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Simulation of square diaphragm as substrate for nanostructured thin film underwater acoustic transducers

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***Abstract*—Acoustic transducers in general and hydrophones in particular are incorporating novel nanostructured materials as piezoelectric electroacoustic transduction mechanisms. One of the first steps in the design of this kind of sensors is to determine the resonance frequency of the potential substrate. The results of modal analysis for three potential material substrates with different thicknesses for depositing nanostructured thin films is presented. Cloud Finite Element Analysis platform was used to calculate the resonant frequencies. A square diaphragm of 20 mm per side made of 0.127 mm thickness PET shows a first resonant frequency vibrating in vacuum and without considering damping effects from a fluid structure interaction is 0.84 kHz, which is in the desired region of operation for detecting underwater objects operating at frequencies below 1 kHz.**

Keywords—Thin film hydrophone, substrate simulation, underwater transducers, PET

I. Introduction

Evolution of underwater transducers has diversified in multiple lines of investigation. Researchers involved in the line related with vector sensors have explored different mechanisms to build vector hydrophones able to determine propagation bearing of an acoustical field using a single sensor, some of the identified mechanisms are: inertia [1-6], mass flow [7- 10]; and vibrational modes [11]. Hydrophone construction using Microelectromechanical systems (MEMS) and Nanoelectromechanical (NEMS) processes allow the implementation of new materials that miniaturizes this kind of sensors [12- 15]. Vector Sensor and MEMS lines of research have integrated by different proposals to optimize sensitivity, directionality, size and cost of the sensors used to transduce underwater acoustical signals.

One of the main areas of current research is electroacoustic transduction using thin films over flexible materials, but as an additional differentiation, thin films are being explored from two perspectives, bulk and nanostructured materials. Sanz-Robinson et al. [16] describe the construction of a microphone using a 28 µm polyvinylidene fluoride (PVDF) diaphragm, which is fixed at two ends with the purpose to employ it in the d31 mode, where the horizontal strain is converted into a vertical potential difference between electrodes. Abdul et. al. [17], report the construction of a MEMS directional hydrophone by micromachining cantilever beams using Aluminum Nitride (AlN), that was designed and simulated using COMSOL® multiphysics in order to predict the frequency response of a cantilever in air and water showing agreement in the resonance frequency between a measured devise using laser vibrometer and the results obtained by Finite Element Modeling (FEM). Li et. al. [18] analyze by Finite Element Analyzes (FEA) a potential structure as MEMS vector hydrophone. The proposed structure consists of a 1700 µm x 1500 µm x 28.2 µm cantilever (with thickness layers of 10 µm for ZnO, 18 µm for silicon and 0.2 µm for silicon dioxide) with a mass in the free end of 500 µm x 1500 µm x 310.2. Li et al. report the thickness optimization by FEM of a piezoelectric micromachined microphone, "based on the analysis of stress evolution in each layer of piezoelectric films" [19].Suma et. al. [20] built an acoustical sensor by depositing a 680 nm zinc oxide (ZnO) film over a flexible substrate of metallic alloy (Elgiloy).

The objective of this work is to determine the dimensions, thickness, and material to be used as substrate for a hydrophone using thin film nanostructured piezoelectric materials. This will be determined by numerical simulations using the resonant modes of a square diaphragm. This work applied basic structural analysis to determine the resonant frequency of potential substrates for nanostructured piezoelectric materials. It can also be used to identify the regions where the greater strains are produced and select the potential areas of the sensor where the piezoelectric material should be deposited.

II. Methodology

The first step to start the design process of an acoustical sensor involves the approximation of the structural response of plates, diaphragms and components considered for transducing the sound to voltage. This estimation and analysis of the frequency response of the electromechanical device can be done through a theoretical approach building a mathematical model of the sensor or by simulating its frequency response using computational tools.

The computational tools employed for selecting the dimensions and thickness of the substrate were cloud-based platforms. Onshape® education standard version to model the 3D shapes and Onscale® free version to simulate the mechanical behavior and its frequency response. Onshape® software was used to do the Computer-Aided Design (CAD) of the structure and Onscale® is a FEA tool that allows to simulate the structural behavior of the sensor designed using Onscale®.

Onshape® is a "cloud native product development platform" capable of providing service for part, assembly and drawing of 3D CAD models, along with data management, collaboration, bill of materials and configurations [21].

Onscale® is a "cloud engineering simulation platform" that allows to import 3D CAD models, assign materials to the model, choose the type of physics that is going to be simulated, assign loads and constraint conditions, mesh, simulate and visualize results [22]. The limitation of using this cloud service is that it does not have the option to simulate fluid structure interaction, which limits the analysis to structural behavior without considering the viscous effects, damping and loads while immersed in a fluid.

III. Computer-aided design and finite Element Analysis of square diaphragms resonance.

In the initial phase a selection of materials and shape is necessary to build the computational model. Particularly, to optimize the thickness of a thin film piezoelectric device an additional simulation related with the strain and stresses that will actuate over the sensor is reported by [19], in order to identify the regions were most of the transduction mechanism will take place over the sensor.

The common practice is to execute a preliminary analysis to estimate structural behavior of the sensor through simulation with FEA software. This simulation was done using the online software Onscale®, using the mechanical environment physics and defining the analysis type as modal. The simulation was configured as follows:

Using online 3D CAD modelling software Onshape®, a list of sensor configuration was built, focusing in a square shape diaphragm (Fig. 1) with varying sides dimensions from 20, 10, 5, 2, and 1 mm per side and using as thicknesses 0.127, 0.254 and 1.016 mm. All of those geometries were used to simulate sensor substrate structure. Once the different structures were built and imported to Onscale®, PET, Alumina and Stainless

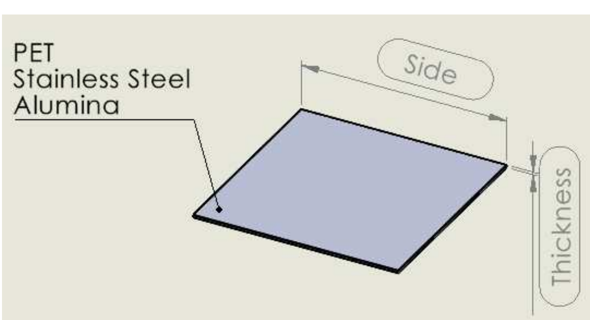


Fig. 1. Square diaphragm with varying parameters for sides, thickness and material.

Steel 304 were assigned as substrate materials using mechanical and thermal parameters shown in Table 1. Onscale® uses as main parameters for the mechanical simulation: density, Poisson's ratio and Young Modulus, which allow to approximate how the structure will vibrate but does not take into consideration other factors as linear elastic material

TABLE 1. MATERIAL PROPERTIES OF SIMULATED SUBSTRATES

Material	Density [kg/m^3]	Poisson's ratio	Young Modulus [Pa]	Specific heat [J/(kg*K)]	Thermal conductivity [W/(m*K)]	Thermal expansion [1/K]
PET	1350	0.337	3E9	1720	0.24	7e-5
Stainless Steel 304	8000	0.270	200E9	510	15.5	17e-6
Alumina	3900	0.222	300E9	8e-6	900	27

properties like the temperature for estimating variations in the values of variables or if the material is isotropic or anisotropic.

In the physics section of the modeler interface, the mechanical environment was configured to do a modal type of analysis, the number of modes to be calculated is configured to 10 and the four sides of the sensor were restrained as fixed faces. Once the parameters were defined, the software automatically defines the mesh and solves the simulation. After the simulation is finished, it displays the 10 vibrational modes of the structure along with a calculation of the mass participation in the three Cartesian axes. The sensor configuration for FEA was:

1. Square plate dimensions: 20 mm x 20 mm, 15 mm x 15 mm, 10 mm x 10 mm, 5 mm x 5 mm, 2mm x 2 mm y 1 mm x 1mm.

2. Square plate thickness: polyethylene terephthalate (PET) 0.127 mm, stainless steel 304 0.127 and 0.254 mm, alumina 0.127 and 1.016 mm.

IV. Results and discussion

The frequencies in kilohertz calculated from each of the simulations are shown in table 2 and plotted in Fig. 2. With the results obtained from the simulation it is possible to select a material, side dimension and thickness. When comparing the behavior of the simulated square diaphragms it was possible to identify that the resonant frequency increased when the side dimensions decreased, or the thickness increased. The results do not consider the effects of the electrode and piezoelectric thin film layers, nor the damping, viscous effects and loads caused by the sensor immersed in a fluid.

Each configuration shows resonant behavior with different frequency regions of operation. The vibrational mode of the sensor structure is used to transduce sound vibrations according to a target frequency. In this case the target region of operation is below 1 kHz. The configuration that shows a first resonant mode near the desired frequency is a square diaphragm of 20 mm x 20 mm x 0.127 mm made of PET.

From the results, it was possible to identify that the first and the sixth mode were the ones in which a greatest mass participation along the z axis was obtained (Fig. 3). In this case z axis is set perpendicular to the surface area of the sensor and presents the greater strain for resonance frequencies that excite the structure by incident sound pressures. The greater strains at the resonant frequencies of the structure allow to assume that the thin film will be subjected to deformations that can produce the greatest voltage response due to the piezoelectric behavior of the deposited materials.

The material selection and dimensions of a substrate define the operation frequency of a structure. When building acoustic sensors, it is important to understand at what frequencies the structure for the sensor will show resonant modes and the regions of stress over the structure that each resonant mode will produce.

The resonant modes define the frequency region of operation of a loudspeaker or microphone in the case of air electroacoustic transducers, as well as for underwater electroacoustic transducers known as projectors or hydrophones. Depending on the type of electroacoustic transducer the resonant frequency should agree with the structure of the manufacturing material or be operated below it.

The identification of stress areas corresponding to each resonant mode allow to identify the location of the strain with greater displacements. In the case of piezoelectric materials, the strain of the structure defines how much charge will be produced.

V. CONCLUSIONS

The results obtained from the configurations simulated allow to identify that the first resonance frequency of a 20 mm x 20 mm x 0.127 mm made of PET, vibrating in vacuum and without considering damping effects from a fluid structure interaction is 0.84 kHz. Under the same assumptions, it was possible to approximate the resonance frequency of other material and thickness substrates, obtaining resonance frequencies above the desired maximum frequency response, which shows that the PET substrate produces the lower frequency responses when using the sensor as a square diaphragm. It was possible to identify that the deformation of the substrate occurs near de central region of the diaphragm,

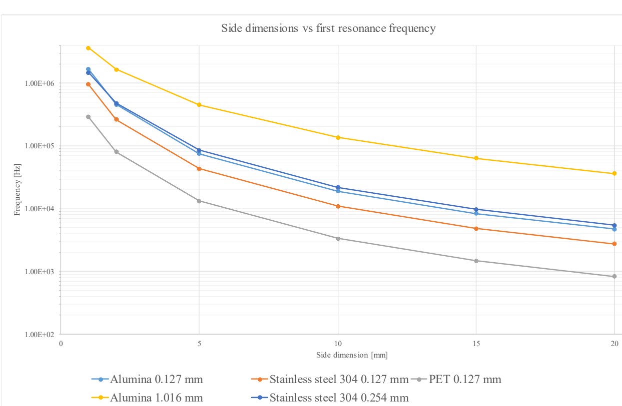
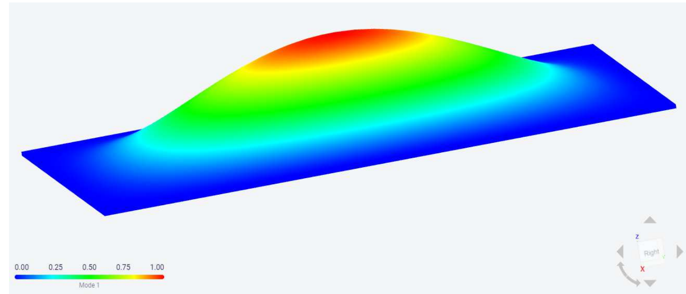
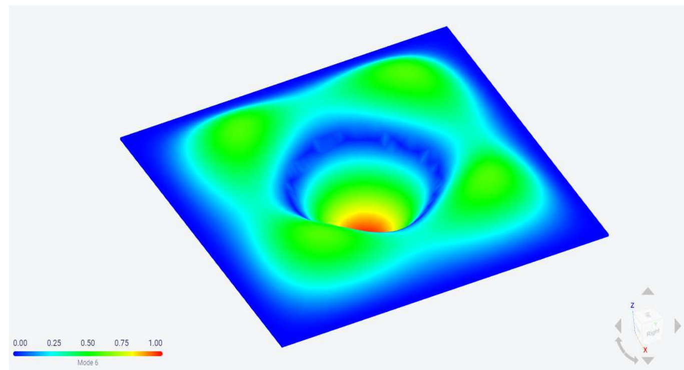


Fig. 2. First resonance mode of simulated substrates

suggesting that the nanostructured material should be deposited mainly on that region.



(a)



(b)

Fig. 3. Resonance modes of 20 mm x 20 mm x 0.127 mm PET diaphragm (a) First resonance mode with a mass participation of 0.49 along the z axis, (b) Sixth resonance mode with a mass participation of 0.18 along the z axis

TABLE 2. FIRST RESONANT FREQUENCY IN KILOHERTZ BY SIDE SIZE, THICKNESS AND MATERIAL

	Side dimensions [mm]					
Material and thickness	**20**	**15**	**10**	**5**	**2**	**1**
Alumina 0.127 mm	4.74	8.41	18.9	75.2	455	1655
Alumina 1.016 mm	36.4	63.5	136	453	1640	3634
PET 0.127 mm	0.84	1.48	3.33	13.3	79.9	288
Stainless steel 304 0.127 mm	2.74	4.85	10.9	43.4	262	951
Stainless steel 304 0.254 mm	5.45	9.69	21.7	85.3	476	1472

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