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Noise and Vibration Recorded on Selected New Generation DP Class Shuttle Tankers Operated in the Arctic Offshore Sector

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ABSTRACT: The purpose of this paper is to highlight the problem of the impact of vibration and noise recorded on selected new-generation DP-class shuttle tankers operated in the Arctic offshore sector. The paper presents the functional and disease effects associated with excessive exposure to these physical factors, the levels of which exceed the normatively acceptable values. The work also discusses the impact of physical factors on the marine environment. The international community recognizes that noise and vibrations from commercial ships may have very negative consequences for both humans (worker's) and marine life, especially marine mammals. However, there are also certain legal requirements in maritime transport that require adaptation to noise and vibration control when working on ships. The acceptable noise and vibration exposure standards set out in European Union Directive 2003/10/EC (2003), the NOPSEMA Regulation (2006), the Maritime Labour Convention (MLC) guidelines (2006) and the recommendations of the International Maritime Organization IMO contained, e.g. IMO MEPC.1 / Circ.833 (2014). These regulations inform employers and employees what they must do to effectively protect both the marine environment and the health and life safety of workers employed in the maritime industry offshore. This study also presents an analysis of the results of noise measurements carried out on selected DP class Shuttle Tanker operated in the Arctic sector offshore. The article presents the methods of noise measurement and assessment, but does not discuss personal protective equipment and ship's noise protection systems.

1 INTRODUCTION

Sea ships are technical objects whose structure is stiffened, and its dynamic behaviour is described by elastic characteristics [1]. The analysis of vibration and noise occurring onboard requires consideration of two groups of identifiable sources of impacts. During operation, they are naturally subjected to external influences of the marine environment, which are the source of vibroacoustic processes occurring in the hull area, and superstructure. An additional source of impacts are local processes, caused by the elastic reaction forces of the hull reinforcement elements, the operation of the propulsion system or other on-board machinery and equipment [2,3]. A full analysis of vibroacoustic impacts requires considering the diverse dynamic characteristics of machines and devices operating locally and their operating modes. Due to the occurrence of concentrated masses, caused by the location of on-board equipment and machinery, the ship's structure is designed considering local stiffness increases [1]. The designed distribution of the load is also significant, which translates into stiffening of the structure, and its type has an intrinsic effect on the damping of vibrations.

Ship vibrations affect the structure of the ship, affect comfort or even be harmful to the crew, and are emitted into the marine environment. From the point of view of the crew, noise and mechanical vibrations occurring in means of sea transport are a serious source of risk of occupational diseases of employees and affect the reduction of work efficiency and work safety. Particularly dangerous for the human body are vibrations with excitation frequencies corresponding to the natural frequencies of individual human organs. Even small vibrations from the environment can induce resonant vibrations of individual organs, leading to pathological phenomena that have a negative impact on human health [4]. In addition, the vibration caused e.g. by reciprocating tools can give rise to a permanent disablement of the hands known as 'dead' or 'white' fingers. In its initial stages, this appears as numbness of the fingers and an increasing sensitivity to cold but in more advanced stages the hands become blue and the fingertips swollen. Those prone to the disability should not use such portable power tools. Others should not use them continually for more than e.g. a maximum of 30 minutes without a break.

The hazards and effects from noise and vibration can be categorized under two headings: short term and long term. The short-term effects from noise and vibration are stress, loss of sleep, temporary deafness, poor communication [4]. All of the above can lead in human life to potential situations, which may result in accidents and incidents. The long-term effect from noise is deafness. The long-term from vibration is disability. The international community recognizes that noise and vibrations from commercial ships may have both short and long-term negative consequences for both human (worker's) life and marine life - especially marine mammals susceptible to underwater-radiated noise from ship's sonars, propellers and thrusters.

When efforts have been made to mitigate noise and vibration, as far as reasonable and practical, evaluation should be undertaken to determine the success or reduction efforts. The successful strategy to reduce radiated noise and vibration should consider interactions and contributions from measures provided to achieve other objectives such as reduction of onboard noise and vibration and improvements in energy efficiency [5].

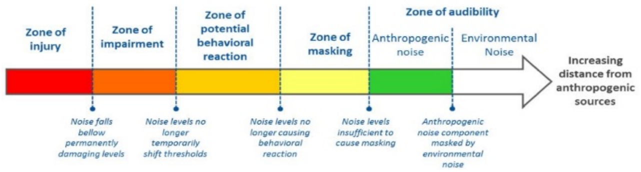

Figure 1. Simplified illustration of potential noise induced effects on marine animals: relationship between noise levels, distance from the source and potential effects. Source: Own research based on MLC 2006 & IMO Resolution MEPC.1/Circ.833 (2014), [5].

According to MLC 2006 (Maritime Labour Convention from 2006) implemented for all shipping industry on 20th August 2013 (ratification date), accommodation, recreational and catering facilities on ships 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 [6]. Acoustic insulation or other appropriate sound-absorbing materials should be used in the construction and finishing of bulkheads, deck heads and decks within the sound-producing spaces as well as self-closing noise-isolating doors for machinery spaces. IMO [5] generated also some guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (e.g. IMO Resolution MEPC.1/Circ.833 (2014)).

2 VIBROACOUSTIC IMPACTS

2.1 *Sources of vibrations and methods of testing*

Mechanical vibrations containing significant components in the low frequency range have several adverse health effects on humans. This is due to the presence of resonant frequencies and their first harmonics in this range, which carry high energy values for elements and parts of the human body. Experimental studies conducted in many scientific and research centres have confirmed the fact of a significant impact of vibrations on functional changes in the nervous system, fatigue, and functional disorders, as well as in the case of long-term exposure, they have shown a destructive nature. The influence of vibrations on humans is shown in Figure 2 [4].

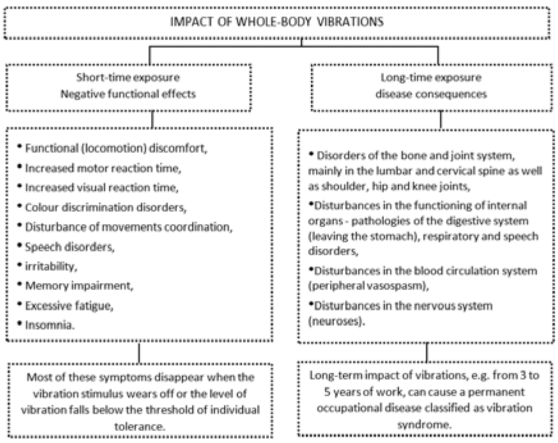

Figure 2. Effects of exposure to vibrations. Source: Own research based on [4].

The assessment can be made on the basis of calculated or measured quantities [9]:

– RMS value, e.g. vibration acceleration [m/s²], compiled in frequency ranges using weighting with correction filters (KB -filter for vibration on ships, or whole-body filters Wd & Wk), in 1/3 octave bands and compared with the values allowed by the standards for each frequency band; this way is called spectral estimation:

$$a_{w,rms} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt} \tag{1}$$

where the values are determined individually for each direction or vectorized for three directions in the Cartesian coordinate system,

– corrected value, e.g. vibration acceleration, calculated with the use of correction filters with parameters depending on the direction of vibration transmission, compared with the permissible value for each direction of vibration impact:

$$a_{xyz,w} = \sqrt{1,4(a_{x,w})^2 + 1,4(a_{y,w})^2 + (a_{z,w})^2} \quad (2)$$

– vibration dose [m^2/s^3], calculated from the weighted value of vibration acceleration:

$$D_d = \sum_{i=1}^{n} (a_{w,i})^2 t_i \quad (3)$$

– dosimetry vibration dose, calculated on the basis of the absorbed vibration dose during the exposure time, for each direction of vibration *k*:

$$a_{eq} = \sqrt{\frac{D_d}{T}} = \sqrt{\frac{1}{T}\int_0^T a_k^2(t)dt} \quad (4)$$

– energetic vibration dose [$m/s^{1.75}$] (vibration dose value) determined on the basis of weighted values of vibration acceleration according to the relation:

$$VDV = \sqrt[4]{\int_0^T a_w^4(t)dt} \quad (5)$$

The main sources of vibration on sea vessels [10-16,24,25]:
– main engine and mechanical transmission assemblies,
– screw and drive shaft arrangement,
– engine exhaust system,
– combustion and electric motors
– exhaust systems of internal combustion engines,
– electricity generators,
– compressors, ventilation and air conditioning systems,
– flow installations,
– ship propellers (propellers and thrusters),
– propeller unbalance: dynamic, hydrodynamic, static,
– machines and auxiliary devices,
– the undulation of the sea.

The processes caused by the interaction of the ship's elements, the operation of equipment, including the ship's engine room and on-board equipment, should be considered from the point of view of the dynamic impact and physical phenomena accompanying material propagation [8,14,16]. Working devices and machines have different masses, geometry, specificity of periodicity of work (continuous, cyclical, sporadic). The operation of the main engine causes the formation of inertia forces, as a result of the displacement of the crank mechanism masses, centrifugal forces, as a result of the rotational movement of the crankshaft and the mass of the connecting rod, forces resulting from the combustion process of the mixture in the cylinders. Vibration levels on vessels affect the health of the crew, the safety of navigation and the durability and reliability of on-board machinery [17]. Vibrations of machines and devices mounted to the ship's structure are a source of material noise, and the sound emitted is transmitted through thin-walled partitions, e.g. through walls, floors and ceilings in rooms as well as bulkheads and structure reinforcements. Vibrations can cause: damage to the structure, reduction of its durability due to fatigue of materials, inefficiency, nuisance or even threat to the crew, they are a source of noise. Noise and vibration verification measurements should be performed accordingly to various standards: ISO 6954, IMO 468, MSC 337, MLC 2006, and industry standards such as ISO 10816 [5].

In addition, local noise or vibration exposure standards apply and should be followed. The permissible values for exposure to mechanical vibrations (resulting from the regulation on the highest permissible intensity) in Polish conditions for general vibrations are [18,19]:
– daytime exposure A.(8) - 2.8 m/s^2,
– exposure up to 30 minutes A.(0.5) - 11.2 m/s^2,
– action threshold value A.(8) - 2.5 m/s^2.

It should be noted that the daily exposure time may be much longer than 8 hours (e.g. 12h, i.e. 720 min) and then the value measured for evaluation is increased by the component resulting from the correction for the exposure time. Measurements of vibration at constant speed, allows to verify the compliance with applicable vibration standards with respect to local sources of vibration.

Standard operating practices, applied by operators, allows to evaluate effects of tools, and equipment used on the ship, and assess processes to determine hazardous vibration (sometimes resulting in hand-arm vibration syndrome), as well as providing guidance of measures from the viewpoint of eliminating, or reducing the effects of hazardous vibration. Hand-arm vibration syndrome (HAVS) is the effect of regular exposure to hand-arm vibration, and may result as a result of injuries to the hands and arms, such as typical physiological effect symptoms: blood circulatory system (white fingers), coldness, sensory nerves numbness, pain in muscles wrist area, grip strength loss, pain inside bones and joints, loss of grip strength etc. In order to prevent protection against local vibrations, questionnaires are carried out among employees who use vibration tools at work, and the questions contained in them clarify the issues of feeling in the fingers, feeling of coldness, pricking and tingling, behaviour of the wrist muscles, forearm, joint, or problems related to grasping and lifting objects [8,20].

In the case of whole-body vibration, International Standard ISO 6954:2000, gives the guidelines for evaluating the habitability of different areas on a ship, based on evaluation the frequency-weighted r.m.s. vibration values [22]. This Standard also includes requirements in fields: instrumentation, procedures, analysis descriptions, and evaluation procedure, for different type of ship specification, various areas of a ship, accordingly to 1-80 Hz frequency range. Table 1 shows the limit values according to the mentioned standard.

Table 1. Overall frequency-weighted $a_{w,\,r.m.s.}$ values from 1-80 Hz, given as guidelines for the habitability of different areas on a ship [22].

Rooms and spaces	Low RMS level, [m/s²]	Maximum RMS level, [m/s2]
Passenger cabins	0.0715	0.143
Crew accomodation areas	0.107	0.214
Working areas	0.143	0.286

In this case, the frequency weighting procedure is the combined frequency weighting, as defined in ISO 2631-2. Guidelines for the values in Table 1, should be understood as upper and lower limit values, which adverse comments are probable, and values below which adverse comments are not probable.

The question is how can we show that we are truly committed to combating noise and vibration on board ships. The Maritime Labor Convention (MLC) [5] approaches to the assessment of vibrations on ships is slightly different. Table 2 presented approach according to Guide for Compliance with the ILO Maritime Labour Convention 2006 (Requirements, ABS, 2014b), and Guide for Crew Habitability on Ships (ABS, 2013) [6].

Table 2. Maximum aw, rms values, based on [6].

Rooms and spaces	Freq. range	Maximum RMS Level, [m/s²]
MLC-accomodation	1-80 Hz	0.214
HAB	1-80 Hz	0.178
HAB+	1-80 Hz	0.143
HAB++	1-80 Hz	0.107

With regard to noise and vibration, DNV Class offers three voluntary class notations: Comfort, vibration of machinery/equipment and underwater noise. The Comfort Class is a systematic evaluation of the comfort on board different ship types. A rating from 1 to 3 reflects “high” to “acceptable” comfort standards. The DNV Vibration Class includes procedures for where and how to measure vibration levels on different machinery, equipment and structures. It is based on values gained through numerous measurements. Ships meeting the requirements will be assigned class notation VIBR. Most of the new generation DP-Class Shuttle (i.e. Beathuk Spirit, IMO No. 9780768 & Dorset Spirit, IMO No.: 9780782) are assigned as a DNV class notation COMF-V for noise and vibration and COMF-C for indoor climate. Both ships operate in the Arctic region in the Canadian offshore sector. The maximum accelerations recorded for these two new generation vessels under dynamic positioning mode were slightly higher for MLC-accom. than the maximum acceptable level (0.214 [m/s²]) and were recorded up to max. level 0.286 [m/s²].

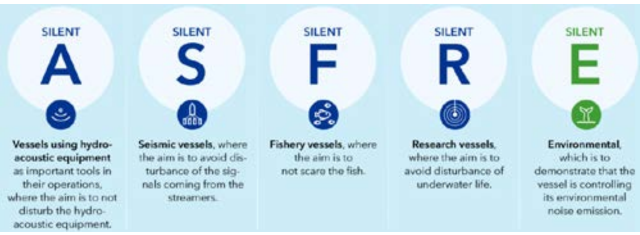

Figure 3. DNV’s different SILENT class notations. Source: DNV Website [6].

DNV [6] was the first classification society to offer an underwater noise notation to ships which do not exceed average to moderate underwater radiation noise (URN) levels. Until recently the DNV SILENT class notation was mostly requested for scientific research vessels, fishing vessels and cruise ships expecting to operate in pristine sea areas. However, MT ONEX Peace, an Aframax tanker built by Hyundai Samho Heavy Industries (HSHI), in June 2021 [6] has become the world’s first merchant vessel to receive DNV’s SILENT-E notation. In such case, Hyundai Heavy Industries has proved its capability to build a high-quality ship with improved fuel efficiency while satisfying eco-friendly underwater noise standards. Currently, we can expect that the topic of reducing vibration and underwater noise will become more important in the marine industry.

2.2 *Noise sources, survey and selected results*

Noise is defined as unwanted sound that may damage a person's hearing. The amount of damage caused by noise depends on the total amount received over time. The degree of risk is affected by the intensity (loudness) and the frequency (pitch) of the noise, as well as the duration and pattern of exposure and the individual's susceptibility to hearing impairment [20,21]. In fact, all ships owners are committed to aim to minimize the generation and emission of noise that lie within the scope of ALARP (as low as reasonably practical), and to set goals for peak and daily noise exposure levels at work. Seafarers usually monitor noise exposure by recording noise in the daily/monthly noise log to identify and, where possible, correct high noise trends. In offshore industry on all new generation DP-Class shuttle tankers and all floating storage and offshore loading units (FSO) the audiometric testing equipment (which must comply with noise standards as per the National Code of Practice) is always available to all crew members. The familiarization process for new crew members on board includes the formal introduction of the Noise Control Policy and the Noise Management Plan [17, 24]. Each new generation shuttle tanker with COMFORT class notation for noise and vibration has also its own ship-specific Noise Management Plan. Contractors are to comply with the noise standards as per the National Code of Practice [17].

The unit of sound level and noise exposure measurement is the Decibel (dB) and is expressed using an algorithmic scale. When considering the effect on human hearing, the A-weighted decibel dB(A) unit is used. This takes account of the response of the ear to different frequencies. As the scale of noise measurement is algorithmic, an increase of 3 dB(A) is a doubling of sound levels. There is a simple guide to indicate whether there may be noise levels with potential for causing hearing damage. If you need to shout to be heard by someone about 2 meters away the probable noise level is likely to be 85 dB. On all new generation shuttle tankers employers must prevent risks to their workers from exposure to excessive noise. ’Excessive noise’ as specified in European Union Directive 2003/10/EC (2003) as well as in NOPSEMA Regulations (2006) means a level of noise above 85 dB(A) averaged over an 8 hours’ period for noise exposure referenced to 20 micro

Pascal's (LAeq,8h); or LCpeak of 140 dB(C) - that is, a C-weighted peak sound pressure level of 140 dB(C) referenced to 20 micro pascals. The influence of vibrations on humans is shown in Figure 4 [4,21].

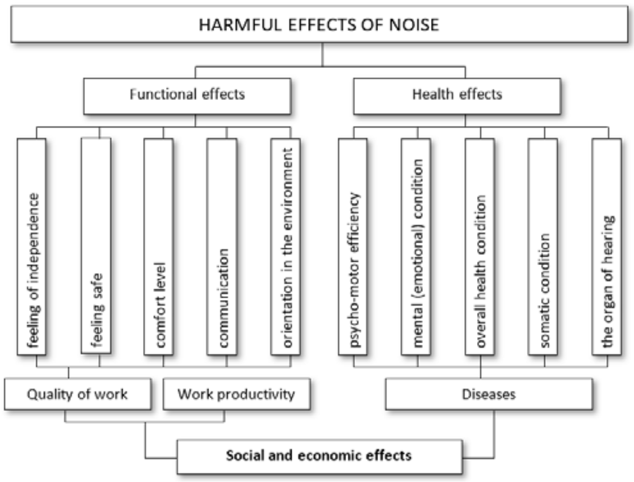

Figure 4. Effects of short and long-term exposure to noise. Source: Own research based on [4].

The parameters to be assessed during the noise impact test are: duration of sound, average, maximum, peak, equivalent of sound pressure level, and level of exposure to noise. The sound pressure level is the logarithm of the ratio of the sound pressure to the reference pressure:

$$L_p = 20\log\frac{p}{p_0}, dB \tag{6}$$

where:
p – measured value of the sound pressure in Pa,
p_0 – reference pressure, p0 = 20 μPa (lower limit of audibility of the human ears).

The sound pressure level measured at a given unit of time is called the instantaneous sound level and is often called SPL (Sound Pressure Level). The equivalent sound level LAeq characterizes an average noise, and it expresses the same energy and at the same time the same risk of hearing damage as measured noise with varying levels. The equivalent level is given by the formula 7 for group of sources or 3 for single source of noise [15,19]:

$$L_{AeqT} = 10\log\left[\frac{1}{T}\sum_{i=1}^{n} t_i \cdot 10^{0,1L_{Ai}}\right] \tag{7}$$

or

$$L_{Aeq,Te} = 10\log\left[\frac{1}{T_e}\int_0^{T_e}\left(\frac{p_a(t)}{p_0}\right)^2 dt\right] \tag{3}$$

where:
$L_{Aeq.T}$ – equivalent A-weighted sound level for the assessment time T,
L_{Ai} – sound level operating at time t_i,
t_i – L_{Ai} level sound duration,
p_a – measured value of the sound pressure in Pa,
T – whole time of work,
T_e - noise exposition time, T_e=8h.

Described below a fragment of the code was written in the Matlab language environment, to calculate the risk of exposure to noise, in accordance to the procedure proposed by the Central Institute for Labour Protection (CIfLP)[19].

```
T=8;                          %8 hours working shift
Te=input('Te= ');             %exposition time
LAeqTe=input('LAeqTe= ');     %equivalent sound pressure
    level
LAmax=input('LAmax= ');       %maximum level, with A-
    characteristics
LCpeak=input('LCpeak= ');     %peak level, with C-
    characteristics
Lex8h=LAeqTe+10*log(Te/T);    %8h exposition level
if ((Lex8h>85)||(LAmax>115)||(Lex8h>135))
        Risk='HIGH';          %non-acceptable levels
elseif ((Lex8<=80) && (LAmax<=109) && (Lex8h<=129))
        Risk='SMALL';             %acceptable levels
else
        Risk=AVERAGE;
end
```

This approach is based on the values characterizing noise in the working environment and the values of the highest permissible intensity (in polish called NDN) for these values [22]. Noise in the working environment is characterized by:
– the level of exposure related to the 8-hour daily working time (LEX.8h),
– maximum sound level A (LAmax),
– peak sound level C (LCpeak).

In this paper we are going to describe a typical procedure connected to noise and vibration awareness on new generation shuttle tankers taking into consideration the best practices observed on MT Beathuk Spirit (IMO No. 9780768) & MT Dorset Spirit (IMO No.: 9780782), which operate in Arctic zone in Canadian sector offshore. Both new generation shuttle tankers are under Altera Infrastructure (ex Teekay) Norway management system, following same safety procedure and in most cases also using the same standard personal protective equipment (PPE) and same machinery on board. On both shuttle tankers ships staff monitor noise exposure by recording noise in the daily/monthly noise log to identify and, where possible, correct high noise trends. In some cases, if needed, the occupational noise survey can be carried out by external company (e.g. [24]). In all our cases surveys were conducted to prevent health impact and hearing damage at plan approval, sea trails and after major modifications. The noise levels were recorded and analyzed by using B&K sound level meter, and the evaluation of comfort rating were based on noise measurements in cabins, public places and working places. Figures 5-11 show the noise levels during the sea trial, compiled for individual occupied zones.

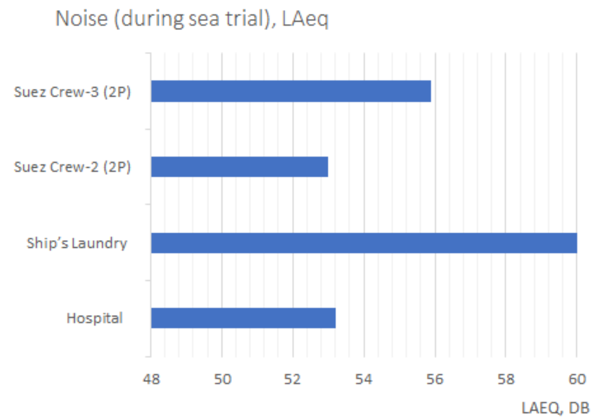

Figure 5. Noise level during sea trial, location: Upper-Deck.

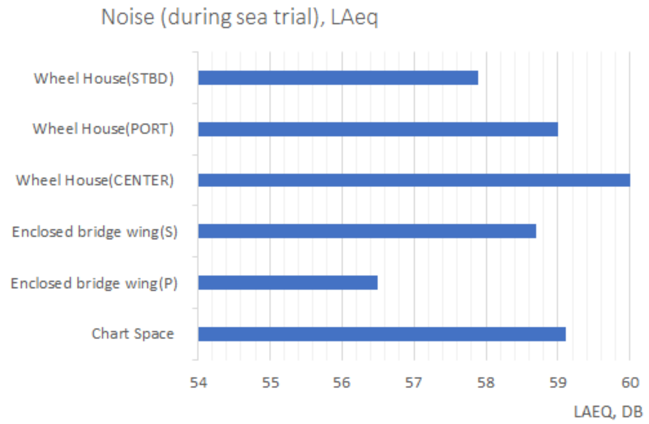

Figure 6. Noise level during sea trial, location: Navi-Deck.

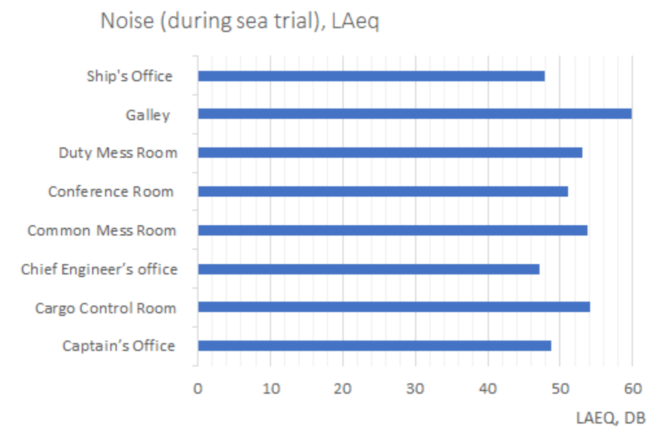

Figure 6. Noise level during sea trial, location: A-Deck.

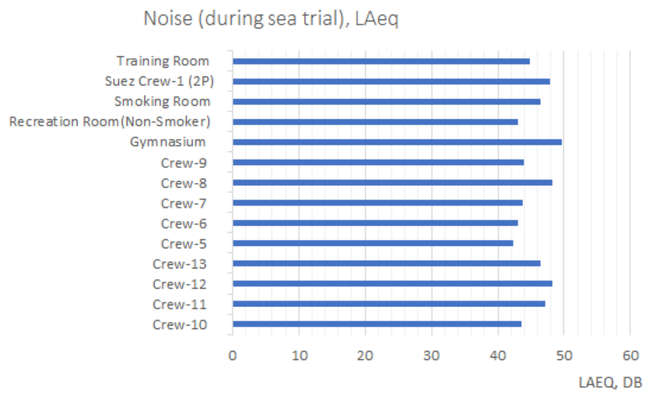

Figure 7. Noise level during sea trial, location: B-Deck.

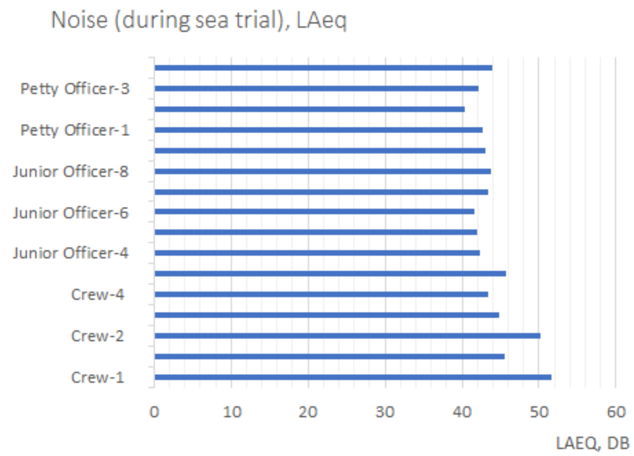

Figure 8. Noise level during sea trial, location: C-Deck.

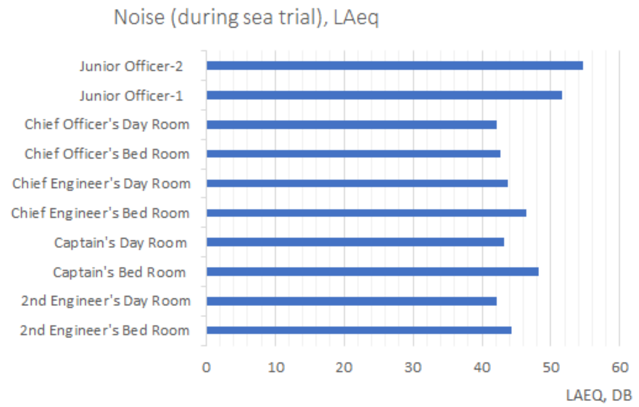

Figure 9. Noise level during sea trial, location: D-Deck.

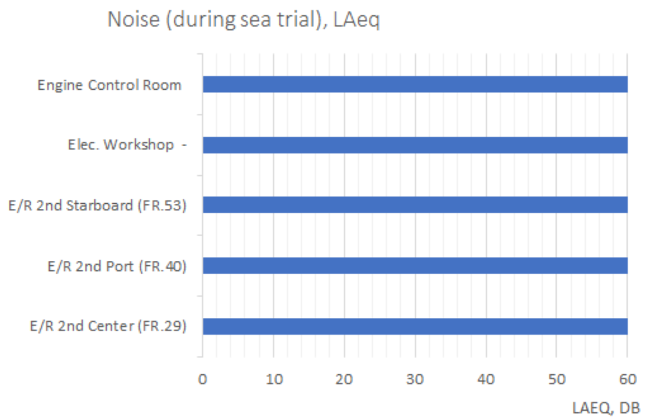

Figure 10. Noise level during sea trial, location: 2nd-Deck.

During the study [23], noise levels were measured to identify equipment and operations which have the potential to cause exposure standard to be exceeded; measure the average noise levels; specify areas where the average sound pressures level (L_{Aeq}) exceeds 85 dB(A) or the peak noise level exceeds 140dB(C) or 135 dB(C) for CIfLP procedure; evaluate noise exposures so that personnel exposed to noise levels; evaluate the suitability of the personal hearing protectors already in use and of alternative protectors if required; inspect noise sources and areas that contribute most to personnel noise exposure; detect noisy equipment and processes; measure noise frequency spectrum of sources noisy processes; measure octave band noise spectrum for noisy equipment and processes, for assessment of hearing protectors; prepare a hearing protection audit; and more. Table 3 presents the list of permissible noise level values.

Table 3. Noise level limits [23]

Rooms and spaces	Limit, dB(A)
Machinery spaces	110
Machinery control rooms	75
Workshops	85
other work areas	85
Navigating bridge	65
Look-out posts	70
Radio rooms	60
Cabins	55
Hospitals	55
Mess rooms	60
Recreation rooms	60
Offices	60
Galleys	75
Serveries, pantries	75
Unoccupied spaces	90

Code on Noise Levels on Board Ships (IMO, 2012) showed approaches to the assessment of noise on ships, which is presented Table 4 [8].

Table 4. Noise level on board ships [8].

Rooms and spaces	Ship size	
	1,600 – 10,000 GT	Above 10,000 GT
Cabin and hospitals	60 dB(A)	55 dB(A)
Mess rooms	65 dB(A)	60 dB(A)
Recreation rooms	65 dB(A)	60 dB(A)
External recreation areas	75 dB(A)	75 dB(A)
Offices	65 dB(A)	60 dB(A)

3 CONCLUSIONS

The article presents the methods of assessing the impact of vibration and noise on humans in terms of occupational exposure to these physical factors. The approach to assessing occupational exposure to vibration and noise is varied, despite the applicable ISO standards and local standards in the shipowner's country. A review of the literature shows that the limit values and level classifications are similar or based on the same ISO standards.

The exemplary results of noise exposure tests presented in the work allow to conclude that, apart from the 2nd-Deck, laundry, center of wheel house on Navi-deck, and gallery on A-Deck, no exceedances of 60 dB(A) occurred, and these that occurred were minor. Exceeding the limit values for cabins and hospitals, mess rooms, recreation rooms, external recreation areas, and offices - did not occur on the analyzed vessel.

Summing up, it can be stated that both MT Beathuk Spirit (IMO No. 9780768) & MT Dorset Spirit (IMO No. 9780782) as a new generation shuttle tanker that operate in the Arctic region meet the DNV Comfort class notation regarding noise and vibration. However, the level of noise and vibration recorded on these ships is too high for these ships to be classified as DNV Silent notation. Silent A class notation is designated for vessels using hydroacoustic equipment as important tools in their operations, where the aim is to not disturb the hydroacoustic equipment. Seismic vessels, were the aim is to avoid disturbance of the signals coming from the streamers can be classified as a SILENT S ships. Fishery vessels, where the aim is to not scare the fish can request for DNV SILENT F notation. Research vessels, where the aim is to avoid disturbance of underwater life can be nominated as a SILENT R ships. The highest SILENT E (Environmental) DNV class notation is designated for ship, which is to demonstrate that the vessel is controlling its environmental noise emission.

MT ONEX Peace, an Aframax tanker built in June 2021 by Hyundai Samho Heavy Industries [6] has become the world's first merchant vessel to receive DNV's SILENT-E notation. It means that Hyundai Heavy Industries has proved its capability to build a high-quality ship with improved fuel efficiency while satisfying eco-friendly underwater noise standards. We can expect that the subject of underwater noise reduction to become more prominent in the maritime industry, in strengthen research and development on low-noise eco-friendly green ships.

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