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Some notes on the sound reduction index of pax cabins panels on cruise ships

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The issue of comfort of passenger ships has became in the last years of paramount importance. In this context the noise and vibration control plays a leading role. The concept of comfort on board is subjective and it is impossible to define it with simple formula. On the other hand, a few number of significant parameters is commonly used to characterize the level of comfort on board of ships, and the sound insulation index is one of the most important. As known, it has a paramount importance in defining the contractual comfort on board of ships. A matter of primary importance is that of setting up the sound insulation index for pax cabins, specifically in relation to the nature and characteristics of the panels between cabins.

1 Introduction

In order to understand the technological process that is taking place today in shipbuilding, following upon the demand for continuous innovation, the global progress made over the last few years in the other transportation sectors should be analyzed.

With regard to comfort, the progress made in this field is such that every one of us feels "uncomfortable" under conditions that until very recently were considered "normal" on board of a ship. Hence the shipping companies demand for ever stricter limits for vibrations and noise, failing which the economic consequences might be very serious. This explains the need for shipyards to cope with the ensuring problems with suitable instruments, from the design to the delivery of the ships.

In the last years, the world demand of passenger ships has registered a constant increase and in this market the European shipyards have played and are still playing a fundamental role.

In view of the strong competition among the different European shipyards, triggered by the shipowners' demand ever more keen to the quality of the product, the ability to offer a ship featuring a high level of comfort represents a decisive factor for the success of a design. In fact, already in the noise and vibrations specifications for the cruise ship "Crown Princess" – the first cruise ship in the uninterrupted series of constructions of Fincantieri shipyard, launched in 1990 – it was apparent that these factors were to prove of great importance.

2 The comfort on board of a ship

Since comfort is a state of well being in body and in mind, comfort is an elusive concept. In fact, we know when we are comfortable, but it is difficult to define precisely what it is that makes us comfortable. Subjective by its very nature, comfort is closely related to moods and emotions: for instance, comfort may be cultural. Indeed, if an individual has resided for a long time in a cold or a hot environment, he or she may not be comfortable in a different climate. In addition, there is no significant short-term temperature adaptation.

Generally speaking, comfort is a subjective human response that can be defined as "a condition or feeling of pleasurable ease, well-being, and contentment". From such definition can be deduced that comfort is a human condition characterized by the growing, as response to a series of stimuli, of a personal sensation, comprehensive of positive and/or negative mental and physical attributes.

The perception of a comfortable situation is due to a complex mechanism in which the different senses are involved and interact one with the other. Therefore, in assessing the comfort of the accommodation areas of a passenger ship it is of great importance to consider the interactions between the different senses, excited by sound, vibrations, air quality and visual stimuli. In other words, all the specific aspects of comfort should be considered by designers at the same time, with the aim of reaching a well balanced combination of the comfort parameters.

The comfort parameters are physical quantity that synthesize the physical factors affecting comfort, i.e. lighting, temperature, noise, vibrations and ship motions. In particular, noise and vibrations are the comfort attributes that mainly influence the perception of well-being of the people on board a cruise ship. In fact, we can say that the active parameters of the comfort on board a ship are vibrations and noise, assuming as passive comfort the furniture and the architectural aspects

3 The role of noise on comfort

The comfort on board a ship expresses the condition of well-being perceived by the persons staying on board and is hardly classifiable with rigid formulas, numbers and limits. As a matter of fact, the situations that can be experienced on board by passengers are very different and, furthermore, the human response to noise and vibrations has a subjective component that cannot be univocally and definitively fixed.

Many times, what seems comfortable for someone, is not for other. The conditions that determine the levels of comfort are, in fact, rather complex since they are the product of both a subjective and an objective component.

To better explain this aspect of the comfort that may seem obscure, let's take into consideration for instance the case of a cabin that, under equal cruising conditions, has been the subject of a comment (that is to say, has proved "not comfortable") only for one voyage. Probably, its habitability was actually satisfactory and the comment was presented by a passenger with subjective demands of comfort higher or simply different from the average requirements.

The situation above mentioned suggests that it is not possible to guarantee a sensation of comfort equally valid for everybody. For this reason, the designer must aim at securing a "suitable" comfort level, because the optimum level depends on the individual feeling of each passenger. However, the threshold of annoyance caused by noise depends on many different physical and psychological factors.

On board of cruise ships the sources of noise are various, each of them having a peculiar energy spectrum affecting in a different way the individual perception of comfort. Other distinctive qualities of the noise sources, which have a significant influence on the perception of comfort, are also duration and pitch, and localization of the source itself. It is indeed well ascertained that a low and intermittent noise is more disturbing and distracting than continuous, high pitch noise is more distracting than low, and non-localized noise is more annoying than localized noise. Furthermore, noise of very varying nature and noise at single frequency are usually regarded as far more annoying than steady sounds of comparable amplitude covering a broad frequency range.

Actually, it may happen that, for instance, even if the noise background levels are low during normal operating conditions of the ship, there occur disturbances – limited over the time – that affect the sensation of comfort in the cabin. Such disturbances may be caused by intermittent fortuitous noise, for instance due to the swimming pool pumps. On the other hand, if a continuous and regular noise (e.g., from) suddenly changes, this could cause in the passenger a feeling of anxiety about on what is happening.

As above-mentioned, the reduction of comfort may however have some other sources. In fact, it may happen that the background noise does not have a spectrum evenly flat: in other words, it may happen that a cabin be not comfortable because, notwithstanding the low air noise level measured, there is a tonal component prevailing on the others. One of the most important causes of this kind of comfort disturbances in the accommodation areas is that due to entertainments system, more specifically, sound from discotheques and theatres.

Sometimes, however, it may occur an apparent increase of noise – specially in the high frequency range – due to the background variation rather than to a real noise increase. In fact, since the perception of comfort depends on the background noise, it varies when the background noise changes.

It could be happen when, for instance, during a show in theatre, the speed of the vessel is reduced in order to avoid sea-induced motions. In this case, the disturbance due to the show noise may increase, and the worst situation takes place when the background noise is very low, so that the music disturbance becomes predominant. If such a problem is so apparent, it could be necessary to increase artificially the background noise (passengers on board of a cruise vessel may indeed accept a higher background noise level compared to hotel rooms ashore).

The effects of such low frequency noise are very different. Indeed, as people’s hearing sensitivity varies from one individual to another it is often the case that a low frequency noise can be heard by one person and not by another. Consequently, it may annoy one person but not the other. Moreover, low frequency noise is sometimes confused with vibration. This is mainly due to the fact that certain parts of the human body can resonate at various low frequencies.

In conclusion, concerning the noise effects, it can be stated that there is not a close correlation between the decreasing level of the sound pressure in dB(A) in the cabins and relevant comfort, because the individual discomfort perception depends on the peculiarities of the noise source.

In confirmation, it has been noticed that the cabins more prone to notes are usually those where the background noise is lower.

Other causes of discomfort on board of a ship are the vibrations originated by engines and propellers or the oscillations of the ship in heavy sea.

4 The noise sources

Stationary noise and vibrations − In the comfort oriented design of a ship, stationary noise and vibrations caused by the machinery (propulsion, ventilation and conditioning, etc.) are considered as the primary source of disturbance in the accommodation decks. In fact, the limit values quoted in the international rules concern the admissible noise and vibrations levels measured on board ships during navigation with reference to those generated by the machinery only (see Fig. 1).

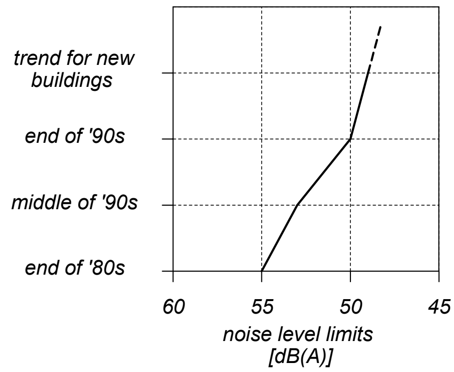

Fig. 1: Trend of the stationary noise values for cabins in cruise ships.

Human activity sources − On the other hand, the comfort of a cabin is measured also on the basis of the noise produced by human activity in the spaces contiguous to the cabin itself, mainly due to entertainment systems.

In the cabins interested by entertainment noise – usually the cabins above or below a show lounge or a discotheque – measurements show that generally the disturbance range from 2 dB to more than 7÷8 dB above the background noise.

It is worth pointing out that the major increase in noise level is in the low frequency range, particularly in the frequency range of 40÷150 Hz. Many times may happen that musical performances and shows produce sound with a highly variable amplitude and frequency content and source level can vary as much as 45÷50 dB.

The first tentative to regulate such kind of noise characterized by a non-stationary origin has been made precisely by the Classification Societies. They started by classifying the different disturbance sources connected with the human activity on board.

To quantify this aspect concerning the habitability of a cabin in connection with non-stationary noise, two types of sound disturbances are taken into consideration, which are correlated to the following indexes:

− the sound insulation index,
− the impact sound insulation index.

The first one, that is to say the sound insulation index, is connected with the noise transmitted by the adjacent spaces, caused by the human activity developed on the basis of the use allocation in said spaces. It is usual to make reference to such a source by classifying it as air-borne noise and it can simply be the noise produced by a television set, if the contiguous space is another cabin, or by the music spread by the plants of a discotheque (noise from the entertainment system). Since this is a noise characterized by a strong variability, it is quite difficult to foresee.

The second one, the impact sound insulation index, is connected once again with the type of the adjacent space, but characterizes the disturbance caused by the noise due to impacts on decks and is substantially a structural noise. It can be, for instance, the noise produced by the passage of persons in a corridor above the cabin, or a noise that is produced by the sport activities in a gym, or even a noise generated by the dragging of chairs on the pool deck. Also this noise is difficult to quantify because its sources may be different and it is strongly affected by the nature of the surface of the deck where it develops.

The foregoing indexes are obtained from measurements that are usually taken when the ship is at the quay since the purpose of such measuring is that of evaluating the effectiveness of the acoustic insulations between the different spaces. Such tests however are not yet sufficient to provide the guarantee of the comfort for the passengers. A very eloquent example is that of the cabins for which a high level of insulation is foreseen in view of the fact that they are adjacent to a discotheque. In this case, the standard measurements of the quality indexes do not provide an actual quantification of the disturbance degree, since it is not possible to take into consideration nor the type of impact, neither the main characteristics of the music, that is to say the type of music (i.e. its low frequency content) and the volume of its spreading.

The Classification Societies' Comfort Classes give some sound insulation index limits to be respected between cabin and public spaces and between cabins to disco/showrooms, which are variable from 55 dB to 65 dB (see Tab. 1).

Sound insulation index [dB]				
	Comfort class *1*			
	DNV	LR	BV	RINA
cabin to cabin top	46	45	42	40
cabin to cabin standard	41	40	40	40
cabin to public space	51	55	55	55
cabin to disco	65	60	65	65

Tab. 1: Sound insulation indexes for passenger accommodation areas.

The measurements based on these limits are the only objective measurements that shipyards can use to guarantee to owners a standard level of comfort, because the performances are just related to the general plant, the structure and the acoustic insulation of the ship.

5 Acoustics definitions

Standardized methods exist for measuring the sound insulation produced by various structures in both laboratory and field environments (actual functional buildings and building sites). A number of indices are defined according to the actual rules, and offer various benefits for different situations.

Sound Reduction Index (R) − This is a measurement, which uses knowledge of the relative sizes of the rooms in the test suite, and the reverberation time in the receiving room. Measurements of the sound reduction index R according to ISO 140 give frequency dependent values. Another standard (ISO 717) describes a method for conversion of these values into a single number quantity characterizing the acoustical performance of the test specimen. This quantity is called *weighted sound reduction index* R_w. The principle of the method is that the measured R-curve is compared to a reference curve, which is shifted in step of 1 dB until the mean unfavorable deviation of the R-values is as large as possible, but not more than 2 dB.

Normalized Level Difference (D_n) − This is an index which is measured in field conditions, between real rooms. It is a measurement which deliberately includes effects due to flanking routes and differences in the relative size of the rooms. It attempts, however, to normalize the measured level difference to the level which would be present when the rooms are furnished, by measuring the quantity of acoustic absorption in the receiving room and correcting the level difference to the level which would be expected if there was 10 m^2 cabin absorption in the receiving room. Detailed, accurate knowledge of the dimensions of the receiving room are required.

Standardized Level Difference (D_{nT}) − Similar to the normalized level difference, this index corrects the measured difference to a standardized reverberation time. For dwellings the standard reverberation time used is 0.5 seconds, for other larger spaces longer reverberation times will be used. A reverberation time of 0.5 seconds is often cited as approximately average for a medium sized, carpeted and furnished living room. Due to not requiring detailed and accurate knowledge of the dimensions of the test rooms, this index is easier to obtain, and arguably of slightly more relevance.

Once the level difference is obtained, the weighted value may be obtained from the corrected spectrum, as described above for the sound reduction index.

6 Cabin panels: theory and practice

For what concerns the requirements that a cruise ship must respect for sound insulation index values between passenger cabins and between public areas and cabins, it is not usual to adopt the single-panel solution, due to weight and fitting drawbacks.

The sound reduction of a single panel, as well known, is frequency selective: at low frequencies the stiffness of the material is the main controlling factor, and just above this point, various resonances cause major variation in sound transmission.

At about one octave above the lowest resonance, the mass of the wall takes over and dominates the sound reduction performance: the sound transmission loss depends on surface density of the panel and increases by 6 dB per octave per doubling of the mass. If we just increase the thickness of a partition to improve the sound insulation in the mass law region, this can lead to worse performance: first of all, the coincidence frequency will reduce, and can fall into a more important region; furthermore, the panel becomes heavier, and lightweight construction is to be preferred.

So instead of using a single-panel solution, a double wall construction is used with an air gap between the leaves. In such a panel configuration the following frequencies become important to the transmission problem:

- the coincidence frequencies f_{c1} and f_{c2} of the two panels,
- the lowest order resonance f_a across the air cavity,
- the lowest order structural resonance f_s (walls act as lump masses, air gap acts as a spring).

In terms of frequency regions, it is worth noting what follows:

- for a very low frequency (i.e., for $f < f_s$), the entire body effectively moves as a single body. Stiffness is controlled by the combined stiffness of panels and air gap. The R-curve decreases 6 dB per octave;
- at f_s an effective coupling between partitions across air gap begins and a poor R value is shown;
- for $f_s < f < f_a$ there is an effective coupling between the leaves due to resonances. The expression for the R-curve is:

$$R = R_1 + R_2 + 20\log(fd) - 29\,\mathrm{dB} \quad (1)$$

  where R_1 and R_2 are the R values of the two leaves and d is the distance between them (air gap thickness) in meter. This gives a 18 dB/Oct reduction, but 15dB/Oct is more normal. Such a formulation is true for structurally isolated leaves.
- for $f > f_a$ the cavity behaves like a usual wave field rather than a spring and the two leaves work independently to give significantly higher R values than the combined mass of the entire partition. A reduction of about 12dB/Oct is expected with an absorbent. The R-curve is:

$$R = R_1 + R_2 + 6\,\mathrm{dB} \quad (2)$$

- the case for f equal to a coincidence frequency (f_{c1} or f_{c2}) leads to more transmission, unless highly damped.

Figure 2 shows the qualitative trend of a typical attenuation curve for a double-panel solution.

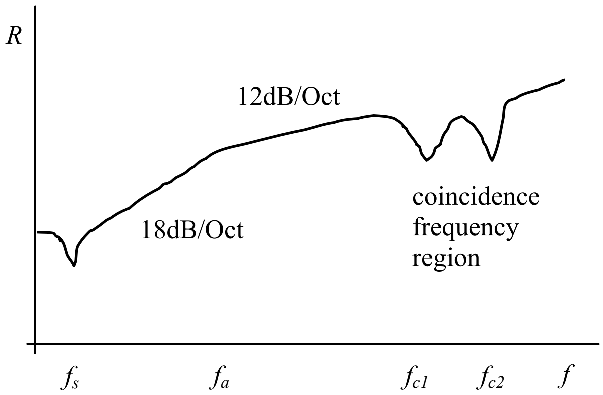

Fig. 2: Double panel attenuation curve (R curve).

6.1 Suggestions for designers

The most important issue for a good design is the acoustical and mechanical isolation between the two panels, that must be guaranteed as much as possible.

The use of absorption in the cavity can prevent build up of reverberant energy, the improvement of the acoustic isolation of panels with mineral wool on one partition will also prevent bridging. On the other hand, filling only gives a small improvement (up to 5 dB) if panels are mechanically coupled. For cruise ship, this solution can be the best one, because its cost is not much and the increase of the weight is negligible, but it is possible, on the contrary, to have problems with the prefabricated cabins. A bigger air gap improves the sound reduction. Typically R_w increases by 3 dB for each doubling of air layer thickness. On board this solution is usually not adopted because the number of cruise cabins decreases.

It is also important to have f_s as low as possible because there is a little attenuation at f_s and a low f_s value gives rise to a lower R-curve gradient.

Moreover, the use of panels of different thicknesses or materials could enable to separate coincidence dips. For practical reasons, mainly due to the manufacture process, this solution is not adopted on board. On the other hand, more mass improves the value of the sound reduction index, but it is important to put attention to the coincidence effects.

On board it is necessary to have a good compromise between the relative increase of weight and the value of the sound reduction index to be respected from ship technical specifications.

For a cruise ship, in particular, good workmanship is the key to good insulation, and, for example, gaps between floor boards will significantly degrade the partition performance. So, for concrete mountings on board, it is important to eliminate holes everywhere.

In the last years, in the technical ship specifications, we find also limits for the R values between cabins and corridors. In many cases it is also necessary to test the R values of the doors in laboratory. For doors, sealing properly around the door (e.g., use of a rabbet) is vital for good performance. Improper sealing around doors degrades performance by about 3÷10 dB, depending on the construction. The gap between the frame and the surrounding structure, in many cases, is fitted with mineral wool to reduce flanking in this area. To have a good insulation index between cabins and corridors, these recommendations are very important: for example, in many cases it is important to avoid to install the air extraction grill because, in this case, the R value dramatically decreases.

Flanking needs also to be considered. In particular, it is necessary to study the airborne and structure-borne path through the porthole, the ceiling and the floor. If the measured values are low or very low, it is very important to make investigations about these paths: many times it is usual to adopt an intensimeter approach.

The sound insulation index is greater when the cabins are totally finished with all the relative furniture, carpet, etc. inside. Therefore, the best time to perform the R measurements on board is at the end of the ship building. On the other hand, if at this stage problems will arise with too high measured R values, the only possible solution is to remove the cabin panels because they are most probably mounted in a wrong way. Due to high shipyard background noise, it is better to perform these measurements on board on evening-night and, if the cabins are without any furniture, the noise source must not be put on steel deck directly.

6.2 Laboratory and on-site measurements

For what concerns passenger-cabin panels, a very important parameter is the so called structure-borne noise radiation efficiency, that is measured usually in laboratories facilities.

The radiation efficiency is normally expressed as a logarithmic quantity named the *radiation index* 10log*σ*.

If the radiation index is determined from sound power measurements in a reverberant room, it can be calculated from the following expression:

$$10\log\sigma = L_w - L_v - 10\log(S/1[\mathrm{m}^2]) + 34\,\mathrm{dB} \quad (3)$$

Alternatively, the radiation index is based on the averaged sound pressure level measured in the receiving room. The formulation for the radiation index becomes:

$$\begin{aligned} 10\log\sigma = {} & L_p - L_v + 10\log V - 10\log T \\ & - 10\log(S/1[\mathrm{m}^2]) + 10\log(1 + F\lambda/8V) \quad (4) \\ & + 20dB \end{aligned}$$

where L_w is the average sound power in dB re. 1 pW, L_p is the averaged sound pressure level in dB re. 20 μPa in the receiving room, L_v is the averaged velocity in DB re. 1 nm/s measured on the surface of the wall, *S* is the area of the test wall in square meter, *V* is the volume in cubic meter of the receiving room, *T* is the reverberation time in seconds, *F* is the total area in square meter of the surface in the receiving room, *λ* is the wavelength in meter of the center frequency of the 1/3 octave frequency band in question. The recorded signals must be filtered and recorded in 1/3 octave frequency bands.

Excitation of the wall with structure-borne noise for the radiation efficiency measurements are performed by means of a vibration exciter coupled to a steel plate, which is resiliently mounted below the wall positioned in the opening. By means of this arrangement (see Fig. 3), a reverberant vibration field can be established in the steel plate coupled to the exciter and transferred to the walls simulating the real conditions occurring in a ship structure.

The sound reduction indexes R_w are written in the cruise ship technical specification and so must be respected on board.

Concerning the sound reduction index between pax cabins, usually after the test in qualified laboratories and the relative certifications, designers take directly on board of ships a number of measurements between pax cabins (more than one hundred). On board, it is also necessary to measure the most important sound insulation indexes between cabins and public areas. In the last years, due to the impressive measurements equipment evolution, the dedicated time for the measurements has been reduced by a great amount. After measurements, a complete report is sent to the owner.

Moreover, some Classification Societies are going to propose the measurements of the insulation indexes also below 100 Hz and, even tough it does not appear to designers to be rational to extend the measurements till this so low limit, Fincantieri has started to measure the insulation indexes below 100 Hz in order to have its own data bank.

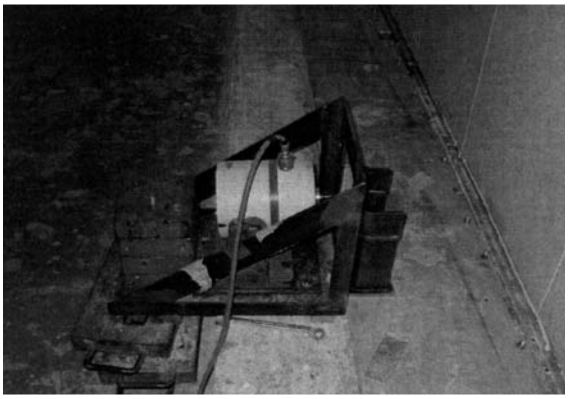

Fig. 3: Laboratory facilities for radiation efficiency measurements.

7 Conclusions

It is possible to affirm that the problem of the comfort has became the first one on a cruise ship. The effective sound insulation (in other words the privacy) is dependent on three factors: firstly how loud the sound, secondly the acoustic performance of the barriers and thirdly how quiet it is in the receiving room. These three factors are independent and the only way to aggregate them in a objective measure is that of referring to the sound reduction index, the only parameter that can be related with some specified numbers. The knowledge of the radiation index is very helpful for the prediction of the real noise in the cabins.

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