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MODELLING OF VIBRATION AND NOISE CONTROL OF A SUBMERGED CIRCULAR PLATE

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This paper presents a numerical approach for modelling of a thin circular plate clamped on the edges in a rectangular enclosure and containing distributed piezoelectric actuators under dynamic mechanical and electrical loadings. The plate is also loaded on one side by heavy fluid (water) and on the other side contacts with air. The finite element method analysis was performed, supported by the ANSYS computer package. The numerical solutions were confirmed experimentally. The obtained results demonstrate a significant reduction of the vibration level and sound pressure level with the use of piezoceramic actuators.

Keywords: structure-borne noise, piezoelectric actuators, finite element analysis.

1. Introduction

Structure-borne noise and structural vibrations that propagate from mechanical or other sources may be reduced by active control or by passive and active isolation and absorbers [3, 9]. DIMITRIADIS *et al*. [2] developed a detailed model that characterize the interaction between the piezoelectric material and the structure so that they could investigate the use of piezoelectric actuators to reduce the sound pressure radiated by thin circular plates. The vibration of circular plate structures excited by piezoelectric actuators were modelled by VAN NIEKERK *et al*. [6], LENIOWSKA [5] and SEKOURI *et al*. [8]. Niekerk *et al*. presented a comprehensive static model for a circular actuator and a coupled circular plate. Their static results were used to predict the dynamic behavior of the coupled system, particularly to reduce acoustic transmissions. Sekouri *et al*. presented an analytical approach to modelling of a circular plate containing distributed piezoelectric actuators under static as well as dynamic, mechanical and electrical loadings. Leniowska presented a general model of a planar vibrating circular plate located in a finite baffle and interacting with fluid. Recently, PAN *et al*. [7] developed a control strategy for a large submerged cylinder using a Tee-sectioned circumferential stiffener and pairs of PZT stack actuators driven out of phase to produce a control moment.

The experiment reported on this paper is a part of research project connected with fluid-structure interaction problems [10]. This study summarises several experimental programs carried out by the author, exploring the potentials of active control of vibrations and sound through the application of a thin round plate supported on the edges in a rectangular enclosure. The plate is loaded on one side by heavy fluid (fresh water) and on the other side has contact with a gaseous medium (air). On the side of the gaseous medium, eight piezoelectric elements are bonded to the plate with a thin layer of glue. Piezoelectric elements are arranged in sets, each containing four elements located on two concentric circles with different radii.

2. Test object and fem model

The analysed structure is a thin, circular plate of radius $\phi = 0.15$ m, thickness $h = 0.21$ mm. The plate is clamped along its edge by a finite rigid co-planer baffle. The plate is loaded on one side by heavy fluid (fresh water) and on the other side has contact with a gaseous medium (air). On the side of the gaseous medium, eight piezoelectric elements are bonded to the plate with a thin layer of glue. Piezoelectric elements are arranged in sets (Fig. 1), each containing four elements located on two concentric circles with different radii and thickness ($h_1 = 0.21$ mm and $h_2 = 0.28$ mm). The same type of piezoelectric were used throughout each experiment. The geometrical model of system circular plate-piezoceramics – aquarium is presented in Fig. 1 and the properties of the plate and piezoceramics are summarized in Table 1.

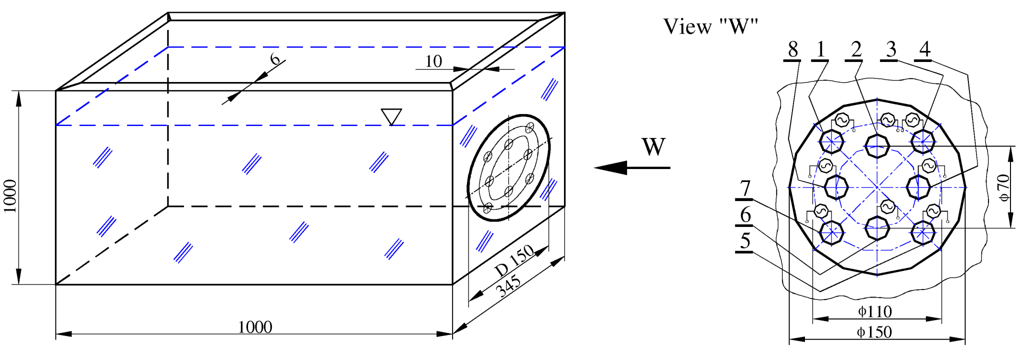

Fig. 1. Geometry of aquarium (1, 3, 5, 7 piezoelements type 1, thickness $h_1 = 0.28$ mm, 2, 4, 6, 8 piezoelements type 1, thickness $h_2 = 0.21$ mm, marked: A2, A4, A6, A8).

FEM analysis of sound radiated by plate vibrations was performed using the Ansys package [1]. Underlying the model is the assumption that there should be at least six grid elements per the considered wavelength. Shell element shell93 and a coupled field element (structure – piezoelectric) solid226 were chosen. These elements are 8-node and 20-node elements, improving the calculation accuracy in relation to 4-node shell63 and 8-node solid5 elements, for the same grid density. The distance between piezoelectric plane (solid element) and the plate's middle surface (shell element) were taken into consideration using rigid region and constraint equations (Fig. 2).

Table 1. Material properties of the experimental plate and piezoceramic.

Piezoceramic P7		Steel	
Density [kg·m^{-3}]	$\rho = 7800$	Density [kg·m^{-3}]	$\rho = 7820$
Elastic constant [10^{-12}m^{2}N^{-1}]	$S_{11} = 15.8$, $S_{12} = -5.7$ $S_{13} = -7.0$, $S_{33} = 18.1$ $S_{44} = 40.6$, $S_{66} = 43.0$	Elasticity modulus [Pa] Poisson ratio	$E = 2.1 \cdot 10^{11}$ $\nu = 0.29$
Charge constants [10^{-12}m·V^{-1}]	$d_{31} = -207$, $d_{33} = 410$, $d_{51} = 550$		
Relative permitivity	$\varepsilon_{11}/\varepsilon_0 = 1930$ $\varepsilon_{33}/\varepsilon_0 = 2100$		

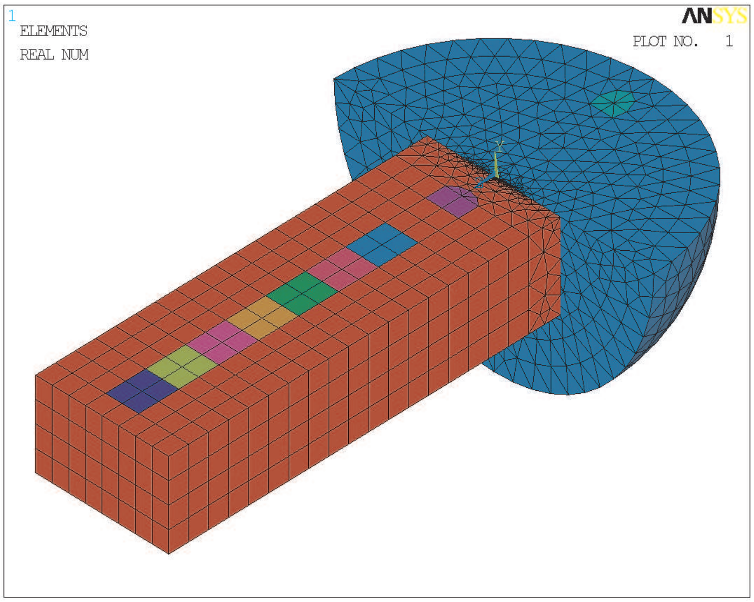

Fig. 2. A half of the aquarium and plate divided into finite elements.

Sound radiated by the vibrating plate is determined in the 0.4 m semi-sphere (Fig. 2) of air surrounding the plate. A discretisation procedure was applied whereby the acoustic volume should comprise nearly 44 thousand fluid30 elements (4-node tetrahedrons) and infinite fluid130 elements on the external surface of the sphere.

The parameters of the acoustic medium assumed for the numerical procedures were: air density – 1.225 kgm^{-3}, speed of sound in air – 343 ms^{-1}, water density – 1000 kgm^{-3}, speed of sound in water – 1490 ms^{-1}. The material damping ratio, independent of frequency is taken as 5×10^{-3} [–] for the whole system.

Values of sound pressure level were calculated at six control volume diameters 0.04 m) in water along the aquarium and at one in volume (diameter 0.04 m) in air at 0.3 m distance from the plate surface (Fig. 2).

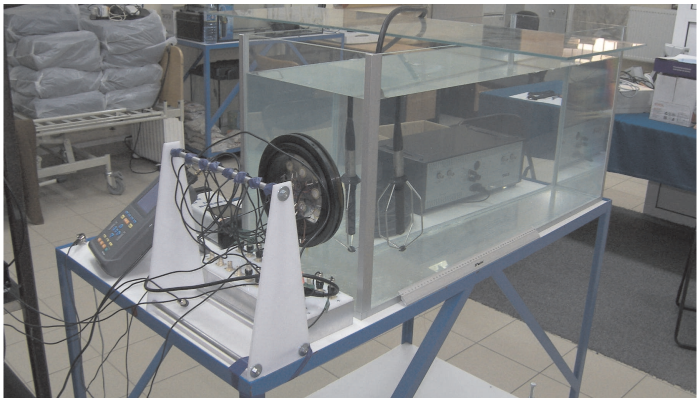

Fig. 3. The view of experimental aquarium and plate with piezoelements.

3. Numerical and experimental results

Assuming that the mode shapes of the plate vibrating in contact with fluid are assumed to be equal to those of plate vibrating in a vacuum, so frequencies of free vibration in fluid can be related to the natural frequencies in a vacuum [4] the following relations between natural frequencies in vacuum and natural frequencies in fluids is obtained:

$$\omega_{Fmn} = \frac{\omega_{mn}}{\sqrt{1+\beta_{mn}}} = \frac{\omega_{mn}}{\sqrt{1+\mathit{\Gamma}_{mn}\dfrac{\rho_F}{\rho_P}\dfrac{r}{h}}}\,, \tag{1}$$

where $\mathit{\Gamma}_{mn}$ – nondimensional added virtual mass incremental factor [4], ρ_p – density of plate material, kgm^{-3}; ρ_F – fluid density, kgm^{-3}; h – plate thickness, m, r – plate radius, m; ω_{mn} – circular frequency of the “dry” plate with piezoceramic, m, n = 0, 1, 2, 3, … .

The harmonic analysis covers the acoustic radiation due to steady-state plate vibrations for the eight modes of resonance vibrations. Each mode was examined individually. The plate was actuated by a single P9 – actuator (marked A2), while the remaining actuators (marked A4, A46, A48) were used to control plate vibrations. Subsequently, the plate was actuated by the next actuator and the remaining actuators (in similar configuration) were used to control plate vibrations. All measurements were repeated seven times and than all data were averaged. Measurements of the acoustic pressure were taken over the whole length of the aquarium, for the fixed position of a hydrophone in the vertical. The effects of a vibrating plate on the acoustic pressure levels outside the aquarium were investigated, too.

To reduce the acoustic pressure level in the control volumes, an assumption was made that the parameter of minimization is the averaged value of the square powered normal velocity on the surface of the panel. It is algebraically convenient to define a cost function – a quadratic function of the response, to simplify the optimization problem.

Accordingly, the cost function is written as (2).

$$J = \sum_{i=1}^{n} \frac{|V_i|^2}{n} = \frac{4 \cdot \pi^2 \cdot f^2}{n} \cdot \sum_{i=1}^{n} A_i^2, \quad \left[\frac{\mathrm{m}^2}{\mathrm{s}^2}\right]. \tag{2}$$

In order to obtain a relatively minimal value of the cost function, the value of voltage amplitude for the first eighth modes control was precisely controlled. The optimization of voltage values utilizes the tool available in the package Ansys. Selected numerical and experimental results are compiled in the Tables 2–4.

In the case of vibration damping for an individual resonant frequency, the displacement response reduction was observed from 5.5 dB up to 25 dB, depending on the

Table 2. Resonance frequencies of the plate with piezoelements.

Resonance frequencies, Hz					
mode	plate with piezo in air		plate with piezo contact with fluid on one side		
	Ansys	experiment	Ansys $*$ Eq. (1)	Ansys + water	experiment
(0,0)	95.0	102.0	17.1	19.9	18.0
(1,0)	197.5	213.2	53.5	62.6	49.0
(2,0)	324.1	313.3	110.9	125.9	104.2
(0,1)	369.5	370.1	96.6	138.0	111.0
(3,0)	482.6	474.7	192.8	198.0	172.8
(1,1)	565.2	571.1	191.3	246.0	191.3
(4,0)	647.4	648.1	—	318.0	254.7
(2,1)	785.9	796.6	313.3	322.0	304.1
(0,2)	827.9	—	—	414.0	255.3
(5,0)	843.2	851.5	—	432.0	462.1

Table 3. Reduction of vibration level (sensor A6, A8) and SPL reduction.

Frequency	Reduction of vibration level, dB		SPL reduction, dB	
Hz	A4	A8	water	air
172.8	16.2	16.5	16.2	4.7
254.7	14.9	14.4	15.2	1.3
304.1	5.8	5.5	5.3	0.8
414.0	21.1	20.5	27.8	22.4
462.1	24.3	25.1	24.8	20.5

Table 4. Reduction of vibration level (sensor A8) and SPL reduction.

Frequency	Reduction of vibration level, dB	SPL reduction, dB	
Hz	A8	water	air
172.8	10.3	13.8	9.5
254.7	7.5	6.8	4.8
304.1	10.1	7.1	4.1
414.0	17.1	31.2	23.2
462.1	22.8	41.9	21.5

resonance frequency. For all considered resonance frequencies, the active treatment resulted in 3–28 dB reduction of sound pressure level in water. Depending on frequency, application of two actuators instead of one improves the reduction of SPL in water by about 2 to 10 dB.

4. Conclusions

The paper is concerned with the problem of active attenuation of plate vibration in contact with fluid. The aim of this work was to investigate how effectively the distribution of actuators should control the vibration and sound transmission through a flexible plate. The geometry and placement of the actuators couple with the plate's vibration modes with fixed point vibration generation. Accuracy of bonding of piezoceramic elements strongly influences the electromechanical performance of piezoelements. Some resonance frequencies errors can be attributed to potential de-bonding. For all considered resonance frequencies and placement of the actuators, the average sound pressure level in the control volumes was significantly reduced in the water and in the air.

The experimental results show that the proposed model can be adopted to large surface elements for structural acoustic noise control in fluids.

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