ACTIVE CONTROL OF A SUBMERGED CIRCULAR PLATE

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Summary: Structure vibrations and structure borne sound may be reduced by passive and active isolation, by passive and active vibration and sound absorbers or by active control. The experiment presented in this paper is a part of an ongoing research project connected with the structural acoustic control in fluid loading structures. The paper presents the opportunity of active control of vibrations and sound through the application of a circular plate containing distributed piezoelectric actuators and sensors. The plate is supported on the edges in a rectangular enclosure and is loaded on one side by heavy fluid (sweet water) and on the other side has contact with a gaseous medium (air). Piezoelectric elements are arranged in sets, each containing four elements located on two concentric circles with different radii.

INTRODUCTION

In recent years, shipboard noise has become a big issue in ship yards as ship's owners and operators are demanding quieter vessels and relevant noise regulations are getting more stringent [ICSV]. Ships have a number of broadband and narrowband underwater noise sources, such as main engine, diesel generator, auxiliary machinery, etc 0, 0. Complex analysis of characteristic of underwater noise allows to find several features typical for underwater noise produced by ships as well as correlations between mechanical activity of ship's mechanism and generated underwater sound 0, 0.The contribution of total energy that is radiated by the moving ship is partially connected with the ships hull vibration due to mechanical activity of machinery inside of the hull. The mechanical vibrations that are transmitted through the hull to the water generates both broadband and narrowband noise 0. Structure vibrations that propagate from sources and transmitted noise may be reduced by passive and active isolation, by passive and active vibration and sound absorbers or by active control 0, 0, 0, 0.

Dimitriadis and Fuller demonstrated that piezoelectric elements bonded to a plate could be employed to reduce the harmonic sound transmitted or radiated from circular plates 0 or rectangular plates 0. They concluded that the shape and position of the actuators markedly affects the distribution of the response among the different modes.

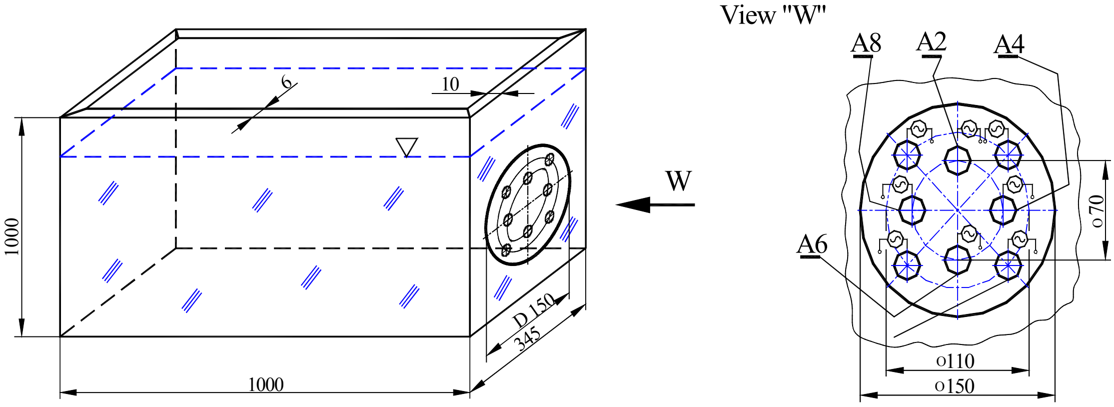
The vibration of circular plates structures excited by piezoelectric actuators has been modelled by Van Niekerk et al. 0, Tylikowski 0 and Sekuori et al. 0. Niekerk et al. presented an active control approach in transient noise transmission through a plate in a circular duct. Sekouri et al. presented the mathematical solution based on Kirchoff plate model for free vibration. Recently, Pan et al. 0 developed a control strategy for a large submerged cylinder by using a Tee-sectioned circumferential stiffener and pairs of PZT stack actuators driven out of phase to produce a control moment. The control of radiated noise from ship's cabin floor has been presented by Won-Ho at al. 0. They concluded that the combined noise level of a cabin could be dominated by the radiated noise from the stiffened steel plate system in combination with deck fool.

Also prediction of natural frequency changes due to the presence of fluid is important for designing structures which are in contact with or immersed in fluid 0. Lamb 0 calculated the change of the natural frequencies of thin circular plate clamped along its boundary and placed in an aparture of infinity rigid plane wall in contact with water. Amabili at al 0 - 0, Kwak at al 0 presented the analytical and numerical approaches used to estimate the natural frequencies of circular and annular plates in contact with a liquid.

The experiment presented on this paper is part of an ongoing research project connected with the structural acoustic control in fluid loading structures 0, 0. The paper presents the opportunity of active control of vibrations and sound through the application of a circular plate containing distributed piezoelectric actuators and sensors. The plate is supported on the edges in a rectangular enclosure and is loaded on one side by heavy fluid (sweet water) and on the other side has contact with a gaseous medium (air). Piezoelectric elements are arranged in sets, each containing four elements located on two concentric circles with different radii.

1. EXPERIMENTAL AND FEM MODEL

The system considered in the study is built up of a thin, circular plate of radius ϕ = 0,15 m, thickness h= 0,21 mm and eight piezoelectric elements. The plate is clamped along its edge by finite rigid co-planer baffle. The baffle with other four rigid walls is formed aquarium filled with water. The plate is loaded on one side by water and on the other side has contact with an air. Piezoelectric elements are bonded to the plate with a thin layer of glue and are arranged in sets (fig. 1). Each set containing four elements with different thickness (h_1= 0.21mm and h_2= 0.28 mm) and sets are located on two concentric circles.



A2, A4, A6, A8 piezoelements thickness h_2=0,21 mm
Fig.1 Geometry of aquarium and plate system

Piezoceramic elements marked A2, A4, A6 and A8 are used during presented experiments. The geometrical model of system circular plate-piezoceramics–aquarium is presented on fig. 1 and the properties of the plate material and piezoceramic are summarized in table .1 and 2.

Tab.1 Material properties of the piezoceramic P7

Piezoceramic P7			
Density [kg·m^{-3}]	Elastic constant [10^{-12} m^2 N^{-1}]	Charge constants [10^{-12} m·V^{-1}]	Relative permitivity
ρ 7800	S_{11}=15.8, S_{12}= –5.7 S_{13}= –7.0, S_{33}= 18.1 S_{44}= 40.6, S_{66}= 43.0	d_{31} = –207 d_{33} = 410 d_{51} = 550	$\varepsilon_{11}/\varepsilon_0$ 1930 $\varepsilon_{33}/\varepsilon_0$ 2100

Tab.2 Material properties of the experimental steel plate

Steel		
Density [kg·m^{-3}]	Elasticity modulus [Pa]	Poisson Ratio
ρ 7820	E $2.1\cdot10^{11}$	υ 0.29

FEM analysis of plate vibrations was performed using the Ansys package 0. Underlying the model is the assumption that there should be at least six grid elements per the considered wavelength. The layer of adhesive agent is not considered in the analysis.

The plate and piezoceramic elements are modelled shell element shell93 and coupled fields element (structure – piezoelectric) solid226 respectively. Piezoelectric layers are modelled by four layers of finite elements. The distance between piezoelectric plane (solid element) and plate middle surface (shell element) were taken into consideration using rigid region and constrain equations. An absorbing material with the sound absorption ratio 0.01 was placed on the external surfaces bounding the water volume, the sound was totally reflected.

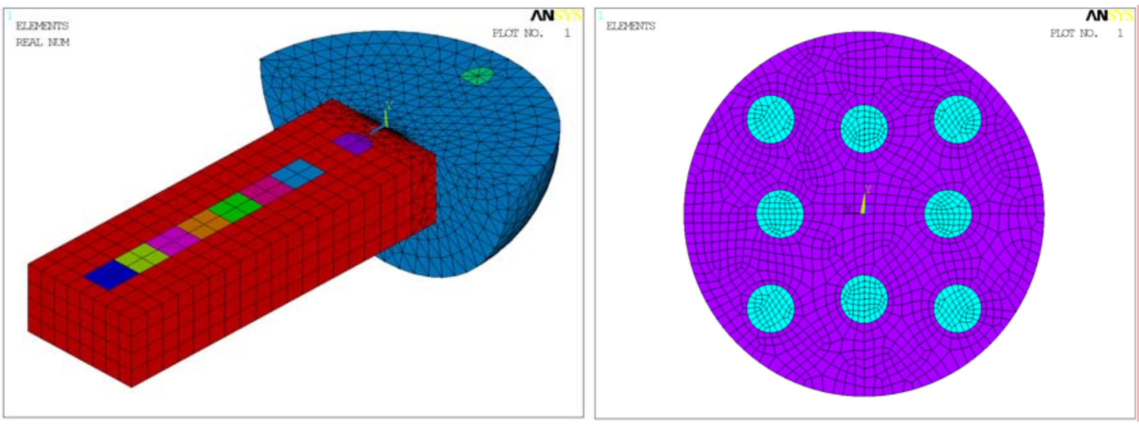


Fig.2 A half of the aquarium and plate divided into finite elements

In the plate-acoustic space model structural sounds produced by the vibrating plate were radiated to the water space and to the semi-sphere (0.4 m) of air surrounding the plate (fig. 2). 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 mesh was finer in the plate's neighbourhood.

The parameters of the acoustic medium assumed for the numerical procedures were: air density - 1.225 kgm^{-3}, speed of sound in air – 343ms^{-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 x 10^{-3} [-] for the whole system.

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

Values of sound pressure level in water is calculated at six control volumes (diameter 0,04 m) 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). Sound pressure level at the control volumes over the whole surface were computed using the acoustic field - structure interaction module available in the ANSYS package.

2. NUMERICAL AND EXPERIMENTAL RESULTS

Assuming: the fluid motion is small, incompressible, inviscid and irrotational, the dynamic loading of the fluid has an insignificant effect on the deflection curve (small changes in the kinetic and potential energies), the plate is thin-elastic plate, the small deflection theory of plates can be applied 0, 0, 0.

Using Rayleigh quotient for coupled vibrations accounts for the square of the natural frequencies of the plate in vacuum ω^2_{mn} and in the fluid ω^2_{Fmn}, one can write:

$$\omega^2_{mn} \approx \left(\frac{U_{mn}}{T^*_{mn}} \right)_{air} \tag{1}$$

$$\omega^2_{Fmn} \approx \left(\frac{U_{mn}}{T^*_{mn} + T^*_F} \right)_{fluid} \tag{2}$$

where: U_{mn} - maximum potential energy of plate, T^*_{mn} - reference kinetic energy, T^*_F reference kinetic energies of the fluid.

According to the assumption, the energies are not changed when evaluated in vacuum or in fluid, the following relations between natural frequencies in vacuum and natural frequencies in fluids is obtained0:

$$\omega_{Fmn} = \frac{\omega_{mn}}{\sqrt{1+\beta_{mn}}} = \frac{\omega_{mn}}{\sqrt{1+\Gamma_{mn}\dfrac{\rho_F}{\rho_P}\dfrac{r}{h}}} \tag{3}$$

where: Γ_{mn} – nondimensional added virtual mass incremental factor tabulated in 0; ρ_p – density of plate material, kgm^{-3}; ρ_F – fluid density, kgm^{-3}; h - plate thickness, m, r – plate radius, m

The circular frequency, ω_{mn} of the "dry" plate with piezoceramic can be obtained from:

$$\omega = \omega_{mn} = \frac{\lambda_{mn}^2}{r_0^2}\sqrt{\frac{D_s}{\rho_p h}} \qquad m=0,1,2,3,\ \ldots\ldots, \qquad n=0,1,2,3,\ \ldots\ldots, \qquad (4)$$

where: D_s – plate (with piezoelements) bending stiffness, λ_{mn} – frequency parameter tabulated in 0;

Tab.3 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 (3)	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

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 actuator A2, while the remaining actuators (A4, A4 and A6 or A4 and A8 were used to control plate vibrations or were used as sensors. All measurements were realized 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 and for variable height yet in a fixed distance from the radiation source.

- outside the aquarium, in one point at 0.3 m distance from the plate surface.

For the reduction of the acoustic pressure level in the control volumes it was assumed, that the parameter of minimization is the averaged value of the square powered normal velocity on the surface of the panel. The cost function is written as:

$$J = \min\sum_{i=1}^{n}\frac{|V_i|^2}{n} = \frac{4\cdot\pi^2\cdot f^2}{n}\cdot\sum_{i=1}^{n}A_i^2, \qquad \left[\frac{m^2}{s^2}\right] \qquad (5)$$

where: A – displacement amplitude, [m]

In order to obtain a relatively minimal value of the cost function, the value of voltage amplitude for the first seven modes control was precisely controlled. The optimization of voltage values utilizes the tool available in the package Ansys. Some numerical results are presented on fig 4a -4c.

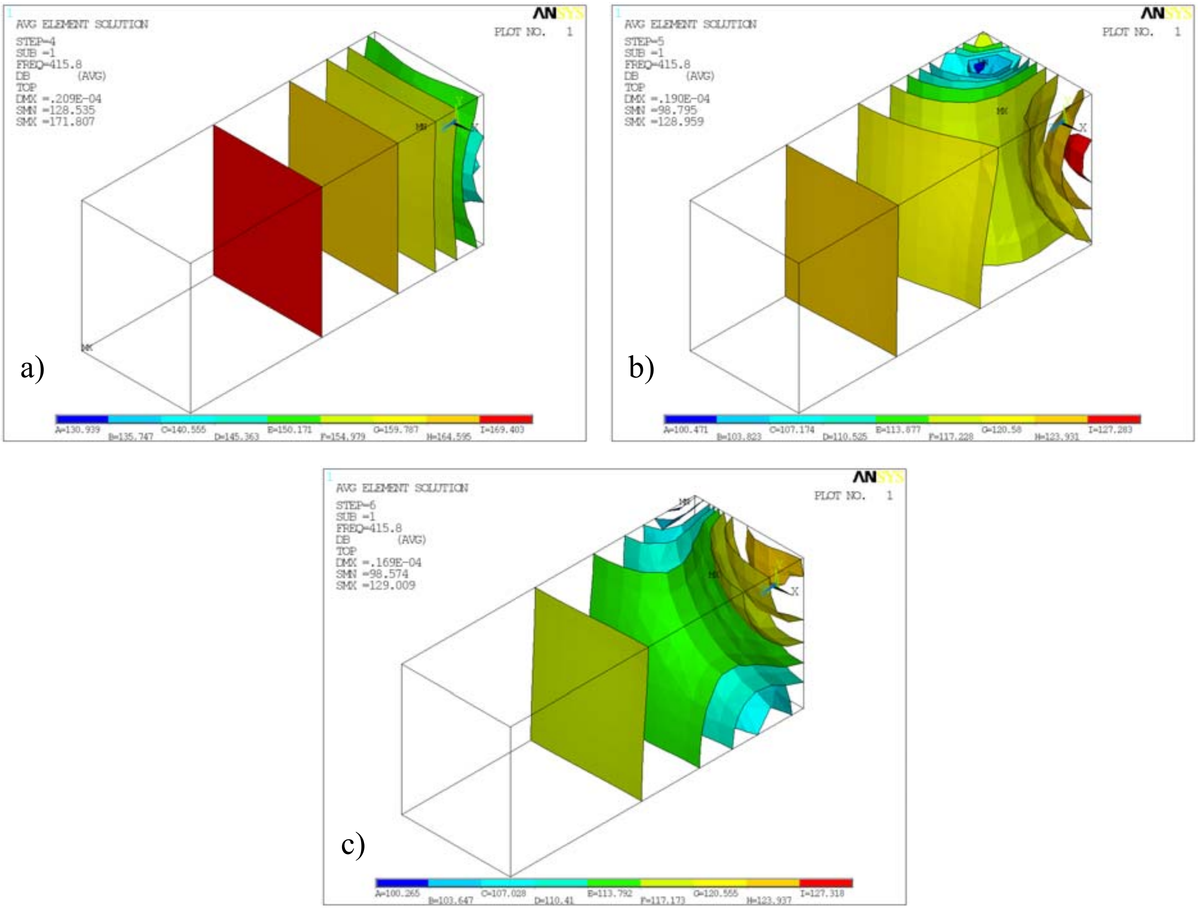
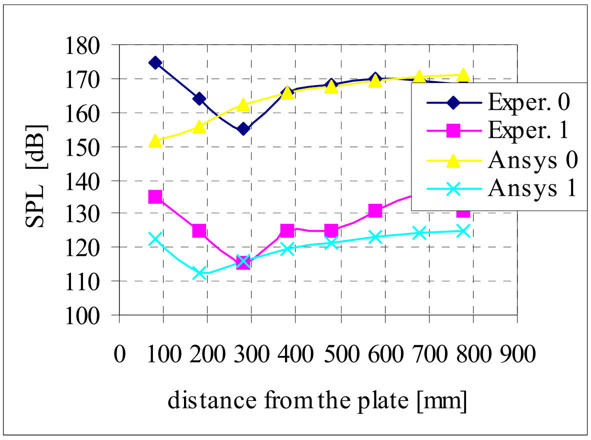


Fig.4 Isosurfaces, SPL in water, frequency 415,8 Hz: a) without reduction, b) actuated A4, c) actuated A46

Tab.4 Reduction of vibration level (sensor A4, actuated A6, A8) and SPL reduction

Frequency	Reduction of vibration level, dB	SPL reduction, dB	
Hz	A8	water	air
212,2	12,3	15,3	9,3
256,1	7,1	6,3	4,1
303,7	6,9	4,0	2,0
414,0	16,0	29,2	24,2
462,1	23,6	43,9	22,5

In the case of vibration damping for an individual resonant frequency, the displacement response reduction was observed from 7 dB up to 23.6 dB, depending on the resonance frequency. For all considered resonance frequencies the active treatment resulted: - in 4 - 44 dB reduction of sound pressure level in water and - in 2 – 24.2 reduction of sound pressure level in air.



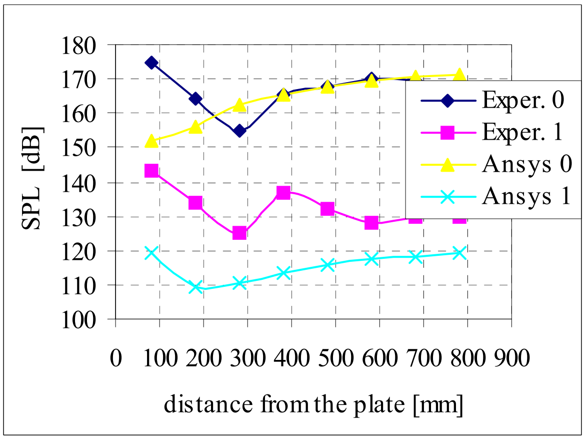


Fig.5 Sound pressure level over the whole length of the aquarium, frequency 416 Hz, 0 – without reduction, 1 – with active reduction, a) actuated A4, b) actuated A4 and A6

The responses at six control volumes appear to have the same response profile but differ in magnitude. Depending on the frequency application of two actuators instead of one increase the reduction of SPL in water by about 2 - 10 dB. Activation of the piezoelectric elements changing the acoustic field in the water, in the water has arisen vortexes. During these activations it is also possible to find a local minimum. In the frequency 462 Hz this phenomena occur at the distance 180 mm from the plate.

4. CONCLUSIONS

The goal of this experiments was to determine how effective the distributed actuators could be in active structural acoustic control. Measurements of the acoustic pressure were taken over the whole length of the aquarium, for the fixed position of a hydrophone in the vertical and also vertical direction.

The finite element method and the non dimensionalized added virtual mass incremental "NAVMI" factors for circular plates placed on an aperture of an finite rigid wall and in contact with a fluid on one side have been used to obtain theoretical natural frequencies, the fluid effects decrease with mode order.

A suitably designed actuator could indeed perform very effectively in reducing acoustic transmissions through plate to the water and to the air. The geometry and placement of the actuators allowed it to couple well with the plate's vibration modes.

During measurements, it was not noticed any changing of sound pressure level in water for variable height yet in a fixed distance from the radiation source. This is probably connected with small vertical dimension of the aquarium.

The proposed method in this paper is readily applicable to the determinations of the natural frequencies of structural systems and can be adopted to large surface elements for structural acoustic noise control in a fluid.

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