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Numerical and experimental investigation of the axi-symmetric fluid transportation device

K. Ragulskis[1], A. Palevicius[1], A. Bubulis[1], L. Ragulskis[2]

[1] *Kaunas University of Technology*

[2] *Vytautas Magnus University*

Introduction

For effective use of the dynamical effects in the vibrational transportation devices it is important to utilize the knowledge of their eigenfrequencies and eigenshapes. The excitation element for the effective performance of the desired dynamical functions is to operate at the frequency nearly coinciding with the eigenfrequency and its location is to be chosen by taking the corresponding eigenshape into account.

Here the eigenpairs of the fluid-structure system are determined by solving the axisymmetric problem using the finite element method. The analysis is based on [1, 2, 3].

Model of the fluid-structure system

The mass matrix of the fluid or the structure is:

$$M = \int N^T \rho N dV , \qquad (1)$$

where ρ is the density of the corresponding media, N is the matrix of the shape functions defined from:

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = N\delta , \qquad (2)$$

where u, v are the displacements in the directions of the axis of coordinates x and y, δ is the displacement vector, that is:

$$N = \begin{bmatrix} N_1 & 0 & \cdots \\ 0 & N_1 & \cdots \end{bmatrix}, \qquad (3)$$

where N_i are the shape functions, the volume element is defined as:

$$dV = 2\pi y dx dy , \qquad (4)$$

where:

$$y = \sum N_i y_i , \qquad (5)$$

where y_i are the nodal y coordinates.

The stiffness matrix of the structure is:

$$K = \int B^T D B dV , \qquad (6)$$

where D is the matrix of elastic constants for the axisymmetric problem:

$$D = \begin{bmatrix} T+\frac{4}{3}G & T-\frac{2}{3}G & T-\frac{2}{3}G & 0 \\ T-\frac{2}{3}G & T+\frac{4}{3}G & T-\frac{2}{3}G & 0 \\ T-\frac{2}{3}G & T-\frac{2}{3}G & T+\frac{4}{3}G & 0 \\ 0 & 0 & 0 & G \end{bmatrix}, \qquad (7)$$

where the modulus of volume compressibility is given by:

$$T = \frac{E}{3(1-2\nu)}, \qquad (8)$$

where E is the modulus of elasticity and ν is the Poisson's ratio, and the shear modulus:

$$G = \frac{E}{2(1+\nu)} . \qquad (9)$$

The matrix B is defined from:

$$\begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{v}{y} \\ \frac{\partial u}{\partial y}+\frac{\partial v}{\partial x} \end{Bmatrix} = B\delta , \qquad (10)$$

that is:

$$B = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & \cdots \\ 0 & \frac{\partial N_1}{\partial y} & \cdots \\ 0 & \frac{N_1}{y} & \cdots \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial x} & \cdots \end{bmatrix}. \qquad (11)$$

The stiffness matrix for the fluid is:

$$K = \int \left(\overline{B}^T \rho c^2 \overline{B} + \widetilde{B}^T \lambda \widetilde{B} \right) dV \qquad (12)$$

where ρ is the density of the fluid, c is the speed of sound, λ is the penalty parameter for the condition of irrotationality. The matrix $\overline{B}$ is defined from:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{v}{y} = \overline{B}\delta , \qquad (13)$$

that is:

$$\overline{B} = \begin{bmatrix} \dfrac{\partial N_1}{\partial x} & \left(\dfrac{\partial N_1}{\partial y} + \dfrac{N_1}{y} \right) & \cdots \end{bmatrix}. \tag{14}$$

The matrix $\widetilde{B}$ is defined from:

$$\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = \widetilde{B}\delta , \tag{15}$$

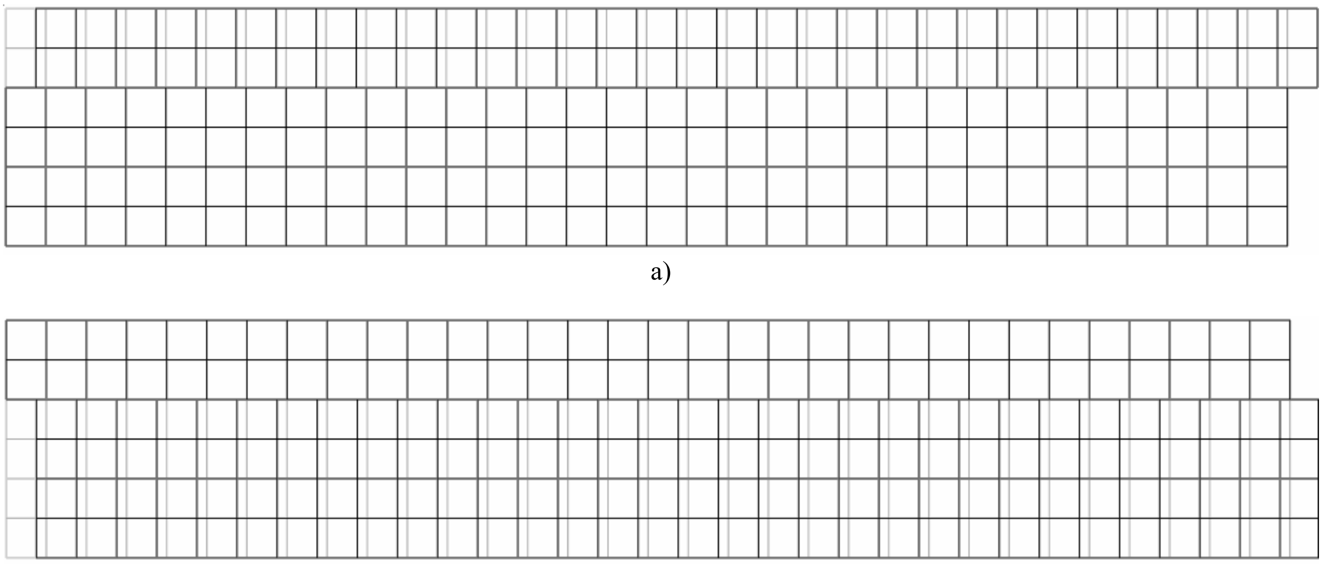
that is:

$$\widetilde{B} = \begin{bmatrix} \dfrac{\partial N_1}{\partial y} & -\dfrac{\partial N_1}{\partial x} & \cdots \end{bmatrix} \tag{16}$$

Numerical investigation of the fluid-structure system

The rectangular domain as a fluid-structure system is analysed. The lower boundary is the axis of symmetry and the displacements normal to it are set to zero. In the lower part of the rectangle we have the fluid and on the upper part the elastic structure. The displacements in the normal direction at the fluid-structure interface are assumed mutually equal, while the tangential ones may be different. The corresponding displacements on the left and the right boundaries for the same values of the y coordinate are assumed mutually equal.

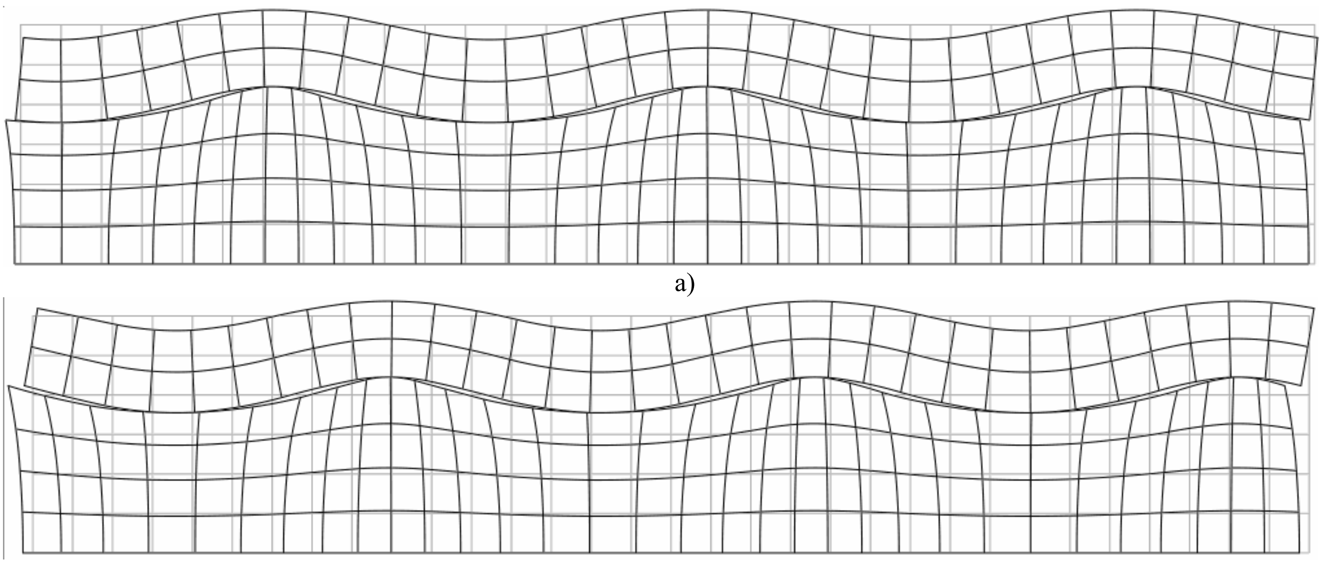
The first two eigenmodes correspond to the rigid body motions and are shown in Fig. 1. The seventh and the eighth eigenmodes both of the same frequency are shown in Fig. 2.



a)

b)

Fig. 1. **The a) first and b) second eigenmodes corresponding to the rigid body motions (the eigenmode is in black, the structure in the status of equilibrium is grey)**



a)

b)

Fig. 2. **The a) seventh and b) eighth multiple eigenmodes (the eigenmode is in black, the structure in the status of equilibrium is grey)**

Experimental analysis of the axi-symmetric fluid – structure system

A number of experimental studies are needed in order to ensure high dynamic accuracy of operation of the vibratory dynamics of the flow of liquid substances. In most cases the exciting frequencies of the axi-symmetric working tube are quite high, and the amplitudes corresponding to them are measured in micrometers. Therefore the holographic method can be effectively applied for the visual representation of wave processes taking place in the tubular vibratory valve ([4], [5]). The most effective method for studying the standing wave processes is the method of holographic interferometry with time averaging ([8], [9]). It should be noted that the most clearly expressed bands in the holographic interferograms are those recorded at the positions of minimum amplitudes ([10]). It is important to obtain the distribution of the vibration amplitudes not only in the middle of dark interference bands, but also at arbitrary positions on the surface of the tube.

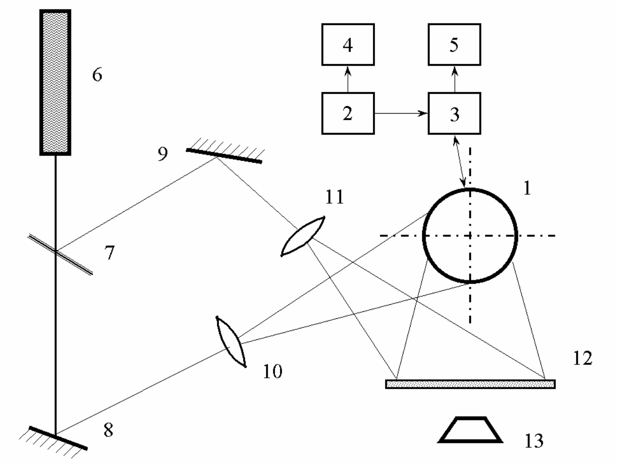


Fig. 3. **The structural diagram of the holography stand: 1 - the axi-symmetric fluid – structure system; 2 - the high frequency signal generator; 3 - the amplifier; 4 - the frequency meter; 5 - the voltmeter; 6 - the source of coherent radiation; 7 - the beam splitter; 8, 9 - mirrors; 10, 11 - lens; 12 - the photographic plate; 13 - the camera**

The amplitudes of vibration of the structure are determined using the methodology presented in [11], [12]. Fig. 3 presents the structural diagram of a stand for experimental analysis of the axi-symmetric fluid – structure system. The stand contains a vibratory valve for controlling the flow of the liquid which consists of a tubular working tube which is harmonically excited by the high-frequency signal generator 2 and the amplifier 3. The signal frequency is monitored by the frequency meter 4, the voltage amplitude of the power supply is monitored by the voltmeter 5. The optical circuit of the stand includes a holographic installation with a helium-neon laser which serves as a source of coherent radiation. The beam from the laser 6 splits into two mutually coherent beams passing through the beam splitter 7. The object beam, reflected from the mirror 8, is split by the lens 10 and illuminates the surface of the tubular working tube 1 and, after reflecting from it, impinges on the photographic plate 12. The reference beam, reflected by the mirror 9, and expanded by the lens 11, illuminates the holographic plate 12 where the interference structure is recorded.

Fig. 4. **Holographic image of the vibrating tube, angle of illumination π/2**

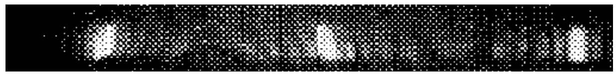


Fig. 5. **Holographic image of the vibrating tube, angle of illumination π/4**

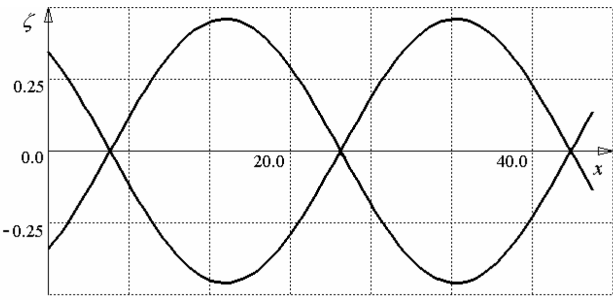


Fig. 6. **Interpretation diagram of the axi-symmetric vibrations of the analyzed tube**

Holographic interferograms of the axi-symmetric vibrations of a vibratory tube are presented in Fig. 4 and Fig. 5. Fig. 6 presents the interpretation diagram for the holographic image presented in Fig. 5 and makes it possible to conclude that transverse vibration of the tube is sufficiently uniform. It should be noted that the frequency of excitation must be selected with care, as the best performance of the vibratory valve is taking place at the resonant frequencies. If the excitation of the transverse vibrations is far away from the resonance frequencies of the tube, the operation of the tabular valve turns to be hardly controlled.

The obtained results enable to optimize the design of the axi-symmetric fluid – structure vibratory systems for controlling and dosing the liquid flow. The following parameters of the system are analyzed and optimized: a) selection of the material of the working tube; b) selection of the area of the transverse cross section of the axi-symmetric tube; c) location of the transverse vibration nodes in the tube; d) determination of the transverse vibration amplitudes along the tube. Maximum uniformity of the transverse vibrations in the axi-symmetric vibratory tube is achieved due to this optimization which leads to more stable operation of the whole system.

Conclusions

The main feature of the presented analysis of the axisymmetric problem of fluid-structure interaction is that the displacements in the normal direction to the fluid-structure interface are assumed mutually equal, while the tangential ones for the ideal compressible fluid may be different.

The obtained multiple eigenmodes for the analysed periodic system may be effectively used for the excitation of wave motion in the fluid transport systems.

Experimental investigations of the axi-symmetric vibrating tube proved the validity of the numerical model used to describe the analyzed fluid – structure system.

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K. Ragulskis, A. Palevičius, A. Bubulis, L. Ragulskis

Skaitinis–eksperimentinis ašiasimetrio skysčio transportavimo įrenginio tyrimas

Reziumė

Gautos tampraus kūno ir skysčio ašiasimetrio uždavinio pirmosios savosios formos. Kartotinės formos periodinėje konstrukcijoje taikytinos banginiam transportavimui. Eksperimentiniai holografiniai tyrimai leido pagrįsti skaitinio modelio pritaikomumą.

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