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Ultrasonic stepped horn design with adaptive modal properties

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High demands on performance, quality and reliability in the development and production of modern technical equipment result in the development of qualitatively new materials and material structures. These new modern materials (ceramics, composites and others) are generally characterized by improved physico-mechanical properties, with the result that this situation leads to relatively large problems in their technological processing [3]. For this reason, the hybrid technology processes are used to process these materials - e.g. combination of conventional technological processes with vibrations (ultrasound). The transmission of vibrations into the technological process is performed by means of the so-called ultrasonic horn, which must be operated in resonant mode. However, during the technological process, ultrasonic horn resonance properties change under load [1]. Design and analysis of stepped ultrasonic horn with adaptive change of modal properties is solved in this paper. Modification of modal properties is carried out using an embedded core which changes distribution of the spatial properties of horn structure.

The structural design of ultrasonic stepped horn with adaptive modal properties is shown in Fig. 1. The stepped horn starting radius is R_0 and the steppped change to radius r is at length L_s. The fundamental part of the ultrasonic stepped horn body has a drilled hole (radius r_c) for insertion of core with a length L_{lc}. The different material properties can be used for body of stepped horn and movable core. The longitudinal displacements of interacting points between the stepped horn body and the core are the same, i.e. perfect adhesion is assumed for the corresponding points.

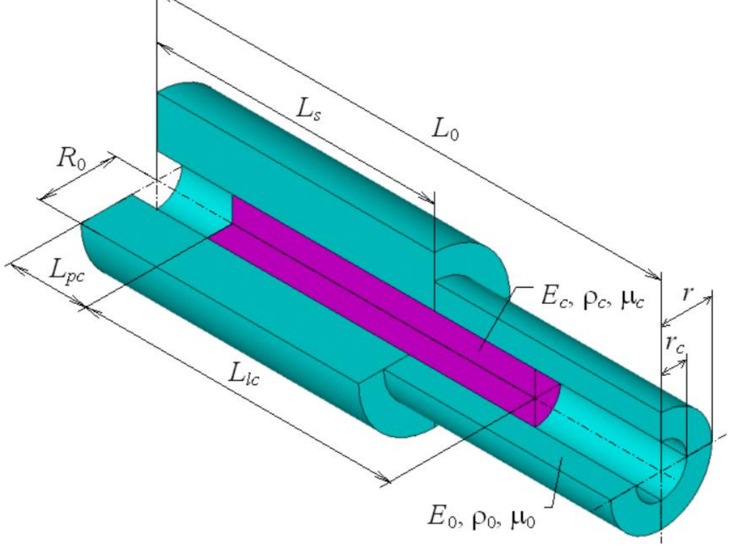

Fig. 1. Structural model of stepped horn

Generally, the partial differential equation (PDE) describing the free longitudinal vibration of *k*-th segment of horn structure is defined [2] in the following form

$$\frac{\partial}{\partial x_k}\left((ES)_k \frac{\partial u_k(x_k,t)}{\partial x_k}\right)-(\rho S)_k \frac{\partial^2 u_k(x_k,t)}{\partial t}=0\,, \tag{1}$$

where $(ES)_k$ is the longitudinal stifness and $(\rho S)_k$ is the unit mass parameter of the *k*-th segment of horn structure, $u_k(x_k,t)$ is the longitudinal displacement of cross-section (contained in *k*-th segment) in positon x_k, *k* is the number of segments (*k* = 4).

By solving the PDE (1) in the form $u_k(x_k,t)=U_k(x_k)T(t)$ [4] and introducing dimensionless parameters, the following ODE is obtained

$$\frac{d^2\bar{u}_k(\xi_k)}{d\xi_k^2}+\beta_k^2\bar{u}_k(\xi_k)=0\,, \tag{2}$$

and the frequency parameter β_k is formulated

$$\beta_k=\omega_{0,m}L_0\sqrt{\frac{\rho_0 S_0}{E_0 S_0}}\sqrt{\frac{\delta_S+\kappa_S(1-\delta_S)+\kappa_{Sc}(\delta_k\kappa_\rho-1)}{\delta_S+\kappa_S(1-\delta_S)+\kappa_{Sc}(\delta_k\kappa_E-1)}}\,, \tag{3}$$

where dimensionless geometrical and material parameters are $\bar{u}_k(\xi_k)=U_k(x_k)/L_0$, $\kappa_S=S/S_0$, $\kappa_{Sc}=S_c/S_0$, $\kappa_E=E_c/E_0$, $\kappa_\rho=\rho_c/\rho_0$, $\xi_k=x_k/L_0$, $\delta_S\langle {=1;\ x\in\langle 0;L_S\rangle \atop =0;\ x\in\langle L_S;L_0\rangle}$, $\delta_{k=1\div 4}\langle {=1;\ S_k=S_0+S_c \atop =0;\ S_k=S_0}$, and cross-sections S_0, S_c, S are defined by

$$S_0=\pi R_0^2\,,\qquad S_c=\pi r_c^2\,,\qquad S=\pi r^2\,. \tag{4}$$

By the formulation of relevant boundary conditions, the frequency determinant is created from which the modified natural angular frequency for stepped ultrasonic horn with adaptive modal properties is determined by

$$\omega_{0,m,j}=\omega_{0,j}\,f_m(\kappa_S,\kappa_{Sc},\kappa_E,\kappa_\rho,\delta_S,\delta_{k=1\div 4})\,, \tag{5}$$

where modified function is expressed by

$$f_m(\kappa_S,\kappa_{Sc},\kappa_E,\kappa_\rho,\delta_S,\delta_{k=1\div 4})=\sqrt{\frac{\delta_S+\kappa_S(1-\delta_S)+\kappa_{Sc}(\delta_k\kappa_E-1)}{\delta_S+\kappa_S(1-\delta_S)+\kappa_{Sc}(\delta_k\kappa_\rho-1)}}\,. \tag{6}$$

and $\omega_{0,j}=\frac{\beta_j}{L_0}\sqrt{\frac{E_0 S_0}{\rho_0 S_0}}$ is *j*-th natural angular frequency for unstepped horn shape with radius R_0 and length L_0.

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