An analysis of whole-body vibration and hand-arm vibration exposure on the Danube ship crew

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Abstract. This paper studies the WBV and HAV exposure on the crew members of river ships. All parameters (acceleration, frequency, exposure duration, etc) negatively influence the performance of the sailing staff. In order to study how the sum of these physical parameters affect people’s work, a full analysis was made on 11 subjects, on 2 river ships, navigating the Romanian Danube area in January 2019. The vibrations transmitted to the subjects were measured with Maestro 01dB. Also, the meteorological parameters were measured with the Kestrel 5000 Portable Weather Station. All parameters were measured on the main deck. Specific questionnaires were used to detect the negative influence of the transmitted vibrations. Subjects are aged between 42 and 61 years old, most of them are smokers and some of them have health problems. According to ISO 20283-5:2016, ISO 8041:2005, ISO 6954:2000, ISO 2631:2018 and Guide for crew habitability on ships: 2016, there are the following stipulated values for work spaces: maximum RMS level must be 0.214 m/s² (for habitability criteria HAB), 0.178 m/s² (for HAB +) and 0.143 m/s² (for HAB ++). Mean values measured for the whole body vibration were 1.2÷1.4 m/s². The average values of the weather parameters, during the entire route, were normal for this period: temperature -11÷4°C, atmospheric pressure 970÷1015 mbar, humidity 75÷80%, wind speed 10÷30 km/h; visibility 1 km, but the extremely dense fog persisted 86.66% of the time. The questionnaire responses showed the presence of musculoskeletal problems in a vibratory environment. Working on a ship is extremely difficult, especially in unfavorable weather conditions. Low temperatures amplify the negative effects of vibrations. It has been found that the values provided by all ISO are far exceeded. Moreover, due to the fact that most ships are old, their operation generates vibrations harmful to physical health. For this reason, a renewal of the fleet is necessary.

1. Introduction
Nowadays, when trying to obtain the highest speeds and powers, while designing a ship, three aspects need to be considered: a) Testing the suggested model; b) Calculation required to complete the ship and c) Analysis of the methods used, to discover new knowledge.

Most of the time, the first aspect is omitted because of high costs. In order to achieve an optimum environment for the crew while working as well as while resting, it is not enough to meet certain criteria given by the current standards. These criteria must be merged in the entire process of designing a ship; therefore the vibrations transmitted by equipment and settings must be taken into account even from the design stage of the ship; they should not be treated separately, only as a consequence of this design.

On a ship, there are a number of vibration generators: the engines (most often Diesel engines), the shaft line, the propeller, etc. Additionally, must be considered the air conditioning systems, the handling systems, the cargo handling, and so on [1-3].
Carlton and Fitzsimmons (2004) [4] have resorted to a phenomenological approach while studying the noise and vibrations produced by propellers; they have tried a practical method to reduce testing time directly at sea or docking downtime. They have experimentally proven that, in relation to Fourier transformation, "wavelet methods and the double integral technique have been shown to have some advantages".

Another disturbing aspect for the people on board are shocks: they can lead to resonance phenomena in the ship [5].

These phenomena vary with the speed of the ship and also depend on the magnitude of the waves, as well as if the ship touches the ground (for a small water depth) [2].

1.1. Habitability Criteria
In 1984, ISO 6954 was introduced on the maximum allowable vibration for seafarers. These values must take into account a number of elements: age, health, sex, etc. Each person reacts differently to the cumulative stressors [6]. This standard analyzed the effects of vibrations ranging from 5÷100Hz so that the maximum of 4mm/s (for the No Complaints Expected zone) is not exceeded. Above these values, studies were performed until the value of 9 mm/s (maximum limit) was reached. In 2000, ISO 6954 was modified and adapted to passenger areas as well. In addition to 1984, the frequency range was changed to 1÷80Hz for speeds and accelerations, to which a conversion factor Cf was added to the peak values. "Cf is equivalent to a crest factor and if not determined by measurement, by finding the ratio of true peak to r.m.s value, should be assumed to have a value of 1.8" [2] (figure 1).

Unfortunately, there is not much reference in the specialty literature to vibration peaks in river navigation in general and on the Danube in particular. [7-15]. For this reason, this paper will study the vibrations on 2 merchant ships.

According to ISO 20283-5:2016, ISO 8041:2017, ISO 6954:2000, ISO 2631-4:2001 and to the Guide to Crew Habitability on Ships:2016 [16-20], only WBV acceleration values are considered; never referring to HAV. In this paper, we will consider HAV, in addition to WBV, as well as other parameters that contribute to the decrease in comfort, and in performance implicitly, of the crew members of river ships.

1.2. Objective
This paper explores how WBV (Whole-body Vibrations) and HAV (Hand-arm Vibrations) negatively influence the performance of crew members of river ships.
2. Materials and methods
In order to study how the sum of these physical parameters, cumulated with the personal characteristics of each crew member, affect people’s work, a full analysis was made on 11 subjects, on 2 river ships, navigating the Romanian Danube sector in January 2019.

The following physical quantities were measured (all parameters were measured on the main deck):
- The personal characteristics of each crew member (table 1);
- The meteorological parameters with the Kestrel 5000 Portable Weather Station;
- Whole body vibrations (WBV) with Maestro 01dB (figure 2);
- Hand-arm vibration (HAV) with Maestro 01dB (figure 3).

| Subject | BMI\(^\text{a}\) | Age (years) | Smoker | Drinkers\(^\text{b}\) | Seniority (years) | Cardio-vascular problems | Personal problems |
|---------|-----------------|-------------|--------|-----------------|------------------|-------------------------|------------------|
| 1       | 31.4            | 45          | Yes    | Yes             | 21               | x                       | x                |
| 2       | 29.8            | 58          | Yes    | Yes             | 38               | x                       | x                |
| 3       | 31.2            | 61          | Yes    | -               | 41               | x                       | x                |
| 4       | 25.6            | 51          | -      | -               | 35               | x                       | x                |
| 5       | 28.8            | 59          | Yes    | -               | 33               | x                       | x                |
| 6       | 31.7            | 42          | -      | -               | 20               |                         |                  |
| 7       | 32.6            | 49          | -      | -               | 25               |                         |                  |
| 8       | 29.1            | 55          | Yes    | -               | 24               | x                       | x                |
| 9       | 26.4            | 47          | Yes    | Yes             | 23               |                         |                  |
| 10      | 23.6            | 47          | Yes    | -               | 22               |                         |                  |
| 11      | 27.8            | 51          | Yes    | Yes             | 31               | x                       | x                |

\(^\text{a}\)Overweight = 25–29.9, Obesity = 30 or greater
\(^\text{b}\)More than 2 glasses of wine/day

The NC (comfort note) was calculated and then compared to the comfort level (determined with the Likert scale) (table 2). This comfort level was described with the Likert scale, for all subjects, and for all stressors. This scale is subjective because each person reacts differently to the same type of stressor. The format of a typical five-level Likert item, for example, could be:

| Points |
|--------|
| Strongly discomfort | 1 |
| Discomfort | 2 |
| Neither discomfort nor comfort | 3 |
| Comfort | 4 |
| Strongly comfort | 5|

![Figure 2](image2.png) Measurement of whole body vibration.  
![Figure 3](image3.png) Measurement of hand-arm vibration.
2.1. Measurement of whole body vibration (WBV)

The evaluation of vibration should include measurements of acceleration mean square (r.m.s.) weighted, which is expressed in m/s\(^2\) for translational vibrations:

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

(1)

where \(a_w\) is the weighted average acceleration, \(a_{w}(t)\) weighted acceleration a function of time, T duration of measurement (s), (ISO 2631-1).

Acceleration r.m.s. weighted must be determined for each axis of translational vibrations. Evaluating the effect of vibration on health should be performed independently on each axis (SR ISO 2631-1:1997).

ISO 2631-1 Section 6 specifies an r.m.s. of acceleration, a based method of evaluation of ride comfort. The weighted r.m.s. acceleration (in m/s\(^2\)) of a discrete time-domain signal is given by:

\[
a_{r.m.s.} = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} a_w(n)^2}
\]

(2)

where \(a_w(n)\) is the \(n\)th sample of the weighted acceleration, and \(N\) is the total number of measurements. The crest factor is given by:

\[
CF = \frac{\text{max}(a_w)}{a_{w,r.m.s.}}
\]

(3)

This is calculated to determine the most appropriate method of analysis. If the crest factor is greater than 9 then be calculated, in addition to r.m.s. maximum value of transient vibration (MTVV) or vibration dose value (VDV); however, it is useful to calculate MTVV or VDV for measurements with crest factor under 9.

Note that ISO 2631-1 does not give a clear indication for interpreting the value MTVV.

The MTVV takes into account occasional shocks and transient vibration by use of an short integration time. The MTVV is defined as the maximum value of the r.m.s. weighted acceleration calculated over a short time period (integration time) as given, in the discrete time-domain, by Rimell and Mansfield [21]:

\[
\text{MTVV} = \max \left( \frac{1}{\tau} \int_{n=0}^{n_0} a_w(n)^2 \right) \quad (n_0 = 0, 1, 2, \ldots, N-1-\tau)
\]

(4)

where \(a_w(n)\) is the current sample of the weighted acceleration, \(\tau\) is the integration time and \(N\) is the total number of samples in the measurement. ISO 2631-1 recommends the use of 1 second as the integration time, i.e. in the discrete time-domain set \(\tau = f_s\), where \(f_s\) is the sampling frequency.

The VDV method uses the fourth power of the vibration magnitude, which is more sensitive to shocks than using the square as in the r.m.s. calculation. VDV (m/s\(^{1.75}\)) is given by:

\[
\text{VDV} = \left( \frac{1}{\nu_s} \sum_{n=0}^{N-1} a_w(n)^4 \right)^{1/4}
\]

(5)

where \(a_w(n)\) is the current sample of the weighted acceleration, \(\nu_s\) is the sampling frequency and \(N\) is the total number of samples in the measurement.

Dose:

\[
L_{eq} = 10 \cdot \log \left( \frac{1}{T} \int_0^T \left( \frac{a_{w}(t)}{10^{-6}} \right)^2 dt \right)
\]

(6)

where \(a_w(t)\) is the frequency weighted acceleration.

The individual axes may be combined to give a total weighted r.m.s. acceleration value, given as:
\[ a_w = \sqrt{\left(k_x^2 \cdot a_{wx}^2\right) + \left(k_y^2 \cdot a_{wy}^2\right) + \left(k_z^2 \cdot a_{wz}^2\right)} \]  

(7)

where \(a_{wx}\) is the weighted r.m.s. accelerations of the x-axis (similarly for y and z-axis) and \(k\) is the axis multiplier given in ISO 2631 [22].

According to table 1: Maximum Weighted Root-Mean-Square Acceleration Level for 1÷80 Hz, Section 3 Whole-Body Vibration, from the same guide, there are the following stipulated values for workspaces: maximum RMS level must be 0.214m/s² (for HAB), 0.178m/s² (for HAB +) and 0.143m/s² (for HAB ++).

The calculations were made with Whole body vibration Calculator – HSE.

2.2. Data processing

1. Root mean square average vibration (\(A_w\)) calculated at the floor:

\[ A_w = \left( \frac{1}{T} \int_{0}^{T} a_w(t) dt \right)^{1/2} \text{ (m/s}^2\text{)} \]  

(8)

2. Vibration dose value (VDV). This value is more sensitive to impulsive vibration and reflects the total, as opposed to average vibration:

\[ VDV = \left( \frac{1}{T} \int_{0}^{T} [a_w(t)]^4 dt \right)^{1/4} \text{ (m/s}^{1.75}\text{)} \]  

(9)

3. The time period needed to reach the value of the exposure which triggers the action (EAV) and the limit exposure value (ELV):

\[ T_{EAV A(8)} = \left( \frac{0.5}{A_w} \right)^2 \text{ (h)} \]  

(10)

\[ T_{ELV A(8)} = \left( \frac{1.15}{A_w} \right)^2 \text{ (h)} \]  

(11)

4. Comfort index: “Factorial analysis was used for the calculation of the effect of each factor on the comfort index”; Karakasis et al., [23] they have defined CI (table 3):

\[ \text{CI} = 1.25^{Z_2} \]  

(12)

\[ Z_2 = \frac{-0.06Z_i^2 + 1.6Z_i - 0.35}{Z_i - 1} \]  

(13)

\[ Z_i = \log(A_w) \]  

(14)

where \(A_w\) is the root mean square average vibration equation (8).

2.3. Measurement of hand-arm vibration (HAV)

Although this type of measurement is not foreseen in the current standards, we considered it necessary to check the level of vibrations transmitted to the hand-arm system as there are certain activities on ships that involve such a stressor. Inside the human hand are mechanoreceptors that react to vibrations of different frequencies (table 4) [24].

| Receptor  | Receptor Field | Density    | Cue                         |
|-----------|----------------|------------|-----------------------------|
| Merkel    | 2 mm           | \~100/cm²  | Skin Indention, Vibrations \~4 Hz |
| Ruffini   | 8 mm           | \~20/cm²   | Stretching                  |
| Meissner  | 5 mm           | \~150/cm²  | Velocity, Vibrations \~80 Hz |
| Pacini    | Palm / Finger  | \~20/cm²   | Acceleration, Vibrations \~40 to 500 Hz |
“Workers exposed regularly to excessive hand-arm-transmitted vibration may be suffer in the long term with disturbances to finger blood flow and to the neurological and locomotor functions of the hand and arm.”

“The daily vibration exposure, \( A(8) \), for a worker carrying out one process or operating one tool can be calculated from a magnitude and exposure time, using the equation:

\[
A(8) = a_{hv} \sqrt{\frac{T}{T_0}}
\]  

(15)

where \( a_{hv} \) is the vibration magnitude \( a_{hv} = \sqrt{\left(a_{hvx}^2\right) + \left(a_{hvz}^2\right) + \left(a_{hvz}^2\right)} \), \( T \) is the daily duration of exposure to the vibration magnitude \( ah \) and \( T_0 \) is the reference duration of 8 hours.”

The exposure action value is 2.5 m/s\(^2\) and exposure limit value is 5 m/s\(^2\) [25] [17].

The calculations were made with Hand-arm vibration calculator - HSE.

3. Results and discussions

The determinations were made in January 2019 for 6 days and a half, running 24 h/day, on a distance of 300 km upstream (Tulcea - Calarasi) and downstream, on the same distance (Calarasi - Tulcea), with two different ships. Ship 1 is older but has been repaired recently; ship 2 is newer. The main cities crossed are Galati (150km), Braila (170km) and Cernavoda (300km).

3.1. The personal characteristics of each crew member

Of the 11 subjects, 4 are obese, 6 are overweight and only one has the normal weight. Overweight people are more likely to get sick than normal weight. Of all subjects, 4 are 45-49 years of age, 3 are between 50-55 years of age, 2 are between 56-60 years of age and one of them is 61 years old. It is noted that the two crews are aging. Also, most sailors are smokers, and 4 of them drink more than 2 glasses of wine/day when they are not aboard the ship. Six of the subjects said they have cardiovascular problems and most of them have personal problems.
3.2. Measurement of meteorological parameters

During the period under review, the weather was extremely bad: the average temperature during the day was -3°C, with snow precipitation of about 25mm/day. To the cold felt, has also contributed the wind that blew constantly at speeds of 20÷30km/h and the humidity that was 75÷80%. The atmospheric pressure varied between 970-1015mbar (figure 4). A dense fog persisted throughout the course (figure 5).

3.3. Measurement of whole-body vibration (WBV)

Measurements of WBV were made on the main deck for all members of the two crews. The first ship has 6 members and the second ship has 5 members (presented in table 1). The results are shown in tables 5 and 6.

In order to better see the difference between the vibrations transmitted by the first ship as against the second one (neglecting for the moment the fact that the crew members have different characteristics), were plotted the five main physical quantities that characterize the whole body vibration: total exposure $A_{r.m.s.}$ (figure 6), total exposure VDV (figure 7), time to reach EAV / time to reach ELV (figure 8).

Assuming that we only refer to the HAB criteria (not HAB + and HAB ++), the maximum RMS level must be 0.214 m/s$^2$ [20].

ISO 2631/2018 states that:

| Exposure action value (EAV) | Exposure limit value (ELV) |
|-----------------------------|-----------------------------|
| 0.5 m/s$^2$ $A(8)$ r.m.s.   | 1.15 m/s$^2$ $A(8)$ r.m.s. |
| 9.1 m/s$^{1.75}$ VDV       | 21 m/s$^{1.75}$ VDV        |

Table 5. Measurement of whole-body vibration for ship 1.

| Subject | Vibration magnitude m/s$^2$ r.m.s. | Exposure duration | Total exposure $A(8)$ (m/s$^2$) | Total VDV (m/s$^{1.75}$) |
|---------|----------------------------------|-------------------|---------------------------------|--------------------------|
|         |                                  | hours minutes     |                                 |                          |
| 1       | 1.356                            | 2 5               | 17.7                            | 0.69                     |
| 2       | 1.257                            | 1 20              | 14.6                            | 0.51                     |
| 3       | 1.4                              | 1 10              | 15.8                            | 0.53                     |
| 4       | 1.322                            | 2 5               | 17.2                            | 0.67                     |
| 5       | 1.566                            | 2 30              | 21.4                            | 0.88                     |
| 6       | 1.354                            | 2 15              | 18.0                            | 0.72                     |

| Time to reach EAV | Time to reach EAV | Time to reach ELV |
|-------------------|-------------------|-------------------|
| VDV option        | $A(8)$ option     | $A(8)$ option only|
| 9.1 m/s$^{1.75}$ VDV | 0.5 m/s$^2$ A(8) | 1.15 m/s$^2$ A(8) |
| hours minutes     | hours minutes     | hours minutes     |
| 0 10              | 1 5               | 5 45              |
| 0 12              | 1 16              | 6 42              |
| 0 8               | 1 1               | 5 24              |
| 0 10              | 1 9               | 6 3               |
| 0 5               | 0 49              | 4 19              |
| 0 9               | 1 5               | 5 46              |

$A(8)$ (m/s$^2$) $= 1.321541$

$VDV (m/s^{1.75}) = 27.900342$
Table 6. Measurement of whole-body vibration for ship 2.

| Subject | Vibration magnitude m/s² r.m.s. | Exposure duration | Partial VDV m/s^{1.75} | Partial exposure m/s² A(8) |
|---------|---------------------------------|-------------------|-------------------------|---------------------------|
|         |                                 | hours minutes     |                         |                           |
| 7       | 1.4                             | 2 5               | 18.2                    | 0.71                      |
| 8       | 1.398                           | 1 20              | 16.3                    | 0.57                      |
| 9       | 1.211                           | 1 10              | 13.6                    | 0.46                      |
| 10      | 1.205                           | 2 5               | 15.7                    | 0.61                      |
| 11      | 1.364                           | 2 30              | 18.6                    | 0.76                      |

| Time to reach EAV (VDV option) | Time to reach EAV (A(8) option) | Time to reach ELV (A(8) option only) |
|--------------------------------|---------------------------------|---------------------------------------|
| 9.1 m/s^{1.75} VDV hours minutes | 0.5 m/s^{2} A(8) hours minutes | 1.15 m/s^{2} A(8) hours minutes |
| 0 10                            | 1 1                            | 5 24                                  |
| 0 8                             | 1 22                           | 7 13                                  |
| 0 14                            | 1 23                           | 7 17                                  |
| 0 9                             | 1 4                            | 5 41                                  |

| Total exposure A(8) (m/s²) | Total VDV (m/s^{1.75}) |
|---------------------------|------------------------|
| 1.417588                  | 25.089403              |

Figure 6. Total exposure Ar.m.s. for all subjects (●) versus the values stated by the Guide for crew habitability on ships/2016, (▬) and ISO 2631/2018: EAV (▬) and ELV (▬)

Figure 7. Total exposure VDV for ship 1 and 2 (█) versus the values stated by the Guide for crew habitability on ships/2016, (█) and ISO 2631/2018: EAV (█) and ELV (█)
For both the crew members on the first ship (Subjects 1–6) and the ones on the second ship (7–11), the calculated values for $A_{r.m.s.}$ are higher than those provided by ISO 2631/2018 as well as those stated in the Guide for crew habitability on ships/2016 (figure 6). Also, for VDV it is found that the values calculated for both ships are higher than those provided by Guide and ISO 2631 (figure 7). These values show that ship 2 generates lower vibrations than ship 1.

The curves in figure 8 are given by the equations:

$T_{EAV1}$:
$$y = 0.0291x^5 - 0.504x^4 + 3.28x^3 - 9.911x^2 + 13.609x - 5.4156$$

$T_{EAV2}$:
$$y = 0.0281x^4 - 0.392x^3 + 1.8177x^2 - 2.6945$$

$T_{ELV1}$:
$$y = 0.154x^5 - 2.6664x^4 + 17.351x^3 - 52.429x^2 + 71.993x - 28.649$$

$T_{ELV2}$:
$$y = 0.1488x^4 - 2.0739x^3 + 9.6157x^2 - 16.547x + 14.254$$

It is noted that for ship 1, the equations are 5-degree polynomial, and for ship 2, the equations are 4-degree polynomial; this difference results from the fact that the two vessels have different engines and structures.

Figure D.3, Exposure Points table (Guide to good practice on Whole-Body Vibration [26], page 46) shows that all subjects (1–11) are in the health hazard area (figure 9).

For both the crew members on the first ship (Subjects 1–6) and the ones on the second ship (7–11), the calculated values for $A_{r.m.s.}$ are higher than those provided by ISO 2631/2018 as well as those stated in the Guide for crew habitability on ships/2016 (figure 6). Also, for VDV it is found that the values calculated for both ships are higher than those provided by Guide and ISO 2631 (figure 7). These values show that ship 2 generates lower vibrations than ship 1.

The curves in figure 8 are given by the equations:

$T_{EAV1}$:
$$y = 0.0291x^5 - 0.504x^4 + 3.28x^3 - 9.911x^2 + 13.609x - 5.4156$$

$T_{EAV2}$:
$$y = 0.0281x^4 - 0.392x^3 + 1.8177x^2 - 2.6945$$

$T_{ELV1}$:
$$y = 0.154x^5 - 2.6664x^4 + 17.351x^3 - 52.429x^2 + 71.993x - 28.649$$

$T_{ELV2}$:
$$y = 0.1488x^4 - 2.0739x^3 + 9.6157x^2 - 16.547x + 14.254$$

It is noted that for ship 1, the equations are 5-degree polynomial, and for ship 2, the equations are 4-degree polynomial; this difference results from the fact that the two vessels have different engines and structures.

Figure D.3, Exposure Points table (Guide to good practice on Whole-Body Vibration [26], page 46) shows that all subjects (1–11) are in the health hazard area (figure 9).

![Figure 8. Difference between $T_{EAV}$ and $T_{ELV}$ for the two ships. (□) - $T_{EAV}$ for ship 1; (○) - $T_{EAV}$ for ship 2; (■) - $T_{ELV}$ for ship 1; (●) - $T_{ELV}$ for ship 2](image)

![Figure 9. Positioning of the $T_{ELV}$ values for each subject in „Exposure points table“](image)
3.4. Measurement of hand-arm vibration (HAV)

Although there is no navigation standard referring to HAV measurements, we considered it to be necessary because there are certain activities where there is a risk of increased vibration levels for the hand-arm system.

Measurement of HAV was made on the main deck for all members of the two crews. The results of the measured acceleration averages are shown in figure 10 (for ship 1) and in figure 11 (for ship 2) for 3 types of maneuvers: a) Moving away from the shore; b) Running; c) Mooring maneuver.

![Figure 10. Calculation of HAV specific physical quantities for ship 1.](image)

![Figure 11. Calculation of HAV specific physical quantities for ship 2.](image)

In these cases, it was considered an average of 5 h/day for the running ship. For ship 1, the daily exposure $A(8) = 2 \text{m/s}^2$ and below is written "WARNING" because it is close to $2.5 \text{ m/s}^2$ (EAV value). For ship 2, $A(8) = 1.9 \text{ m/s}^2$, meaning "Exposure likely to be below $2.5 \text{ m/s}^2$". These values confirm that ship 2 generates lower vibrations than ship 1.

Using equations (12), (13) and (14), the comfort index was calculated and graphically plotted (figure 12 - for ship 1 and figure 13 - ship 2).

It is found that the average of CI $\in (1; 2)$ and the graphics plotting indicates that the degree of discomfort is “Strong” for both ships (the values being approximately equal).

4. Conclusions

This cruise happened during very harsh weather conditions, and the cold feeling was amplified by the wind blowing strong. It snowed, sleet and the fog persisted most of the time. Crew members are aging, most of them being overweight and smokers; more than half of the subjects have cardiovascular problems. Also, the ships are not very modern, thus amplifying the vibrations transmitted to the crews. Thus, total exposure $A(8)$ (m/s$^2$) to WBV for the first ship are:
Figure 12. The dependence of the comfort index on the total acceleration transmitted to the subjects – for ship 1.

Figure 13. The dependence of the comfort index on the total acceleration transmitted to the subjects – for ship 2.

Figure 14. Subjects' perception on the discomfort created by vibrations from ship 1.

Figure 15. Subjects' perception on the discomfort created by vibrations from ship 2.
• 517.54% higher than HAB
• 164.31% higher than Exposure action value
• 14.91% higher than the Exposure limit value
and for the second ship are:
• 562.42% higher than HAB
• 183.51% higher than Exposure action value
• 23.26% higher than the Exposure limit value

With regard to HAV, the daily exposure A(8) (m/s²) for both ships is close to the EAV value = 2.5 m/s². The feeling of pain in the hands is also amplified by the fact that the entire ship’s equipment, which is touched, is frozen.

However, the subjects responded to the Likert item in an extremely optimistic manner. From calculations, the Comfort Index was equal to 1 (equivalent to "Strongly Discomfort") for both ships. The average of the subjects' responses on the two ships is around 3 (figures 14 and 15), which is equivalent to "Neither discomfort nor comfort". This may prove two scenarios: either people got used to these vibrations or do not feel them anymore, or they did not declare the truth for fear of losing their job, especially since they are no longer young so they could be able to find something better.

As anticipated, there are several vibrations that are transmitted through the hand-arm system as well and can become dangerous to people's health.

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