ARCHIVES OF ACOUSTICS
30, 4, 533–551 (2005)

EXPERIMENTAL ASSESSMENT OF COUPLING LOSS FACTORS OF THIN RECTANGULAR PLATES

R. PANUSZKA, J. WICIAK, M. IWANIEC

University of Science and Technology AGH
Laboratory of Structural Acoustics and Intelligent Materials
Al. Mickiewicza 30, 30-059 Kraków, Poland

(*received March 9, 2005; accepted September 2, 2005*)

Knowledge of Coupling Loss Factors (CLF's) for energy flow evaluation in structural elements of complex mechanical systems is fundamental. Several experiments were conducted to evaluate CLFs of different perpendicular connections of rectangular plates. The method of energy storage was conducted under acoustic free-field conditions, and a large number of thin plates with different designs of junctions were examined. The tests included two types of connections: welded line junction and point junctions. In the first type of connection, the influence of the thickness ratio of plates on CLFs values was tested. In the second type of connection the influence of the point of distribution at junctions on CLFs values were tested. Other tests were done to establish the impact of junction design on CLFs. Welded line junctions have a tendency to decrease the CLFs when the ratio of thickness of plates is increased. The CLFs also increase with density of joining points. Maximal values of CLFs were observed for spot-welded junctions. Mid-values were represented by screw-bolted joints and the lowest values by riveted junctions.

Key words: statistical energy analysis, coupling loss factor, rectangular plates connections, welded junction, point junction, acoustic power flow.

1. Introduction

Statistical Energy Analysis (SEA) is a useful tool for designers to predict power transmission paths, energy distributions, and radiation of complex mechanical systems [26, 27]. Fast computer modeling vibrational and acoustical parameters of complex mechanical systems are achieved from commercial computer codes [31] such as: SEAM, developed by Cambridge Collaborative Inc. [30], AutoSEA, developed by Vibro-Acoustic Sciences Ltd. [3], and AARCSEA, developed by Atlantic Applied Research Corp. [18]. The design process can be followed by computer simulations of prototypes, modification of existing constructions in acoustical modernization, then by comparing several different solutions, and optimizations constructions [13, 15, 20, 41]. In Poland the building acoustics approach was at the Institute of Building Technology in Warsaw [19], and at the Structural Acoustics and Intelligent Materials Laboratory AGH University of Science and Technology in Krakow with FEM evaluations of coupling loss factors [24, 25], car muffler energy flow [44], ribbed panels energy ratios [29], structural modification [16, 17], flexural plates [43] and many other applications in acoustical engineering [36, 37, 38] and the reciprocity law developed at the Department of Mechanics and Vibroacoustics of the same University [10].

The SEA method has been developed for middle and high audio-frequencies [28, 11]. New solutions based on a hybrid approach combining finite element analysis (FEA) in the low-modal density regions and statistical energy analysis (SEA) in the high-modal density regions will soon benefit the systems which require wider frequency band solutions [14].

When using the SEA method, the balance of energy is fundamental. The structure is assumed to be built on a set of simple elements including beams, plates and rods which are called subsystems. Coupling Loss Factors (CLF), Modal Densities (MD) and Dissipation Loss Factors (DLF) are parameters of the SEA subsystems.

Coupling Loss Factors describe particular types of joined elements and junctions. They can be obtained by theoretical modeling [2, 8, 22, 23, 27, 42, 46], or by experimenting in the laboratory or *in situ* conditions [1, 9, 35, 47]. Further development of data bases of CLFs with more sophisticated junctions used by designers is needed to improve the calculations and to eliminate the sources of errors.

The main purpose of this research was to make experimental evaluations and statistical summaries of CLFs values for a variety of mechanical junctions over a frequency range and then to make comparisons. These experiments were performed on thin rectangular plates connected perpendicularly on a common edge. Two kinds of junctions have been examined, welded line and point kind junctions. In the welded line, the influence of thickness ratio of the connected plates on CLFs was evaluated. In the point-kind junction, the effect of distribution of point junctions on CLFs along a common edge was estimated. Using theoretical expressions for wave approaches, the coupling loss factor relationships were derived and compared with experimental data.

Additional investigations were made to establish the influence of different point-kind junction designs on the transfer of energy by connections. This was conducted to show that the simple models often used in engineering are not always suitable to use for sophisticated practical cases of welded, spot-welded, riveted or screwed junctions [34].

Currently, several direct and indirect methods for CLF evaluation are developed. Direct methods with input power measured by an impedance head or a force transducer with an accelerometer pair [13]) and ones indirect the like the power injection method [1], the energy difference method [5], the mobility method and structural intensity techniques [31]. Authors used the indirect approach to test the energy stored in subsystems [13, 35].

2. Sea matrix – coupling loss factors of joined plates

2.1. Energy balance equation

At present the Statistical Energy Analysis is still one of the best coded energy flow methods. In this method, the response of each subsystem on the frequency band is calculated by using the resonant modes of the associated conservative subsystem. SEA requires the use of CLFs or transmission coefficients (τ) between any connected subsystems. DLFs and Modal Densities (MD) of subsystems are also required. For a system with N subsystems, the power balance equation can be written in the matrix form

$$\omega[A]\begin{bmatrix} E_{1,\text{tot}}/n_1 \\ E_{2,\text{tot}}/n_2 \\ \vdots \\ E_{n,\text{tot}}/n_N \end{bmatrix} = \begin{bmatrix} W_{1,\text{in}} \\ W_{2,\text{in}} \\ \vdots \\ W_{N,\text{in}} \end{bmatrix} \tag{1}$$

where

$$[A]=\begin{bmatrix} \left(\eta_1+\sum\limits_{i\neq 1}^{N}\eta_{1i}\right)n_1 & -\eta_{12}n_1 & \ldots & -\eta_{1N}n_1 \\ -\eta_{21}n_2 & \left(\eta_2+\sum\limits_{i\neq 2}^{N}\eta_{2i}\right)n_2 & \ldots & -\eta_{2N}n_2 \\ . & . & \ldots & . \\ -\eta_{N1}n_N & . & \ldots & \left(\eta_N+\sum\limits_{i\neq N}^{N}\eta_{Ni}\right)n_N \end{bmatrix} \tag{2}$$

$\eta_{i,\text{tot}} = \eta_i + \sum \eta_{ij}$ is the total loss factor for each subsystem, η_i is the DLF of the i^{th} subsystem, η_{ij} is the coupling loss factor between the i^{th} and j^{th} subsystems, $n_i(\omega) = N/\Delta\omega$ is the modal density of resonant frequencies in $\Delta\omega$, N_i is the number of resonant modes in $\Delta\omega$ band, $E_{i,\text{tot}}$ is the total time-averaged energy in the frequency band $\Delta\omega$ of the i^{th} subsystem and W_{in} is the time-averaged power of inputs from the applied excitations.

SEA CLFs can be calculated from theoretical formulas or the measured data [12]. DLF's are evaluated from measurements and include two parts of dissipated energy. The first is the energy dissipated by the material structure. The second is dissipated by radiation of the structure to the surrounding air. The part dissipated by the material can be obtained from measurements or from the literature. The part dissipated by radiation of the structure can be obtained from radiation loss factors measured or estimated from the theory [33].

The CLF indicates the efficiency of vibration power transmission from one subsystem to another. Coupling Loss Factors between subsystem i and subsystem j is defined as follows [6]:

$$\eta_{ij} = \frac{W_{ij}}{\omega E_{i\,|E_j=0}}, \tag{3}$$

where W_{ij} – power flow between subsystem i and j, E_i, E_j – energies in subsystems i and j respectively.

There are modal and wave approaches when deriving CLF expressions for junctions. In the modal approach, the power flow between two continuous systems is found by averaging the power flows over each mode and frequency band. This average over all possible mode-to-mode couplings produces an estimate for the coupling loss factors [40]. In the wave approach, the vibrations are considered in terms of elastic waves, which propagate through the structure and are partially reflected and transmitted at structural discontinuities such as plate and plate or plate and beam junctions [6]. In this method, the CLF can be related to the power transmissibility for semi-infinite structures. Below, the wave approach expressions are outlined for line junctions (Subs. 2.2) and point junctions (Subs. 2.3. and 2.4.).

2.2. Line junctions

Since the power transmission coefficient has been defined as the ratio of the power transmitted through the junction to the power incident on the junction from Eq. (3) and [26], we have:

$$\eta_{ij} = \frac{c_{gi} L_c}{\omega \pi A_{i,j}} \tau_{ij}, \tag{4}$$

where

$$c_{gi} = 2c_b = 2\sqrt{\omega \kappa c_l} = 2\sqrt{\frac{\omega h c_l}{2\sqrt{3}}}, \tag{5}$$

$$c_l = \sqrt{\frac{E_i}{\rho(1-\nu^2)}}. \tag{6}$$

The index i describes the plate being excited while j concerns the second plate. The constants are: c_{gi} – group velocity, c_b – wave phase velocity, κ – bending radius of gyration, h – thickness of the plate, c_l – longitudinal wave velocity, A_i, A_j – areas of plates i or j, ν – Poisson's ratio, τ transmission coefficient for flexural waves. In the case of plates of the same material with different thickness we obtain [6]:

$$\tau_{ij} = \frac{2}{\sigma^{-\frac{5}{4}} + \sigma^{\frac{5}{4}}} \tag{7}$$

and CLF

$$\eta_{ij,\mathrm{lin}} = \frac{4}{\sqrt[4]{3}\pi}\sqrt{\frac{E_i}{\rho(1-\nu^2)}}\frac{L_c\sqrt{\omega h}}{\omega A_i(\sigma^{-\frac{5}{4}} + \sigma^{\frac{5}{4}})}, \tag{8}$$

where $\sigma = \dfrac{h_j}{h_i}$ is the thickness ratio,

2.3. Stiff bridges

Expressions for the configuration with stiff bridges were proposed by [21]:

$$\eta_{ij,br} = \frac{2\mathrm{Re}(z_i)\mathrm{Re}(z_j)}{\pi\omega\eta_i \mid z_i + z_j \mid^2}. \tag{9}$$

There are two cases. The first one is when the coupling occurs far away from the edges of the plate, and the second concerns an edge coupling. Expressions for impedance are given by Eqs. (10) and (11)

$$z_i^{2D} = 8\rho h_i \kappa c_l, \tag{10}$$

$$z_i^{2D} = 3.5\rho h_i \kappa c_l. \tag{11}$$

Parameter n_i represents the modal density of plate i or j:

$$n_{i(j)} = \frac{\sqrt{3}}{2\pi}\frac{A_{i,j}}{c_l h_{i(j)}}. \tag{12}$$

2.4. Point connection

Models depend on flexural wavelength, λ_b, and the distance between the points of connection. Six cases can be distinguished basing on the ratio of wavelengths [32]. For plates of the same material, expressions are given below in Eqs. (13) and (14) and concern the point-like junctions or line-like junctions respectively.

$$\eta_{12}^{\star} = \frac{3.5Nh_1c_{l1}}{\sqrt{3}\omega A_1}\frac{h_1^2h_2^2}{(h_1^2 + h_2^1)^2}, \qquad \text{for} \;\; \lambda_b < l, \tag{13}$$

$$\eta_{12}^{\star\star} = 4\sqrt{\frac{2}{3}\frac{l}{A_1}}\sqrt{\frac{h_2c_{l1}}{\omega}}\frac{h_1^{\frac{3}{2}}h_2^{\frac{3}{2}}}{(h_1^{\frac{3}{2}} + h_2^{\frac{3}{2}})^2}, \;\; \text{for} \;\; \lambda_b > 1.5\,l, \tag{14}$$

where λ_b – flexural wavelength of plate, l – point spacing. In the case of flexural wavelengths between l and $1.5\,l$

$$\eta_{12}^{\star\star\star} = 0.5(\eta_{12}^{\star} + \eta_{12}^{\star\star}). \tag{15}$$

That is, how the average value of the CLFs given by Eqs. (13) and (14) is estimated.

2.5. *Energy storage model*

The assumption was made that two joined perpendicular plates can be considered as two flexural plate subsystems with negligible power flow in air volume between the plates. The power balance equation can be written as:

$$\begin{bmatrix} \eta_1+\eta_{12} & -\eta_{21} \\ -\eta_{12} & \eta_2+\eta_{21} \end{bmatrix} \begin{bmatrix} E_{1,\mathrm{tot}} \\ E_{2,\mathrm{tot}} \end{bmatrix} = \begin{bmatrix} W_{1,\mathrm{in}}/\omega \\ W_{2,\mathrm{in}}/\omega \end{bmatrix}. \tag{16}$$

Input of energy $W_{1,in}$ occurs only to the first subsystem, then $W_{2,in}=0$ and

$$(\eta_2+\eta_{21})E_{2,\mathrm{tot}} = \eta_{12}E_{1,\mathrm{tot}}. \tag{17}$$

Assuming reciprocity, $\eta_{ij}n_i = \eta_{ji}n_j$

$$\eta_{21} = \frac{\eta_2 E_{2,\mathrm{tot}}}{N_2/N_1 E_{1,\mathrm{tot}} - E_{2,\mathrm{tot}}}. \tag{18}$$

The average energy stored in a thin plate can be obtained from the mean square velocity

$$E_{i,\mathrm{tot}} = m_i < v_i^2 >= \rho A_N h_i < v_i^2 >, \tag{19}$$

where $< v_i^2 >$ is the mean square velocity of vibrations of the i-th plate.

Finally, the equation for two flexural plates is

$$\begin{aligned} \eta_{12} &= \frac{\eta_2}{\left(\dfrac{A_1}{A_2}\right)\left(\dfrac{h_1}{h_2}\right)\left(\dfrac{\rho_1}{\rho_2}\right)\left(\dfrac{< v_1^2 >}{< v_2^2 >}\right) - \dfrac{n_1}{n_2}} \\ &= \frac{\eta_2}{\left(\dfrac{A_1}{A_2}\right)\left(\dfrac{h_1}{h_2}\right)\left(\dfrac{\rho_1}{\rho_2}\right)\left(\dfrac{< v_1^2 >}{< v_2^2 >}\right) - \left(\dfrac{A_1}{A_2}\right)\left(\dfrac{h_2}{h_1}\right)\left(\dfrac{c_{l2}}{c_{l1}}\right)}. \end{aligned} \tag{20}$$

This equation was used for calculations of CLFs, based on experimental data with anechoic conditions of propagation. To estimate the DLF, the decay rate method was used [27, 35]. This method is based on the transient response of a resonant mode with linear damping for a reverberant plate. The dissipation loss factor can be obtained:

$$\eta = \frac{2.20}{f_n T_{60}}, \tag{21}$$

where T_{60} – reverberation time, time taken to decay 60 dB, f_n – center frequency in band n.

3. Models in simulation – examples

One method of calculating the unknown values of coupling loss factor for complex connections of plates is to divide a complex mechanical system in the phenomenological way into simple elements (subsystems). These subsystems usually can be easily described by SEA parameters. Figure 1 shows the elements of mechanical SEA models of the investigated junctions: (a) – welded modelled as a line and (b) – screw bolts, point welded, or riveted modelled by point junction.

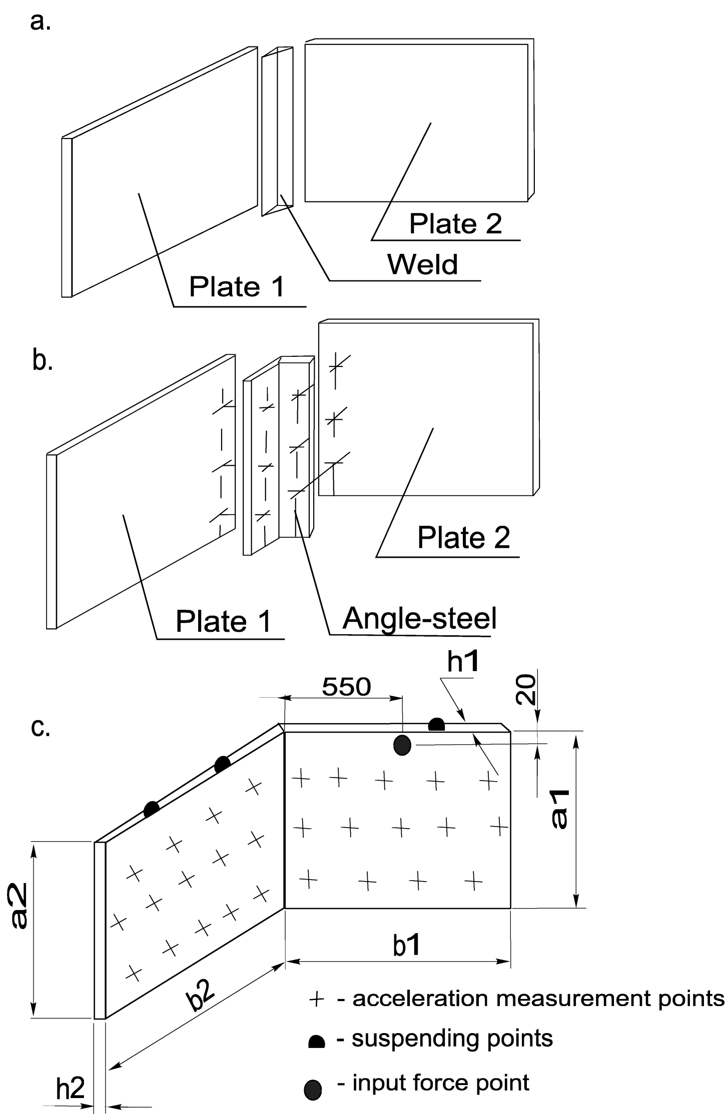

Fig. 1. Plate connections: a) line-welded, b) point with angle steel, c) distribution of measurement, suspended and input force points in plates.

3.1. Line junction

The SEA subsystem model of the welded junction (Fig. 2a) consists of two rectangular flexural homogenous plates and the weld. The input power is injected into the first subsystem. Then Eq. (22) represents in a matrix form the power flow in the system.

$$\begin{bmatrix} \eta_1 + \eta_{12} & -\eta_{21} & 0 \\ -\eta_{12} & \eta_2 - \eta_{21} + \eta_{23} & -\eta_{32} \\ 0 & -\eta_{23} & \eta_3 + \eta_{32} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} W_1/\omega \\ 0 \\ 0 \end{bmatrix}. \tag{22}$$

Power flow between the first and third subsystems is obtained from Eq. (20) and then CLF can be shown in an equivalent form:

$$\eta_{13}^e = \frac{\eta_2}{\left[\dfrac{\eta_3(\eta_2 + \eta_{21} + \eta_{23}) + \eta_{32}(\eta_2 + \eta_{21})}{\eta_{12}\eta_{23}}\right] - \dfrac{\eta_1}{\eta_3}}. \tag{23}$$

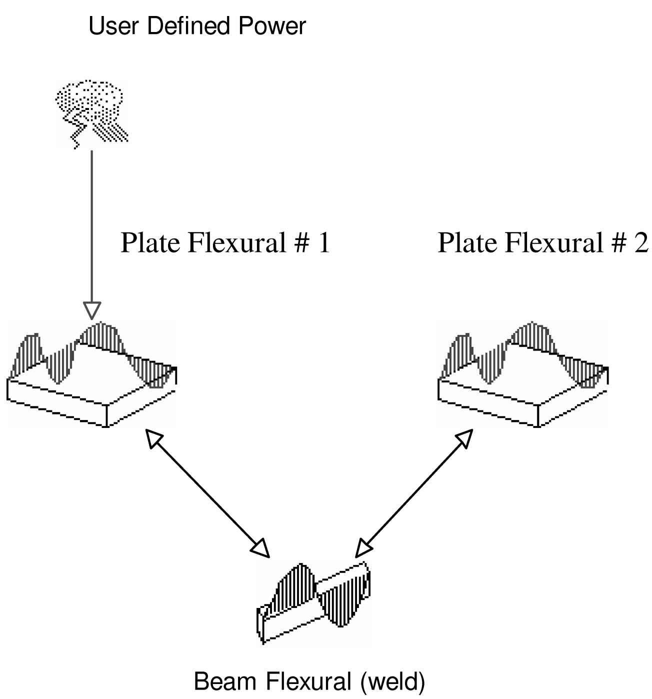

Fig. 2a. SEA model: line-welded junction.

3.2. Point junction

This model is built of four subsystems with input power injected into the first subsystem. Plates are rectangular, flexible, homogenous and with angled steel, which can be considered two L-connected plates, with a frictionless connection. SEA model is shown in Fig. 2b. The power flow represents the following matrix:

$$\begin{bmatrix} \eta_1+\eta_{12} & -\eta_{21} & 0 & 0 \\ -\eta_{12} & \eta_2+\eta_{21}+\eta_{23} & -\eta_{32} & 0 \\ 0 & -\eta_{23} & \eta_3+\eta_{32}+\eta_{34} & -\eta_{43} \\ 0 & 0 & -\eta_{34} & \eta_4+\eta_{43} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} W_1/\omega \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{24}$$

Assuming that subsystems 2 and 3 have the same stored energies, equivalent CLF between the first and fourth subsystems equals

$$\eta_{14}^e = \frac{\eta_2}{\left[\frac{(\eta_4+\eta_{43})(\eta_2\eta_3+\eta_2+1+\eta_3+\eta_{21})+\eta_4(\eta_2\eta_{34}+\eta_{21}\eta_{34}+\eta_{34})}{\eta_{12}\eta_{34}}\right] - \frac{\eta_2}{\frac{\eta_1}{\eta_4}}}. \tag{25}$$

Computer simulations were carried out with AutoSEA code, developed by Vibro-Acoustic Sciences Ltd. [3]

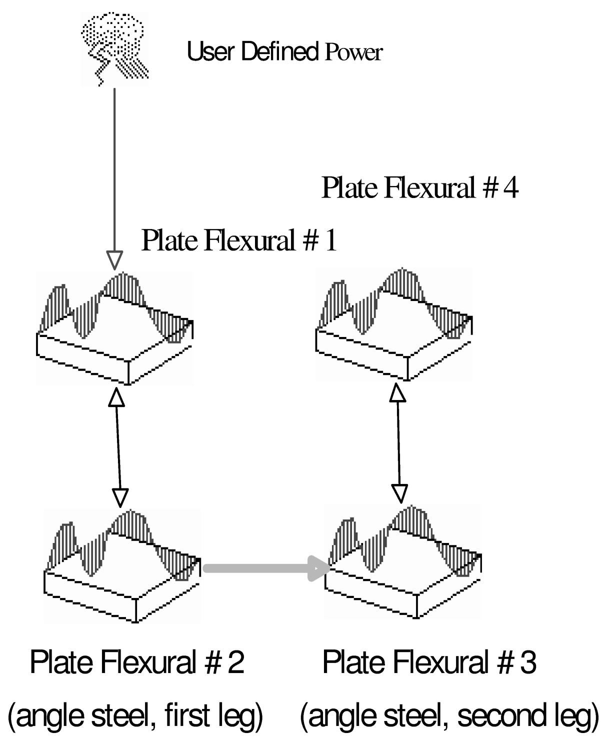

Fig. 2b. SEA model: point type junction.

4. Experiment

The experimental set-up consisted of joined plate structures hung from a vertical duralumin base on nylon threads, additional vibration isolation was suspended by rubber tapes. The standard steel plates were joined perpendicularly to each other (Fig. 1). Two main kinds of junctions have been tested: welded line and point junctions. In a welded example the influence of the thickness ratio of the plates on CLFs was analyzed. In the point-kind of junction, the effect of distribution of connecting points was under consideration. The program of experiments include tests performed on welded, screw-bolded, spot-welded and riveted junctions. The construction details of a variety of joined plates are listed in Table 1.

Table 1. The variety of design and parameters of tested joints of plates.

Type of connections				
Linear		points		
Welded		Screw-bolts	Rivets	Spot Welded
Plate Dimensions [m]	number of points in connections	Plate Dimensions [m]		
$a_1 = 0.65$				
$a_2 = 0.65$				
$b_1 = 1.20$	2			
$b_2 = 1.00$	3	$a_1 = 0.65$	$b_1 = 1.20$	$h_1 = 0.001$
$h_1 = 0.001$	4	$a_2 = 0.65$	$b_2 = 1.00$	$h_2 = 0.001$
$h_1 = 0.0015$	5			
$h_1 = 0.002$	9			
$h_1 = 0.003$				
$h_2 = 0.001$				
Material of plates				
Constructional Steel $E = 2.110^{11}$ [kg·m^{-1}s^{-2}], $\rho = 7820$ [kgm^{-3}], $\nu = 0.3$, E – Young modulus, ρ – material density, ν – Poisson ratio.				

In order to evaluate the energy stored in vibrating plates, the measurements of amplitudes of velocities of vibrating plates were carried out in an anechoic chamber. Evaluation of CLFs were processed with Eq. (20). All experiments were conducted in the frequency range 100 Hz – 100 kHz in $1/3$ octave bands. Experimental set-up consists of input power measurement systems built of an impedance head BK 8000, amplifiers BK 2635, dual channel analyzer BK 2043, graphic equalizer, two accelerometers BK 4344, two amplifiers BK 2635 and a RTF electrodynamic shaker suspended from the frame (Fig. 3). Systematic measurements of all sets of the examined plates' connections were carried out with eight repetitions for sets of fourteen measured points over the surface of the plates (Fig. 1c).

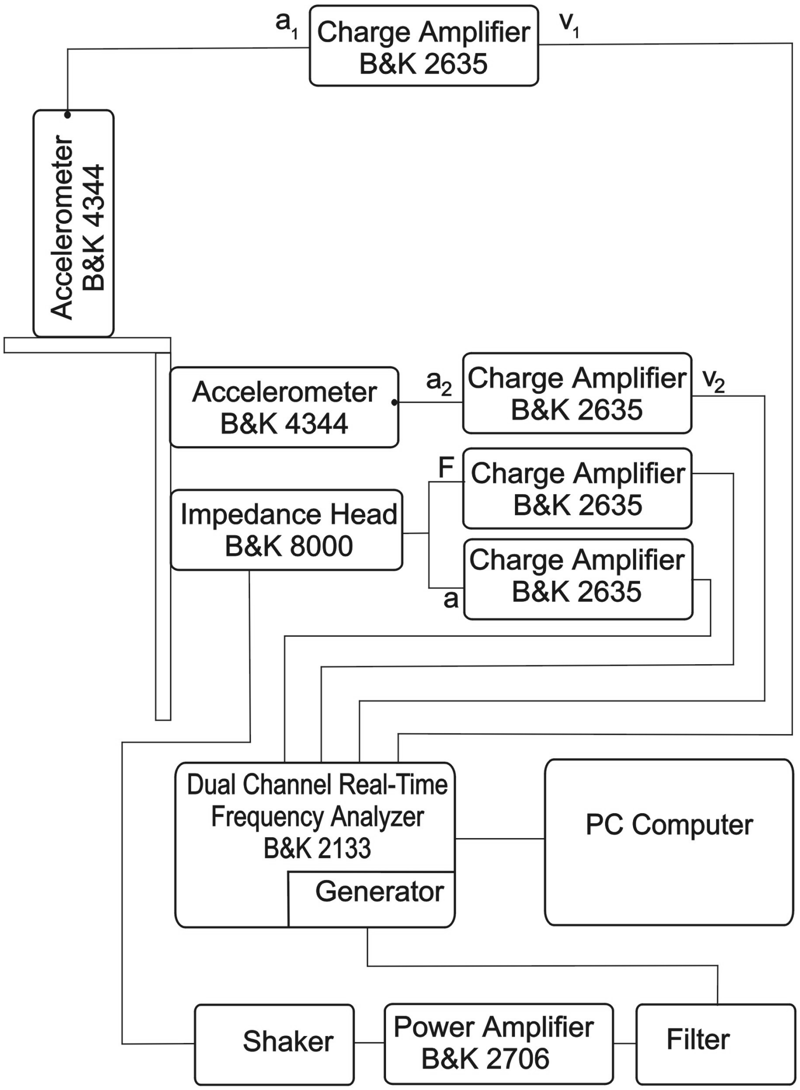

Fig. 3. Measurement set-up.

Additional measurements of reverberation time T of plates were conducted for evaluations of Dissipation Loss Factors of the material of plates. The decay method with white noise signals from a loudspeaker were used to excite the plates. DLF's were calculated using Eq. (21). The results of DLFs of plates with a thickness of 0.001[m] are shown in Fig. 4. There are two cases: a homogenous steel plate, and a steel plate covered on the edges by damping viscoelastic tapes. The plate with damped edges was used in further CLFs investigations. The reason for additional damping was to increase the directivity of energy flow from plate **1** to plate **2**.

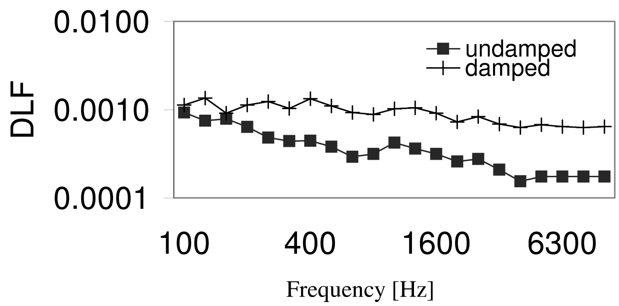

Fig. 4. DLFs of steel plate damper on circumferences and undamped, thickness 0.001 [m].

5. Results and evaluation

5.1. Statistical evaluation

To choose a probabilistic model for a set of measurements, a Kolmogorov–Smirnov goodness-of-fit test was applied. The hypothesis that the values of the measurements fit an exponential distribution at the $\alpha = 0.05$ significance level was studied. The variance has been used to analyze the hypothesis that Coupling Loss Factors are independent of the type of junctions described by the parameters shown in Table 1. A two-way analysis of F-distribution of variance at the $\alpha = 0.05$ significance level was used.

The estimation of the F factor and the critical value at the $\alpha = 0.05$ significance level are shown in the Table 2. This table also contains D factor values and critical values of D at the $\alpha = 0.05$ significance level. Two conclusions are: – A. In the analysis of the entire range of frequencies all investigated values were greater than F values at a level of significance of $\alpha = 0.05$. Thus, according to the Fisher distribution test, the coupling loss factors depend on the thickness ratio of connected plates, the joining elements spacing, and the type of joining. – B. The null hypothesis cannot be rejected because the experimental data fits an exponential distribution at the $\alpha = 0.05$ significance level and then the exponential approximation is the best model for this data.

Table 2. The tested F and D factors, critical values at the $\alpha = 0.05$ significance level.

Type of junction	$F_{0.05}$	F	$D_{0.05}$	D
Line welded	2.09	3.78	1.09	0.17–0.24
Point: screw-bolts, distribution distance $l = 0.075$ [m]	2.09	18.7	1.09	0.12–0.13
Point: screw-bolts, rivets, spot welded, distribution distance $l = 0.075$ [m]	2.09	0.7	1.09	0.17–0.32

5.2. *Line junctions*

Junctions were tested with a fillet weld triangular 0.0004 [m]. CLFs were measured with two different thickness ratios 1.5:1 and 3:1. The result for the ratio 3:1 is shown in Fig.5. Comparisons of exponential values of CLFs for three different thickness ratios for connected plates (1:1.5; 1:1; 1:3) lead to the conclusion that there is evidence of decreasing of the CLFs up to 6-7 dB for larger ratios of thickness. This is more evident in higher frequency bands, where large decreases of density of modes appear. In the lowest frequencies this effect is below 2.5 dB. The agreement of experimental and theoretical (Eq. (4)) CLFs was observed, and larger differences according to Eq. (8) are shown in Fig. 6.

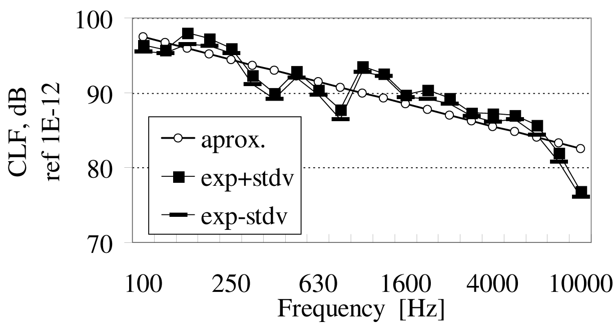

Fig. 5. Experimental values of CLFs for plates joined with weld thickness 0.0004[m], thickness ratio 3:1 (0.003[m] and 0.001[m].

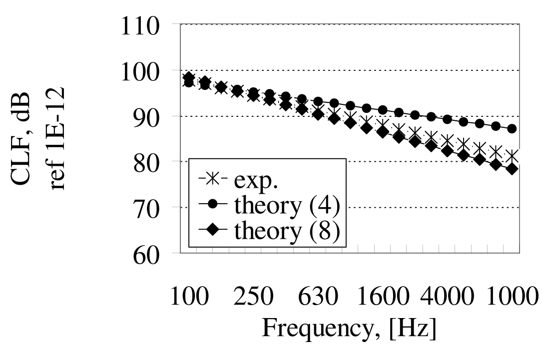

Fig. 6. Experimental and theory CLFs (Eq. (4) and Eq. (8)) for weld joined plates, thickness ratio 1.5:1.

Results shown in Fig. 5 and Fig. 6 demonstrate that the theoretically obtained values of CLFs for both the line and stiff bridge models are closer to the experimental values when we are increasing the thickness of the injected plate. Results in Fig. 5 show that the experimental data fits very well between the line junctions and the stiff bridges models. When increasing the plate thickness, the data for stiff bridges approaches the experimental data more closely. The conclusion is that junction cannot be modeled as a line.

5.3. *Point junctions*

The example of measured CLFs of point screw-bolts joining plates is presented in Fig. 7. This example represents data with five joining screw-bolts at the distance 0.300[m]. The distribution of measured data fits the exponential approximation with ca. 5dB standard deviation.

Another screw-bolt junction of plates CLFs for five different densities of connecting points is shown in Fig. 8. Maximal values of CLFs were obtained from junctions of larger density of connecting points (maximum was nine). This tendency is similar for all other screw junctions of plates. Increasing differences were observed at low frequencies up to 5 dB at 100 Hz.

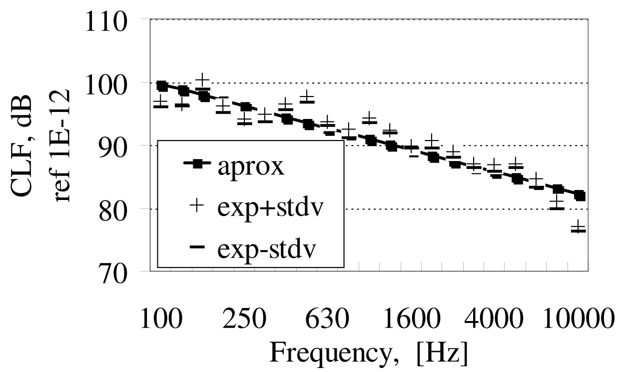

Fig. 7. Experimental CLFs for point screw-bolts junctions' plates: five joining screws, distance of screws 0.300[m].

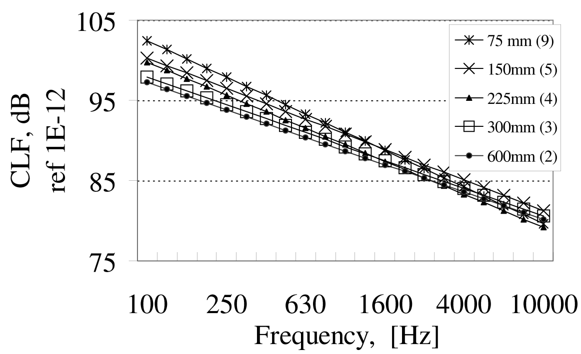

Fig. 8. Experimental CLFs for point screw-bolts junctions, variety of density of joining screw.

The CLFs shown in Fig. 9 present a good agreement between the theory and experiment and up to 3–4 dB difference between the simulation and the experiment. It was possible to observe that in the case of a small number of connecting points, the best agreement is at high and low frequency ranges, while for larger density the agreement is better at a low frequency range. One possible explanation is that increasing of the density of connecting points is a reason of the increase of constructional friction and up to a 10 dB difference between the theoretical and measured results. Constructional friction introduces additional losses of energy, which were not included in the calculation models. This is evident in the middle band of frequencies about 1kHz. Good agreement is observed between the measured and simulated results with a maximal differences of 4–5 dB. According to the results shown in Fig. 7 – Fig. 9, it can be concluded – theoretical values come closer to the experimental data at higher frequencies. The greatest variations of the calculated and experimental CLFs occur at the middle frequencies (500 Hz – 1250 Hz). When the density of connecting points is lower then the calculated CLFs fit better to the results obtained experimentally.

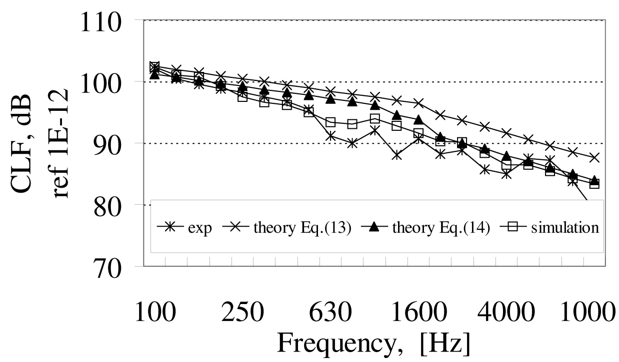

Fig. 9. An example of experimental, theory Eq. (13), (14) and simulated CLFs for spot welded junction, nine joining points, distance of spot welds $l = 0.075$[m].

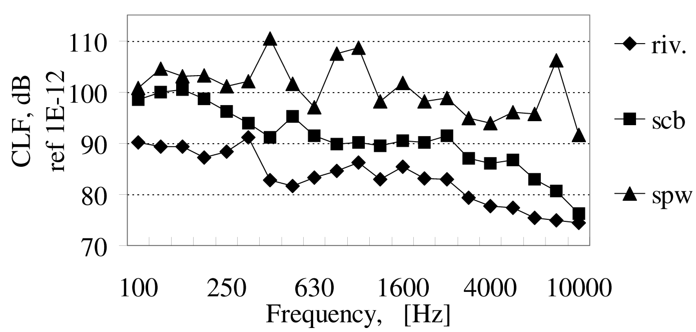

Fig. 10. Experimental CLFs for point junctions: screw-bolts, rivets and spot welded.

Studies of the impact of examined technology of junction on CLFs are shown in Fig. 10. Three exponential fitting curves represent trends of CLFs with marked – screw-bolts, – rivets and – spot-welded. These factors depend significantly on the construction of point connections. The largest values of CLFs were obtained for spot-welded junctions, while middle values were for screw bolts and the lowest values were for riveted joints. The maximal differences occurred at high frequency bands up to about 20 dB at 10 kHz. At low frequencies these values differ by 10dB up to 13 dB at 100 Hz. This shows the importance of technical realization of connections on CLFs, which cannot be simply modeled like the contacts of plates or linear junctions.

5.4. *Evaluation of results*

The following are: experiment versus Line Junction and Stiff Bridges Models, Experimental and Point Connection Models, Point Junction – Different Design and Experimental Data versus Code Simulations.

Experimental values match better the theory for both the line junction and stiff bridge models when increasing the thickness of the excited plate. The results shown in Fig. 6 and results of other similar tests illustrates that the experimental data matches well the models of line junction and stiff bridges. When increasing the plate thickness, the data for stiff bridges approaches the experimental data more closely as the junction can no longer be considered a line junction. The experimental data fits the stiff bridges model better than the line model, which can not be considered for a plate of larger thickness.

CLF factors depend on construction of the point connections. The examined connections show that the lowest values of CLFs were obtained from rivets, followed by screwed and spot-welds, respectively. The simulation output of CLFs appear consistently lower than the experimental values. This was expected since the real joints have a higher density of modes with additional forms of transfer of energy between the subsystems. Simulation of the weld junction using the bending beam was not satisfactory but it was encouraging. The point junctions correspond with the experimental data quite well. Differences that occur at low frequencies are results of using a smaller density of modes in simulations models.

6. Conclusions

Coupling Loss Factors for different perpendicular junctions of thin rectangular plates were examined experimentally and approximated by expressions for wave approaches as line junctions, stiff bridges, or point connections. An energy storage model was presented for evaluation of CLFs in plate junctions. Fisher distribution test F showed that coupling loss factors depended on changes of the thickness ratio between the connected plates, joining element spacing in junctions, and the type of point junction.

Experimental tests included two groups of connections of plates: welded line junctions, and point junctions with rivets, screw-bolded, and spot-welded. Welded line junction tests showed a tendency for decreasing of the CLFs when the ratio of thicknesses of the plates is increasing up to 6–7 dB for larger ratios of thicknesses. The CLFs depend significantly on the density of distribution of joining points. There is an evidence of increasing CLFs with increasing number of joining points in junctions. This impact is larger for low frequencies than for high frequencies.

Comparison of the results of CLFs with different design of junctions showed that it is possible to control the energy flow. For point junctions, CLFs depend considerably on the type of junction. For the tested thin plates, maximal values of CLFs were observed for spot-welded junctions. Mid-values were represented by screw-bolted and the lowest values by riveted junctions. Typical graphs show the values up to 20 dB higher of spot-welded junctions compared to joints riveted for high frequencies and about 10 dB at low frequencies. Consequently, expected vibrational power flow across the riveted junctions will be by about 20 dB lower than similar spot welds.

Experimental data matched well the point connection models. Using these kinds of models in computer simulations, better agreement with real conditions can be achieved. In the case of line models certain corrections have to be done which will include other forms of flow of vibrations and dissipation in the junction.

Acknowledgments

This work was carried out in the Laboratory of Structural Acoustics and Intelligent Materials, University of Sciences and Technology Kraków. The support offered by the State Committee for Research Development of Poland is sincerely acknowledged.

References

[1] BIES, D.A., HAMID, S., *In situ determination of loss and coupling loss factors by the power injection method*, J. Sound Vib., **70**, 187–203 (1980).

[2] BOSMANS, I., MEES, P., VERMEIR, G., *Structure-borne sound transmission between thin orthotropic plates: analytical solutions*, J. Sound Vib., **191,** 75–90 (1996).

[3] CONTACT BREMNER P., Vibro-Acoustics Science Inc., 5355 Mira Sorrento Place, Suite 100, San Diego, CA 92121, Telephone: (619) 597-7535 for more information on AutoSEA.

[4] CLIFTON, S.M., *AutoSEA user guide*, Vibro-Acoustic Science Publication, V.1.3, 1993.

[5] CRAIK, R.J.M., *A study sound transmission through buildings using statistical energy analysis*, Ph.D.thesis, Herriot-Watt University, U.K. 1980.

[6] CREMER, L., HECKL, M., UNGAR, E.E., *Structure-borne sound*, Spring-Verlag, Berlin 1988.

[7] CROCKER, M.J., PRICE, A.J., *Sound transmission using statistical energy analysis*, J. Sound Vib., **9,** 469–486 (1969).

[8] CUSCHIERI, J.M., SUN, J.C., *Use of statistical energy analysis for rotating machinery, Part I: Determination of dissipation and coupling loss factors using energy ratios*, J. Sound Vib., **170,** 181–190 (1994).

[9] CUSCHIERI, J.M., SUN, J.C., *Use of statistical energy analysis for rotating machinery, Part III: Experimental verification with machine on foundation*, J. Sound Vib., **170,** 201–214 (1994).

[10] ENGEL, Z. GAWLIK, M., *Vibroacoustic reciprocity principle in examination of musical instruments*, Archives of Acoustics, **27,** 4, 263–276 (2002).

[11] FAHY, F.J., *Sound and structural vibration: radiation, transmission and response*, Academic Press, London 1985.

[12] FAHY, F.J., JAMES, P.P., *A study of the kinetic energy impulse response as an indicator of the strength of coupling between SEA subsystems*, J. Sound Vib., **190,** 363–386 (1996).

[13] FREDO, C.R., *Prediction of structure-borne sound in a simplified model of a motor vehicle using the method of statistical energy analysis*, Chalmers University of Technology, Goeteborg, Report E88-02, 1988.

[14] GARDNER, B.K., SHORTER, P.J., BREMNER, P.G., *Combining statistical energy analysis in re-sound mid frequency vibroacoustic analysis*, JASA, **112,** 5., Pt.2 of 2., 2302, (2002).

[15] HYNN, P., KLINGE, P., VOUKSINEN, J., *Prediction of structure borne sound transmission in large ship structures using statistical energy analysis*, J. Sound Vib., **180,** 583–607 (1995).

[16] IWANIEC, M. PANUSZKA, R. WICIAK, J., *The evaluation of the influence of modification of plates connection on value of the vibrational energy flow transmission*, Proceedings of the Openm Seminar on Acoustics, OSA'96. 283–286, 1996.

[17] IWANIEC, M. PANUSZKA, R. WICIAK, J., *Application of the SEA method for modification of the structure of walls of acoustic enclosure*, Proceedings of the XXVI Winter School on Noise Control, Poland. 35–42, 1996.

[18] CONTACT KERN, F., Atlantic Applied Research Corp., 4A Street, Burlington, MA 01803, Telephone (617) 27302400 for more information on AARC-SEA.

[19] KIERZKOWSKI, M., *Metoda pomiaru bocznego przenoszenia dźwięku w budynku* [in Polish], Doctoral Thesis, Institute of Buildings Technology, Warszawa 1983.

[20] LALOR, N. STIMPSON, G. *FEM+SEA+Optimalization=Low Noise*, Proc. ATA Conf. on Vehicle Comfort. Bologna 1992.

[21] LALOR, N., *The Evaluation of SEA Coupling Loss Factors*, Proc. School on Energy Methods in Vibroacoustics – Supplement. Table 2. Krakow, University of Science and Technology, AGH, 1996.

[22] LANGLEY, R.S., *A general derivation of the statistical energy analysis equations for coupled dynamic systems*, J. Sound Vib., **135,** 499–508 (1989).

[23] LANGLEY, R.S., *A derivation of the coupling loss factors used in statistical energy analysis*, J. Sound and Vib., **141,** 207–219 (1990).

[24] LEMMEN, R.C.I., *Finite element method in power flow analysis and statistics energy analysis*, Proceedings of the IV-th School on Energy Methods in Vibroacoustics, Zakopane 25–35, 1995.

[25] LEMMEN, R.C.I., *Using the finite element method for calculating of the coupling loss factors of two connected rectangular plates*, The Archive of Mechanical Engineering, **44,** part 1, 21–42, (1997).

[26] LYON, R., MAIDANIK, G., *Power flow between linearly coupled oscillators*, J. Acoust. Soc. Am., **34,** 623–639 (1962).

[27] LYON, R., *Statistical energy analysis of dynamical system – theory and applications*, M.I.T. Press, 1975.

[28] LYON, R., DEJONG, R., *Theory and application of statistical energy analysis*, Butterworth-Heinemann, Boston 1995.

[29] MALCHAREK, P. MARCZUK, R. PANUSZKA, R., *The analysis of the acoustical power radiation from ribbed panels by SEA and experimental methods*, Journal of Mechanics, AGH University, 4, 403–416 (1996).

[30] CONTACT MANNING, J., Cambridge Collaborative Inc., 689 Concord Avenue, Cambridge, MA 021138, Telephone (617) 876-5777 for more information on SEAM.

[31] MING, R., *The Measurement of Coupling Loss Factors using the Structural Intensity Technique*, J. Acoust. Soc. Am., **103,** 410–407 (1997).

[32] MULLER B.B.M., *1995 Statistische Energie Analyse, Grundlangen und anwendungen*, 28–29 Marz, Planneg/Munchen, Germany 1995.

[33] NORTON, M.P., *Fundamental of noise and vibration analysis for engineers*, Cambridge University Press, 1999.

[34] PANUSZKA, R., *The influence of stiffness and boundary conditions of thin rectangular plates on radiated acoustic power*, Applied Acoustics, **46,** 345–362 (1995).

[35] PANUSZKA, R. SMALS, N. FORTUIN J., *Method of estimating the coupling loss factor for a set of plates*, Journal of Mechanics, University of Science and Technology AGH, Krakow, **10,** 2, 5–20 (1991).

[36] PANUSZKA, R., *Energy methods in vibroacoustics*, Ed. Polish Acoustical Society, Kraków 1994.

[37] PANUSZKA, R., *Energy methods in vibroacoustics*, (chapter of the book ed. by Z. Engel), Science and Life, Warszawa 1995.

[38] PANUSZKA, R. [Ed.] and CIEŚLIK, J. IWANIEC, M. WICIAK, J. Applications of AutoSEA Software in Practice. Ed. Polish Acoustoical Society. ISBN 83-903701-1-5, (1995).

[39] SCHEAFFER, L., MCCLAVE, J.T., *Probability and statistics for engineers*, PWS-KENT Pub. Com., Boston 1986.

[40] SCHORTON, T.D., LYON, R.H., *Power flow and energy sharing in random vibration*, J. Acoust. Soc. Am., **43,** 1332–1343 (1968).

[41] STEEL, J.A., *The prediction of structure vibration transmission through a motor vehicle using statistical energy analysis*, J. Sound Vib., **193,** 691–703 (1996).

[42] WESTER, E.C.N., MACE, B.R., *Statistical energy analysis of two edge-coupled rectangular plates: ensemble averages*, J. Sound Vib., **193,** 794–822 (1996).

[43] WICIAK, J. PANUSZKA, R., *Estimation of the CLF factors for flexural plates in SEA modelling*, Proceedings of the V-th School on Energy Methods in Vibroacoustics, Zakopane, 197–200, 1996.

[44] WICIAK, J. IWANIEC, M. PANUSZKA, R., *The prediction of the structure borne sound on the surfaces of car muffler*, The Archive of Mechanical Engineering, **44,** 3, 279–290 (1997).

[45] WICIAK, J., *The analysis of the transmission structure borne sound in complex mechanical systems on example of thin plates*, PhD. Thesis. Library of University Science and Technology, AGH, Kraków 1998.

[46] WOHLE, W., BECKMANN, TH., SCHRECKENBACH, H., *Coupling loss factors for statistical energy analysis of sound transmission at rectangular structural slab joints. Part I*, J. Sound Vib., **77,** 323–334 (1975).

[47] WOHLE, W., BECKMANN, TH., SCHRECKENBACH H., *Coupling loss factors for statistical energy analysis of sound transmission at rectangural structural slab joints. Part II*, J. Sound Vib., **77,** 335–344 (1975).