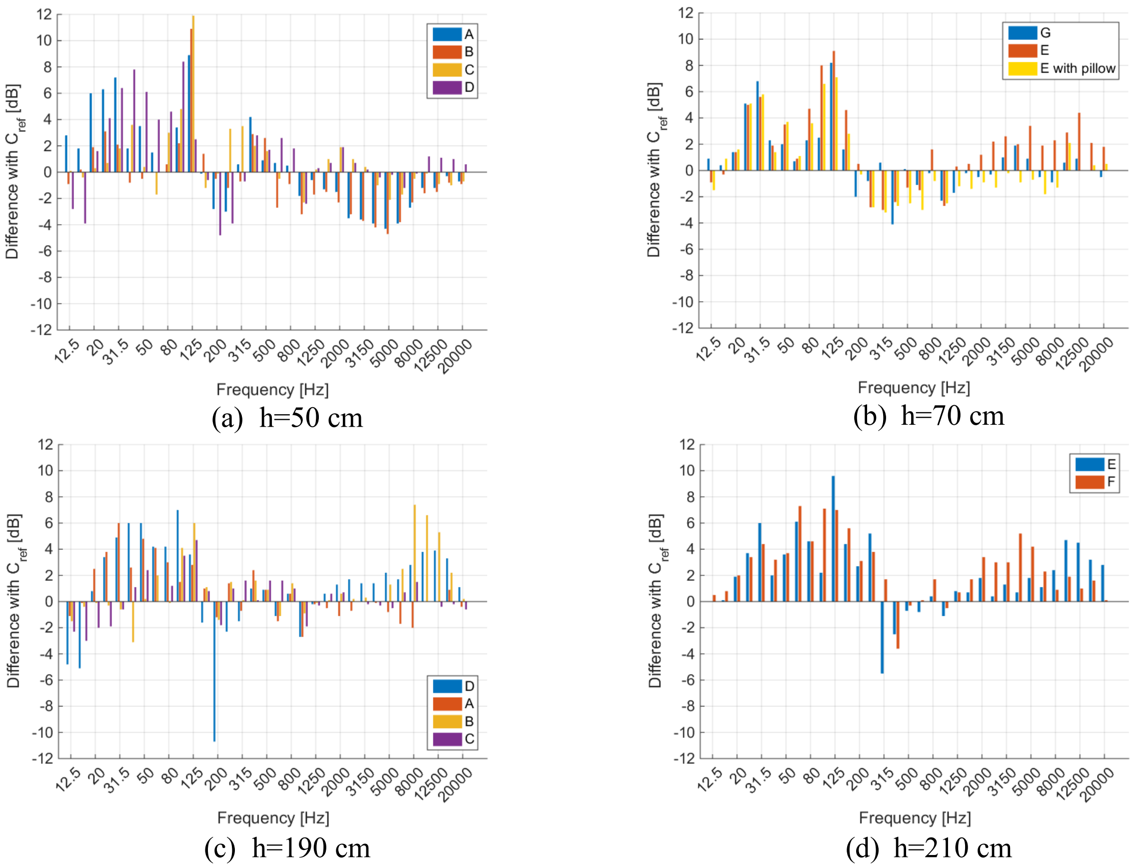
- at few frequencies significant differences are present;
- in some cases (see f.i. in figure 2a around 100 Hz) the presence of peaks can be noted;
- some of these peaks disappear at different heights (see figure 2c);
- in general, the reference position seems to feature lower values in the low-frequency range.

The behaviours described suggest that the modal response of the room can influence the sound energy distribution inside the cabin. This is particularly interesting for the measurement points E and G, where passengers presumably put their heads while sleeping: in these points, although the level increase is lower than 0.5 dB(A) in respect to the reference position, the 1/3 octave band spectra is definitely higher in the low frequency range. Looking at Figure 3, it can be seen that this happens for frequencies below approximately the 1/3 octave band centred at 160 Hz. At higher frequencies the difference from the reference point spectrum is not always in the same direction. In particular the reference point measures are lower for points at 70, 190 and 210 cm heights while are in general higher for the 50 cm height. For frequencies around 250 Hz the spectrum of the reference measurement point is higher than the other measurement points.



(a) h=50 cm (b) h=70 cm
(c) h=190 cm (d) h=210 cm

Figure 2: Sound pressure level spectra at different heights.



(a) h=50 cm (b) h=70 cm
(c) h=190 cm (d) h=210 cm

Figure 3: Differences between measurement points at different heights and the reference position.

It also worth noting that, within such a small cabin, for single frequency bands, differences of about 12 dB can be found.

In the following paragraph, simulations to find eigenfrequencies and related eigenmodes are carried out and analysed.

4. Eigenmodes analysis

As above mentioned, resonance can be a problem in a small environment like the cabin of a ship. The low frequency induced vibrations can shake windows and excite vibrations in floor, ceiling and furniture. This occurs for the eigenfrequencies of the room, well separated from each other in the low-frequency range, while at medium and high frequencies they are closely packed (with less than a halftone between them) so that individual resonances are insignificant and negligible.

Eigenmodes analysis can be numerically carried out by means of the finite element method. For this reason, a three dimensional model of the cabin was realized and analysed with the software COMSOL Multiphysics version 5.2a.The model assumes that all boundaries are perfectly rigid (sound hard boundaries). To properly resolve the expected wavelength, a widespread rule of thumb is to have 6 second-order elements per wavelength, which is considered a reasonable trade-off between computational effort and accuracy. The mesh for the geometry of the cabin considered was thus created in order to meet this requirement. From the eigenmodes analysis, it was found that the lowest axial resonance (1,0,0) for the cabin is at 81.887 Hz, while the (0,1,0) is 35.491 Hz and the (0,0,1) is 74.658 Hz (see Figure 4). In Figure 5 a few representative eigenmodes with the relative eigenfrequencies of the cabin are reported. The colour scale represents the modal shapes highlighting nodes in blue and peaks in red on a normalised scale between zero and one. For the relative eigenfrequency if an area of the room is in blue means that measurements taken in that positon feature in principle a cancellation of the sound wave resulting in lower sound levels while in red areas the sound pressure is amplified. Coherently with the analysis of the spectra carried out in the previous paragraphs, the reference position at the centre of the room lays always on a node (blue colour) meaning that for the represented frequencies the reference point features lower levels than the other measurement locations. Further, it is quite evident that positions situated in proximity of the corners of the room feature a sound concentration, as expected. Such concentrations are often located in the position where the head of people sleeping in the bed are placed (see e.g. in Figure 5 frequencies corresponding to 119.75 Hz and 178.13 Hz). This raises again the problem of a proper evaluation of the comfort performances of the cabin that cannot be effectively carried out by a single point measure located at the centre of the room.

A further consideration can be made regarding the local peak that can be observed in Figure 2 at the 31.5 Hz third octave band for every spectrum analysed. As already mentioned, from the finite element analysis the (0,1,0) frequency was found to be 35.491 Hz, which falls in the third octave band centred at 31.5 Hz. The above analysis can represent a powerful tool also at a design stage. As a matter of fact, an assessment of the acoustic response of the cabin in terms of eigenfrequencies and eigenmodes leads to the knowledge of the most critical frequencies and of the spatial distribution of peaks. Such analysis allows to take countermeasures to improve the acoustic comfort of the cabin already at a design stage (e.g. changing the pillow position in the beds, avoiding cabin shapes with geometrical dimensions whose eigenfrequencies correspond to the fundamental harmonics of the engines, etc.).

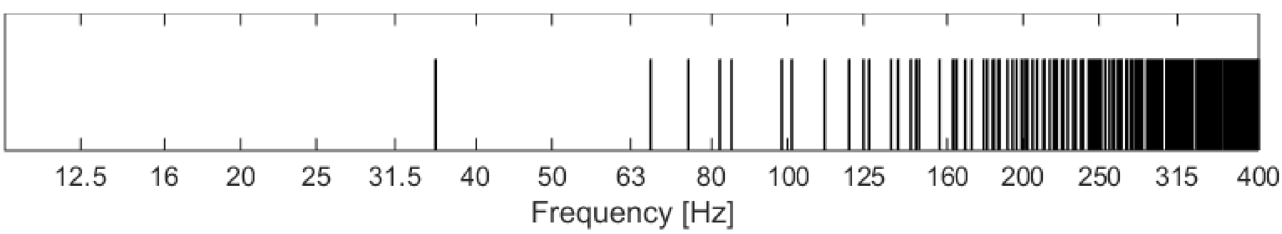


Figure 4: Eigenfrequencies location.

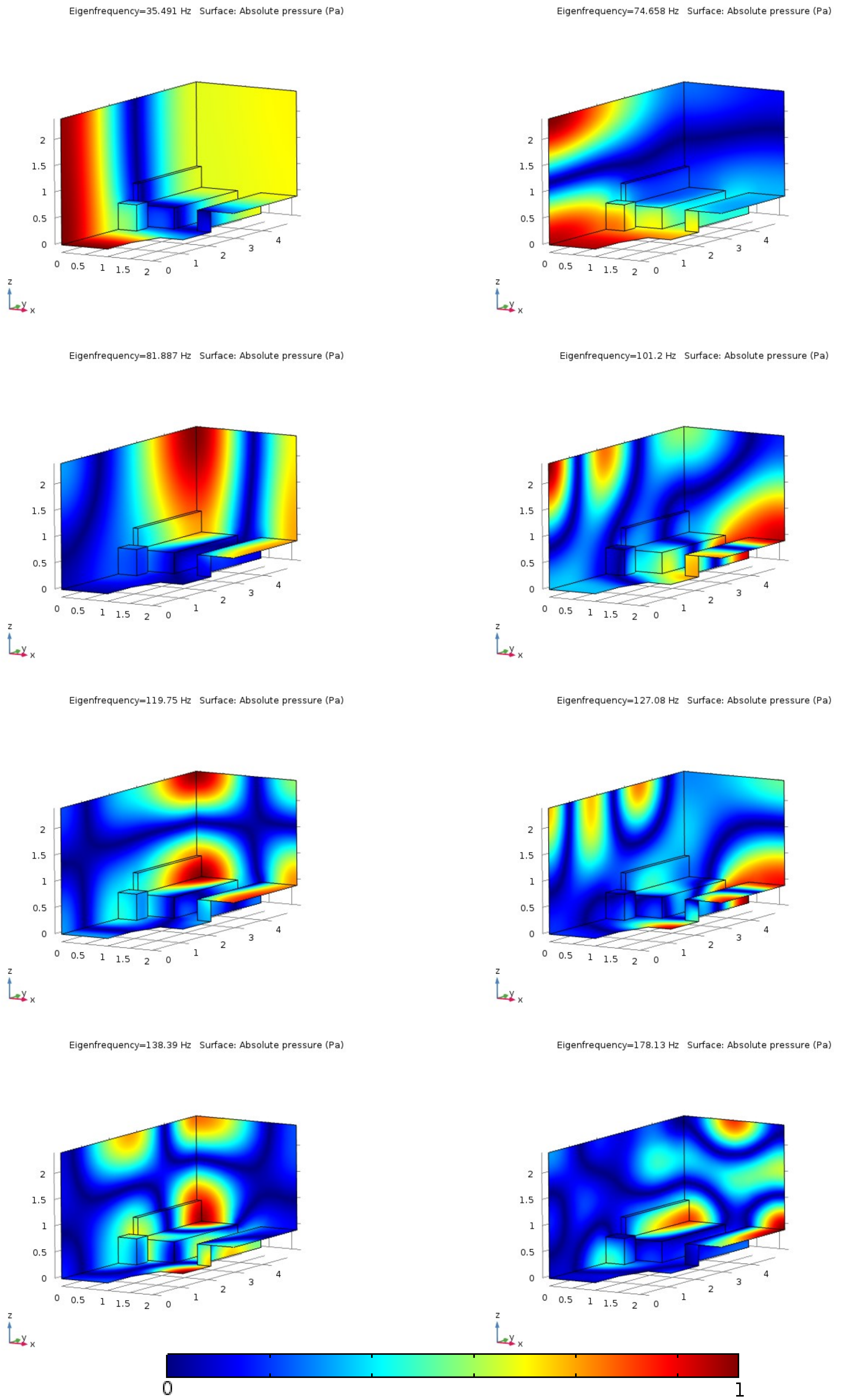


Figure 5: Examples of eigenmodes simulated for the cabin.

5. Conclusions and recommendations

In the present paper the spatial distribution of noise levels in a standard ferry passenger cabin was presented and analysed. Measures were carried out in different position within the cabin at different heights and compared with the standard measurement position located at the centre of the cabin at a height of 1.5 m. In that position usually are carried out the official tests to certify the noise levels present in the cabin and assess compliance to specifications or limit levels. The analysis of the 1/3 octave band spectra at the different locations showed that significant differences can be found in the spectra depending on the survey position within the cabin. Maximum deviations from the standard measure are found to be of 2.7 for the overall dB(A) level and up to 12 dB for specific 1/3 octave frequency bands. In order to better understand the acoustical behaviour of the cabin, an analysis of the eigenfrequencies and related eigenmodes was carried out. The calculated eigenmodes showed, as expected, a sound concentration in the corners of the cabin giving results in agreement with the measured spectra. Such noise concentrations are often located where the head of people sleeping in the beds are placed.

The above analysis highlights (at least in the presented case) that the spatial distribution of noise levels within the cabin may very well have an impact on the perception of the acoustic comfort by the passenger and that a single point measurement located in the centre of the cabin it is not representative of the acoustic quality of a standard passenger cabin. This aspect becomes particularly important when measured levels are compared to design specifications and to limitations imposed by law.

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