



GUIDANCE NOTES ON

NOISE AND VIBRATION CONTROL FOR INHABITED SPACES

SEPTEMBER 2017

**American Bureau of Shipping
Incorporated by Act of Legislature of
the State of New York 1862**

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Foreword (1 September 2017)

Working and living onboard vessels imposes a series of generally low-frequency mechanical vibrations as well as single-impulse shock loads on the human body. Also, exposure to noise is characteristic aboard vessels.

Low-frequency vibrations are **created** by vessel motions, which are produced by the various sea states in conjunction with vessel speed and point of sail. These motions can result in motion sickness, body instability, interruptions of task performance, sleep interruption and fatigue, increased health risk aggravated by shock loads due to slam, and reduced human efficiency.

Higher-frequency vibration influences comfort and is often associated with rotating machinery. The imposition of higher frequency vibrations (about 1 to 80 Hz) induces corresponding motions and forces within the human body creating discomfort and reduced human efficiency.

With regard to noise, the above can similarly affect exposed humans, notably with sleep interruption and resulting fatigue, discomfort, and reduced efficiency. Also of concern are transient and permanent hearing loss, masking of audible signals, and interruption of speech communication.

The concerns related to levels and characteristics of noise and vibration are covered in a series of ABS Guides related to habitability on ships and offshore structures*. To be granted any of the associated habitability notations, specific noise and vibration criteria must be met. ABS clients in pursuit of these notations have requested guidance on how to control levels of noise and vibration in inhabited spaces. As a result, these *Guidance Notes for Noise and Vibration Control in Inhabited Spaces* have been created.

The information presented in this document is for guidance only, and is intended to support vessel designers and operators in controlling vessel noise and vibration in the general case, and more specifically in meeting the requirements of the ABS Habitability Guides. **Adherence** to some or all of the guidance in this document affords no guarantee that a habitability notation will be granted.

The September 2017 edition of these Guidance Notes incorporates information from the new IMO Code on Noise Levels On-board Ships (IMO Resolution MSC.337(91)) and the International Labour Organization's Maritime Labour Convention (ILO MLC).

These Guidance Notes become effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of these Guidance Notes is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

* Note: The ABS Habitability Guides are:

- *ABS Guide for Crew Habitability on Ships*
- *ABS Guide for Crew Habitability on Workboats*
- *ABS Guide for Crew Habitability on Offshore Installations*
- *ABS Guide for Crew Habitability on Mobile Offshore Drilling Units (MODUs)*
- *ABS Guide for Habitability of Industrial Personnel on Accommodation Vessels*



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SECTION 1 General

1 Introduction

1.1 General

Work-related hearing loss and vibration-related health effects are critical workplace safety and health issues. Seafarers may experience motion sickness, body instability, fatigue, and noise-induced hearing loss, one of the most common occupational diseases.

Adverse/improper noise and vibration levels can also cause speech interference, mask warning signals, interfere with concentration and thought processes, disrupt sleep, and **create harmful** living and working conditions. If designed appropriately, however, vessels complying with proper noise and vibration levels can provide an environment for improved crew performance, safety, comfort, and communication, and have an overall positive psychological effect on seafarers.

1.3 Addressing Noise and Vibration *(1 September 2017)*

The **recommended** way to meet noise and vibration criteria is to undertake noise and vibration **analyses very early in the design process** and apply appropriate controls **to mitigate areas of potential concern**. Noise and vibration analysis includes:

- Identifying sources of noise and vibration
- Modeling noise and vibration within the vessel
- Calculation of exciting forces (frequency and amplitude)
- Location of force application and response of the vessel structure in the positions of interest
- Modeling the source-path-receiver phenomenon
- Using this information to review the existing design for opportunities to improve noise and vibration levels

Therefore, this analysis requires methods which can use design information as input data and calculate the expected noise and vibration levels at positions of interest. It is suggested that the exciting forces should be determined for conditions when the propulsion machinery runs at not less than 80 percent maximum continuous rating (**MCR**) for noise and between 80 and 105% for structural vibration analyses.

1.5 New Industry Requirements *(1 September 2017)*

There are several industry requirements relating to noise exposure levels for seafarers. These include the IMO Code on Noise and the International Labour Organization's (ILO) Maritime Labour Convention, 2006.

1.5.1 IMO Code on Noise

On 1 July 2014, the International Convention for the Safety of Life at Sea (SOLAS) was amended to make the "Code on Noise Levels On Board Ships" (the Noise Code) mandatory for new vessels.

The *IMO Code on Noise Levels On-board Ships (IMO Resolution MSC.337(91))* is now in force and includes requirements limiting noise for certain types of vessels in excess of 1600 gross tons. The Code also includes noise from the operation of thrusters and from noise in port that is related to cargo operations. There are also requirements for acoustic insulation.

This Resolution sets out mandatory maximum noise level limits for machinery spaces, control rooms, workshops, accommodation and other spaces on board ships. The Code supersedes the previous non-mandatory Code, adopted in 1981 by resolution A.468 (XII).

The purpose of the new Code is to provide standards on preventing noise levels hazardous to human health and reduce seafarers' exposure to such noise levels. It gives consideration to the need for communication, the ability to hear audible alarms, the protection of seafarers from possible noise-induced hearing loss, and the provision of an acceptable degree of comfort during rest hours.

The new IMO criteria have been incorporated into the existing ABS suite of Habitability Guides supporting the various **HAB** notations. These are the:

- *ABS Guide for Crew Habitability on Ships*
- *ABS Guide for Crew Habitability on Workboats*
- *ABS Guide for Crew Habitability on Offshore Installations*
- *ABS Guide for Crew Habitability on Mobile Offshore Drilling Units (MODUs)*
- *ABS Guide for Habitability of Industrial Personnel on Accommodation Vessels*

1.5.2 ILO MLC 2006

The *International Labor Organization (ILO) Maritime Labour Convention (MLC)*, 2006 was ratified and came into force in August of 2013 by port States having adopted the Convention. Within the maritime sphere, the ILO provides legal instruments aimed at protecting and improving seafarers' working and living conditions. The Convention provides the, as yet, most comprehensive Code regarding seafarers' rights, and the obligations of States and shipowners with respect to these rights. The Convention incorporates the fundamental principles of many ILO Conventions and brings together and updates 68 existing ILO instruments (Conventions and Recommendations) into one document.

The MLC has Regulations, both objective and subjective, relating to whole-body vibration and noise levels aboard vessels. Examples are listed below:

- i) Regulation A3.1.6(h) states: *"accommodation and recreational and catering facilities shall meet the requirements in Regulation 4.3, and the related provisions in the Code, on health and safety protection and accident prevention, with respect to preventing the risk of exposure to hazardous levels of noise and vibration and other ambient factors and chemicals on board ships, and to provide an acceptable occupational and on-board living environment for seafarers."*
- ii) MLC Regulation A3.1.6(h) calls out Regulation 4.3. Below are listed the physical design and arrangement related aspects of Regulation 4.3 including:
 - a) A4.3.1(b) *"reasonable precautions to prevent occupational accidents, injuries and diseases on board ship, including measures to reduce and prevent the risk of exposure to harmful levels of ambient factors and chemicals as well as the risk of injury or disease that may arise from the use of equipment and machinery on board ships."* NOTE: Ambient factors refer to improper levels of vibration, noise, lighting, and indoor climatic qualities.
 - b) A4.3.2(a) *"take account of relevant international instruments dealing with occupational safety and health protection in general and with specific risks, and address all matters relevant to the prevention of occupational accidents, injuries and diseases that may be applicable to the work of seafarers and particularly those which are specific to maritime employment;"* NOTE: Occupational disease refers to disorders such as noise-induced hearing loss, tinnitus, and musculoskeletal injuries/disorders (e.g., lower and upper back and neck issues).

- c) A4.3.4 “Compliance with the requirements of applicable international instruments on the acceptable levels of exposure to workplace hazards on board ships and on the development and implementation of ships’ occupational safety and health policies and programmes shall be considered as meeting the requirements of this Convention.” The more common international instruments related to the “ambient factors” of noise and vibration are the new IMO Code on Noise and ISO 6954: 2000, Mechanical vibration – Guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships.

The IMO Code on Noise and the ISO 6954 vibration criteria have been incorporated into the existing ABS suite of Habitability Guides supporting the various **HAB** notations and into the *ABS Guide for Compliance with the ILO MLC, 2006 Title 3 Requirements*, and the associated **MLC-ACCOM** notation. Both of these notations support the demonstration of vessel compliance with the physical design and arrangement requirements, including acceptable conditions of onboard ambient environmental factors of MLC Title 3. Neither of these Guides address the procedural or management system requirements required by the ILO MLC.

3 Application (1 September 2017)

These Guidance Notes are intended to assist the marine community (shipyards, designers, regulators, and owners) in addressing noise and vibration issues and important design parameters. The information in these Guidance Notes is recommendatory and should be strongly considered when designing any new vessel in order to provide the safest and most productive working environment **for seafarers**. The cost of fixing noise or vibration **issues can be as much as** ten times more expensive after construction than if incorporated into the design from the preliminary design stage. Therefore, careful consideration should be given to designing in noise and vibration reduction elements.

5 Scope (1 September 2017)

These Guidance Notes are intended to provide a basic understanding and overview of the critical factors controlling noise and low-frequency vibrations onboard vessels and to gain **better understanding** of the important concepts of noise and vibration, design parameters, terminology, analysis methods, acoustic and vibration treatments, and other important data to consider when dealing with noise and vibration.

These Guidance Notes also include basic terminology and definitions of acoustic and vibration terms, a description of noise and vibration generating mechanisms, specifics on noise and vibration sources in ships, information regarding noise and vibration transmission through the hull structure, an overview of methods used for noise and vibration analysis, and noise and vibration control during the design stage or during modernization. With the proper understanding of how noise and vibration is generated, controlled and measured, vessels can be more easily designed to reduce noise and vibration in a straightforward, economic, and optimal manner, thus improving seafarer levels of habitability, **safety**, and task performance.

The main philosophy of these Guidance Notes is that noise and vibration **issues** can be **identified** and **resolved through** proper attention to the **vessel’s** acoustic and **vibratory** design; including program planning, analysis, treatment selection, construction Quality Assurance (QA), and verification testing.

7 Terminology

Acceleration: A vector that specifies the time rate of change of velocity (units of m/s²). The acceleration of the vibratory motion of a structure can be specified in terms of the peak, average, or root-mean-square (rms) magnitude of the acceleration in a given direction. In this document, the acceleration levels are given in terms of the rms acceleration amplitude.

Acceleration Level: L_A , in dB, of a vibrating body is 20 times the logarithm to the base 10 of the ratio of the acceleration to a reference acceleration (standard reference acceleration level is 10⁻³ cm/s²).

$$L_A = 20 \log (a/a_{ref}) = 10 \log (a/a_{ref})^2.$$

Acoustic: For the purposes of this document, “acoustic” refers to both noise and vibration related phenomena.

Acoustic Absorption: The change of sound energy into some other form, usually heat, in passing through a medium or on striking and being reflected from a surface.

Acoustic Power: See “sound power” or “sound power level”.

Airborne Sound (or Noise): Sound or noise that is transmitted through air or by means of paths in air. Since air cannot support shear, only pressure waves with longitudinal displacement can be transmitted through air.

Amplitude: The value of vibratory response due to a steady state periodic process. Amplitude may be measured as displacement, velocity or acceleration and may be presented as a peak level or a root mean square (rms) level.

A-weighted Sound Pressure Level: The magnitude of a sound, expressed in decibels (i.e., 20 micropascals); the various frequency components are adjusted according to the A-weighted values given in IEC 61672.1 (2004) in order to account for the frequency response characteristics of the human ear. The symbol is L_A , and the unit is dB(A). The measurement L_{Aeq} is an equivalent continuous A-weighted sound pressure level, measured over a period of time.

Bending Mode: Mode of vibration in which cross-sections of a beam, shaft, or structure undergoes translation and rotation. Type of translational mode usually found in slender structures with evenly distributed mass and stiffness.

Calibration Checks: Field calibration of a measuring instrument conducted before and after a field test, using a reference calibrated signal or through zero calibration.

Comfort: The ability of the crew to use a space for its intended purpose with minimal interference or annoyance from noise.

Crest Factor: The ratio of the peak value to the root-mean-square (rms) value of the acceleration after it has been frequency weighted by the appropriate frequency weighting network.

$$\text{Crest Factor} = \frac{\text{weighted peak acceleration}}{\text{weighted rms acceleration}}$$

Damping: The dissipation of energy with time or distance. In this document, damping generally refers to dissipation of vibrating energy in structures.

Decibel (dB): A dimensionless unit of measure of the ratio of two quantities, P_1 and P_2 , each of which is equal to or proportional to power. Ten times the logarithm to the base 10 of the ratio, P_1/P_2 , has the dimensions of dB.

Direct Sound Field: A sound field in which energy is flowing outward from the source without interference from surrounding surfaces. The sound field very close to a source, even in a reverberant room, is a direct field. Sound fields outdoors are direct fields at all distances from the source and are referred to as “free sound fields” or “free fields”.

Duration: Is represented by the length of exposure to sound.

Dynamic Positioning: A system to automatically maintain a workboat’s position and heading by controlling propellers and/or thrusters. Dynamic positioning can maintain a position to a fixed point over the bottom, or in relation to a moving object (such as another vessel). It can also be used to position the vessel at a favorable angle towards wind, waves, and current.

Equivalent Continuous A-weighted Sound Pressure Level: The A-weighted sound pressure level of a notional steady sound, over a certain time interval, which would have the same acoustic energy as the variable-loudness real sound under consideration, over that same time interval. The symbol is L_{Aeq} ; the unit is dB(A).

Excitation: A time-dependent stimulus (force or displacement) that produces vibration. Excitation may be transient, random, and periodic. A steady-state periodic excitation, like that produced by propellers or propulsion engine, is of interest in these Guidance Notes.

Exciting Frequency: Is the number of cycles of the excitation completed during a given time unit. It may be shaft rate (number of a shaft revolution per second), or blade rate (shaft rate multiplied by number of propeller blades). Under steady state condition, the frequency of vibration is always equal to the exciting frequency. An exciting force at any frequency potentially can excite all modes of the elastic body. However, amplitude of vibration depends on how close the excitation frequency is to any of the natural frequencies. The modes where the natural frequency is close to the exciting frequency will be most active and dominate in vibration response.

Flanking Path: A circuitous path by which sound is transmitted around the main transmission path (e.g., paths by which sound is transmitted from machine to foundation bypassing transmission through resilient mounts or gaps around the perimeter of the panel or cracks and openings in the panel through which sound bypasses transmission through the panel).

Free Sound Field (Free Field): A sound field in a homogeneous, isotropic medium free from boundaries. The sound pressure level decreases by 6 dB per doubling of distance from the source.

Frequency: The number of complete cycles of a periodic process occurring per unit time. Frequency is expressed in Hertz (Hz) which corresponds to the number of cycles observed-per-second.

Frequency Band: An interval of the frequency spectrum defined between upper and lower “cut-off” frequencies. The band may be described in terms of these two frequencies, by the width of the band, and by the geometric mean frequency of the upper and lower cut-off frequencies (e.g., “an octave band centered at 500 Hz”).

Frequency Weighting: A transfer function used to modify a signal according to a required dependence on vibration frequency.

- In human response to vibration, various frequency weightings have been defined in order to reflect known or hypothesized relationships between vibration frequency and human response.
- The frequency weighting used to evaluate whole-body vibration in these Guidance Notes is W_m (whole-body) for all three axes (x, y, and z), in accordance with ISO 6954.

Hard Mounting: Rigid attachment of a machine to its sub-base or foundation.

Harmonic: (1) An integral multiple of a given frequency; a sinusoidal component of a periodic wave. (2) A signal having a frequency that is a harmonic (sense 1) of the fundamental frequency.

Inception Speed: Vessel speed at which a propeller starts to cavitate.

Intensity of Noise: Is represented by the loudness of the sound.

Isolation: The coupling of a vibrating structure (e.g., machine) to another structure (e.g., foundation or hull) by means of resilient or compliant supports that prevent the transmission of the vibration from the vibrating structure to the coupled structure.

Level: In acoustics, the level of a quantity is the logarithm of the ratio of that quantity to a reference quantity of the same kind. The base of the logarithm, the reference quantity, and the kind of level needs to be specified. Examples are sound power levels, sound pressure levels, and acceleration levels. Levels are always expressed in decibels (dB).

Manned Space: Any space where a seafarer may be present for twenty (20) minutes or longer at one time during normal, routine daily activities. Such spaces would include working or living spaces.

Mode and Mode Shape: A predetermined distribution of vibration amplitude that occurs when an elastic body vibrates freely at any of its natural frequencies. This distribution is called a ‘mode’. These modes are enumerated, with the lowest mode number corresponding to the lowest natural frequency. Each mode has a specific shape of amplitude distribution with *nodes* (null amplitude points) and maximums of vibration.

Multi-Axis Acceleration Value: The Multi-Axis Acceleration Value is calculated from the root-sums-of-squares of the weighted rms acceleration values in each axis (a_{xw} , a_{yw} and a_{zw}) at the measurement point using the following expression:

$$a_w = \sqrt{a_{xw}^2 + a_{yw}^2 + a_{zw}^2}$$

where a_{xw} , a_{yw} and a_{zw} are the weighted rms acceleration values measured in the x-, y- and z-axes, respectively.

Multi-Axis Vibration: Mechanical vibration or shock acting in more than one (1) direction simultaneously.

Natural Frequency: Is the frequency at which structures vibrate freely after a single impulse or impact. A mass-spring system has only one natural frequency. An elastic body like a ship hull (or parts of the hull) has a multitude of natural frequencies. Usually, only the lower natural frequencies are of practical significance.

Noise: Any undesired sound or any erratic, intermittent, or statistically random oscillation.

Noise Level: Noise levels in this document refer to the sound pressure levels that describe a particular noise environment.

Noise Reduction: The difference (in decibels) between the sound pressure levels on different sides of a boundary construction is defined as the noise reduction (NR). Unlike transmission loss, noise reduction is dependent not only on the intervening structure but also the source and receiver room acoustic properties. Noise reduction can also refer to the number of dB by which sound pressure levels are reduced in a single space or at a fixed location due to introduction of noise control treatments.

Octave: The frequency range bounded by upper and lower frequency limits f_u and f_l , where $f_u = 2f_l$. Octave bands are usually specified by their geometric mean frequency, called the band center frequencies. The standard octave bands covering the audible range are designated by the following center frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. The corresponding upper and lower frequencies are 22/45, 45/89, 89/177, 177/354, 354/708, 708/1416, 1416/2832, 2832/5664, 5664/11,328, 11,328/22,656.

Overall Root Mean Square Acceleration: Is the root from the arithmetic mean of the squares of the vibration spectrum components.

Peak Value: The largest deviation of a signal from the arithmetic mean of that signal. The positive peak value is the maximum positive deviation; the negative peak value is the maximum negative deviation.

Period: Is the minimum time between consequent repeating amplitudes.

Pure Tone: Sound wave whose sound pressure at a point varies sinusoidally with time and is characterized by its singleness of pitch. The time interval for one complete cycle of the sinusoidal pressure variation is known as the period.

Radiation Efficiency: The radiation efficiency of a vibrating surface is proportional to the acoustic power radiated per unit surface area per unit of mean-square velocity of vibration averaged over the radiating surface. It is the measure of the efficiency with which a given surface converts vibratory energy to acoustic energy.

Reference Calibration: Calibration of measuring instrument conducted by an accredited Testing and Calibration Laboratory with traceability to a signal or through zero calibration.

Resonance: (1) The phenomenon of amplification of a free wave or oscillation of a system by a forced wave or oscillation of exactly equal period. The forced wave may arise from an impressed force upon the system or from a boundary condition. The growth of the resonant amplitude is characteristically linear in time. (2) Of a system in forced oscillation, the condition that exists when any change, however small, in the frequency of excitation causes a decrease in the response of the system.

Reverberant Field: That part of the radiated sound field where the sound waves reflected from the boundaries of the enclosure are superimposed upon the incident field. The reverberant field may be called a diffuse field if a great many reflected wavetrains cross from all possible directions and the sound-energy density is very nearly uniform throughout the field.

Reverberation Room: A room in which all boundaries are hard and the sound field is reverberant over nearly the entire room volume with the exception of a small region around the source.

Soft Surface: A surface that is a good absorber of sound.

Sound: A disturbance (i.e., oscillation in pressure) that propagates through an elastic material (air, water) at a speed characteristic of that medium. The physical quantities of most interest are the sound pressure and sound power.

Sound Energy: The energy that sound waves contribute to a particular medium.

Sound Field: A region containing sound waves. Sound fields are typically described as reverberant or direct.

Sound Pressure: The total instantaneous pressure at a point in the presence of a sound wave minus the static pressure at that point.

Sound Pressure Level: SPL, in dB, is 20 times the logarithm to the base 10 of the ratio of the pressure of this sound to a reference pressure. The sound pressure, p , is the root-mean-square value of the instantaneous sound pressure over a time interval at the point under consideration.

Source Level: In this document, either the sound power level of an airborne noise source or the acceleration level of a structure-borne noise source.

Spectrum: (1) The spectrum of a time-varying phenomenon is the description of its resolution into components, each of different frequency and (usually) different amplitude and phase. (2) Also used to signify a continuous range of components, usually wide in extent, within which waves have some specified common characteristic (e.g., “audio-frequency spectrum”).

Stationkeeping: Maintaining a seagoing vessel in a position relative to other vessels or a fixed point.

Structure-borne Sound (or Noise): Sound or noise that is transmitted through structures that are capable of supporting shear. Thus, structure-borne sound may be in the form of longitudinal or flexural waves.

Thruster Conditions: Those conditions when thrusters are used to maintain the vessel’s position and heading during stationkeeping.

Transit Conditions: Those conditions where the vessel is transitioning (moving) from one location to another.

Transmission Loss: The sound transmission loss (TL) of a partition, in dB, is the difference between incident sound intensity level and transmitted sound intensity level. It can be expressed as 10 times the logarithm to the base 10 of the reciprocal of the transmission coefficient, τ .

Turn: A change of direction in a passageway or duct where the angle of direction change is at least 30 degrees.

Vibration: The variation with time of the magnitude of a quantity which is descriptive of the motion or position of a mechanical system, when the magnitude is alternately greater and smaller than some average value. Also referred to as structure-borne noise.

Vibration Level: Measure of the amplitude of vibration.

Vibration Spectrum: Is usually the acceleration squared as a function of frequency.

Wave: A disturbance which is propagated in a medium in such a manner that at any point in the medium the quantity serving as a measure of the disturbance, such as pressure or particle displacement, is a function of the time, while at any instant in time the displacement at a point is a function of the position of the point. (Excerpt from American Standard Acoustic Terminology).

Weighted Root-Mean-Square Acceleration Value (a_w): The weighted root-mean-square (rms) acceleration, a_w , in meters-per-second squared, is defined by the expression:

$$a_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt}$$

where $a_w(t)$ is the weighted acceleration as a function of time in meters-per-second squared (m/s^2) and T is the duration of the measurement in seconds.

Weighted Spectrum: Is the spectrum corrected by some filtering values, depending on frequency; this correction accounts for the sensitivity of a human body to vibration in different axes.

Whole-body Vibration: Mechanical vibration (or shock) transmitted to the human body as a whole. Whole-body vibration is often due to the vibration of a surface supporting the body.



SECTION 2 Vibration

1 Background (1 September 2017)

“Only costly noise and vibration countermeasures remain after the keel laydown of a ship.” (ISSC 2012)

Working and/or living onboard vessels can impose a series of low- and high-frequency mechanical vibrations, as well as single-impulse shock loads on the human body (whole-body vibration). Low-frequency vibrations are also imposed by vessel motions, which are produced by the various sea states in conjunction with vessel speed. Among other things, these motions can result in increased health risks aggravated by shock loads induced by vessel slamming. Vessel slamming may be caused by dynamic impact loads being exerted on the vessel’s bottom or bow flare due to vessel size, speed, and wave conditions.

High-frequency vibration is often **caused by** rotating machinery. The imposition of higher frequency vibrations induces corresponding motions and forces within the human body (**whole-body vibration**), creating discomfort and possibly resulting in degraded performance and health (Griffin, 1990) *Handbook of Human Vibration*. **For the ambient environment related to whole-body vibration, the frequency range of interest is from 1 to 80 Hz.**

3 Scope (1 September 2017)

This Section contains information regarding the proper design and consideration of vibration reduction elements. The design goals are to reduce vibrations to a safe level, thus improving habitability and seafarer task performance in different environments on ships.

This Section contains nine Subsections. Subsection 2/5 presents an overview of shipboard vibration. Subsection 2/7 describes sources of vibration. Subsection 2/9 discusses hull and structure vibration response. Subsection 2/11 is devoted to modeling of Shipboard Vibration at design stage. Subsection 2/13 describes how to design to reduce vibration. Finally, Subsections 2/15 and 2/17 outline vibration plan implementation details and a summary of the information contained in this Section.

5 Overview of Shipboard Vibration

5.1 Elastic Vibration

One of the challenges in the design of modern ships is the avoidance of excessive elastic vibration of the hull structures in response to external or internal forces. Such vibration may cause discomfort and interfere with performance of crew duties. Severe vibration may lead to structural damage and negatively influence operation of mechanical and electrical equipment on board.

Elastic vibration can be excited in the form of vertical and horizontal bending, torsional and axial modes of elastic structures of the whole hull, as well as in the form of local vibration of sub-structures and components. Typically, propellers excite the most significant vibration. Flexural vibration can also be excited by forces from reciprocating, and to a lesser degree, rotational machinery, and by external forces of sea waves impacting a vessel.

5.3 Vibration Study and Source Design (1 September 2017)

A typical vibration study can be divided into two parts, analysis of dynamic forces exciting the hull and the response of the hull and its substructures.

Looking at the sources of vibration, it is easiest to start at heavy pieces of mechanical equipment and work ‘backwards’. It is important to remember that vibration does not really pass through air; it travels along ‘things’ and the routes that it follows are as important as the vibrations themselves. The most basic forces of interest are those generated by engines, machinery, propellers, and shafts. **These forces vary with engine load, the speed and draft of the ship and with environmental conditions.** Other common sources of vibration include gears, screws, hulls, thrusters, fans, compressors, pumps, pipes, and valves. It is assumed that shafting, torsional, whirling, lateral, and axial vibration analyses are carried out as part of the standard design, either by the equipment vendor or a third party. This is especially critical when either or both of the coupled equipment items are isolation mounted and require a flexible shaft coupling to take up their expected relative movements.

Selecting low vibration machinery and minimizing propulsor/thruster excitation are the better approaches to avoiding excessive vibration levels. Foundations for shaft bearings should be stiff enough to prevent excessive low frequency vibration. The strategy of selecting low vibration machinery is so critical due to a limited or restricted ability to change the hull size and shape later in the design.

7 Sources of Vibration

7.1 Machinery Excitation

Unbalanced or misaligned machinery, particularly propulsion machinery such as the main propulsion engines, is the major source of excessive vibration and can develop excitation forces in the frequency range of interest – both for the equipment and structure in the vicinity of the machinery. These frequencies of excitation match either the rotation rate, or twice the rotation rate.

7.1.1 Diesel Engines (1 September 2017)

Diesel engines, whether low, medium or high speed – two or four stroke, generate significant force and moment-coupled vibration excitation. The diesel firing forces, which depend on rotation rate and number of cylinders, are impulsive in nature, which causes components of vibration at many harmonics of the firing frequency. Low-speed propulsion diesel engines are typically more of a concern than high-speed diesel engines because their low excitation frequencies are more likely to lie in the range of a hull natural frequency.

As a result, diesel engines, and other reciprocating machinery, may develop **unbalanced** forces and moments, which are sufficient to create excessive ship vibration. These forces/moments may excite the machinery itself, **engine or other machinery** foundations, the hull girder, **propeller shaft** or other structures within the vessel.

The excitation of a reciprocating engine can be divided into two parts:

- Unbalanced inertial
- Firing forces/moments

The unbalanced inertial forces are associated with the rotating or reciprocal masses. The frequencies of resulting forces are multiples of shaft rotation rate.

A 4-cycle engine has twice as many ‘firing’ harmonics as a 2-cycle engine. Analytical calculations of diesel engine generated forces are not easily undertaken and should be left to the diesel engine vendor. When possible, it is preferable to use experimental data taken on actual diesel engine foundations for a vibration study. Force or vibration levels may be used as input data for response calculation involving structural modeling of the foundation and portions of neighboring vessel structure.

7.1.2 Other Mechanical Sources of Vibration

Other machinery-related concerns are reciprocating refrigeration, air compressors, eccentric rotors, bent shafts, mechanical looseness, rotor rub, bearing problems (whirling, clearances, etc.), and pumps.

7.3 Propulsion and Shafting Excitation

The basic design purpose of the **propulsors** is to generate steady thrust to the vessel. In addition, this propulsor **may generate** undesired fluctuating dynamic forces and moments due to its operation in a non-uniform wake and due to passage of the blades close to hull and appendages.

7.3.1 Hull Pressure vs. Bearing Forces (1 September 2017)

In addition to propeller induced unbalanced forces (2/7.1), there are two other types of fluctuating forces. These are hull pressure forces and bearing forces. The hull pressure originates from the hydro-acoustic pressure variations caused by the passage of a propeller through non-uniform inflow or wake, and the amplitude of excitations depends on the uniformity of the axial and tangential wake profile. These hull pressure forces are affected by propeller-hull clearance in vertical and horizontal directions, by blade loading, and by changes in the local pressure field around the blades. Given a realistic hull form, it is impossible to achieve a uniform inflow. However, the design should strive for as clean an inflow as possible.

Bearing forces are caused by fluctuating forces on the blade during a propeller rotation which generate both vertical and horizontal forces on the shaft. These vertical and horizontal forces produce lateral and axial forces and moments on the support bearings and thrust bearing. The frequencies of these forces and moments are the same as for the hull pressure, shaft rate, blade rate, and multiples. The thrust bearing forces provide an excitation to the propulsion system in the longitudinal direction; the fluctuating torque produces shaft torsional vibration. The blade frequency vertical bearing force, when combined with same frequency vertical hull pressures, provides the overall vertical excitation of the hull in the vertical direction. Similarly, the combined horizontal forces excite the hull in the horizontal direction. Dynamic unbalance of any component of the system (propeller, shaft, coupling, gear, and engine) will increase the resulting hull vibration levels.

The decision on the number of blades for the propeller is expected early in the design process. The frequency of propeller blade rate excitations depends on the shaft rotation rate and the number of blades. This applies for all types of screw propellers and impellers, including conventional, controllable pitch, ducted, nozzles, thruster propellers, and pods.

7.3.2 Cavitation (1 September 2017)

Where there is the occurrence of cavitation (the sudden formation and collapse of low-pressure bubbles in liquids by means of mechanical forces, such as those resulting from rotation of a propeller), there is a significant increase in the hull pressure forces. Again, the cavitation performance of the propeller is related to the amplitudes of the blade rate and blade harmonic vibration, and also the broad-band vibration excitations covering a wider frequency range. The cavitation characteristics of the propeller along with the wake interaction and the number of propeller blades with the range of shaft rotation rates all determine the amplitude and frequency of propeller vibration. The resulting hull pressures may be calculated during the design stage based on parameters such as propeller rpm, clearance, blade form, and hull form.

7.3.3 Thrusters

Another significant vibration source is the bow or stern thruster(s). These units can be located relatively close to accommodations and can cause high vibration (and noise). As discussed above for the prime propulsor, inflow and propeller design control the induced vibration levels.

It is assumed that shafting, torsional, whirling, lateral, and axial vibration analyses are carried out as part of the standard design, either by the equipment vendor or a third party. This is especially critical when either or both of the coupled equipment items are isolation mounted and require a flexible shaft coupling to take up their expected relative movements.

7.5 Hydrodynamic Excitation (1 September 2017)

Hydrodynamic vibration excitation is a flow-related phenomena within the frequency range of 1 to 80 Hz that indicates whole body vibration. The sources of this vibration are generally hull shape, hull appendages, and openings, tunnels or chests subjected to interactions with flow. Vibration excitation induced by hydrodynamic sources is typically unintentional and should be avoided. Some examples of hydrodynamic sources of whole-body vibration excitation includes: