Finite element Analysis study of P-U based Acoustic Vector Sensor for Underwater Application in COMSOL

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Abstract: In this paper we present an analytical study to find energy coupled to visco-elastic rubber and also studied the effect of materials used for protective casing on the signal received at the center of the Acoustic Vector Sensor (AVS) using finite element analysis using COMSOL. We have chosen polyurethane, aluminum, nylon and titanium materials for studying this effect. We have found that the there is hardly any energy loss due to visco-elastic rubber and polyurethane. They provide minimum energy attenuation in signal as compared to other materials such as aluminum, titanium and nylon for the frequency band of 100 Hz to 5 kHz.

Keyword: Acoustic Vector Sensor (AVS), Direction of Arrival (DoA), Finite Element Method (FEM), Particle Velocity.

1. Introduction:

Acoustic vector Sensor (AVS) is a device used for finding Direction of Arrival (DoA) of an acoustic source using particle velocity and pressure measured at the acoustic center of the device. There are mainly two types of AVS; P-P and P-U based AVS. P-P based AVS indirectly measures particle velocity and pressure using pressure gradient and pressure mean of two closely spaced hydrophones placed at some distance apart, whereas P-U based AVS use inertial sensors and a hydrophone to measure particle velocity and pressure, „„,. In this work we have studied P-U based AVS. The advantage of using P-U based AVS is that it provides higher directivity as compared to single omni-directional hydrophone, also the size of P-U based AVS is more compact as compared to the hydrophone array for getting the same performance. There are numerous designs of P-U based AVS; we have followed the design in which an inertial sensor is encapsulated by a rigid sphere within viscoelastic rubber and covered by a rigid protective casing. In this paper we study the effect of materials used for protective casing and also its thickness on the signal received at the center of the AVS using COMSOL. We have chosen polyurethane, aluminum, nylon and titanium materials for studying this effect. We have found that the polyurethane provides minimum attenuation as compared to other materials.

Section II of the paper covers mehodology. Section III covers analytical study to find the energy coupled to viscoelastic rubber. Section IV describes the simulation setup in COMSOL. Section V present results and discussion and section VI presents the conclusions.

2. Methodology:

Acoustic intensity is the time average of the instantaneous product of the pressure and particle velocity signal,

$$\widehat{I_r} = < V_r(t)p(t) >_t$$

2.1 P-U measurement principle:

P-U based AVS consists of an inertial sensor and omni-directional hydrophone to measure particle velocity and pressure by which we can calculate intensity and thereby DoA of an acoustic source. P-U based AVS is based on the principle that when a free to move an acoustically small spherical body (dimensions<<wavelength) is immersed in a medium, it responds directly to the surrounding particle motion due to the acoustic field.

So when a rigid sphere with radius r and density ρ_s is immersed in an infinite viscous fluid medium of density ρ_o and viscosity η, is ensonified with a acoustic plane wave causing a particle velocity of V_o, then the resulting velocity of the sphere V_S is:

$$V_s = V_o \frac{3 - j\frac{9}{2}\frac{\delta_n}{r}}{2\gamma + 1 - \frac{9}{2}\frac{\delta_n}{r}}$$

where $\gamma = \frac{\rho_s}{\rho_0}$ is specific gravity of the sphere, $\delta_n = \sqrt{2\eta/\omega\rho_o}$ is the viscous penetration depth and r is the radius of the sphere. The above equation is valid only when the size of the sphere is small compared to the wavelength. For $r >> \delta_n$ i.e when size of the sphere is much larger than the viscous penetration depth:

$$\frac{V_s}{V_o} = \frac{3}{2\gamma + 1}$$

$$\frac{V_s}{V_o} = \frac{3\rho_o}{2\rho_s + \rho_o}$$

Thus, a free to move, acoustically small body having neutral buoyancy and encapsulating an inertial sensor will produce an electrical output proportional to the particle motion parameters (velocity/acceleration). If the body is positively buoyant, then the amplitude of body's motion is larger than that of fluid. If the body is negatively buoyant, then the amplitude of the motion of the body is reduced as compared to that of the fluid. The phase of the particle motion is preserved in both the cases. Consequently, an inertial transducer (accelerometer, gyroscope or geophone) embedded in the body, produces a signal that can be related to the acoustic particle motion. If this sensor is coupled with a pressure sensor, the acoustic intensity can be determined.

2.2 Design of P-U based AVS

P-U based AVS consists of a tri-axial accelerometer encapsulated by syntactic foam, viscoelastic rubber that encapsulate the syntactic foam body and a protective shield encapsulate this viscoelastic rubber body. The rigid protective casing is used so that AVS can withstand hydro static pressure. The acoustic impedance of viscoelastic rubber is close to that of water, hence it is acoustically transparent and passes only acoustical vibration while it act as a suspension system to suppress non acoustical vibration. The foam body is spherical in shape and its volume and density designed to provide neutral buoyancy to AVS. Acoustic wave cause movement of tri-axial accelerometer which will give the DoA of an acoustic source, so the accelerometer should move freely for correct DoA estimation.

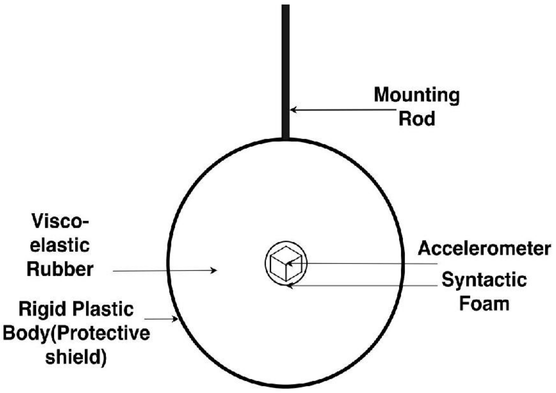

Fig 1: P-U AVS diagram

Sound waves cause movement of elements of the accelerometer in syntactic foam, by which the accelerometer generates signals indicating the velocity of sound and direction from which the sound propagates. This configuration provides for an AVS with improved sensitivity in an environment of rigid structures, improved insulation from noise produced by such structures, and can be further adapted to float freely. The device can thus be mounted on the shipboard structure with a minimum of self-noise and without loss of signal sensitivity because of nearby rigid structures.

3. Energy coupled to the visco-elastic rubber

In this section, we have derived the relationship between the energy content at the visco-elastic rubber due to incident pressure signal coming from water. Let the acoustic impedance of water is denoted by Z_w and the acoustic impedance of visco-elastic rubber by Z_{vr}.

i. The speed of sound in rubber c_{vr} = 900-1050 m/s,

ii. The acoustic impedance of viscoelastic rubber Z_{vr} by taking $c_{vr} = 1050$ m/s in kg$m^2 s^1 10^6$

$$Z_{vr} = \rho_{vr} c_{vr} = 1.27$$

iii. The acoustic impedance of water $Z_w = 1.5$ kg$m^{-2} s^1 10^6$

The reflection coefficient of the signal traveling from sea water to visco-elastic rubber by using the acoustic impedance of water and rubber can be calculated as:

$$\Gamma = \frac{Z_w - Z_{vr}}{Z_w + Z_r}$$

$$\Gamma = 0.08$$

By using the value of the reflection coefficient we can find energy coupled to the visco-elastic rubber given as.

$$E_{coupled} = E_{incident}(1 - |\Gamma|^2)$$

$$\frac{E_{coupled}}{E_{incident}} = 99.36\%$$

$$V_{vr} = V_w 0.9936$$

Thus, about 99.36 % of the incident energy is coupled to the visco-elastic rubber.

4. Simulation setup in COMSOL Multiphysics

In this section we have described the model setup, boundary conditions, material properties and meshing in COMSOL.

4.1 Model Setup

The cross section of the sensor as show in figure 2, a work plane revolved 360 degree to get the 3D Geometry. The geometry is symmetric about z axis, The cross section of the sensor show spherical shell structure of 5.8 cm radius and 1mm thickness filled with water and surrounded by the primary water domain of 100 cm radius and followed by a PML water region of 50 cm thickness.

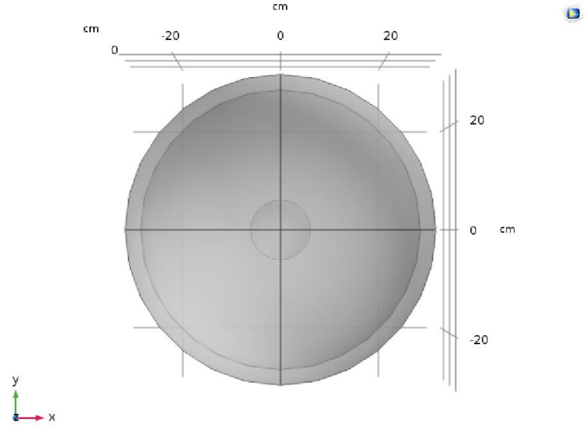

Fig 2 : Model Setup in Comsol

4.2 Boundary Condition

Acoustic shell interaction in frequency domain of Acoustic Module is used here. Polyurethane, Nylon, Aluminum and Titanium shell are assigned to linear elastic material. Structural equations are solved in linear elastic material.

4.3 Material Property and Meshing

The shell has been applied with Titanium, aluminum, nylon and polyurethane and water material respectively as available in the material library. The material properties are given in table I, where E is Young’s Modulas and v is Poisson’s Ratio.

Material	**Density(kg/m^3)**	**E(GPa)**	**v**
Nylon	1150	2	0.4
Aluminum	2730	69	0.33
Polyurethane	1030	0.033	4
Titanium	4940	105	0.33

Table 1: Material Properties

Structural domains have been assigned with a very fine mesh for solving the structural equations with a good accuracy. The outer PML water region is assigned with a swept mesh of fourteen layers for gradual decomposition of the acoustic pressure as shown in figure 3.

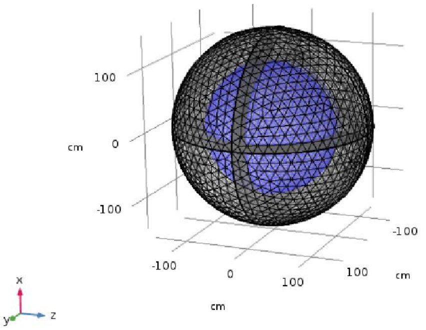

Fig 3: Model mesh

5. Results and Discussions

Simulation has been done for the frequency range starting from 200 Hz to 5 kHz with step size of 200 Hz for nylon, polyurethane, aluminum and titanium. Energy ratio has been calculated by taking the ratio of energy calculated with and without spherical shell at the center as shown in figure 4, and then taking the logarithm of calculated energy ratio. Figure 5 shows the total acoustic pressure distribution at 5 kHz. From figure 6 and 7 we can see that polyurethane and nylon provide minimum attenuation as compared to other material. Also Nylon and polyurethane provide minimum variation as compared to other material by varying the frequency

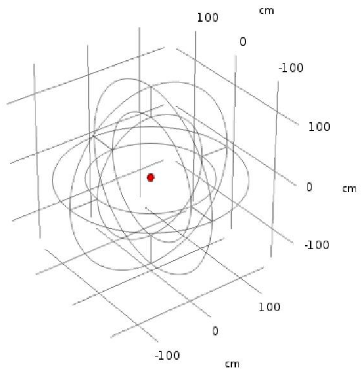

Fig 4: Setup for calculation of energy

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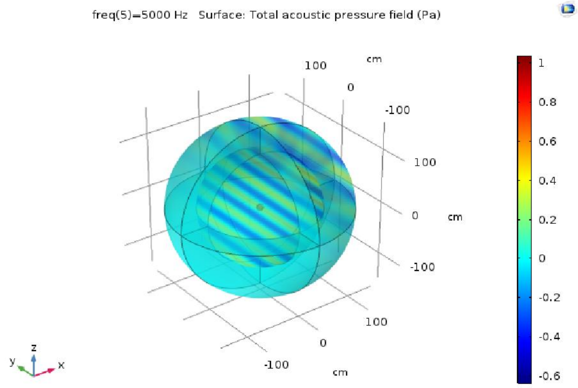

Fig 5 : Total acoustic pressure

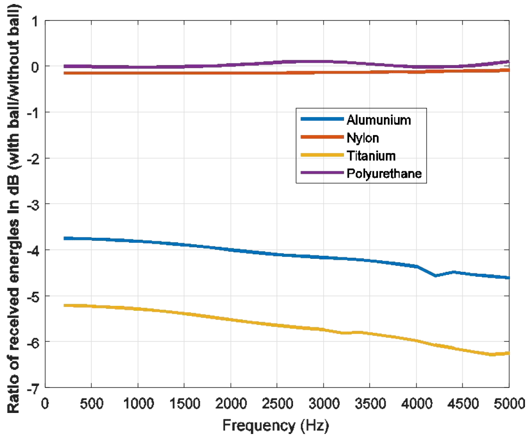

Fig 6: Ratio of received energy of polyurethane and nylon by varying frequency

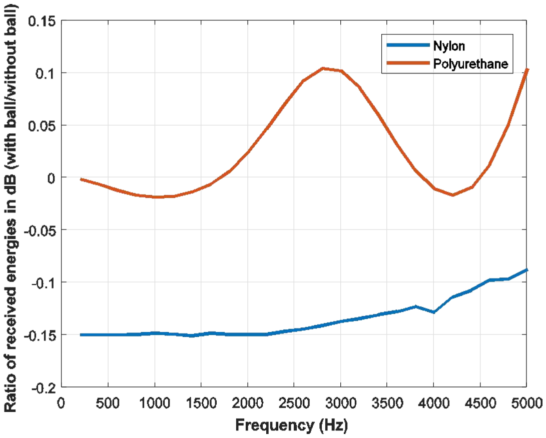

Fig 7: Ratio of received energy of different material by varying frequency

6. Conclusion

In this paper an analytical study to find energy coupled to visco-elastic rubber has been done and also acoustically shell interaction in frequency domain has been simulated using COMSOL Multiphysics software. It was found that there is hardly any energy loss due to visco-elastic rubber. It is concluded that the Polyurethane and nylon provide minimum attenuation as compared to titanium, aluminum. Between polyurethane and nylon, nylon provide minimum attenuation. Hence polyurethane is most suitable material for making the protective shield of AVS.

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