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I. Grushetsky

Krylov Shipbuilding Research Institute
44, Moskovskoe shosse, Saint Petersburg, 196158, Russia, e-mail: editor@ejta.org

Internal loss factors of ship structures and its application for computing vibration and noise

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Results of internal loss factors (ILF) measurements for different ship structures are presented. It is found that dispersion of ILF is quite large. Origin of dispersion is mainly random. Statistical properties of ILF as random value are evaluated on the basis of measurement results. Computational example for vibration propagation on ship-like structure is presented. At that Statistical Energy Analysis (SEA) and probabilistic approach are used. ILF, which are generated on the basis of statistical properties, are used as input data. Calculated results show possible dispersion of vibration of distant ship structures up to 7–10 dB. Appropriateness of probabilistic approach and approximate techniques for computing of vibration and noise on ships are justified.

INTRODUCTION

Statistical Energy Analysis (SEA) is usually used for computing of vibration and noise on ships [1, 2]. This approach is most suitable since the ship is a very complex structure consisting of a lot of components; and only approximated calculations are reasonable. Internal loss factors (ILF), coupling loss factors (CLF) and input powers injected from external sources (machinery and equipment) are used as input data in a set of energy balance equations. CLF and input power can be calculated analytically [3–8 et al.] or numerically [9–12 et al.]. ILF can be *only measured* in real conditions (the value which can be measured on ship is total loss factor (TLF), difference between ILF and TLF is explained in section 1.2). ILF for ship structures in a wide frequency range was found in a few works [5, 13][1]. But data is presented quite briefly and, by author's preliminary hypothesis, does not reflect in full measure possible variety of TLF which is caused by variety of ship structure. Therefore TLF measurements were carried out on a lot of different, but quite typical, structures. The results are presented in this paper. It was found, that ILF of ship structures are really different. On the basis of obtained data, probabilistic approach is suggested to use for computing vibration and noise on ships, considering ILF as random quantity. An example of computing is presented.

[1] Some information on measured TLF is presented in some other sources. But it is impossible to use these data in practical computing for some reasons. For example, TLF in [4] were obtained at some intermediate stage of ship building.

1. INTERNAL LOSS FACTORS OF SHIP STRUCTURES

1.1. Measurement technique

TLF of ship structures was determined using initial decay rate method. The technique, which was probably used M. Heckl for the first time [14], is similar to technique for determination of reverberation time in rooms. Lump hammer (5 kg weight) was used for structures excitation. TLF is calculated by formula $\eta = 2{,}2/fT$, where f — is the frequency, Hz; T — is the reverberation time, s. This technique is comparatively easy for application in real conditions and has some advantages in comparison with other techniques. In particular, well-known technique for TLF determination, which is based on a width of resonant peaks, is not effective when modal density is high and when peaks are not clearly defined (when TLF is high, what really occurs). Besides, calculations of vibration and noise on ships are carried out in frequency bands (octave or third-octave) and therefore we should have TLF in the same frequency bands. The technique, based on a width of resonant peaks, does not provide TLF in frequency bands directly. Other technique, based on energy conservation law (power injection technique [15 et al.]), requires too great number of measurements and therefore it is not suitable for real ship conditions.

We should note one disadvantage of initial decay rate method which is caused by manual analysis of decay curve and its approximation by straight line. In most cases, decay curve is complex, irregular and ambiguous, therefore subjective errors are quite possible[2]. Moreover, we can suggest that the subjective error is main component of total error. According to some studies [16], subjective error is comparable with objective error when reverberation time is measured in reverberation room. It occurs under the condition, that the decay curve in reverberation room is quite well-defined. Numerical assessment of subjective measurement errors is a topic of special study, which we did not carry out. To decrease errors, measurements with following averaging were done in several points and impacts were done in other several points. Positions of measurement and impact points were random. If dispersion of the results was too large (according to expert assessments) then additional measurements were carried out.

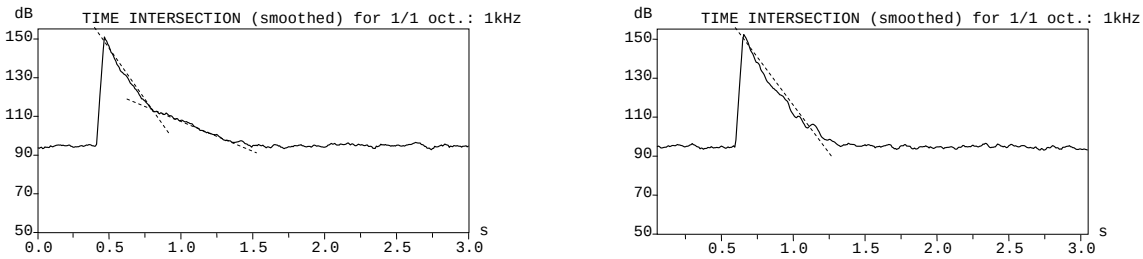
In some cases, decay curve could not be approximated accurate enough by only one straight line. Two or even three lines are required. The unique TLF corresponds to each line. It is usually considered that several different modes with different damping, which are in one frequency band, generate complex decay curve. Ship is a structure consisting of a lot of components therefore the process of complex decay curve generation has the feature, which is demonstrated below by an example of simple “box” model.

The “box” consists in metal plates 0.7 mm in thickness. Dimensions of side walls are 0,6×0,9 m, top wall — 0,6×0,6 m. TLF of “box” walls are different: TLF of side walls exceeds TLF of top wall. One can see two sections on decay curves for side walls in some frequency bands (fig. 1a). Decay curve for top wall can be approximated by only one straight line. Measured TLF are presented in fig. 2. One can see that TLF for side wall, which is obtained using the second section on decay curve, is approximately the same as TLF for top wall. The second section on decay curve for side wall disappears after top wall removing (fig. 1b).

[2] Automated processing for reverberation time determination, which is built in some devices, yields, as a rule, worse results in comparison with manual processing when curve decay is complex and ambiguous.

Obtained results can be explained in the following way. Vibration energy propagates over the "box" after impact. Vibration decay in side walls occurs faster. In some time point, vibration in side walls becomes caused by energy inflow from top wall, which has less damping.

The similar processes probably occur in ship structures. The section of decay curve, which goes after the initial one, can be caused by oscillations of adjoining structures if they have lower ILF. I.e. irregularity of decay curve for excited structure may be caused not only by different decay rate of different eigenmodes, but also by different decay rate of different structural components of ship, adjoining ones first of all.



a) b)

Fig. 1. Decay curve of side wall after impact:
a) "box" with top wall, b) "box" without top wall (octave band 1000 Hz)

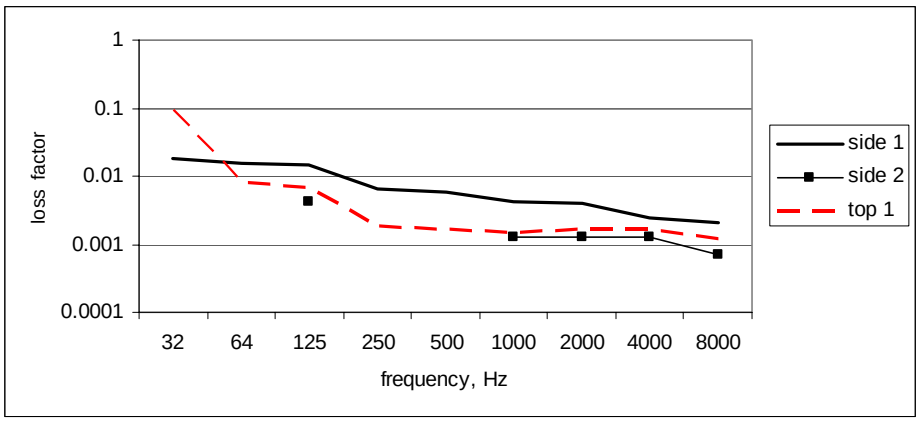


Fig. 2. TLF of side wall defined using initial section of decay curve ("side 1") and using next section ("side 2") and TLF of top wall ("top 1")

According to measurement results presented below, we can reveal (quite tentatively of course) two groups of structures: the structures with comparatively high and comparatively low TLF. Two or more sections on decay curve are typical for structures with comparatively high TLF first of all. Analysis confirms that the second (and the following) section on decay curve for structures with comparatively high TLF corresponds to vibration decay in structures with comparatively low TLF. Such vibration arises in structures with high TLF owing to reverse energy inflow from structures with low TLF after initial energy outflow from excited structure with high TLF.

Thus, TLF of excited structure should be defined on the basis of initial section of decay curve. TLF, presented in this paper, were defined exactly in the same way.

1.2. Physical meaning of measured TLF

Measured TLF (η_t) of structure, which is a component of a ship, is caused by internal losses in the structure (η_i — internal loss factor, ILF), by energy outflow out of the excited structure into adjoining structures (η_c) and by radiation losses (η_r):

$$\eta_t = \eta_i + \eta_c + \eta_r . \quad (1)$$

To evaluate components of TLF, besides measurements on completely built ship, measurements were carried out on a fragment of ship structure, suspended by means of portal crane, and on uncompleted ship, when structures have been already welded, but no equipment (machines, pipes, cables etc.) was fixed (ship on building berth). It was found that TLF of structures on completely built ship are significantly more than TLF of the same structures on uncompleted ship. The results of consecutive measurements for one of platform are presented in fig. 3 as an example.

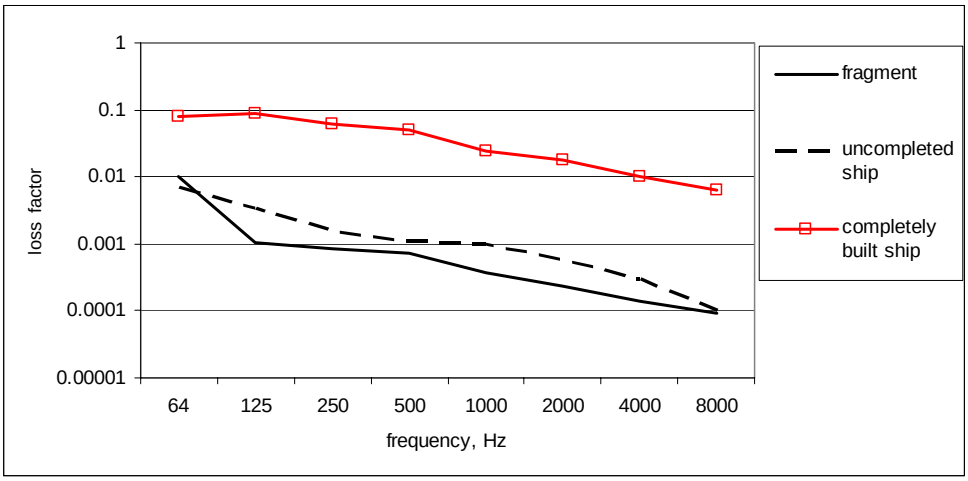


Fig. 3. TLF of platform at different stages of ship building

The measured TLF of fragment is caused by internal and radiation losses: $\eta_t = \eta_i + \eta_r$. When the fragment is fixed in the ship, TLF increases because of outflow appearing into adjoining structures (η_c). Internal (η_i) and radiation (η_r) losses do not change significantly. Next, along with increasing amount of equipment inside ship, ILF increases. At the same time relative energy outflow into adjoining structures and surrounding media remains approximately the same. Since TLF of structures of completely built ship is significantly more than TLF of structures on uncompleted and unequipped ship, we can be sure that TLF, measured on completely built ship, is fully caused by internal losses. I.e. measured TLF can be considered as ILF.

1.3. Measurement results

Measurements were carried out on ship 100 m in length and of 2 thousand tons displacement. ILF were obtained for 19 different ship structures: boards, bottom, inner bottom, platforms, decks, bulkheads, foundation, supporting frame. Properties of these structures (thickness, ribs, material: steel, aluminium, glass-fiber plastic) are different, some structures are coated by damping material, bottom and boards are in contact with water, different equipment, pipelines, electric cables, decorative coats etc. are fixed to most of structures. I.e. the structures differ in different features, which may influence significantly on losses. Indeed, one can see from measurement results, presented in fig. 4, that ILF of structures may differ by 10 times.

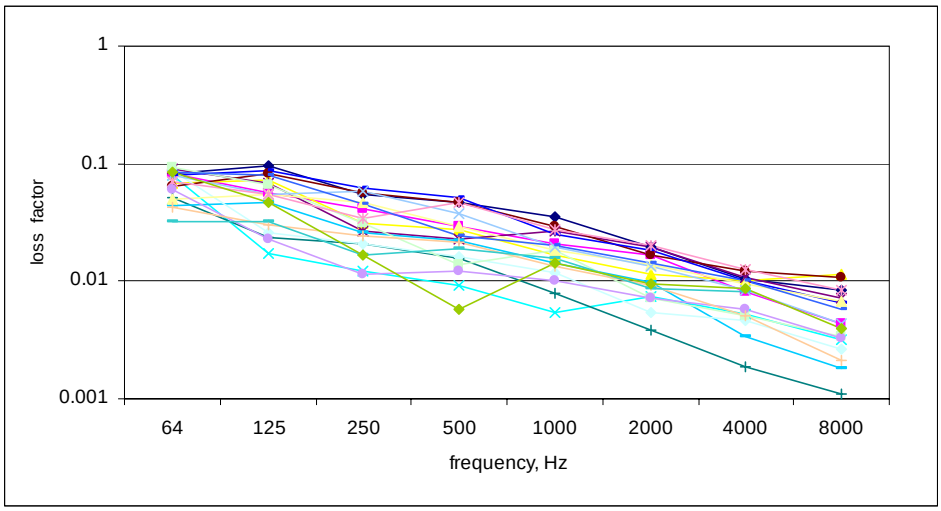


Fig. 4. ILF for 19 ship structures

Analysis of measurement results allows to reveal some general conformities. In particular, comparatively high ILF is peculiar to structures coated by damping materials and for horizontal structures (platforms, decks). ILF for other structures are comparatively low. Mean values of high and low ILF differ by 2–2.5 times.

Similar grading of ship structures agrees with that one that is suggested in [13], where the structures are divided into horizontal and vertical. It should be noted that the newly obtained results (averaged over the structures without coating) nearly coincide with results presented in [13] at frequencies 500–4000 Hz (fig. 5). It seems that these mean ILF are typical for most ships.

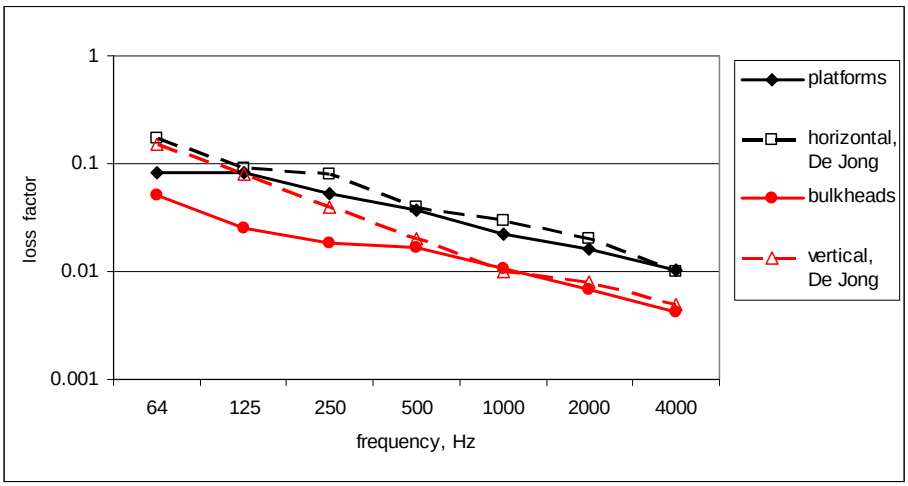


Fig. 5. ILF of platforms and bulkheads without coating and
ILF of horizontal and vertical ship components presented in [13] (De Jong)

Division of the structures into two large groups is relative. ILF may differ by 2-3 times and even more within each group. As an example, mean, maximal and minimal ILF for two mentioned groups are presented in fig. 6. It seems impossible to divide structures into more narrow groups using available information. Probably that influence of some structures features on ILF can be found under more detailed study. But it seems unreal to assign specific ILF for specific structure when computing of ship noise and vibration is carried out at design stage; some generalized data have to be used. Therefore obtained data is seemed sufficient for practical computing.

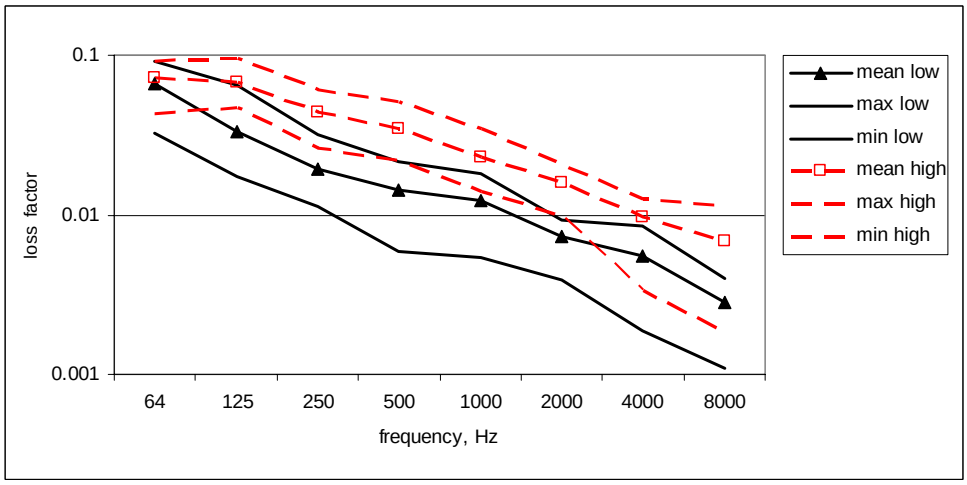


Fig. 6. ILF of two groups of ship structures: with relatively high and relatively low ILF
(mean, maximal and minimal values)

1.4. Application of measurement results

When ILF dispersion is so large, the computing that uses mean values as input data may yield the results which significantly differ from real (measured) values[3]. We may suppose that probabilistic approach for computing is more suitable. ILF should be considered as random value, which statistical properties can be defined from measuring data.

2. ILF STATISTICAL PROPERTIES

Quite suitable distribution law for measured ILF is normal distribution of logarithm ILF ($\lg \eta_i$). On the basis of this hypothesis and measured data, statistical properties of ILF (mean value and standard deviation) are defined. Using ILF statistical properties, one can generate random ILF for probabilistic computing of vibration and noise on ship. More correctly logarithms of ILF are generated, which are further converted into ILF by formula $\eta_{ig} = 10^{\lg \eta_{ig}}$ (index "*g*" means generated value). 500 random values of ILF in each octave band are presented in fig. 7 as an example. Statistical properties of generated assembly (mean value and confidence limits for confidence probability 0.95) and mean, maximal and minimal measured values are also presented in fig. 7. It can be seen that generated ILF correspond to measured ones.

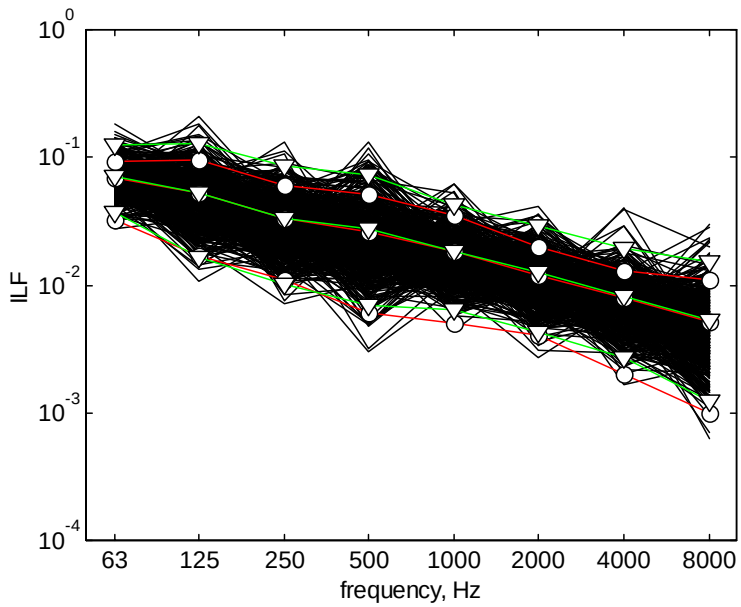


Fig. 7. Internal loss factors (ILF):

△ measured data (mean, maximal and minimal values);

—— generated values (in according to normal distribution law of $\lg \eta_i$, 500 random values in each octave band);

○ mean values of generated ILF and confidence limits for confidence probability 0.95

[3] Of course, there are other sources of errors, which are not considered here.

3. PROBABILISTIC COMPUTING OF SHIP STRUCTURE VIBRATION (EXAMPLE)

Let us consider possible dispersion of computed results, caused by uncertainty of ILF only. For that, computation example of vibration in ship-like structure is carried out.

Ship-like structure, consisting of 22 equal steel plates 3×3 m in size and 0.7 mm in thickness, presented in fig. 8a, is used for SEA calculations. Energy of external sources (W), which is equal to 1, is injected in plate (1). Coupling loss factors are calculated from known energy transmission coefficients via plate junctions, which are approximately equal to 0.5 for L-shaped junction, 0.2 — for T-shaped junction and 0.1 — for X-shaped junction. Energy propagation along structure is only considered, compartments are not included in a set of energy balance equations. ILF is random value excluding ILF of six gray flank plates (fig. 8a) which is fixed 0.9 in order to approximately simulate irreversible outflow out of considered fragment of ship.

The procedure is similar to that one, which was used in [17] for evaluation of CLF uncertainty influence.

1. Random ILF are generated for each subsystem.
2. Set of energy balance equations is solved for random assembly of input data.
3. This procedure is carried out many times.
4. On the basis of solutions assembly, statistical properties of calculation results are defined.

Vibration energy of plates 1, 2, 3 and 4 (see fig. 8a), calculated for 500 random sets of ILF, is presented in fig. 8b. Confidence intervals and width of confidence intervals are presented in fig. 8c and 8d correspondingly. It can be seen from the figure that the width of confidence intervals (the possible range of calculated vibration levels) runs up to 7–10 dB for distant plates (2, 3 and 4).

CONCLUSIONS

Internal loss factor (ILF) is one of the quantities used for vibration and noise computing carried out at ship designing. ILF can be obtained from measurements on real ship only. At that, known data on ILF of ship structures is quite limited. To obtain additional information, ILF were measured on a set of typical ship structures.

The main conclusion from measurement results is that the dispersion of ILF is significant: maximal and minimal measured ILF differ by 10 times. ILF depends on assemblage of numerous and quite uncertain factors. For example, ILF depends significantly on amount of different equipment, pipelines, electric cables, decorative coats, etc. which are fixed to most of ship structures and on fastening properties.

Analysis of all the data allows to reveal some general principles. In particular, higher ILF is typical for structures coated by damping materials and for horizontal structures (even if they are not covered by damping materials). ILF of such structures higher by 2–2.5 times than ILF of other structures. However ILF dispersion within these two groups is significant.

When ILF dispersion is significant and mainly random, it seems impossible to fix specific ILF for specific structure when computing is carried out at ship designing. Some mean values are used in practice. However, presented example of probabilistic SEA computing for ship

shows that dispersion of vibration for structures, distant from source of vibration, which is caused by uncertainty of ILF only, runs up to 7–10 dB. Uncertainty of other input data used in SEA (coupling loss factors, input power [17]) will lead to increasing of computing results dispersion.

Mean calculated results do not provide clear view on expected vibration and noise when dispersion of results is so large. Random approach for computing, when results are presented in the form of mean values and possible deviation, is more appropriated.

Expected large dispersion of calculated results is caused by real uncertainty of physical properties of ship structures, including ILF uncertainty discussed in this paper. The consequence from this fact is the fundamental impossibility to carry out any accurate calculations. Only approximate calculations, based on SEA for example, can be reasonable.

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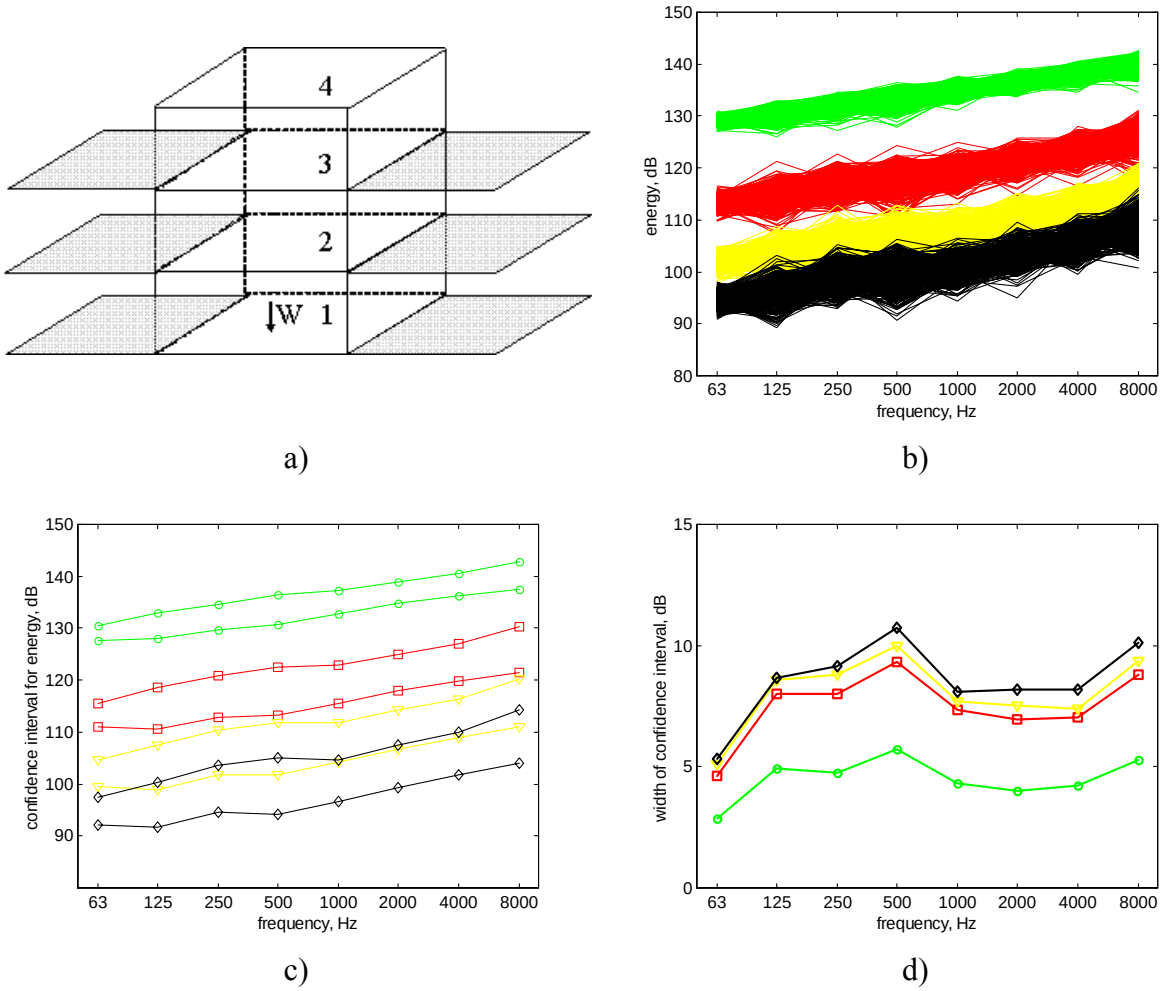

Fig. 8. Fragment of a ship-like structure for computational example (a) and vibration energy for plates 1 (green, ○), 2 (red, □), 3 (yellow, ▽), 4 (black, ◊):
b) all values, c) confidence intervals, d) width of confidence intervals

REFERENCES

1. Computing of noise levels in ship compartments. Techniques. (*in Russian*). OCT 5.0173-75, 1975.
2. «Designer Noise» (software for prediction noise levels on surface ship). Noise Control Engineering, Inc., USA.
3. Gutin L. Ya. Selected works. Leningrad, «Sudostroenie», 1977.
4. Nikiforov A. S., Budrin S.V. Propagation and absorption of vibration on ships. (*in Russian*). Leningrad, «Sudostroenie», 1968.
5. Boroditsky L. S., Spiridonov V. M. Structure borne noise control in ship compartments. (*in Russian*). Leningrad, «Sudostroenie», 1974.
6. Lyapunov V. T., Nikiforov A. S. Vibration insulation in ship structures (*in Russian*). Leningrad, «Sudostroenie», 1975.
7. Popkov V. I. Vibration diagnostics and decreasing of ship machinery. (*in Russian*). Leningrad, «Sudostroenie», 1974.
8. L. Cremer, M. Heckl, E. E. Ungar. Structure-Borne Sound, 2nd edition, Springer, Berlin, 1988.
9. I. Grushetsky, A. Smol'nikov. FEM application for calculation of coupling loss factors used in SEA, L-shaped beams case. Electronic Journal «Technical Acoustics», http://www.ejta.org, 2004, 6.
10. I. Grushetsky, A. Smol'nikov. Determination of coupling loss factors for two beams using FEM. Electronic Journal «Technical Acoustics», http://www.ejta.org, 2005, 24.
11. C. Simmons. Structure-borne sound transmission through plate junctions and estimates of SEA coupling loss factors using the finite element method. JSV. 1991, V. 144, pp. 215–227.
12. C. Hopkins. Statistical energy analysis of coupled plate systems with low modal density and low modal overlap. JSV. 2002, V. 251, No 2, pp. 193–214.
13. Richard G. De Jong. Statistical Energy Analysis of Ship Structure-borne Sound. Inter-Noise 2003, Seogwipo, Korea, August 25–28, 2003, paper № 121.
14. M. Heckl. Measurement of absorption coefficients on plates. JASA, 1962, 34(6), 803–808.
15. Brandon C. Bloss, Mohan D. Rao. Estimation of frequency-averaged loss factors by the power injection and the impulse response decay methods. J. Acoust. Soc. Am. 117 (1), January 2005.
16. Bogolepov I. I. Noise control in industry. (*in Russian*). Leningrad, «Sudostroenie», 1986.
17. I. Grushetsky, A. Smol'nikov. Computing of coupling loss factors using FEM, probabilistic approach. Electronic Journal «Technical Acoustics», http://www.ejta.org, 2006, 10.