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General theory of vibroacoustic simulation of blast resistance of the bearing building constructions

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Abstract. The report considers the history of development of general theory of vibroacoustic simulation of distribution of broadband dynamic loads on bearing structures of buildings and structures. The following examples show the principles of construction of their direct and inverse vibroacoustic models in series and in parallel. It has been proven that the topology of the original schema is completely the same as that of its inverse model. This makes it possible to conclude that inverse vibroacoustic models of building structures are most convenient for design modeling of complex and multi-connected mechanical oscillatory systems. It is shown that vibration acoustic models for the first time allowed to create algorithms of automated design simulation of explosion resistance of bearing building structures in a wide band of numerous resonances of frequency reaction of the construction structure and its elements to explosive pulse loads.

1 Introduction

To date, one recognized method of numerical modeling has been the finite element method. The unique capabilities of this method have led to its mass use in almost all common software complexes of automated modeling. The need to develop new numerical modelling techniques arose in the late 20th century due to the engineering needs of high technology research. Such research should include subtle technological experiments aboard space stations, such as engineering the growth of semiconductor crystals. The main hope of space technologists was the potential for a super-thin laboratory to be created on board the spacecraft in weightless conditions. This made it possible to expect the "ideal" semiconductor crystals needed by the electronic industry to grow under orbital conditions to create precision devices with high sensitivity and noise immunity.

However, despite the absence of gravity and ideal weightlessness, the first orbital experiments disappointed space technologists with the presence of a high level of vibrations (so-called on-board microgravity) on board the space station. These vibrations were generated by a large number of onboard vibration instruments, including gyroscopes, fans, pumps, etc.

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In this regard, the scientific cooperation of a number of leading institutes of the industry, NASA (customer NASTRAN), ESA and RAS in 1993 was tasked to develop a method of calculated simulation of the distribution of vibrodynamic loads on elements of technological equipment and the power (bearing) structure of the orbital complex MIR [1]. The main purpose of this development was to create design models for precision vibration isolation of on-board process equipment, which was used to grow defect-free crystals in space weightlessness conditions.

Among several proposals on modeling methods, as the most universal, the method of vibroacoustic modeling or vibroacoustic analogy developed by the head of the industry research laboratory of Roscosmos in the NIU MGSU, Professor M.S. Khlystunov (Hlystunov) was selected [1,2]. The use of software systems based on the finite element method was rejected due to the high dynamic error [3-9].

The General theory of vibroacoustic analogies was developed by Professor M. S. Hlystunov in the 90s for the calculation of vibroactivity (microgravity) in the quiet technological compartments of space laboratories [2].

This theory was based on five basic laws of linear dynamic interaction of building structures elements. These laws were formulated by Professor M. S. Hlystunov in the following form.

1. The laws of dynamic equilibrium in the nodes of building structures:

The first law. For all collinear components of vectors of dynamic power loads in an ideal node of a building structure it follows that the difference of the sums of the spectra of incoming and outgoing groups of these components is an empty set.

The second law. For all collinear components of vectors of dynamic power loads moments in an ideal node of a building structure it follows that the difference of the sums of the spectra of incoming and outgoing groups of these components is an empty set.

2. The law of dynamic continuity of connections in the nodes of building structures:

The third law. The spectra of collinear components of displacements, velocities, and accelerations acting in an ideal node of a building structure, that is, the ends of elements of a building structure connected in the node are equivalent or equal-power sets.

3. An integral formulations of these laws is also possible:

The fourth law. The incoming and outgoing flows of the amount of movement in an ideal node of a building structure are equal in size and direction.

The fifth law. The incoming and outgoing flows of the moment of the amount of movement in an ideal node of a building structure are equal in size and direction.

The special theory of vibroacoustic analogies by Prof. M. Hlystunov considers vibroacoustic analogs for nonlinear cases, including node destruction, when the above five laws are violated.

A similar task arose in the late 1990s in the field of construction design due to the growing terrorist threat and the need for calculated simulation of explosion resistance of structural structures of buildings. The progressive collapse of the whole entrance of the residential building due to the gas explosion in only one of the apartments in Magnitogorsk for the new year 2019 and a number of other disasters confirm the urgency of the problem of explosion resistance of the structural structures of civil engineering facilities.

In this regard, it seems very promising to use the method of design vibroacoustic mode in construction design to assess the explosion resistance of structural structures of buildings and structures.

The general and special theory of vibroacoustic modeling was developed by the M.S. Hlystunov. The general theory of the method formulates the principles of calculated simulation of linear problems of distribution of broadband impact and vibration-dynamic loads on structural elements. A special theory of the method formulates the principles of calculated simulation of nonlinear problems of distribution of broadband impact and vibration-dynamic loads on structural elements. Among the nonlinear tasks, the author of the method refers to the tasks of modeling the distribution of dynamic loads on structures with defects and/or with a high degree of physical wear. This report considers the main provisions of the general theory of the method of calculated vibroacoustic modeling of building structures.

2 Frequency response of design elements

The basic concept of the general theory of vibroacoustic modeling is the frequency response coefficient or dynamic stiffness $K(j\omega)$ of the structural element on impact (impulse or explosion) $F(j\omega)$.

In the following we will introduce the designations: $p = j\omega, j = \sqrt{-1}, \omega$ - circular frequency of oscillations; $F(p)$ for the power impulse spectrum and $K(p)$ for the frequency response coefficient. Similar to Hook 's law in static for dynamics, we have the following equation:

$$F(t) = K(t)v(t) \Rightarrow F(p) = K(p)V(p) \Rightarrow F(j\omega) = K(j\omega)V(j\omega) \quad (1)$$

or a dual equation with frequency compliance:

$$v(t) = \frac{\bar{K}(t)}{F(t)} \Rightarrow V(p) = \frac{\bar{K}(p)}{F(p)} \Rightarrow V(j\omega) = \frac{\bar{K}(j\omega)}{F(j\omega)} \quad (2)$$

where $K(p)$is the frequency response or dynamic stiffness, $\bar{K}(p)$ is frequency compliance or dynamic compliance, $V(p)$ is strain rate, respectively.

Dynamic stiffness and dynamic compliance can be verified experimentally, according to formulas:

$$K(p) = \frac{F(p)}{V(p)} \Rightarrow \bar{K}(p) = \frac{V(p)}{F(p)} \quad (3)$$

Fig.1 shows an example of the dynamic rigidity of the construction beam, which can be mathematically represented by the expression (4):

$$\bar{K}(p) = \grave{} \frac{\prod_{i=2}^{M} \bar{K}_{ai}(0)\left[T_{ai}^2 p^2 + 2\xi_{ai} T_{ai} p + 1\right]}{\prod_{j=1}^{N} \frac{1}{\bar{K}_{rj}(0)}\left[T_{rj}^2 p^2 + 2\xi_{rj} T_{rj} p + 1\right]} \quad \forall (N \geq M) \quad (4)$$

where $j = 2n + 1,\ \ i = 2n,\ \ n = 0,1,2,3, \ldots$; N is equal to the number of resonances of the structural element and M is equal to the number of its anti-resonances.

The equations of the vibration velocity spectrum versus the power dynamic load spectrum (1) and (2) by electromechanical analogy can be interpreted as follows. In equation (1), the force dynamic load can be considered as a vibroacoustic stress, the dynamic stiffness as a vibroacoustic impedance, and the velocity of vibration displacements as a vibroacoustic current. In this way we will get a system of direct dynamic electromechanical analogues:

$$F(j\omega)\ P\ U(j\omega);\ V(j\omega)\ P\ I(j\omega);\ K(j\omega)\ P\ Z(j\omega). \quad (5)$$

From the dual (1) equation (2) with frequency compliance, the following inverse dynamic electromechanical similarities can be obtained:

$$V(j\omega)\ P\ U(j\omega);\ F(j\omega)\ P\ I(j\omega);\ \bar{K}(j\omega)\ P\ \bar{Z}(j\omega). \quad (6)$$

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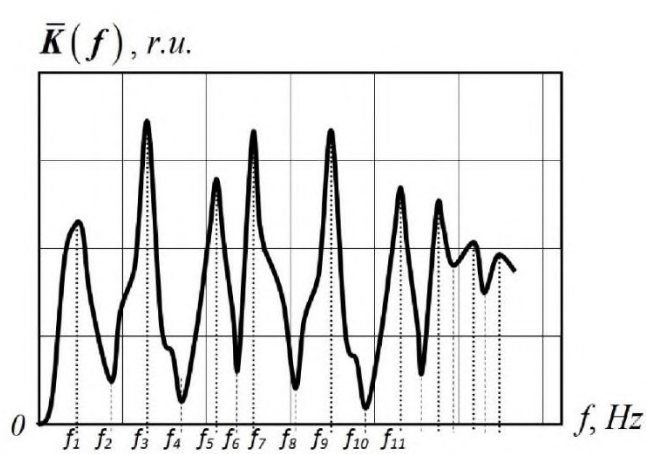

Fig. 1. Example of frequency reaction (dynamic stiffness) of the construction beam as a function of frequency.

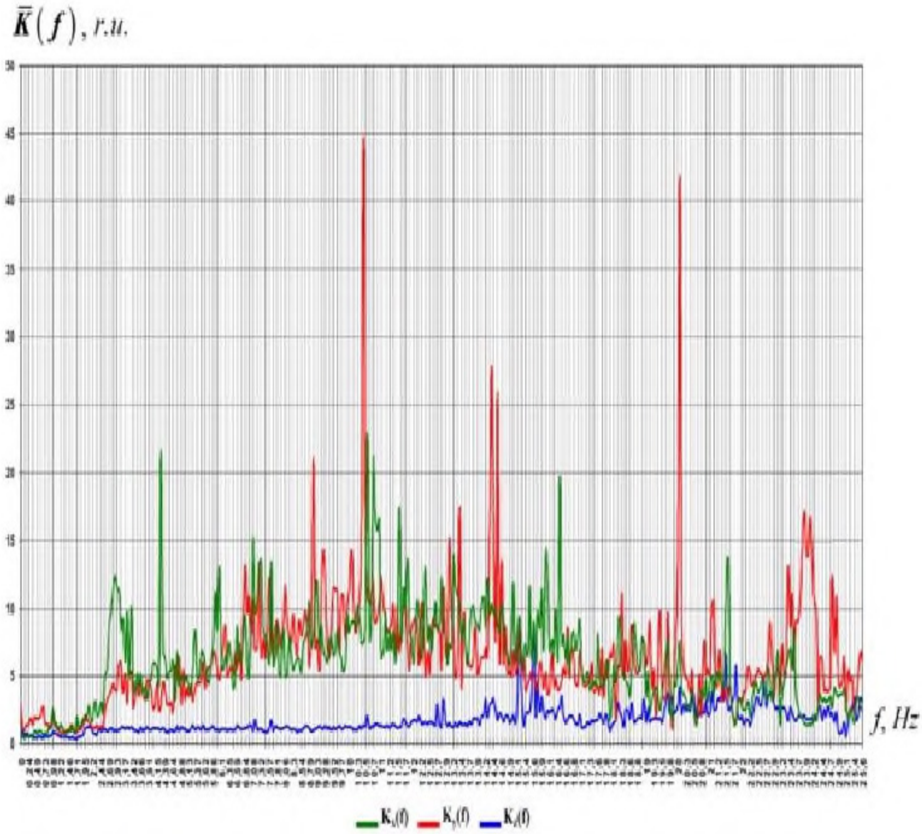

Fig. 2. Example of frequency response (dynamic stiffness) of the bearing structure of the building of the real shopping center as a function of frequency.

As can be seen from Figure 2, the function of the frequency response of the construction structure of a real building is much more complicated than the same function for an individual element of the construction structure in Figure 1. Therefore, it is not possible to use the finite element method for the design simulation of the explosion resistance of such a design, which confirms the feasibility of using the vibroacoustic simulation method and electromechanical analogues.

3 Vibroacoustic models of serial and parallel connections of structural elements

In fig. 3. direct and inverse vibroacoustic models and their electromechanical analogues of serial connection Fig.3a) of three structural elements are presented.

The diagram in Fig.3b) uses direct vibroacoustic similarities (5). The diagram in Fig.3c) uses inverse vibroacoustic similarities (6).

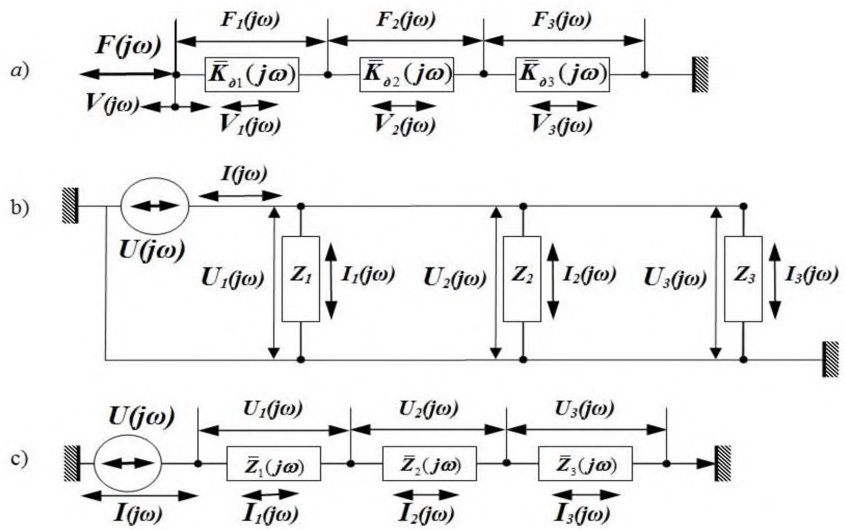

Fig. 3. Dynamic loading circuit of serially connected structural elements (a) and equivalent electrical circuits constructed in accordance with direct (b) and inverse (c) vibroacoustic analogues.

Where $F(j\omega), F_1(j\omega), F_2(j\omega), F_3(j\omega)$ are, the external loads on the structure, respectively, and its distribution on the corresponding structural elements;

$V(j\omega), V_1(j\omega), V_2(j\omega), V_3(j\omega)$ - the speed of vibration forms at the point of application of external loads, respectively, and the speed of vibration forms of the corresponding structural elements;

- rigidity, respectively, and compliance of the respective structural elements;

$U(j\omega), U_1(j\omega), U_2(j\omega), U_3(j\omega)$ - the electrical voltages at the points of its application, respectively, and its distribution on the corresponding structural elements;

$I(j\omega), I_1(j\omega), I_2(j\omega), I_3(j\omega)$ - electric currents at the points of external load applications respectively, and its distribution on the corresponding structural elements;

$Z_1(j\omega), Z_2(j\omega), Z_3(j\omega)$ are the vibroacoustic impedances of the respective structural elements;

$\bar{Z}_1(j\omega), \bar{Z}_2(j\omega), \bar{Z}_3(j\omega)$are the vibroacoustic conductivities of the corresponding structural elements;

Mechanical diagram of vibration-dynamic loading of structure of three serially connected elements is shown in Fig.3a.

Forces and speeds of vibration displacements in the diagram in Fig.3a) are related by the following expressions:

$$F(j\omega) = F_1(j\omega) = F_2(j\omega) = F_3(j\omega) \quad (7)$$

$$V(j\omega) = V_1(j\omega) + V_2(j\omega) + V_3(j\omega) \quad (8)$$

$$\bar{K}_\partial(j\omega) = \bar{K}_{\partial 1}(j\omega) + \bar{K}_{\partial 2}(j\omega) + \bar{K}_{\partial 3}(j\omega) \quad (9)$$

$$K_\partial(j\omega) = \frac{1}{\bar{K}_{\partial 1}(j\omega) + \bar{K}_{\partial 2}(j\omega) + \bar{K}_{\partial 3}(j\omega)} = \\ = \frac{K_{\partial 1}(j\omega)K_{\partial 2}(j\omega)K_{\partial 3}(j\omega)}{K_{\partial 1}(j\omega)K_{\partial 2}(j\omega)+K_{\partial 2}(j\omega)K_{\partial 3}(j\omega)+K_{\partial 3}(j\omega)K_{\partial 1}(j\omega)} = \quad (10)$$

For dynamic load, an expression similar to Hook 's law in static mechanics can be represented as follows:

$$F(j\omega) = K_\partial(j\omega)v(j\omega) \Rightarrow F(j\omega) = \frac{v(j\omega)}{(\bar{K}_{\partial 1}(j\omega)+\bar{K}_{\partial 2}(j\omega)+\bar{K}_{\partial 3}(j\omega))} . \quad (11)$$

Using the dual vibroacoustic analogy of Khlystunov [2] the dynamic loading of a structure of three serially connected elements can be represented by two equivalent vibroacoustic schemes: straight (Fig.3b) and inverse (Fig.3c).

The diagram in Fig.3b) uses direct vibroacoustic analogy (5). The diagram in Fig.3c) uses inverse vibroacoustic similarities (6).

Comparing the circuits in Fig.3b) and Fig.3c), it can be concluded that the use of inverse analogues allows to obtain an equivalent vibroacoustic loading scheme similar in topology to the original, i.e. the mechanical scheme in Fig. 3a). This property is useful when constructing equivalent vibroacoustic schemes of dynamic loading of complex multi-connected mechanical systems, for example, in design simulation of distribution of dynamic loads in a real construction structure.

Mechanical diagram of vibration-dynamic or explosion loading of three parallel elements is shown in Fig.4a).

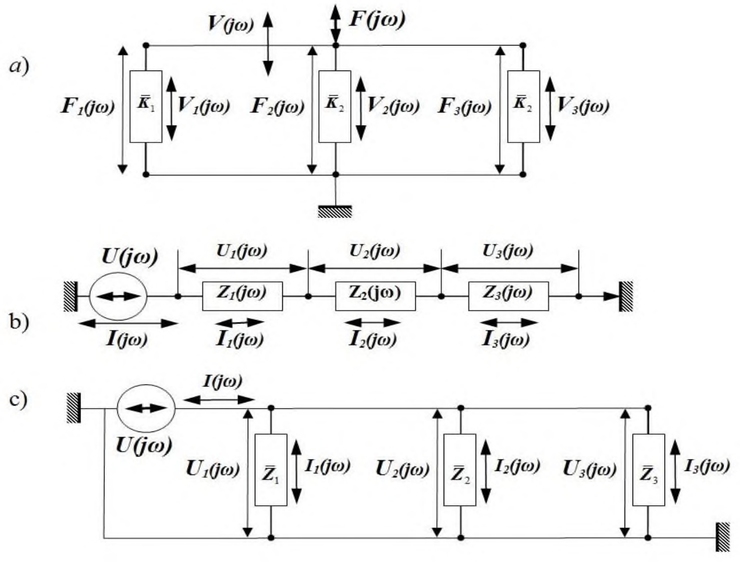

Fig. 4. Dynamic loading circuit of parallel connected structural elements (*a*) and equivalent electrical circuits constructed in accordance with direct (b) and inverse (c) vibroacoustic analogues.

Where $F(j\omega), F_1(j\omega), F_2(j\omega), F_3(j\omega)$ are the external loads on the structure, respectively, and its distribution on the corresponding structural elements;

$V(j\omega), V_1(j\omega), V_2(j\omega), V_3(j\omega)$ are the speed of vibration forms at the points of application of external loads, respectively, and the speed of vibration forms of the corresponding structural elements;

$K_{\partial 1}(j\omega), K_{\partial 2}(j\omega), K_{\partial 3}(j\omega)$are the stiffnesses of the respective structural elements, respectively;

$\bar{K}_{\partial 1}(j\omega), \bar{K}_{\partial 2}(j\omega), \bar{K}_{\partial 3}(j\omega)$are the frequency compliances or dynamic compliances of the respective structural elements, respectively;

$U(j\omega), U_1(j\omega), U_2(j\omega), U_3(j\omega)$ are the electrical voltage at the points of its application, respectively, and its distribution on the corresponding structural elements;

$I(j\omega), I_1(j\omega), I_2(j\omega), I_3(j\omega)$ are electric current at the points of external load application, respectively, and its distribution on the corresponding structural elements;

$Z_1(j\omega), Z_2(j\omega), Z_3(j\omega)$ are the vibroacoustic impedances of the respective structural elements;

$\bar{Z}_1(j\omega), \bar{Z}_2(j\omega), \bar{Z}_3(j\omega)$ are the vibroacoustic conductivity of the corresponding structural elements.

Forces and speeds of vibration displacements in the original diagram in Fig.4a) are related by the following expressions:

$$F(j\omega) = F_1(j\omega) + F_2(j\omega) + F_3(j\omega) \tag{12}$$

$$V(j\omega) = V_1(j\omega) = V_2(j\omega) = V_3(j\omega) \tag{13}$$

On the vibroacoustic model on Fig.4b constructed using direct electromechanical analogues, the forces and speeds of vibration displacements will be related by the following expressions:

$$U(j\omega) = U_1(j\omega) + U_2(j\omega) + U_3(j\omega) \tag{14}$$

$$I(j\omega) = I_1(j\omega) = I_2(j\omega) = I_3(j\omega) \tag{15}$$

where $F(j\omega)\ P\ U(j\omega);\ V(j\omega)\ P\ I(j\omega);\ K(j\omega)\ P\ Z(j\omega).$

On the vibroacoustic model on Fig.4c constructed using inverse electromechanical analogs, the forces and speeds of vibration displacements will be related by the following expressions:

$$F(j\omega) = F_1(j\omega) + F_2(j\omega) + F_3(j\omega) \tag{16}$$

$$V(j\omega) = V_1(j\omega) = V_2(j\omega) = V_3(j\omega) \tag{17}$$

$$I(j\omega) = I_1(j\omega) + I_2(j\omega) + I_3(j\omega) \tag{18}$$

$$U(j\omega) = U_1(j\omega) = U_2(j\omega) = U_3(j\omega) \tag{19}$$

where $F(j\omega)\ P\ I(j\omega);\ V(j\omega)\ P\ U(j\omega);\ \bar{K}(j\omega)\ P\ \bar{Z}(j\omega).$

4 Conclusion

The collapse of the entrance in a multi-stores residential building in Magnitogorsk after the explosion of gas in one of the apartments confirms the urgency of the problem of explosion resistance of civil engineering objects. In this regard, we find it very promising to use the method of calculated vibroacoustic modeling in construction design for design evaluation of explosion resistance of bearing structures of buildings and structures. The general theory of this method presented in this report formulates the principles of design modeling of linear tasks of distribution of wideband impact and vibration-dynamic loads on structural elements. To date, this is the only method that can also be used in automated software complexes.

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