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PREDICTION OF OCTAVE NOISE SPECTRA IN ACCOMODATIONS IN THE SUPERSTRUCTURE OF A SHIP

EDWARD SZCZERBICKI

Ship Research Institute, Technical University of Gdańsk
(80-952 Gdańsk, ul. Majakowskiego 11/13)

ANDRZEJ SZUWARZYŃSKI

Technical Research Department, Maritime Institute
(80-307 Gdańsk, ul. Abrahama 1)

This paper presents the results of the second stage of investigations aimed at the development of an effective method for predicting noise levels in accomodations in the superstructure of ships. The present procedure is based on a statistical model of multiple regression and uses standard results of noise measurements on board ships. It permits prediction of noise levels in 6 octave bands over the frequency range 63-2000 Hz, with an accuracy comparable to those of the equivalent foreign methods.

1. Introduction

Noise, which is one of the most annoying factors affecting the life and work of crews on board ships, is an inevitable phenomenon. The activity of man concentrates therefore on the development of methods for acceptable its harmful effect. Because of the necessity of providing the crew with correct conditions of rest after work, this applies particularly to accomodations in the superstructure. The elimination of excess noise levels is secured by the consideration of the acoustical aspect at the early stage of the ship design.

In view of its simplicity, the method presented in [6] for predicting A-weighted noise levels can be used already at the preliminary stage of the ship design. Its efficient application can provide a valuable tool for the designer in arranging accomodations in the superstructure of a ship. The case may arise when for some reasons (functional requirements, rules of classification institutions etc.) some accomodations are located in the regions where the predicted A-weighted noise level exceeds the permissible value. In such cases it is necessary to undertake some technical means of noise control, which consist in

– reduction of the noise transmitted by the source to the structure (e.g. by the use of elastic mountings);

– decrease of the noise level in accomodations by insulation (e.g. floating floors).

The design of noise reduction means requires the knowledge of its frequency characteristic in a given accomodation. The results of octave bands noise prediction over the frequency range 31.5-8 kHz are commonly used for this purpose [5, 8]. Thus, the present paper gives an extension and modification of the method presented in paper [6], in order to permit such prediction in accomodations in the superstructures of ships.

2. Modification of the calculation algorithm

The model of multiple regression according to which the calculations were made was presented in [6, 7]. The assumptions of this model and the manner of estimation of its parameters remained unachanged, with one exception. It is now assumed that the values of the dependent variable observed are implementations of the $(n \times m)$ – dimensional random matrix Y (whereas previously Y was a n-element random vector), where n is the number of measurements and m is the number of octave bands at which noise levels were measured. On the basis of the results obtained, it was found that

1. The procedure of matrix inversion used in [6], which was based on the traditional Gauss algorithm, proved to be numerically unstable with a considerable increase in the column dimension of the matrix X. A numerically unstable algorithm does not assure that a solution can be achieved with error at the level of the inevitable error which results from the approximate representation of data in a computer. It most often involves large relative errors which prevent the use of the calculated results in practice.

2. For all the octave bands different systems of parameters have an essential effect on the noise level. In the course of calculations it is therefore necessary to change continuously the dimension of the matrix X in relation to the elimination of variables not essential for a given octave. The traditional Gauss algorithm prevents efficient performance of this operation.

3. The expansion of the set of explanatory variables brought the large probability of there being a linear or close to linear relationship among them. With a limited accuracy of computer calculations, this can prevent the satisfaction of the basic condition required by the standard procedures for the solution

of systems of linear equations (such being the Gauss method), i.e. a full column order of the matrix of the coefficients of a system of equations.

In view of the problems given above, the method for noise level prediction in octave bands was based on a standard model of multiple linear regression, with, however, some essential modifications to the algorithm given in [6]. The most important of these modifications is the use of the Gauss-Jordan algorithm to solve a system of normal equations.

The modified Gauss-Jordan algorithm was developed by EFFROYMSON and BEAL in the 1960s. In the present paper the authors have used the procedure given by BARTKOWIAK in [1, 2]. This algorithm offers the following possibilities, which are particularly convenient in regression analysis,

1. Direct estimation of the coefficient of multiple correlation, on the basis of which it is possible to conclude about the quality of the approximation of the variable Y by the calculated regression equation.

2. Successive introduction of dependent variables into the regression set.

3. When the diagonal element of the matrix of the coefficients of a system of normal equations which corresponds to the variable to be introduced into the regression set is close to zero, this signifies that this variable is an almost linear function of the variables which are already in the regression set. Such a variable is automatically neglected by the algorithm, since it does not bring any new information about the dependent variable Y, and its introduction into the set would prevent the matrix of the coefficients of the system of normal equations from being positively defined.

The programme for the calculations of octave spectrum prediction was written in Fortran 1900 and introduced into an Odra 1325 computer. In view of the required capacity of the operational memory, of the order of 30 k words, the calculations were made on an Odra 1305 computer. The range of the calculations included

– estimation of the coefficients of regression equations,
– estimation of the coefficient of multiple correlation,
– evaluation of the coefficients of the regression equation,
– verification of the results obtained.

3. Data for calculations — selection of explanatory variables

Table 1 shows chosen results of measurements taken in 400 accomodations in 25 ships of different types and size. The differences $L_{\max}$-$L_{\min}$ in particular octave bands take values of the order of 40 dB. It can be stated that the permissible values defined by the curve $N55$ are most often exceeded for octave bands with centre frequencies from 63 Hz to 2 kHz, sometimes even reaching values of more than 20 dB. The considerations below are concerned with the frequency range given above.

Table 1. Selected results of noise measurements in 400 accomodations

Centre frequency of octave band [Hz]	Noise level [dB]			Number of accomodations with permissible level
	$L_{\min}$	$L_{\max}$	L_{dop}	L_{dop} exceeded
31.5	66	99	93	8
63	62	93	79	80
125	51	94	70	95
250	45	80	63	103
500	40	76	58	116
1000	32	67	55	80
2000	26	65	52	44
4000	22	58	50	20
8000	18	54	49	4
A-weighted noise level	46	77	60	128

L_{dop} – permissible level

The calculations aimed at the generation of regression equations and their verification were made with the results of noise level measurements in 6 octave bands for 422 accomodations in 20 ships. Table 2 gives the basic data for these ships. The measurements were taken according to the standard ISO 2923 – *Acoustics Measurement of Noise on Board Vessels.* Sound level meters complying with the requirements of the International Electronical Commission IEC 179, equipped with octave or 1/3 octave filters satisfying the requirements of IEC 225, were used in the measurements. All the available observations were divided into two sets: one used for the estimation of the parameters of the model and the other destined for prediction on the basis of the estimated regression equations with the view to their verification. Table 2 shows this division.

One line of the matrix X of observations made on the independent variables corresponds to each line of the matrix of observations made on the dependent variable Y (values of noise levels measured in 6 octave bands). Selection of the explanatory variables took into account the significance of their effect on the noise level and their availability at the early stage of the ship design. On the basis of the prediction methods known from the literature [3-5, 8] and analysis of the results of noise measurements on ships, five groups of parameters affecting the noise level in the superstructure were distinguished. These

Table 2. Characteristics of the ships whose data were used in the calculations

No	Ship type	Deadweight	Main engine		Revolutions of generating set	Number of measurement points	Purpose
		TDW	power [kW]	revolutions [min^{-1}]	[min^{-1}]		
1	bulk carrier	37840	8824	115	750	46	estimation of parameters of regression model
2	bulk carrier	9810	3434	800	1800	23	
3	bulk carrier	32000	8832	122	750	20	
4	bulk carrier	5735	2502	242	1500	22	
5	bulk carrier	14180	5446	155	750	29	
6	bulk carrier	25500	7066	199	750	38	
7	bulk carrier	3610	1656	225	500	12	
8	bulk carrier	14036	5888	150	750	17	
9	general cargo ship	11760	5299	139	500	13	
10	general cargo ship	7490	3270	430	1000	14	
11	general cargo ship	7350	5299	135	500	22	
12	semi container ship	12000	12806	122	720	13	
13	semi container ship	16000	17075	122	720	5	
14	con-ro	22000	21344	122	750	28	
15	bulk carrier	23785	7066	119	500	13	verification of regression equations derived
16	bulk carrier	52020	10739	134	750	10	
17	bulk carrier	39900	8832	122	720	28	
18	general cargo ship	14000	7618	120	720	15	
19	general cargo ship	11630	5888	135	500	5	
20	semi container ship	17000	17060	122	750	49	

groups are related to the characteristics of:

- the main engine,
- the generating set,
- the screw propeller,
- the sound propagation paths in the superstructure,
- other technical and operational parameters of the ship.

As a result of the optimization (in a statistical sense) of the sought regression relation, the following set of explanatory variables was established,

x_{i1} – the rated power of the main engine [kW],

x_{i2} – the rated revolutions of the main engine [$\min^{-1}$],

x_{i3} – the ratio of the operational revolutions to the rated ones,

x_{i4} – the producer of the ship (each shipyard uses some characteristic designs which are based on experience and result to a large extent from the availability of technical means and a general technological level),

x_{i5} – the rated revolutions of the generating set [$\min^{-1}$],

x_{i6} – the shape of the stern part of the hull (the distances between the top of the propeller blade and the shell plating over the propeller are significant acoustically),

x_{i7} – the distance between the centre of the accomodation and the edge of the generating set, defined by the number of frames,

x_{i8} – the position of the generating set in terms of height, defined by the successive number of the deck or platform from the inner bottom up,

x_{i9} – the kind of mounting of the generating set (rigid or elastic),

x_{i10} – the blade frequency of the propeller (the product of the rotation frequency of the shaft and the number of propeller blades),

x_{i11} – the Froud number, $F = V/(gL)^{1/2}$, which is the relative speed of the ship, where V is the speed of the ship [m/s], g is the acceleration of gravity [$\mathrm{m/s^2}$] and L is the length of the ship [m],

x_{i12} – the distance between the centre of the accomodation and the edge of the main engine, defined by the number of frames,

x_{i13} – the position of the accomodation along the axis of the ship, defined by the number of the frame on which the centre of the accomodation is,

x_{i14} – the position of the accomodation in terms of height, defined by the successive number of the deck or platform from the inner bottom up,

x_{i15} – 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_{i16} – the position of the accomodation with respect to other accomodations (three positions were distinguished: direct vicinity to an accomodation with a noise source, vicinity to a workshop or store, position over another accomodation),

x_{i17} – the correction coefficient accounting for the nonlinearity of the damping characteristic of structure-borne sound in terms of height, where $i = 1, 2, \ldots, n$ is the number of observations.

Some of the above variables define the properties which cannot be measured. For these a digital coding system was assumed, with the principle that the values of the independent variables encoded must be in direct proportion to the corresponding values of the dependent variable.

4. Discussion of the calculated results

The parameters of the model were estimated on the basis of the results of the noise measurements on ships whose data are given in Table 2. The following linear-logarithmic form of the regression relation was assumed,

$$y_i = \sum_{j=1}^{17} b_{ij} d_{ij} + b_{i0} \quad (i = 1, 2, \ldots, 6), \tag{1}$$

where y_i is the noise level in the ith octave band [dB], b_{ij} are the regression coefficients ($i = 1, 2, \ldots, 6$; $j = 0, 1, \ldots, 17$), d_{ij} are the parameters affecting the noise in the accomodation ($i = 1, 2, \ldots, 6$; $j = 1, 2, \ldots, 17$), where

$$d_{ij} = \begin{cases} x_{ij} & \text{for } j = 3, 4, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, \\ \log x_{ij} & \text{for } j = 1, 2, 5, 13; \; i = 1, 2, \ldots, 6. \end{cases}$$

In order to check the validity of the present model, the coefficients of multiple correlation were estimated for particular octave bands. The estimated results, given in Table 3, confirm the correctness of the set of explanatory variables and forms of the regression relation assumed here. In turn, Table 4 shows an evaluation of the significance of the estimated coefficients of regression equations. Statistical conclusions were drawn at the significance level $\alpha = 0.1$. When it was found that the regression coefficient under investigation is not different from zero at the significance level α assumed, the corresponding variable was eliminated from the regression set. Such a procedure optimizes the final solution. In most cases the significance of particular explanatory variables depends on the octave band. This is a result of the physical nature of the generation and propagation of noise on board a ship.

Table 3. The values of the coefficients of multiple correlation

Centre frequency of octave band [Hz]	63	125	250	500	1000	2000
Value of coefficient of multiple correlation	0.783	0.843	0.828	0.840	0.850	0.837

Table 4. The results of the significance test of the coefficients of the regression equations

Number of regression coefficient	Centre frequency of octave band [Hz]					
	63	125	250	500	1000	2000
1	+	−	−	−	−	−
2	+	+	+	+	+	+
3	−	−	−	+	+	+
4	+	+	+	+	+	+
5	+	−	−	+	+	+
6	+	+	+	+	+	+
7	−	+	+	+	+	+
8	−	+	+	+	−	+
9	+	+	+	+	+	+
10	−	+	+	+	+	+
11	−	−	−	−	−	−
12	−	+	−	+	+	+
13	+	+	+	+	+	+
14	+	+	+	+	+	+
15	−	−	−	−	−	−
16	−	+	+	+	+	−
17	−	−	−	+	+	+

+ significant coefficient, − insignificant coefficient

The most significant test of the usefulness of the regression equations derived is the verification of the predictions calculated from these equations, by comparing them with the measured results. Such a comparison was performed for 120 accomodations of 6 ships whose data are given in Table 2. Table 5 shows, for particular octave bands, the parameters of the distribution of the differences obtained between the calculated and measured levels. The low mean values for the bands over the range 63-1000 Hz indicate the lack of an essential trend in these octaves. Only in the octave band of 2000 Hz it is possible to notice a distinct trend for the method to exaggerate the prediction results. However, it can readily be seen in Table 1 that in this band the permissible noise level is

Table 5. The parameters of the distribution of the differences between the calculated and measured noise levels for 120 accomodations

Parameter of difference distribution	Centre frequency of octave band [Hz]					
	63	125	250	500	1000	2000
mean value	−1.6	0.1	1.3	1.2	1.7	3.4
standard deviation	4.0	4.0	2.8	3.9	4.1	5.4

Table 6. Comparison of the accuracy of three methods for prediction of octave noise spectra

Authors of method	Characteristic of samples used for verification of method		Parameters of distribution of set of differences	Centre frequency of octave band [Hz]					
	number of ships	number of accomodations		63	125	250	500	1000	2000
Kihlman Llunt	2	12	mean value	−1.33	−2.00	−0.08	−0.50	−1.57	−1.17
			standard deviation	2.96	4.35	4.60	3.37	3.17	1.75
Buiten	11	160	mean value	0.49	−1.31	0.55	0.80	0.56	no data
			standard deviation	4.49	3.89	3.86	4.12	4.35	no data
present method	6	120	mean value	−1.60	0.10	1.30	1.20	1.70	3.40
			standard deviation	4.00	4.00	2.80	3.90	4.10	5.40

rarely exceeded. The standard deviations given in Table 5 can be taken as some additional measure of the accuracy of the method, which indicates the scatter of the magnitude of the differences about their mean value. In the next section this accuracy is examined in greater detail.

5. Evaluation of the accuracy of the present prediction method

Among the many papers on the prediction of noise levels in octave bands (e.g. [3-5, 8]), none contains a full algorithm permitting a direct use of the methods described in them. In all cases, apart from the basic principles of the construction of the model used and a general description of its solution, these publications contain information on the accuracy of the prediction results obtained. Table 6 gives the parameters of the distributions of the differences between the calculated and measured levels, for three methods: of Kihlman and Plunt [4], Buiten [3] and the one used here. In view of the small number of samples used to verify the first method, its results have only an illustrative character. Of Buiten's method it can be said that it shows hardly any trend (the mean values being close to zero) but rather large standard deviations, which cause prediction error of the order of ±4-10 dB in the 95 per cent confidence interval [3]. It can be seen from the data in Table 6 that the present method does not differ greatly in terms of accuracy from the other equivalent methods used at present for prediction of noise levels in octave bands.

Table 7. The distribution of the magnitude of error in predicted noise levels for 120 accomodations

Range of error [dB]	Probability of error					
	centre frequency of octave band [Hz]					
	63	125	250	500	1000	2000
±2	0.39	0.46	0.40	0.32	0.28	0.27
±4	0.61	0.73	0.80	0.63	0.67	0.47
±6	0.85	0.82	0.97	0.85	0.82	0.62
±8	0.94	0.94	1.00	0.99	0.92	0.75
±10	1.00	0.99	1.00	1.00	0.99	0.88
±12	1.00	1.00	1.00	1.00	1.00	0.93

The present prediction method permits an evaluation of its error ex ante, i.e. when the prediction is performed. The standard prediction errors estimated in the course of calculations vary between 3 and 4.5 dB for all octave bands. This assures a prediction accuracy of the order of ±6-8 dB in the 95 per cent confidence interval. This is confirmed by Table 7 which shows the probability of error occurring in particular intervals, calculated from the results of the verification of the present method which were discussed previously (Table 5). The fact that there may be some parameters which can essentially affect the noise level and which are not accounted for in the present model, should be given as the most probable cause of error in the present method. This is also the main explanation given by other authors for inaccuracies in their methods [3, 4, 8].

6. Conclusions

1. The method for prediction of octave spectra presented here and the method for A-weighted noise level prediction published previously [6] are based on a methodological approach which is different from those followed previously in the development of methods for noise level prediction. The present approach consists in omitting the stage of complicated and expensive laboratory research carried out on physical models and in concentrating on a deeper statistical analysis of standard measurement results. The results obtained to date confirm the validity of this direction of research.

2. The present method for octave spectrum prediction is efficient, which was shown in the course of verification. The results obtained using the regression prediction of noise levels are comparable to those of equivalent foreign methods.

3. The regression prediction is quite simple in application, since it involves one calculation step, whereas the foreign methods mentioned above require at least several steps.

4. None of the published foreign methods can be used directly. The relevant algorithms are unknown outside the research centres where they have been developed and their use by Polish shipyard has always the character of an expensive service.

5. The present method, as all empirical ones, requires continuous updating and supplementing of the set of measurement data from which the relevant regression equations are generated.

6. The accuracy of the present method will be increased and its small permanent trend eliminated in the next stage of the authors' investigations. It will be possible to attain this end when the set of independent variables has been extended and there are more measurement data.

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