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NOISE PREDICTION ON SHIPS

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This paper presents the results of the first stage of investigations aimed at the development of an effective method for predicting noise on ships. The results of measurements taken on Polish ships by the Technical and Research Department of the Maritime Institute under the departmental problems 103 and 104 were used. A statistical method of multiple linear regression was used for data processing. Calculated and measured results were compared. It has been shown that statistical methods are valid for predicting noise in the accomodation in the superstructure of a ship. The direction of further research, intended to improve the method presented, is defined.

1. Introduction

Noise control is particularly important on a ship where the crew not only work but also rest. The people on board a ship are exposed to much higher noise levels than are found in the conditions on land. It is most important to secure low noise levels in accomodations so as to assure good rest after work.

The permissible noise levels on sea-going merchant ships were established in Poland by the regulation of the Minister of Navigation on October 28, 1978. According to this regulation the noise level in accomodation on a ship should not exceed 60 dB(A). In practice this value is very often exceeded. The results of measurements of noise levels taken in 1360 accomodations on 45 ships of different types are shown in Fig. 1. It follows from this figure that the permissible noise level is exceeded in almost 30 percent of the accomodation.

It is difficult to solve the problem of excessive noise on a ship which is already operational. The possible effects achieved by improving the existing structures are usually incomparably small compared to the expense involved. Constructing a "silent" ship requires efforts towards noise reduction at the preliminary design stages. Noise level prediction in accomodation in the superstructure of a ship is difficult because of the complexity of the problem resulting from the existence of a large number of noise sources of differing characteristics and from a complex steel structure which is the propagation path of the sound

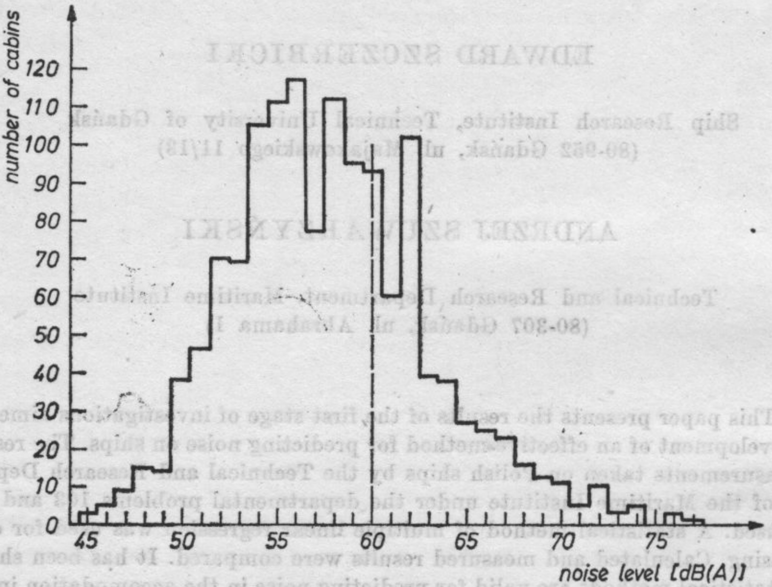

Fig. 1. The distribution of noise levels in accomodations in the ships of PLO and PŻM

The sources that determine noise in accomodation in the superstructure include: the main engine, the auxiliary engines, the gearbox and the screw propeller [1, 5]. There are a number of other sources such as ventilation systems, pumps, loading winches etc., but these are only important locally. The sound generated by the noise sources mentioned above is transmitted to accomodation in the superstructure, mainly by the structure of the ship in the form of longitudinal, torsional, transverse and flexural waves [6]. These wave motions are coupled, which makes it difficult to analyze them theoretically. Thus the methods for noise prediction given in the literature [1, 2, 5, 6, 7, 10] are based on a simplified model of sound propagation in the structure of a ship. It is generally assumed that one wave motion dominates and determines the flux of energy propagated [6]. A block diagram of the analysis of sound propagation in the structure of a ship, which is similar in all the known methods, consists of four stages [5]: determination of source strength, definition of propagation paths in the steel structure, determination of coupling between the steel structure and the cabin lining, and coupling between the cabin lining and the ambient air. Each stage is repeated for all the main noise sources (cf. [2, 10]). The total noise level in a given accomodation is obtained by summing the contribution of the individual sources.

The input data in the first stage, i.e. the levels of structureborne sound at the foundations of the machinery, are obtained, in the present methods, from measurements. These measurements are taken at experimental posts in a shipyard or onboard ships. There are also empirical formulae which permit the calculation of these values (e.g. in [1, 10]). The second stage requires information about the paths of sound propagation and the damping properties of the structure. These properties are usually determined by model investigations [5, 6] or exciter investigations on real objects [10]. For the third and fourth stages, the necessary data on the characteristics of the lining system can be obtained by laboratory investigations or from calculations.

The methods currently used for noise prediction cannot be regarded as methods for the calculation of the real noise levels in an accomodation; they can, however, be a source of valuable suggestions for the designer. As in all engineering calculations, noise prediction has a limited accuracy. The noise prediction programme developed by Det Norske Veritas assures an accuracy of 3-5 dB [6, 7]. Comparison of calculated results, obtained from an algorithm proposed by Buiten and Aartsen [1], with measured values showed that in 46 percent of the cases the difference in the levels of the estimated and the measured noise did not exceed 3 dB (A). The standard deviation of the difference between the measured and the calculated values did not exceed 4 dB (A).

The methods presented — of necessity only briefly — for noise level prediction are based on a simplified analytical model involving a number of empirical coefficients. Application of these methods at the stage of planining or preliminary designing can be very difficult in view of the lack of sufficient data, e.g. designs of: the steel structure, the arrangement of the machinery in the engine room, the linings, etc.. It is therefore necessary to develop a method based on simple parameters which permits noise level prediction. It is also possible to use statistical methods for this purpose, an example of which is the prediction [9], at an early design stage of the vibration characteristics of a ship.

2. Multiple regression model

The present model, on the basis of which the calculations were made, is known as a standard linear model of multiple regression [3, 4, 8]. This model assumes that the values observed for a dependent variable are realizations of the n-element random vector $\boldsymbol{Y}$, which can be written as $\boldsymbol{X\beta}+\varepsilon$, where $\boldsymbol{X}$ is the $(n \times K)$ - dimensional matrix of observations of order K, consisting of values taken by K explanatory variables, $\boldsymbol{\beta}$ is a column vector of K unknown parameters, $\boldsymbol{\varepsilon}$ is an n-element vector of random components, whose vector of conditional expected value and conditional matrix of covariance are, for a given $\boldsymbol{X}$, equal to $E(\boldsymbol{\varepsilon}|\boldsymbol{X}) = 0$ and $V(\boldsymbol{\varepsilon}|\boldsymbol{X}) = \sigma^2\boldsymbol{I}$, respectively, where σ^2 is an unknown positive parameter, while $\boldsymbol{I}$ is a unit matrix of the n-th degree. Since the assumptions are conditionally made with respect to $\boldsymbol{X}$, nothing is lost when the matrix $\boldsymbol{X}$ is considered to be a matrix with nonstochastic elements equal exactly to the values observed for the explanatory variables.

The parameters of the present model are estimated by the method of least squares, i.e. by minimizing the sum of the squared deviations (remainders) from the hyperplane of regression. This leads to a solution [3, 8], where the vector $\boldsymbol{b}$ obtained by test from the formula

$$\boldsymbol{b} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{X}^T\boldsymbol{Y}, \tag{1}$$

is an unweighted estimator of the regression coefficients. According to the Gauss-Markov theorem this is the best unweighted linear estimator.

The quantity R, calculated experimentally from the formula

$$R = \sqrt{1 - \frac{\boldsymbol{Y}^T\boldsymbol{Y} - \boldsymbol{b}^T\boldsymbol{X}^T\boldsymbol{Y}}{\boldsymbol{Y}^T\boldsymbol{Y} - \frac{1}{n}(\mathbf{1}^T - \boldsymbol{Y})^2}}, \tag{2}$$

where $\mathbf{1}^T$ is an n-dimensional line vector of unity, is the estimate of the correlation coefficient, which measures the degree of correlation of variable Y with all the independent variables.

Statistical conclusions about the regression coefficients, i.e. the construction of confidence intervals and significance testing, are drawn on the basis of the t distribution for n-K degrees of freedom for an assumed confidence level.

It is interesting to note here the importance of the significance testing of the regression coefficients. The results of the test which give coefficients insignificantly different from zero permit gradual elimination from the model of explanatory variables, of those with no influence (or very small influence) on the value of the dependent variable.

The classical method of least squares loses its optimum character when a significant autocorrelation of random errors occurs. The von Neumann test can be used to check this significance, by approximating the distribution of the relevant statistics (the so called von Neumann quotient) by the normal distribution with a mean $2\,n/(n-1)$ and the variance $4/n$. When the test shows a high value of the autocorrelation coefficient P, then it should be estimated and subsequently all the observations should be transformed accordingly [3]. Using the transformed vector of dependent variables, $\boldsymbol{Y}^*$, and the transformed matrix of independent variables, $\boldsymbol{X}^*$, the method of least squares serves again to give the final estimated parameters of the model.

The linear regression function is a convenient prediction tool, and it should also be noted that the technique of prediction based on the regression model is considered to be one of the best. In order to implement practically the calculation process related to this technique, the programme whose block diagram is shown in Fig. 2 was written in Algol 1900 and introduced into an Odra 1325 computer.

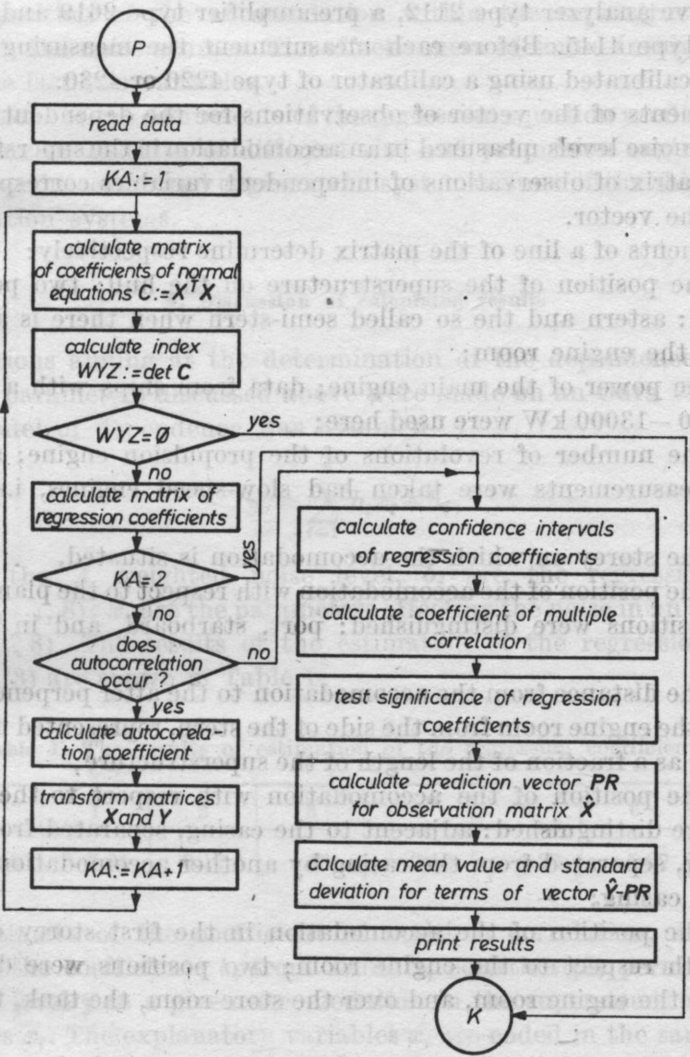

Fig. 2. A block diagram of the estimation of the parameters of the model of linear and multiple regression

KA – auxiliary variable, *X*, *Y* – given matrices whose elements are used for estimation of the parameters of the model, $\hat{X}$, $\hat{Y}$ – given matrices whose elements are not included in estimation of the parameters of the model

3. Data for calculations

The calculations used the results of measurements of noise levels taken by the Maritime Institute on Polish ships. In each case these measurements were taken on a ship with a typical load, at a sea state below 3, with revolutions of the propeller screw being no less than 95 percent of rated revolutions. The measurements used Brüel and Kjaer instrumentation in the following systems: a precision sound level meter type 2204 and a condenser microphone type 4145 or a 1/3 octave analyzer type 2112, a pre-amplifier type 2619 and a condenser microphone type 4145. Before each measurement the measuring system was checked and calibrated using a calibrator of type 4220 or 4230.

The elements of the vector of observations for the dependent variable are values of the noise levels measured in an accomodation in the superstructure. One line of the matrix of observations of independent variables corresponds to each element of the vector.

The elements of a line of the matrix determine respectively:

x_{i1} — the position of the superstructure on the hull; two positions were distinguished: astern and the so called semi-stern when there is an additional hold behind the engine room;

x_{i2} — the power of the main engine; data from ships with a main engine power of 3000 –13000 kW were used here;

x_{i3} — the number of revolutions of the propulsion engine; all the ships on which measurements were taken had slow-speed engines, i.e. below 250 revs./min.;

x_{i4} — the storey on which the accomodation is situated,

x_{i5} — the position of the accomodation with respect to the plane of symmetry; three positions were distinguished: port, starboard, and in the plane of symmetry;

x_{i6} — the distance from the accomodation to the after perpendicular or the bulkhead of the engine room from the side of the stern, represented in a dimensionless manner as a fraction of the length of the superstructure;

x_{i7} — the position of the accomodation with respect to the casing, four positions were distinguished: adjacent to the casing, separated from the casing by a corridor, separated from the casing by another accomodation, outside the area of the casing;

x_{i8} — the position of the accomodation in the first storey of the superstructure with respect to the engine room; two positions were distinguished: directly over the engine room, and over the store-room, the tank, the workshop etc.

The parameters defining the position of the accomodation were coded in such a manner that they could be used in the regression model. The position of the superstructure astern was given the value of 1, while that on the semi-stern was assigned 2. The same coding principle was assumed for the variables x_{i5},

x_{i7} and x_{i8}. E.g. the four possible positions connected with the variable x_{i7} were given the values of 1, 2, 3 and 4, respectively. If an independent variable takes more than two values, then the principle should be maintained that these must be in direct proportion to the corresponding values of the dependent variable.

The selection of explanatory variables took into consideration the significance of their contribution to the noise in the accomodation and the ease of determinating them in the preliminary design stage. The first three variables describe the influence of propulsion system. The variables x_{i4}, x_{i5} and x_{i6} define the position of the accomodation within the superstructure and the distance from the noise sources. The effectiveness of sound insulation is determined by the last two variables.

Calculations of the coefficients of the regression equation used data from 300 accomodations on 15 ships of different size and propulsion engine power, but with similar architecture and engine room systems. None of the ships had special sound insulation systems.

4. Discussion of calculated results

Calculations aiming at the determination of the dependence of the noise level on the parameters discussed above were made on an Odra 1325 computer. A linear model of dependence was assumed

$$y = \sum_{i=1}^{8} b_i x_i + b_0, \tag{3}$$

where y is the A weighted noise level, b_i are the regression coefficients $(i = 0, 1, 2, \ldots, 8)$, x_i are the parameters affecting the noise in an accomodation $(i = 1, 2, \ldots, 8)$. The results of the estimation of the regression coefficients of equation (3) are shown in Table 1.

Table 1. The results of estimation of the regression coefficients

i	0	1	2	3	4	5	6	7	8
b_i	62.46	−3.05	0.17	1.21	−0.16	−0.28	−5.07	−0.37	3.25

The estimate of the coefficient of multiple correlation, $R = 0.8$. After insertion of the coefficients b_i from Table 1, equation (3) permits calculation of the noise level y in a given accomodation in the superstructure, defined by the variables x_i. The explanatory variables x_i are coded in the same way as the relevant elements of the matrix of observations X used to calculate the coefficients of equation (3). The high coefficient of multiple correlation and the results of significance testing of regression coefficients indicate the validity of the linear model assumed.

In order to check practically the usefulness of the formula derived, noise levels were predicted for a matrix of observations $\hat{\boldsymbol{X}}$ (independent variables) which was not included in the establishment of the model. The vector of point predictions $\boldsymbol{PR}$ (calculated from formula (3)) obtained was compared with the corresponding results of measurements of the noise level $\hat{\boldsymbol{Y}}$. By calculating the mean and the standard deviation of the elements of the vector $\boldsymbol{W} = \hat{\boldsymbol{Y}} - \boldsymbol{PR}$, additional quantities were obtained, which may serve to evaluate the quality of the prediction, and at the same time to evaluate the relation of the model to

Table 2. Comparison of predicted and measured levels of noise

	Ship data	Noise level [dB (A)]		Differences in noise levels $W = \hat{Y} - PR$ [dB (A)]	Parameters characterizing the distribution of values of W
		predicted PR	measured $\hat{Y}$		
1	2	3	4	5	6
A	bulk carrier, superstructure astern, power 5888 kW, revolutions 145 per min	63.2	65	1.8	the mean value $\overline{w} = -0.37$ the standard deviation $\sigma = 1.44$
		63.0	65	2.0	
		61.0	62	1.0	
		63.2	62	−1.2	
		61.3	60	−1.3	
		60.8	60	−0.8	
		56.6	57	0.4	
		55.3	55	−0.3	
		55,0	55	0.0	
		56.1	57	0.9	
		55.1	53	−2.1	
		54.8	53	−1.8	
		57.6	55	−2.6	
		55.2	54	−1.2	
B	bulk carrier, superstructure astern, power 5300 kW, revolutions 130 per min	63.6	64	0.4	the mean value $\overline{w} = -0.89$ the standard deviation $\sigma = 1.45$
		60.6	62	1.4	
		60.0	60	0.0	
		59.2	58	−1.2	
		57.7	56	−1.7	
		60.3	61	0.7	
		59.5	61	1.5	
		53.9	54	0.1	
		54.0	55	1.0	
		55.9	60	4.1	
		56.0	57	1.0	
		54.1	55	0.9	
		55.3	58	2.7	
		53.8	54	0.2	
		53.7	56	2.3	

cd. Table 2.

1	2	3	4	5	6
		60.0	62	2.0	
		59.5	62	2.5	
		58.5	59	0.5	
		57.0	56	−1.0	
		55.1	55	−0.1	
		60.1	61	0.9	
		59.6	60	0.4	
		58.3	61	2.7	
		60.0	62	2.0	
		59.5	61	1.5	
		54.0	54	0.0	
		53.6	52	−1.6	
		53.0	51	−2.0	the mean value $\overline{w} = -0.77$ the standard deviation $\sigma = 2.11$
C	semi-containership, superstructure on the semi-stern, power 17075 kW, revolutions 120 per min	52.0	52	0.0	
		51.8	53	1.2	
		51.8	52	0.2	
		52.0	52	0.0	
		54.4	54	−0.4	
		53.4	54	0.6	
		52.4	48	−4.4	
		51.9	51	−0.9	
		51.6	47	−4.6	
		51.6	49	−2.6	
		53.2	51	−2.2	
		52.4	50	−2.4	
		51.4	49	−2.4	
		51.6	47	−4.7	
		51.6	49	−2.6	
		52.6	51	−1.6	

reality. The results for 59 accomodations on 3 ships are shown in Table 2. By considering all the values of the difference w (column 5, Table 2), their mean and the standard deviations were calculated, thus obtaining $\overline{w} = -0.25$ and $\sigma = 1.92$. The mean value close to zero (at the significance level 0.05 there is no justification for rejecting the hypothesis $H_0 : \overline{w} = 0$) indicates that the method presented has no constant trend. The standard deviation can, however, be regarded as the mean difference between the estimated and measured values.

The distribution parameters calculated for the individual ships, shown in column 6, Table 2, permit the statement that the prediction for ships *A* and *B* is in better agreement with the empirical values than for ship *C*. This is also indicated by the results obtained for the individual accomodations (column 5, Table 2). This results from the fact that the parameters of ships *A* and *B* lie in the variability intervals of the corresponding parameters of the input test. The parameters of ship *C* exceed, however, these intervals. This indicates that extrapolation causes a decrease in accuracy.

5. Remarks and conclusions

1. The harmful effect of noise on the human organism and the scope of this phenomenon should generate an interest in these problems from the owners of ships and shipbuilders. The research towards the prevention of excessive noise levels gives only sufficient effect when it is introduced at a sufficiently early stage of the ship design.

2. Prevention should be based on the prediction of noise levels in accomodations of the superstructure. The results obtained and their comparison with the measured data indicate the validity of the model assumed and permit the statement that the application of the method of multiple regression in noise prediction on ships gives good results.

3. The present model, because it is based on a statistical method, considers one of the very important factors that sometimes determine the noise level, i.e. the technology and workmanship used in ship building.

4. The present method of noise prediction, due to its simplicity, can be used at a very early stage of the design.

5. The range of application of the correlation and the regression methods is in each case defined by the two following principles:

(a) If there is a causal relation between the phenomena investigated, then the power of this relation can be determined by the correlation calculus. If the power is large enough (i.e. when $R^2 > 0.5$) it is worthwhile to seek the equation of the hyperplane of regression, and to use it subsequently as a prediction tool.

(b) If there is an assumption that a causal relation exists between the phenomena investigated, then the presence of a distinct correlation in sufficient numerical material strengthens, to a large extent, the hypothesis that the causal relationship exists.

The first of the principles mentioned above was followed in the selection of the explanatory independent variables. That there is a causal relation between the values of these variables and the noise level at a point defined by these variables seems evident.

Further investigations should be performed in the two directions:

(a) expansion of the set of independent variables according to the second of the principles mentioned above;

(b) adoption of the present method to prediction of octave spectra.

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