OVERVIEW OF COMFORT CRITERIA FOR VIBRATION ASSESSMENT PROPOSED BY ISO 6954 AND DIFFERENT CLASSIFICATION SOCIETIES

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ABSTRACT

The goal of this paper is to present an overview of the evolution of vibration criteria assessment specified through different international standards focusing on a comparative analysis between two versions of ISO 6954: v1984 and v2000. The changes proposed by ISO 6954 – 2000 made the object of different investigations published during recent years and this problem have been also undertaken by the last ISSC Committee II.2 2006 (Dynamic Response). Some of these investigations are referenced and analysed here. The overview proposed in this paper includes the points of view of different stakeholders involved in ship design: shipyards, ship-owners / operators and mainly the classification / technical assistance point of view – Tecnitas (Bureau Veritas Group) experience acquired through the vibration assessment for different types of ships. The comfort requirements of several classification societies are also presented in the paper focusing on Bureau Veritas class comfort notation.

INTRODUCTION

Vibrations on board have worried owners and shipyards since several years. With the increase of the size of the ships and simultaneously the increase of their power propulsion plants over the past fifty years, vibratory problems appear to be more and more frequent [1]. As ships' vibrations and their consequences, both in structural and human point of views, could not be ignored anymore, a need of normalized standard was imperative.

In 1970, several members of the Technical Committee 108 were working together to establish vibration levels for the crew of a ship. Their work leads to the writing of ISO 6954 standard in 1984. Bureau Veritas was part of this project and in the same time decided to publish a Guidance Note [2] on vibration problems. Onboard experiences and vibration recordings had lead to define two acceleration curves in terms of frequency. Three zones were for instance delimited. Figure 1 shows the 1970's Bureau Veritas vibration horizontal limits with the ISO 6954:1984 limits in dotted lines.

Nowadays, vibration levels are fixed by national or international standard, like ISO, or classification societies with their own knowledge and experiments. As the years go by, these vibration levels were revised downwards as passengers and crews complained about vibration nuisance and wanted more comfort. So (inter)national standards and comfort notation of several classification societies were forced to review and adapt their limits to answer to the market requirements.

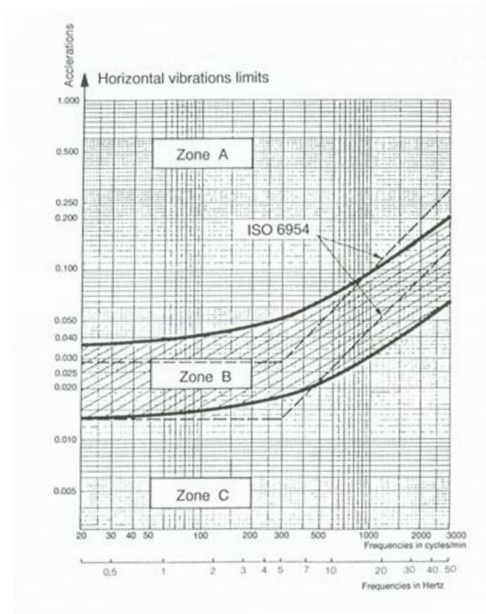

Figure 1 - Bureau Veritas horizontal limits / ISO 6954:1984 limits

The present paper describes the first version of ISO 6954 international standard (1984) and its evolution to the 2000 version. Particular attention is paid for this second edition and its way to deal with the vibration phenomena. On the other hand, the evolution over the years till today of the Bureau Veritas comfort class notation is presented as well as a comparison with the other class societies comfort criteria in terms of vibration limits.

We should mention here that assessment of vibration level, as any "design problem" is a matter

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involving different points of view of different stakeholders, mainly the shipyards and the ship-owners/operators. Basically, the requirements coming from shipyards and operators should be the same, as both are concerned by the same sector of the market. But it seems that in practice their point of view is very often different, even divergent. In order to illustrate this aspect and also the position of the classification societies and standards makers, we give here an extract from G.C. Volcy (1995) [3]: "….I can define these, humorously perhaps, by saying that there are never any serious vibrations on board ship as far as the shipyard is concerned, but, according to the ship-owner, there are always severe vibratory levels that the crew, machinery and navigation equipment cannot endure! In view of such a situation, it was the task of vibration specialists to be objective. In other words, they had to determine limits which, in the real world, were reasonable, and try to avoid creating problems between the shipyards and ship-owners…"

FROM ISO 6954:1984 TO ISO 6954:2000

In 1946, a delegation from twenty-five countries decided to create a new international organization. The aim of this entity would be "to facilitate the international coordination and unification of industrial standards". The International Organization for Standardization (ISO) was born. We were in February 1947. Nowadays ISO is the world's largest developer of standards. This non-governmental organization is composed by national standards institutes of 155 countries, on the basis of one member by country. The main activity is the development of technical standards. The choice of a standard development depends on the market requirements. The work is carried out by experts from the industrial, technical and business sectors which have asked for the standard. As the world market is always moving and technology knowledge is improving more and more, the already existing standards should follow this great worldwide dynamic. That's why, every five years, ISO requires a review of its standards "to decide whether they should be maintained, updated or withdrawn".

ISO 6954 first edited in 1984 was the first international guidelines in marine fields concerning the evaluation of vibrations in ships. ISO 6954:1984 [4] is applicable for merchant ships of length between perpendiculars 100 m or greater.

This standard is a guideline to evaluate the severity of vibration in living areas on ships and is based on experimental measurements database to correlate vibratory levels and the sensation of discomfort. The overall shipboard vibration is evaluated in terms of maximum repetitive values in a frequency range from 1 Hz to 100 Hz. Every living area on board, without any specific distinction, is covered by this standard. It is specified that this guideline is not appropriate to define the acceptance for machinery or equipment.

The ISO 6954:1984 contains a graph completed by a table which indicates the criteria to apply. Three zones are delimited with two curves. The upper curve is a constant acceleration (285 mm/s^2) curve from 1 Hz to 5 Hz, and then a constant velocity (9 mm/s) curve from 5 Hz to 100 Hz. This curve represents the level from which "adverse comments (are) probable". The lower curve is built in the same schema: a constant acceleration (126 mm/s^2) curve from 1Hz to 5 Hz and then a constant velocity (4 mm/s) curve from 5 Hz to 100 Hz. This curve represents the vibratory level below which "adverse comments (are) not probable". The zone between the two curves "reflects the shipboard vibration environment commonly experienced and accepted." (words in brackets are directly extracted from the ISO 6954:1984). All these values are applied for each single frequency component of each motion directions (longitudinal, transversal, vertical).

The ISO 6954:1984 is ended with an annex to assure the compatibility of this guideline with the ISO 2631-1 on the crew exposure to whole-body vibration.

It is mentioned in the standard that time averaged r.m.s. are often measured instead of maximum repetitive values. In order to keep the consistency between the measurement practice and the standard requirements, a conversion formula based on an appropriated conversion factor is proposed. The use of this conversion factor to the peak values is the major difficulty of this standard and causes many disagreements between the parts. In fact, if it is not possible to determine the crest factor by measurements (ratio of true peak to r.m.s. value), its value is fixed to 1.8. Carlton and Vlašić (2005) [7] conclude that it could be very difficult to measure the crest factor at every measurement location mainly due to the variation of vibration signatures around the ship. Obviously the fixed value of the crest factor is very often used when the check of limit state proposed by ISO 6954:1984 is performed.

Another important critical analysis of ISO 6954:1984 is formulated in 2006 ISSC Committee II.2 [6] in relation with the definition of the maximum repetitive value (MRV). MRV is not simply defined and this could be a source of ambiguity in the assessment of the vibration level.

With the market evolution and the new customers' requirements, the need of a review of the ISO 6954 standard was necessary. So the 1984 edition of ISO 6954 was fully revised and since 2000, a new release replaces henceforth this guideline [5].

ISO 6954:2000 is now applicable either for merchant ships or passenger ships. No ship length size is indicated. The aim of the standard is to evaluate vibration in terms of habitability in living areas and to provide guidelines for instrumentation, measurement methodology and reporting. It refers to normative documents which focused on the assessment of human response to vibration. This standard does not cover the assessment of low-frequency ship motion.

The overall shipboard vibration is evaluated in terms of overall frequency-weighted root mean square (r.m.s.) value in a frequency range from 1 Hz to 80 Hz. The combined frequency-weighted curve according to ISO 2631-2 is applied to all measurements, for any direction. Then the highest value obtained, without preferential direction, is used for the habitability evaluation.

The frequency-weighted root mean square acceleration is calculated according to the following formula:

$$a_w = \left[\sum_i \left(W_{mi} . a_i \right)^2 \right]^{1/2}$$

Where

W_{mi} weighting factor for the i[th] one-third-octave band

a_i r.m.s. acceleration for the i[th] one-third-octave band

The frequency-weighted r.m.s. acceleration a_w is expressed in meters per second square (m/s²) for translational vibration and in radians per second square (rad/s²) for rotational vibration.

According to ISO 2631-2 – "Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration" – which is a normative reference of the ISO 6954:2000, the overall frequency-weighted function W_m is the product of band limiting (high pass and low pass) and a pure frequency-weighted function:

$$W_m = |H_h| \times |H_l| \times |H_t|$$

Where:

$$|H_h| = \sqrt{\frac{f^4}{f^4 + f_1^4}} \text{ and } f_1 = 10^{-0.1} Hz$$

$$|H_l| = \sqrt{\frac{f_2^4}{f^4 + f_2^4}} \text{ and } f_2 = 100 Hz$$

$$|H_t| = \sqrt{\frac{f_3^2}{f^2 + f_3^2}} \text{ and } f_3 = \frac{1}{0.028 \times 2\pi}$$

It should be noted that these calculations are not applicable for transient vibration.

On contrary to the ISO 6954:1984 which does not specify living areas, the second edition ISO 6954:2000 clearly makes distinction between three types of living areas:

- passenger cabins,
- crew accommodation areas,
- working areas.

Vibration levels vary with the specified area.

As the 1984 version, ISO 6954:2000 defines three zones delimited by either two acceleration curves or two velocity curves in function of frequency. In the same way, the lower curve represents the vibratory level below which "adverse comments are not probable"; the upper curve represents the vibratory level above which "adverse comments are probable"; and the area between the two curves represents vibratory level "commonly experienced and accepted" (words in quotation marks are directly extracted from the ISO 6954:2000). Acceleration or velocity vibration values of each motion direction (longitudinal, transversal, vertical) could be evaluated according to their belonging zones with these criteria.

This guideline gives also indications on the way to collect vibratory data. Measuring and recording equipments are subject to be in accordance with the ISO 8041 – "Human response to vibration – Measuring instrumentation" – requirements. In addition, an equipment verification of this compliance with the ISO 8041standard should be done regularly and recorded. Measurements fittings should be calibrated before and after the measurements to be sure of their good working.

To comply with the ISO 6954:2000, vibratory levels should be measured in the three translational direction of the ship (longitudinal, transversal and vertical) at least at two locations on each deck. For the other locations, this standard requires measurements only in the vertical direction. Anyway, it is specified that locations and orientations of transducers in living areas should be "in sufficient quantity" and "in order to characterize satisfactorily the vibration of the ship with respect to habitability".

Concerning the measurements fittings, the ISSC 2006 Committee II.2 [6] presents a table which summarizes the recommended parameters of Fast Fourier Transform (F.F.T.) to use to apply ISO 6954:2000 (see Table 2).

Parameters of FFT	Recommendation
Measurement duration	$T \geq 60$ sec
Sampling frequency	$f_s \geq 200$ Hz
Block size	$n \geq 1024$
Frequency resolution	$\Delta f = f_s / n \leq 0.25$ Hz
Anti-leakage window & overlap	Hanning, 50% or more
Averaging over blocks	Power averaging of Fourier spectrum or arithmetic (linear) averaging of PSD.

Table 2 – Recommendation of FFT parameters for evaluation by ISO 6954:2000

ISO 6954:2000 gives also restriction about sea trials conditions to accept measurements data. A straight course of the ship during recording with constant speed is required. To get rid of the sea effects on the ship, the standard advises to have a maximum sea state of three, a fully-immerged propeller and a sufficient water depth which is empirically fixed to at least five times the draught of the ship. If these conditions are not fulfilled, the new trials conditions have to be clearly notified in the final delivery report.

ISO 6954:2000 contains in annex an example of test report template. This guideline proposes to collect general information in the delivery report which warrants knowing:

- On which ship are performed the measurements?
- By whom?
- Where?
- And how?

The standardization of equipment, measurements procedures and reporting is necessary to collect coherent data, and by this way to allow the comparison between ships (with the same particulars or not), and to constitute a reliable database.

COMPARATIVE ANALYSIS

Considering the above descriptions, it is clear that the theoretical and practical approaches have changed between the two versions of the ISO 6954 standards.
The comparative analysis presented in this paragraph is realised from the classification / rule maker point of view and it is based on the following criteria:

- the accuracy of the proposed methodologies for the vibration assessment
- the allowance of a clear and coherent control of the involved parameters in order to avoid subjective aspects that can occur during the checking of vibration level
- the respect of recent requirements of market regarding the acceptable vibration level

First of all, we should remark that the principle of vibration level assessment is different between the two versions of ISO 6954. While 1984 version requires a collection of single frequency components to be checked individually, the 2000 version attends to consider a single vibration value to be representative of the total vibration signature for a given part of the ship.
A numerical investigation of the differences between the two versions of ISO 6954 has been performed by Bureau Veritas and the results are presented here.

Three velocity vibratory spectra have been recorded in aft part of merchant ships. These spectra have been selected for their representative form as they present a different repartition of vibratory energy along the measured range spectrum. The figure 3 compares the mentioned three spectra with the ISO 6954:1984 requirements.

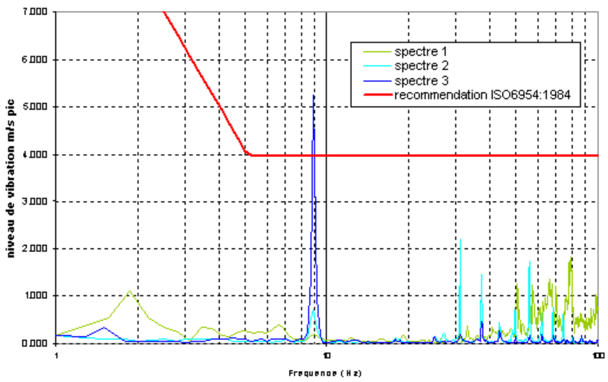

Figure 3 – Vibratory spectra and ISO 6954:1984 vibration level limit.

The three spectra could be described as follows:

- Spectra n°1 has a large band form. Half of the energy is distributed between 40 Hz and 100 Hz.
- Spectra n°2 has 80% of the energy which is distributed between a finite numbers of spectrum lines.
- Spectra n°3 has 90% of the energy concentrated on a single spectrum line due to propulsion.

Table 4 shows now the calculation of the vibration levels according to ISO 6954:2000.

<table>
<tr><td colspan="3">Overall weighted-frequency r.m.s. values calculated in the range of 1 Hz to 80 Hz according to ISO 6954:2000</td></tr>
<tr><td></td><td>Calculated velocity r.m.s. value (mm/s)</td><td>Required value by the standard (mm/s)</td></tr>
<tr><td>Spectra n°1</td><td>3.3</td><td rowspan="3">3</td></tr>
<tr><td>Spectra n°2</td><td>1.95</td></tr>
<tr><td>Spectra n°3</td><td>2.23</td></tr>
</table>

Table 4 – Comparison between calculation and standard ISO 6954:2000 requirement

This example show that 2000 version is more exigent for large band spectra, but it could be less restraining than 1984 version for some particular types of spectra presenting a concentrated energy (see No 3 spectra on figure 3).
In our opinion, the most important improvement of the accuracy from 2000 version is the allowance to take into account the energy distributed on several discrete frequencies or the large band spectra.
Other numerical comparisons have been published by Carlton & Vlašić [7] and Toyama et al., Matsumoto et al. [6].

An interesting numerical example is given by Francesco de Lorenzo & Marco Biot (2006) [8]. This example concerns a passenger ship already in operation without any noticeable vibration problem. The allowable vibration level assessed with ISO 6954:1984 was found equal to 32% of the lower limit, when with the similar spectra assessed with ISO 6954:2000, the allowable vibration level was found 93% higher than the lower required limit. So the obtained results in the overall weighted frequency r.m.s. value is now between the two curves defined by the standard, closest to the upper limit than to the lower one.
It is difficult to make a general critic on the 2000 version on the base of this investigation because only an isolated case is presented and the identification of vibration problems on board is “subjective” as the authors underline in the beginning of their paper.

The problem of the evaluation of the severity of the transient vibration is also included in the 2006 ISSC Committee II.2 [6]. It is mentioned that, even r.m.s. value is a good indicator to evaluate the severity of the vibration when the crest factor is lower than nine, r.m.s. value could underestimate the severity of the vibration when the crest factor is higher than nine, which is the case for the transient vibration. The recommendation of ISSC (2003) Committee for the evaluation of the severity of the transient vibration, which occurs at low frequency, is to use the fourth power vibration dose value for the measurement of this phenomenon.

Secondly, ISO 6954:2000, with a reference to ISO 2361-1:1997, gives a more precise definition of the overall frequency-weighted r.m.s. value. The fact that the value used for the evaluation of the vibration level is now based on a clearly defined mathematical formula is an improvement compared to ISO 6954:1984. In fact, in the 1984 version standard, the definition of MRV is not simply given, as it is mentioned in 2006 ISSC Committee II.2 [6]. This lack of precision could lead to confusion and to different interpretation of the definition of MRV.
In addition to that, the use of r.m.s. values is more coherent because these values are often used to perform measurements instead of MRV, as it is underline in the note of 1984 version. So with the use of r.m.s. values, there is no more need to a subjective correction.

Following the trend of modern rules (in all fields of activity), ISO 2000 is more detailed. A clear guideline on the equipment, the measurement methodology, the transducers' locations and orientations, the way to report the obtained results is now included in this version. Every step of the data collecting approach is detailed and normalized. Another evolution relatively to the 1984 version is the definition of several class areas (A, B, C), which allow the distinction between passengers and crew.

Some authors criticise the validity of 2000 version application for small crafts. In fact, there is no specification regarding ship length in this standard. This problem has been carefully investigated by Bureau Veritas. In order to take into account the length (and also the type) of the ship, as well as the concerned part of the ship, different allowable vibration levels are required by Bureau Veritas comfort class notation (see next paragraph).

Francesco de Lorenzo & Marco Biot [8] underline the trend of the cruise market to decrease the levels of acceptable vibration on board for both passengers and crew accommodation areas. The below graph is extracted from their paper and illustrates the evolution of peak limit values from the end of 80's to nowadays for cruise ships.

Following the conclusion of several authors referenced above, 2000 version seems to be globally more severe than 1984 version, which respects the general trend for new buildings showed in graphic 5.

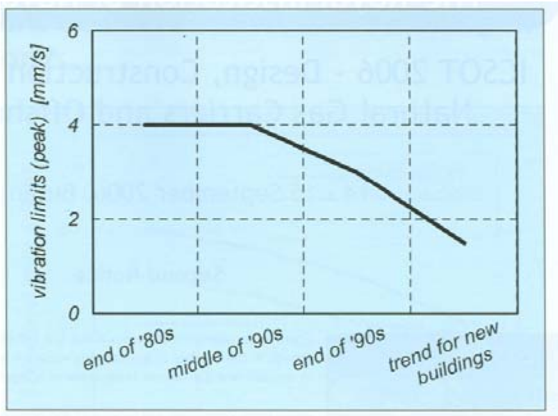

Figure 5 - Trends in vibration limits for passenger accommodation areas on cruise liner
Extracted from [8]

The field of applicability of 2000 still concerns merchant ships but it is extended to passengers' ships. Ever since, the 2000 standard should answer to the comfort requirements of passengers which are quite high as the passenger's comfort expectations are the same onboard than ashore (see Carlton and Vlašić [7]). As mentioned above, three classification areas (A, B, C) with their own associated vibration limit are defined in the 2000 version. These areas' distinction enables to take into account separately the passengers' expectations (which is the brand image of the owner) and the crew's requirements (which more concern the ship exploitation).

We can observe that, year by year, ship-owners and shipyards have been familiar with the principle of vibration level assessment of the ISO 6954:1984. Now that this principle has changed, the correlation between all these accumulated data and the 2000 version is not so obvious and lead to some hesitation with the use of the ISO 6954:2000. A difficulty which results of this change in the principle of the vibration level assessment is the agreement between ship-owners and shipyards on the acceptable value definition to be written in new building contract.

BUREAU VERITAS COMFORT CLASS NOTATION

Under the word "comfort", it is used to understand both vibration and noise low levels to minimize the inconvenience felt on board. In this part, only the evolution of the vibration comfort class notation in Bureau Veritas is developed.

During the 60's, Bureau Veritas has investigated vibration levels assessment in terms of:

- damages induced to equipments or machines installed on board or to the steel-work due to absorption of fatigue potential of the concerned materials,
- complaints of the crew or passengers about the discomfort felt on board or about the decrease of their performance due to vibrations.

The results of these investigations was, as already mentioned in the introduction, the publication of a guidance note [2] in 1970, under the title 'Recommendations designed to limit the effects of vibrations on board ships'.

This guidance note was applicable for steel ships without distinction. One chapter was written on the permissible limits concerning the discomfort on the crew. These permissible limits should have been considered as recommendations and were presented as two acceleration curves in function of frequency (see figure 1, in the introduction). As in the ISO 6954:1984 [4], three zones were defined:

- Zone A: zone in which difficulties due to vibrations are generally encountered
- Zone B: zone in which a formal judgement on the acceptability, or not, of vibration level is difficult to establish particularly because of the vibration feeling subjective nature
- Zone C: zone in which there is generally no complaints.

and the indicated values in the graph correspond to the maximum peak value of accelerations.
The main difference between ISO 6954:1984 and Bureau Veritas guidance note was the distinction between horizontal and vertical vibration directions. To remind, ISO 6954:1984 presented one graph for the vibration level assessment which is valid in any direction. But Bureau Veritas conviction was that, as human body vibration feeling depends on the vibration direction (generally, the crew is more affected by horizontal vibrations) and as measurements were done in terms of maximum peak value for each direction, the acceptable vibration limits could not have been the same for any direction. So the guidance note presented two graphs, one for the vertical vibrations and another for the horizontal ones, each of them presenting different acceptable vibration limits. This distinction between horizontal and vertical direction was kept as long as maximum peak values measurements were done to evaluate the vibration levels.

A new release of this guidance note [9] was published in 1979 to take into account the experience acquired by Bureau Veritas during its last ten years interventions on vibration problems.

In 1999, a rule note [10] was attended to define the comfort on board including noise and vibration in way to introduce the notion of "comfort mark" in the steel ships rules. This note presented the broad outlines of what would become the comfort notation: conditions of attributions, testing conditions, instrumentation, guidelines for measurements, vibrations limits and the evaluation of vibration levels.

Following this note, the comfort class notation was fully integrated in the 2000 version of the Bureau Veritas Steel Ships Rules [11].

Since 2000 and until now, the comfort class notation is delivered on the basis of measurement results performed during sea trials or in service. With the obtained measurements results, a comfort grade is given. Three different grades from 1 to 3 are defined. Grade 1 represents the highest class notation, i.e. the most comfortable level. Generally grade 3 corresponds more or less to the vibration limits of the ISO 6954 referenced in the comfort class. This notation does not cover high speed crafts which have not the same kind of behaviour in the vibrations field. In the same way, testing conditions regarding propeller output, equipments running during the tests, loading condition and course of the considered ship, water depth and weather conditions, still remain the same up to now.

In the 2000 comfort class notation (COMF-VIB), ships were divided into three main categories to take into account on their different behaviours in the point of view of noise and vibration:

- ships less than 65 m,
- passengers ships of 65 m and upward, including yachts and pleasure crafts,
- cargo ships of 65 m and upward.

For each of these categories, requirements on location and numbers of measurements to do on board are detailed.

This COMF-VIB v.2000 has referred to ISO 6954:1984 standard [4], and according to it, MRV was measured on a frequency range from 1 Hz to 100 Hz.

As already mentioned above, Bureau Veritas has made a distinction between vertical and horizontal vibrations. That's why, in COMF-VIB v.2000, all the measurements should have be taken in the vertical direction, and special recommendations according to the category of the ship were given for the horizontal measurements direction.

Without any constraints regarding instrumentation given in ISO 6954:1984, requirements on instrumentation were also included in the comfort class notation.

Another difference to point out between the ISO 6954:1984 recommendations and the comfort class notation requirements was the introduction of the determination of a "vibration equivalent level". In fact, according to the comfort class, MRV measured was compared to the acceptable vibration limits and when the spectrum presents several important components, an "equivalent vibration level" was estimated. The spectrum was weighted according to horizontal or vertical weighting curves (depending on the measurement direction), and then the equivalent vibration level was obtained by the r.m.s. of the weighted main components of the spectrum. In fact, this approach is now closer to ISO 6954:2000 recommendations.

In each one of the three ships categories, the comfort class grade was evaluated by a vibration limit in specific areas types. For example, in a passenger ship, the grade 3 corresponded to a vibration limit of 3mm/s in a passenger cabin and a vibration limit of 4mm/s in a crew cabin. By comparison, in a cargo ship, the grade 3 required a vibration limit of 4mm/s in all the cabins. This distinction between the living areas enables to take into account in the vibration level assessment the function of this area. So the comfort class notation adapts the vibration requirements depending to the type of the ship but also to different zones on board where measurements are done.

The COMF-VIB v.2003 [12] has brought some modifications compared to the 2000 version. The most appreciable changes have affected the measurements areas on passengers' ships.

Since 2005, the vibration comfort class notation [13] refers to the ISO 6954:2000 [5]. So the vibration level criteria and the measurements are now expressed in terms of overall frequency-weighted r.m.s. velocity (mm/s) in a frequency range from 1 Hz to 80 Hz in the COMF-VIB v.2005 and in the COMF-VIB v.2007.

In order to include this new way to evaluate the severity of the vibration level and the more accurate recommendations of the ISO 6954:2000 standard about the instrumentation and measurements methodology, the comfort class notation has been reviewed. Mainly, the instrumentation has to be calibrated in situ, before and after the tests, and measurements have still to be taken in vertical direction each time, and in horizontal direction on specified locations depending on the ship’s category. But now the vibration limits are applicable for any direction.

In the same release of the comfort class notation (COMF-VIB v.2005), the number of ships categories has gone up from three to four. Yachts are now a category apart. In addition, the measurements area locations for the vibration limits assessment are more detailed for each category.

The last version, COMF-VIB v.2007 [14], retains the same requirements as for the 2005 version in terms of instrumentation, measurements methodology and vibration levels assessment. This version also refers to the ISO 6954:2000. The main changes are a re-evaluation of the vibration limits for cargo and passenger ships of 65 m and upward to be more adapted to the trend of the market.

Through this description of the vibration comfort assessment evolution in the Bureau Veritas, three main steps could be drawn:

- Since the 60's, Bureau Veritas was investigated the vibration phenomenon and published guidance notes to assist and advise ship-owners and shipyards to deal with these particular problem. The vibration limits were assessed through two acceleration or velocity curves, with a clear distinction between vertical and horizontal vibrations.
- Since 2000, Bureau Veritas has created its own comfort class notation. This additional class is based on the ISO 6954:1984 recommendations In addition, ships are dividing into three categories chosen for their representative vibration behaviours and the notion of an equivalent vibration level, which use weighting curves and r.m.s. value, is included.
- Since 2005, the comfort class notation requirements are based on the ISO 6954:2000 recommendations. The three defined above categories of ships move to four categories and the vibration limits are regularly re-evaluated to take into account the trend of the market.

The assessment of the vibration level is not necessarily done through measurements on board. Tecnitas / Bureau Veritas performs vibration analysis using finite element method to assess vibration level.

The aim of the three-dimensional finite element vibration analysis is not to obtain the overall vibration level due to all the equipment and auxiliaries on board, but to predict the vibration level on several areas on the ship due to identified excitations sources, generally propellers, main engine, generators…So the frequency range of calculation is chosen according to the correspondent excitations source. For example, if we want to assess vibration level due to propeller excitations, calculations are performed on a frequency range extending over the second harmonic of propeller excitations. In this case, as it can be assumed that the response will be negligible in the upper frequency range (from second harmonic + 20% up to 80 Hz), we can accept to perform calculations on a reduced frequency range although ISO 6954:2000 requires vibration level assessment in frequency range from 1Hz to 80 Hz.

As real ships do not present purely symmetric or anti-symmetric vibration modes, the whole ship is modelled with an adequate mesh size and elements' types to be representative of the global vibration behaviour including the sub-assemblies (like superstructures) vibration behaviour in the selected frequency range. Line shafting and oil film characteristics (stiffness and damping) in the bearings are included in the finite element model for accuracy of calculated interactions between propulsive plant and hull.
Two loading conditions are investigated (in general ballast and full load conditions) and virtual added mass of water associated to the outside shell is taken into account.
Calculations of ship's natural frequencies and their corresponding mode shapes are first performed. Then we calculate the forced response due to the excitations using modal superposition method. The obtained results are velocity vibration level in function of frequency at several points on the ship, generally located in accommodation areas to allow measurements correlation afterwards.
The overall weighted-frequency r.m.s. values of these spectra are then calculated in accordance to the ISO 6954:2000 in the studied frequency range.

COMFORT CRITERIA FOR VIBRATION OF DIFFERENT CLASSIFICATION SOCIETIES

As Bureau Veritas, other classification societies has created and developed their own comfort class notation.
An exhaustive comparison of the required vibration criteria in force in August 2006 by different classification societies has been carried out by 2006 ISSC Committee II.2 [6]. The results of this analysis are summarised in the table 6 below.
Six classification societies are concerned by this comparison: ABS (2001), Bureau Veritas (2005), DNV (2003), Germanisher Lloyd's (2004), Lloyd's Register (2004) and RINA (2004).

As a general remark, all European classification societies propose recently reviewed versions of their comfort class notations (2003 – 2005). Criteria based on the overall frequency weighted r.m.s. value, similar with ISO 6954:2000 formulation, are used by BV, GL and LR. The requirements of DNV and RINA are closer to ISO 6954:1984 (peak value for single frequency component).

The 2006 ISSC Committee II.2 [6] observes that, all European comfort class notation require a vibration level limit for cabins lower than the ISO 6954, either the 1984 version for DNV and RINA or the 2000 version for Bureau Veritas, Germanisher Lloyd's and Lloyd's Register.

This comparison shows that, with a nuance for ABS which has chosen a different frequency range for the vibration level evaluation, the classification societies have the same trend to be more exigent in terms of comfort than the ISO 6954 (all versions included).

Class	Class notation	Vibration criteria
ABS (2001)	Maximum weighed r.m.s. acceleration level according to frequency weighing based on BS6841 (1987) in 0.5 – 80 Hz	
	COMF: for passenger comfort	$a_w = 0.315\ m/s^2$
	COMF+: for passenger comfort	$a_w = 0.2\ m/s^2$
	HAB: for crew habitability	$a_w = 0.4\ m/s^2$
	HAB+: for crew habitability	$a_w = 0.315\ m/s^2$
BV (2005)	Overall frequency-weighed r.m.s. velocity (mm/s) values from 1Hz to 80Hz	
	COMF-VIB 1 on passenger ships COMF-VIB 1 on cargo ships	v_w=1.7 mm/s for top level cabins v_w=3 mm/s for cabins
DNV (2003)	Vibration velocity level in mm/s peak for single frequency components in 1-100Hz	
	COMF-V (1) for cabins on passenger ships	a =47.1 mm/s² (1-5Hz) v = 1.5 mm/s (5-100Hz)
	COMF-V (1) for cabins on cargo ships	a = 78.5 mm/s² (1-5Hz) v = 2.5 mm/s (5-100Hz)
GL (2004)	Overall frequency-weighed r.m.s. value from 1Hz to 80Hz	
	GL-HC (hc_{pass}=E) on passenger ships ($V \leq$ 25kn)	v_w = 0.8 mm/s for first-class cabins v_w = 1.2 mm/s for crew cabins
LR(2004)	Overall frequency-weighed r.m.s. velocity values from 1Hz to 80Hz	
	PAC 1 on passenger ships CAC on cargo ships	v_w=1.5 mm/s for superior cabins v_w=3.5 mm/s for crew accommodation
RINA (2004)	0 - peak value of harmonic components of structural velocity from 1 to 100Hz	
	COMF-VIB A	v =1.0 mm/s for suite in passenger spaces v =2.0 mm/s for crew cabins

Table 6 – Comparisons of comfort criteria for vibration
Table extracted from ISSC 2006 [6]

As other classification societies, Bureau Veritas is subject to the trend of the market. The release of its comfort class notation has been driven up to now by the evolution on:

- the division into categories to be at best representative of the vibratory behaviour of the many existing types of ships
- measurements locations distribution along the concerned ship and their numbers to have a good representation of the overall vibration environment on board
- vibration limits to answer to the market requirements

With these points of view, Bureau Veritas has gone one step further in its comfort class notation in the offshore field.

The additional comfort class notation COMF HEALTH-VIB for vibrations on offshore units [15] is also attributed from measurements results. This notation evaluates the habitability on the base on two different requirements:

- comfort requirements for accommodation areas
- health requirements to protect workers from risk arising due to physical agent. These requirements are applicable in working areas.

In this notation, only two grades exist (grade 1 and grade 2), with grade 1 still corresponding to the most comfortable class notation.

In the comfort point of view, the vibration level criteria are expressed both in terms of:

- overall frequency-weighted r.m.s. acceleration (m/s²) in a frequency range from 1 Hz to 80 Hz,
- single frequency r.m.s. acceleration (m/s²) limit curves, either in vertical or in horizontal direction.

Health vibration levels are assessed through overall frequency-weighted r.m.s. acceleration exposure criteria and single frequency r.m.s. acceleration criteria.

The assessment of the severity of vibration level is done, in one way, as the COMF-VIB v.2005, with the use of overall frequency-weighted r.m.s. value according to ISO 6954:2000. But, as we have seen in this paper, although it is stricter for the large band spectra, it is not the case when the spectrum energy is concentrated on one or few single spectrum lines. Then, to remedy to this phenomenon, vibration limits are added for single frequency values. With this combination of the two vibration criteria, we have tried to cover all naval particularities spectrum which could cause discomfort feelings.

CONCLUSION

Nowadays vibration problems are still of great interest for ship-owners and shipyards, not only in relation with health problems apparition or security reasons, but also for comfort requirements and constraint evaluation. So vibration limits on board are by definition subject to evolution.

A comparative analysis between two versions of ISO 6954:2000 and 1984 is carried out in this paper. The main differences are underlined and illustrated through a numerical investigation performed at Bureau Veritas. A literature survey on this subject is also presented.

The second part of the paper gives an exhaustive description of Bureau Veritas comfort class notation and it's evolution since 2000. Some connections between this notation and ISO standard are identified and commented. A short comparison between different classification societies' comfort criteria for vibration is also included in this part.

At the end, a brief description of the Bureau Veritas comfort class notation applied to the offshore units is presented. This particularity is to combine the both the vibration level assessment of the ISO 6954:1984 (peak value for single frequency component) and those of the ISO 6954:2000 (overall weighted-frequency value).

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