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VIBRATION ATTENUATION AT ASYMMETRIC CROSS-FORM JOINTS OF BUILDINGS

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Abstract. The aim of the work is to estimate sound energy transmission through asymmetrical cross-junctions in buildings. Several kinds of these joints have been investigated. Theoretical calculation model to obtain transmission loss was developed and a system of equations established. The equations were solved and expressions were obtained for predicting transmission loss. Using this procedure for different structural connections, the simplified calculation formulas were received for different cases of asymmetrical cross-joint. The influence of geometrical parameters and material properties were determined for the sound energy attenuation in the joints of buildings. The obtained results may be applied for evaluation of influence flanking noise transmission through different asymmetric cross-junctions in buildings.

Keywords: structural acoustics, vibration, transmission loss, asymmetric cross-joints.

1. Introduction

Researchers have been investigating the process regarding the transmission of sound energy through the joints of buildings for many years. One of the originators Cremer L. identified [1] the calculation expressions of transmission loss when the bending waves propagate through the joints. Kihlman T. [2] estimated the transmission of longitudinal waves, although his method is rather complicated and requires many initial data. Craven P. G., Gibbs B. M. estimated [3, 4] sound energy attenuation at the joints of buildings by using thin-plate theory.

Afterwards this theory was developed into another theory - statistical energy analysis (SEA). Craik R. J. M. in his works [5, 6] referred to it as SEA theory. He also systematised research results of sound attenuation at the joints and presented transmission coefficient prediction expressions for appropriate corner, tee and cross-joints. Hopkins C. applied SEA theory for calculations of joints [7] and compared the obtained results similar to the calculated results obtained by finite elements method (FEM) and with the results of experimental survey [8, 9].

As light-structures started to be used in buildings, the joints have also changed. Joints with elastic layers have appeared. The current and other problems related to sound transmission through the joints of light-structures were analysed by Mees P. et al [10–12]. Evaluation of sound power transmission through heavy- and light-structures has therefore become a relevant issue. Successful theoretical models of this type of structural connections were developed by Zhang X. M. [13].

In modern construction there appear more and more non-traditional solutions with asymmetrical joints. It is quite difficult to evaluate the sound energy transmission through the joints, as appropriate methodology does not prevail. With the help of the methodology presented in EN 12354-1:2000 [14] it is possible to evaluate only symmetric joints. As there is no comprehensive survey results of such asymmetric structural connections, it will be referred only to a few surveys performed in order to determine sound transmission throughout asymmetric joints. Reis F. was one of a few who had established [15] that tee joints do not depend upon the layout of the elements but only upon their properties. However, this assumption is only valid under certain conditions [16–18].

The aim of this work is therefore to define the simplified calculations and expressions of vibration attenuation in various asymmetric cross-junctions of buildings and to evaluate the parameters that influence the attenuation level at a joint.

2. Propagation of sound waves at joints

Transmission coefficient g is the main indicator to evaluate the sound power reduction in joints of buildings. It is a ratio of powers, ie out-going from the joint and incident on it:

$$\gamma_{ij} = \frac{W_{tr}}{W_{inc}} . \tag{1}$$

In order to define transmission coefficient it is necessary to perform the following actions:

- describe the waves that develop in each joint element;
- describe boundary conditions;
- define the amplitude of each wave leaving the connection;
- define calculations and expressions of the transmission coefficient.

The prevailing assumption is that the elements of the cross-joint are semi-infinite plates, which are connected to the beam. This beam has no mass and is not deformed in their planes, which are perpendicular to the joint. It is considered that bending waves are generated within the elements; nevertheless, the effect of longitudinal waves is not considered as a means of simplification of calculations.

2.1. Sound wave equation and properties

Sound wave properties in a plate are defined according to the power and moment effect into the element (Fig 1).

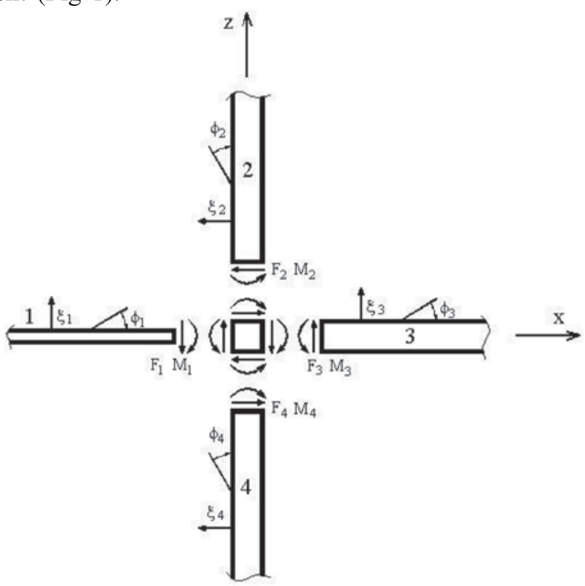

Fig 1. Co-ordinate system for the cross-joint

Interaction of the mentioned powers and moments is described by the equation, the so-called wave equation:

$$\frac{B}{m}\frac{\partial^4 \xi}{\partial x^4} + \frac{\partial^2 \xi}{\partial t^2} = 0 . \qquad (2)$$

Application of the equation (2) allows to establish various wave properties. Displacement of the element ξ within a generated wave may be expressed via the wave amplitude A, which appears in the positive x-axis direction and via the number of waves k:

$$\xi = A\cos(wt - kx) . \qquad (3)$$

Furthermore, it is more convenient to use a complex notation and as a result the equation (3) can be re-written:

$$\xi = A\mathrm{Re}\left(e^{i(wt-kx)}\right) = A\mathrm{Re}\left(e^{-ikx}e^{iwt}\right), \qquad (4)$$

where Re( ) means a real part. For consistency, only the real part shall be used and for this reason all equations omit Re ( ).

Bending wave incidents on the joint from the first plate at angle θ. The wave amplitude is unitary. Number of waves k_x in the direction of x-axis is $k$cosq, and number of waves k_y in the direction of y-axis is $k\sin\theta$. Displacement ξ of this incident wave will be equal to

$$\xi_{inc} = e^{-ik_1\cos\theta x}e^{-ik_1\sin\theta y}e^{iwt} . \qquad (5)$$

Two bending waves develop from the joint into each plate – ie travelling and near field waves:

$$k = \pm w^{1/2}\left(\frac{\rho_s}{B}\right)^{1/4}; \quad k_n = \pm i w^{1/2}\left(\frac{\rho_s}{B}\right)^{1/4} = \pm ik , \qquad (6)$$

where ρ_S – surface density (kg/m^2), B – bending stiffness per unit width for a plate (Nm).

Trace of wavelength in the direction of y-axis is equal to all waves in all plates. The current dependence is expressed via the incoming wave into the joint and is used to define the angle at which waves leave the joint:

$$k_1\sin\theta_1 = k_i\sin\theta_i . \qquad (7)$$

In general, any wave that leaves the joint in the plate i holds the following form:

$$\xi_i = A_i e^{\pm ik_{xi}x}e^{-ik_1\sin\theta_1 y}e^{iwt} . \qquad (8)$$

Travelling and near field waves were described with reference to their number:

$$k_{xi} = \pm i\sqrt{k_i^2 - k_i^2\sin^2\theta_1} = \pm ik_i\cos\theta_i , \qquad (9)$$

$$k_{xi} = \pm\sqrt{k_i^2\sin^2\theta_1 - k_i^2} . \qquad (10)$$

The reflected travelling wave on the first plate will be reflected at the same angle as the incoming wave. Travelling wave will develop in the negative direction of x-axis and in the positive direction of y-axis.

The displacements of all plates are:

$$\xi_1 = \left(e^{-ik_1\cos\theta_1 x} + A_1 e^{ik_1\cos\theta_1 x} + A_{n1}e^{kn_1 x}\right)e^{-ik_1 x}e^{-ik_1\sin\theta_1 y}e^{iwt}, \qquad (11)$$

$$\xi_2 = \left(A_2 e^{-ik_2\cos\theta_2 z} + A_{n2}e^{-k_{n2}z}\right)e^{-ik_1\sin\theta_1 y}e^{iwt} , \qquad (12)$$

$$\xi_3 = \left(A_3 e^{-ik_3\cos\theta_3 x} + A_{n3}e^{-k_{n3}x}\right)e^{-ik_1\sin\theta_1 y}e^{iwt} , \qquad (13)$$

$$\xi_4 = \left(A_4 e^{ik_4\cos\theta_4 z} + A_{n4}e^{k_{n4}z}\right)e^{-ik_1\sin\theta_1 y}e^{iwt} . \qquad (14)$$

2.2. Boundary conditions

Applying the simplest and most commonly used case, it may be assumed of that there are no displacements at the joint. The condition, stating that the displacement at the edge (where $x = 0$ and $z = 0$) of the first plate ξ_1 is equal to zero, can be simplified (11) according to the first equation of expression:

$$1 + A_1 + A_{n1} = 0. \quad (15)$$

Accordingly, it can be found that:

$$A_2 + A_{n2} = 0, \quad (16)$$

$$A_3 + A_{n3} = 0, \quad (17)$$

$$A_4 + A_{n4} = 0. \quad (18)$$

In case of the rigid joints, if one of the planes rotates, the others also must rotate in the same way of the angle, so that the angles between members remain constant. Power balance is necessary for the sum of moments, which act into the joint element, to be equal to zero. For this reason, rotation of the first and the second plates are $\phi_1 = \phi_2$. Expressing the rotations by the displacement condition $\phi = \partial\xi / \partial x$ (at presence of $x = 0$ and $z = 0$), it may be found that

$$\frac{\partial \xi_1}{\partial x} = \frac{\partial \xi_2}{\partial z}. \quad (19)$$

By introducing ξ and A_n values respectively, the following equations are obtained:

$$A_1(-k_{n1} + ik_1\cos\theta_1) + A_2(-k_{n2} + ik_2\cos\theta_2) = k_{n1} + ik_1\cos\theta_1,$$
$$A_1(-k_{n1} + ik_1\cos\theta_1) + A_3(-k_{n3} + ik_3\cos\theta_3) = k_{n1} + ik_1\cos\theta_1, \quad (20)$$
$$A_1(-k_{n1} + ik_1\cos\theta_1) + A_4(k_{n4} - ik_4\cos\theta_4) = k_{n1} + ik_1\cos\theta_1.$$

The final equilibrium condition is: the sum of moments which act into the joint is equal to zero. This is characterised by the expression (Fig 1)

$$M_1 - M_2 - M_3 + M_4 = 0. \quad (21)$$

In the latter, the moments M_i can be substituted by appropriate moment values that are expressed in terms of displacements by the equation (2):

$$-B_1\left(\frac{\partial^2\xi_1}{\partial x^2} + \mu_1\frac{\partial^2\xi_1}{\partial y^2}\right) + B_2\left(\frac{\partial^2\xi_2}{\partial z^2} + \mu_2\frac{\partial^2\xi_2}{\partial y^2}\right) + B_3\left(\frac{\partial^2\xi_3}{\partial x^2} + \mu_3\frac{\partial^2\xi_3}{\partial y^2}\right) - B_4\left(\frac{\partial^2\xi_4}{\partial z^2} + \mu_4\frac{\partial^2\xi_4}{\partial y^2}\right) = 0. \quad (22)$$

By introducing ξ and A_n values respectively, the following equations are obtained:

$$A_1(B_1k_1^2)+A_2(-B_2k_2^2)+A_3(-B_3k_3^2)+A_4(B_4k_4^2)=-B_1k_1^2. \quad (23)$$

The equations (20) and (23) are integrated into the system of equations:

$$\begin{cases} A_1(-k_{n1} + ik_1\cos\theta_1) + A_2(-k_{n2} + ik_2\cos\theta_2) = k_{n1} + ik_1\cos\theta_1 \\ A_1(-k_{n1} + ik_1\cos\theta_1) + A_3(-k_{n3} + ik_3\cos\theta_3) = k_{n1} + ik_1\cos\theta_1 \\ A_1(-k_{n1} + ik_1\cos\theta_1) + A_4(k_{n4} - ik_4\cos\theta_4) = k_{n1} + ik_1\cos\theta_1 \\ A_1(B_1k_1^2) + T_2(-B_2k_2^2) + A_3(-B_3k_3^2) + A_4(B_4k_4^2) = -B_1k_1^2. \end{cases} \quad (24)$$

A legend is introduced to simplify calculation:

$$x = \frac{k_2}{k_1} \quad y = \frac{k_3}{k_1} \quad z = \frac{k_4}{k_1}, \quad (25)$$

$$X = \frac{B_2k_2^2}{B_1k_1^2} \quad Y = \frac{B_3k_3^2}{B_1k_1^2} \quad Z = \frac{B_4k_4^2}{B_1k_1^2}, \quad (26)$$

$$a_1 = 1 + \sin^2\theta_1 \quad a_2 = 1 - \sin^2\theta_1. \quad (27)$$

Consequently, the system of equations (24) is rearranged to:

$$\begin{cases} A_1(-\sqrt{a_1} + i\sqrt{a_2}) + A_2\left(-\sqrt{x^2+\sin^2\theta_1} + i\sqrt{x^2-\sin^2\theta_1}\right) = (\sqrt{a_1} + i\sqrt{a_2}) \\ A_1(-\sqrt{a_1} + i\sqrt{a_2}) + A_3\left(-\sqrt{y^2+\sin^2\theta_1} + i\sqrt{y^2-\sin^2\theta_1}\right) = (\sqrt{a_1} + i\sqrt{a_2}) \\ A_1(-\sqrt{a_1} + i\sqrt{a_2}) + A_4\left(\sqrt{z^2+\sin^2\theta_1} - i\sqrt{z^2-\sin^2\theta_1}\right) = (\sqrt{a_1} + i\sqrt{a_2}) \\ A_1 + A_2(-X) + A_3(-Y) + A_4(Z) = -1. \end{cases} \quad (28)$$

In the presence of normal incident angle of bending wave, which passes throughout the wave amplitudes A_2, A_3 and A_4 of the joint:

$$A_2 = \frac{zy(1-i)}{Xyz + Yxz + Zxy + xyz}, \quad (29)$$

$$A_3 = \frac{xz(1-i)}{Xyz + Yxz + Zxy + xyz}, \quad (30)$$

$$A_4 = \frac{xy(i-1)}{Xyz + Yxz + Zxy + xyz}. \quad (31)$$

Sound power that is transmitted to the joint depends upon the wave amplitude and incident angle. Next phase is to define simplified calculations and expressions of the transmission coefficient.

3. Estimation of vibration transmission coefficient

Calculation of transmission coefficient γ_{1i} according to Cremer L. [1], when the vibration starts from the first joint element towards the other ones, is made according to

$$\gamma_{1i} = \frac{\rho_{si}k_1\cos\theta_i}{\rho_{s1}k_i\cos\theta_1}|A_i|^2. \quad (32)$$

Insertion of expressions of appropriate equations (29–31) into the equation (32) and rearranging terms, allows to determine the following:

$$\gamma_{12} = \frac{X\sqrt{x^2 - \sin^2\theta_1}}{\cos\theta_1}|A_2|^2, \quad (33)$$

$$\gamma_{13} = \frac{Y\sqrt{y^2 - \sin^2\theta_1}}{\cos\theta_1}|A_3|^2, \quad (34)$$

$$\gamma_{14} = \frac{Z\sqrt{z^2 - \sin^2\theta_1}}{\cos\theta_1}|A_4|^2. \quad (35)$$

Possible asymmetric cases of cross-joints situations are:

1) no equal elements in a joint,
2) two equal elements in a joint,
3) three equal elements in a joint.

The equal elements are considered to be the elements of the same cross-section height h and (or) made of material with the same surface density ρ_S and same longitudinal wave-speed c_L. In the article, the third case of asymmetry was addressed, but was the one least examined.

Joints with three equal elements may be divided into three groups – depending on the asymmetry of the elements:

- o asymmetry of the first element,
- o asymmetry of the second (fourth) element,
- o asymmetry of the third element.

For each case, the appropriate transmission coefficient calculation expressions are now defined.

3.1. Asymmetry of the first element

In case of asymmetry of the first element (Fig 2), all other elements are equal – the second, the third and the fourth ($h_2 = h_3 = h_4$, $\rho_{S2} = \rho_{S3} = \rho_{S4}$ and $c_{L2} = c_{L3} = c_{L4}$). Therefore, the members of equation (29–31) are $x = y = z$ and $X = Y = Z$. In order to simplify the calculation, it was considered that the falling angle of the wave into the joint is normal.

Inserting the latter expressions into equations (29–31) and the received results into equations (33–35) enables to obtain the simplified expressions of the transmission coefficient

$$\gamma_{12} = \gamma_{13} = \gamma_{14} = \frac{2Xx}{(x + 3X)^2}. \quad (36)$$

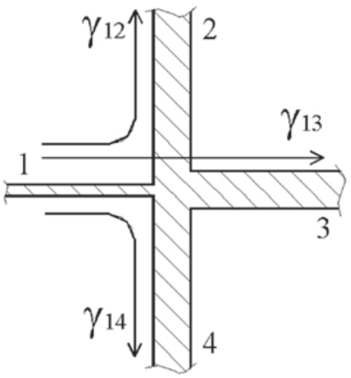

Fig 2. Principal diagram of the cross-joint with the first asymmetrical element

3.2. Asymmetry of the second (fourth) element

When there are three equal elements in the cross-joint, the second element is asymmetrical (Fig 3) and all other elements are equal ($h_1 = h_3 = h_4$, $\rho_{S1} = \rho_{S3} = \rho_{S4}$ and $c_{L1} = c_{L3} = c_{L4}$). Then members of equations (29–31) are $y = z = 1$, also $Y = Z = 1$.

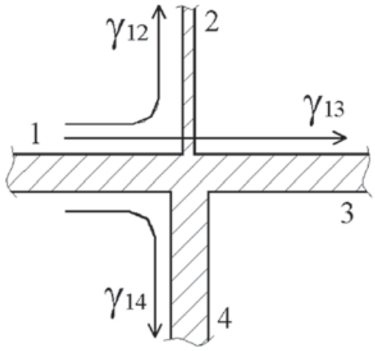

Fig 3. Principal diagram of the cross-joint with the second asymmetrical element

If the latter values are used in the equations (29–31) and (33–35), the simplified expressions of transmission coefficient for this case of cross-joint can be obtained:

$$\gamma_{12} = \frac{2Xx}{(X + 3x)^2}, \quad (37)$$

$$\gamma_{13} = \gamma_{14} = \frac{2x^2}{(X + 3x)^2}. \quad (38)$$

Similar results can be obtained in case of the asymmetry of the fourth element (Fig 4). Then γ_{12} will be equal to γ_{13} and can be calculated by formula (38). Value γ_{14} can be found by (37) expression.

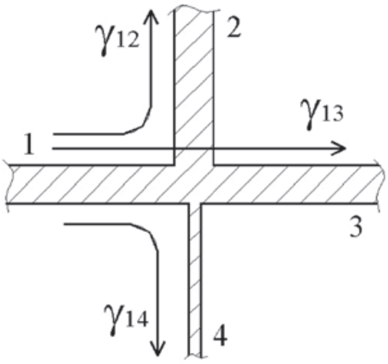

Fig 4. Principal diagram of the cross-joint with the fourth asymmetric element

3.3. Asymmetry of the third element

In Fig 5, the first, second and fourth elements will be the same ($h_1 = h_2 = h_4$, $\rho_{S1} = \rho_{S2} = \rho_{S4}$ and $c_{L1} = c_{L2} = c_{L4}$), therefore the members of the equation (29–31) are $x = z = 1$ and $X = Y = Z$

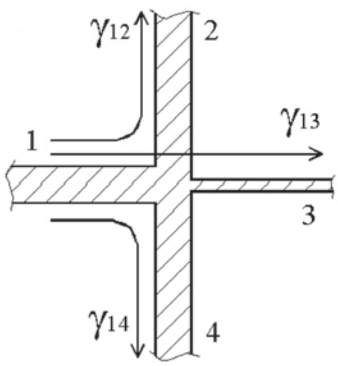

Fig 5. Principal diagram of the cross-joint with the third asymmetric element

These values were similarly used for previous cases in Eqs (29–31) and (33–35) and simplified calculation expressions of the transmission coefficient were obtained:

$$\gamma_{12} = \gamma_{14} = \frac{2y^2}{(Y+3y)^2}, \tag{39}$$

$$\gamma_{13} = \frac{2yY}{(Y+3y)^2}. \tag{40}$$

4. Calculation results

Using the formulas (36–40) the influence of geometrical parameters and material properties on the asymmetric cross-joints with three equal elements, can be defined. Transmission coefficient γ_{1i} is represented in the diagrams as the transmission loss R_{1i}:

$$R_{1i} = 10\log\frac{1}{\gamma_{1i}}. \tag{41}$$

In order to define the influence of geometrical parameters, it is considered that all the elements were made from material with the same surface density ρ_S and the same longitudinal wave-speed c_L. Dependence of transmission loss upon the cross-section height h alternation of the asymmetrical element in respect to other (equal) elements is represented in Figs 6, 8 and 10.

In order to define the influence of material properties it was considered that all elements were made from material with the same cross-section height h. Transmission loss dependence upon longitudinal wave-speed c_L, in regard to the asymmetrical element in the joint, is represented in Figs 7, 9 and 11.

In Figs 6–11 transmission loss R_{1i} dependence upon ratio of element properties is represented. For example,

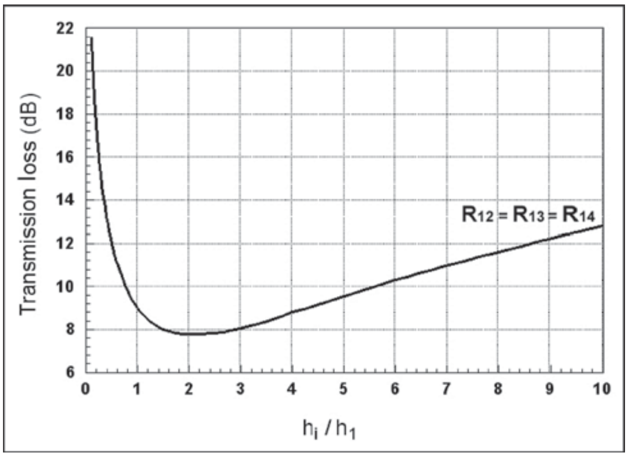

Fig 6. Transmission loss in cross-joint with the asymmetry of the first element. Influence of geometrical parameters

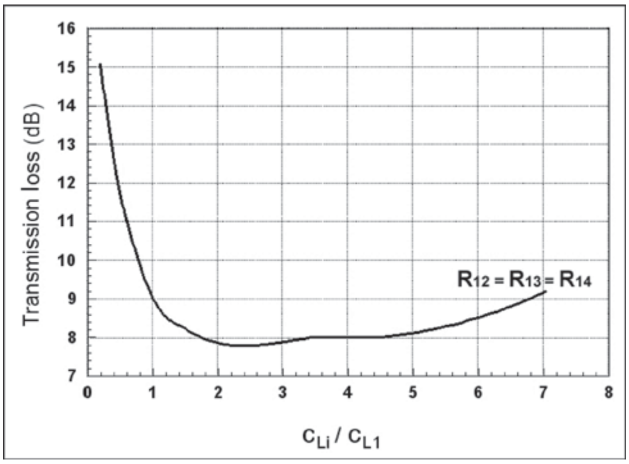

Fig 7. Transmission loss in cross-joint with the asymmetry of the first element. Influence of material properties

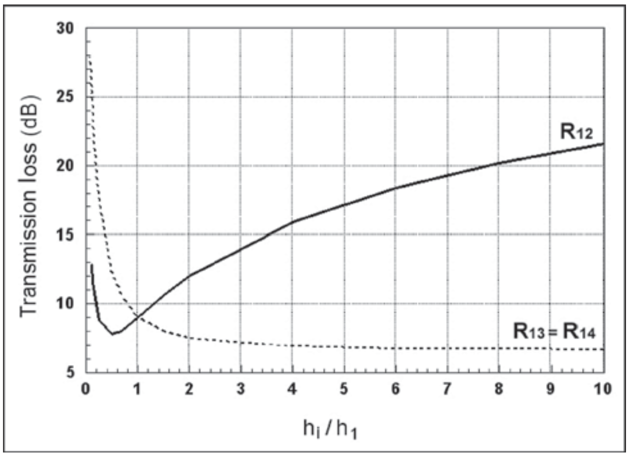

Fig 8. Transmission loss in cross-joint with the asymmetry of the second element. Influence of geometrical parameters

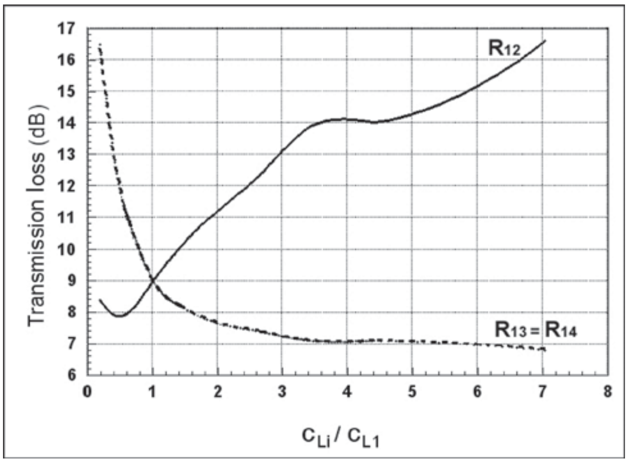

Fig 9. Transmission loss in cross-joint with the asymmetry of the second element. Influence of material properties

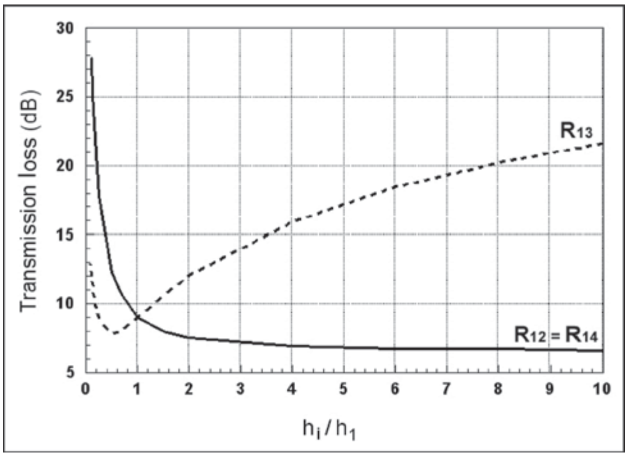

Fig 10. Transmission loss in cross-joint with the asymmetry of the third element. Influence of geometrical parameters

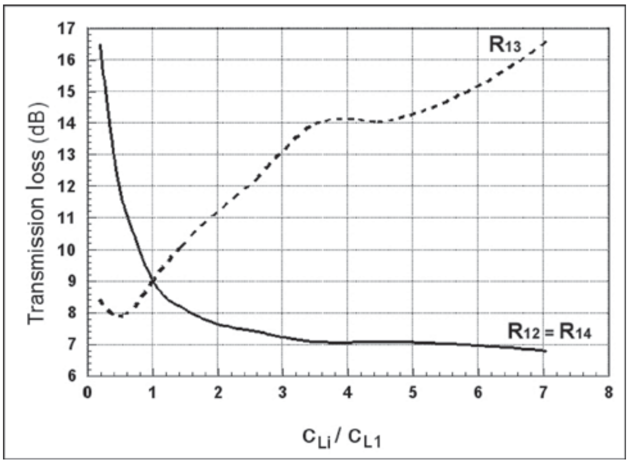

Fig 11. Transmission loss in cross-joint with the asymmetry of the third element. Influence of material properties

in Fig 8: R_{12} transmission loss is shown when vibration propagates from the first element of the joint into the second one. In this case transmission loss depends on the ratio h_2 / h_1, which varies from 0,1 to 10.

Influence of geometrical parameters and material properties is shown in Figs 6, 7 for the joint with asymmetry of the first element (Fig 2). Therein, it can be remarked that vibration attenuation into all elements is equal. Although it is considerably higher in the case when the cross-section height of the first element is far lower than of the one of other elements. Similarly, the situation remains the same if the longitudinal wave-speed of the first element is considerably lower than of the other elements.

Vibration attenuation is represented in Figs 8, 9 for the joint with asymmetry of the second element (Fig 3). Attenuation is maximal when the power is transmitted into the second element and when there is the greatest difference of material properties and geometrical parameters between these elements. A little amount of vibration loss is noticed when noise is transmitted into the other elements. Similar results are obtained in a joint with the fourth asymmetric element (Fig 4).

Influence of geometrical parameters and material properties is represented in Figs 10 and 11 for the joint with asymmetry of the third element (Fig 5).

Calculation results were compared with other authors' theoretical results of vibration attenuation at asymmetrical or cross-joints [5, 15]. The present results confirm the proposition that vibration attenuation at junctions does not depend mostly on the joint form but depends on geometrical and material properties.

For practical evaluation of the present calculations, it would be advisable to perform experimental tests investigating in practice and more in detail the vibration attenuation performance of asymmetric cross-joints.

5. Conclusions

Simplified expressions for transmission coefficient calculation have been suggested for asymmetric cross-joints, where three equal elements prevail with the same cross-section height and/or with the same material properties. With their help the following has been found:

1) ten times increase of cross-section height of asymmetric element with respect to other joint elements: vibration energy losses may reach 28,1 dB;
2) 1,8 times (almost double) increase of longitudinal wave-speed of asymmetric element material with respect to other joint elements: the latter index may increase up to 17,3 dB;
3) vibration attenuation at asymmetric cross-junctions does not depend mostly on the form of junction but depends on geometrical and material properties.

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VIBRACIJŲ SILPIMAS ASIMETRINĖSE KRYŽIAUS FORMOS PASTATŲ JUNGTYSE

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Santrauka

Pagrindinis darbo tikslas yra nustatyti garso energijos slopinimą asimetrinėse kryžiaus formos pastatų konstrukcijų jungtyse. Analizuoti keli asimetrinių kryžiaus formos mazgų tipai. Sudarytas teorinis vibracijų perdavimo koeficientų skaičiavimo modelis ir gauta lygčių sistema. Ją išsprendus, nustatytos vibracijų perdavimo koeficiento (perdavimo nuostolių) supaprastintos skaičiuojamosios išraiškos. Kartojant šią procedūrą, gautos supaprastintos lygtys įvairiems asimetrinių mazgų atvejams. Naudojantis gautomis išraiškomis, nustatyti pagrindiniai parametrai, turintys įtakos garso energijos slopinimui pastato jungtyse. Gauti rezultatai gali būti panaudoti netiesioginio triukšmo sklidimo įvairiomis asimetrinėmis kryžiaus formos jungtimis įtakai įvertinti.

Raktažodžiai: struktūrinė akustika, vibracijos, perdavimo nuostoliai, asimetriniai mazgai.

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