Modeling and Simulation of MEMS Vector Hydrophone for Suppressing Vibration Output

Jin-long SONG, Ren-xin WANG, Chen-yang XUE, Wen-dong ZHANG and Chang LIU

Science and Technology on Electronic Test and Measurement Laboratory, North University of China, Taiyuan 030051, China

*Corresponding author

Keywords: Modeling and simulation, Wide bandwidth, Vector hydrophone, Suppressing vibration output.

Abstract. The influence of vibration on the output of hydrophone having a serious disturbance on the measurement of sound. To suppress the output of hydrophone caused by vibration promoting its engineering application, a crafty piezoresistive eight beams vector hydrophone with thick thickness of mass block was designed. The models of presented hydrophone were established. Based on the models, a method optimizing the thickness of mass block to suppress the output caused by vibration, but hardly no influence on the output of hydrophone resulted by sound. The FEM simulation results demonstrate the practicality of this method. The output caused by vibration is minimum and output resulted by sound has hardly influence when the thickness of mass block is 230 μm for the designed hydrophone. This is beneficial to the engineering application of vector hydrophone.

Introduction

Since the propagation distance of sound wave in water is much larger than that of electromagnetic wave, sound is widely used in the field of underwater up to now. Sonar system, which mainly used for underwater target recognition and location, geological exploration and various underwater military activities, such as submarine detection, unmanned navigation and monitoring, is typical application of sound in water [1-4]. It is widely concerned by researchers all over the world. Hydrophone is an important part of sonar system. According to working principles, it can be divided into piezoelectric, optical fiber and piezoresistive modes. Compared with its counterparts, the piezoresistive bionic vector hydrophone based on MEMS (Micro-Electro-Mechanical System) developed by North University of China has the characteristic of low cost and fine consistency [3, 5]. So, it has great advantage in hydrophone network.

Vector hydrophone extensive used in various floating carriers, such as buoys and torpedo. The output signal of hydrophone caused by the vibration will disturb even cover up the signal generated by sound [6-8]. This is an unavoidable problem for the engineering application of vector hydrophone. Complex elastic suspension and back-end circuit filtering are usually adopted to suppress output caused by vibration [9]. However, the effect of this method is limited and increases the complexity of the system. Zhang of North University of China proposed a structure that with two same cilia placed symmetrically on both sides of the vector hydrophone [10]. Sound can pass through the hat with little loss on the top side cilia, but hardly no sound can pass through the package on the bottom side cilia. The both two cilia can be affected by vibration and enable the output caused by vibration counteract each other. However, this raise the complexity of assemblage of hydrophone. In addition, it is of great difficult to make the two cilia symmetry[11].

Based on above reasons, a new structure with large thickness of mass block is designed. The mass block for suppressing vibration output is machined in the process of hydrophone fabrication based on MEMS technology. In this paper, the mathematical models were established, the FEM simulation was also conducted to verify the models.
Establishment of Model of Vector Hydrophone

The vector hydrophone consists of a sensitive cilium, a mass block, eight beams and four frames, as shown in Fig 1. P type piezo-resistors are fabricated with boron doped on the surface of beam ends. Four piezo-resistors at specific locations make a Wheatstone bridge. Usually, the location of center of piezo-resistors is \( x \) (from frame to mass block) or \( l-x \), so that the absolute relative changes of piezo-resistors are the same. The cilia and mass block are taken as rigid body. The beams along X and Y direction are called X-beams and Y-beams for short.

![Figure 1](image.png)

Figure 1. Structure of designed vector hydrophone (a) axonometric view (b) orthographic view.

Vector Hydrophone Subject to Vibration

For the structure characteristics of the hydrophone in X and Y axes, vibration in Y direction is similar to that in X direction. Only vibration in X and Z direction are analyzed in this paper.

**Vibration in Z Direction**

As the hydrophone is symmetric about X and Y axis, all the beams share the same deflection and stress when vibration in Z direction. Based on the knowledge of material mechanics, the longitudinal stress on the top surface of beam at location \( x \) is expressed by Eq. 1.

\[
\sigma_l = -\frac{3(m+m')a_z(x-l/2)}{4wt^2} \tag{1}
\]

where \( m \) and \( m' \) are the mass of mass block and cilia, respectively. \( a_z \) is the vibration signal in Z direction, \( l, w \) and \( t \) are the length, width and thickness of beam, respectively.

**Vibration in X Direction**

Because the ratio of in plane bending moment of Y-beams to out plane bending moment of Y-beams is \( t/w \), the width and thickness of beam are usually hundreds of microns and several microns to more than ten microns, respectively. The bending in plane of Y-beams is ignored. Therefore, Y-beams are subjected to out plane bending and twist, X-beams are impacted by out plane bending and compression or stretching. The stress at location \( x \) of the two X-beams on the left side of Y axis is the same, but opposite sign with the stress at location \( x \) of the two X-beams on the right side of Y axis. The four Y-beams also have the same phenomenon. So, only longitudinal stresses of beam B4 and B6 are analyzed in this paper.

The longitudinal stresses at location \( x \) of surface of beam B6 and B4 are expressed by Eq. 2 and Eq.3.

\[
\sigma_2 = -\frac{3a_x(1^2+3bt-6bx-3lx)}{4wt^2[6b^2+6d^2+(2+\varepsilon)l^2+6bl]} (mh - m'H) - \frac{(m+m')a_x}{4wt} \tag{2}
\]

\[
\sigma_3 = -\frac{9da_x(l-2x)}{4wt^2[6b^2+6d^2+(2+\varepsilon)l^2+6bl]} (mh - m'H) \tag{3}
\]

where \( a_x \) is vibration in X direction, \( b \) is half of the length of mass block, \( d \) is half of the distance between the two adjacent parallel beams, \( \varepsilon \) is a constant, \( \varepsilon = 1/(1 + \mu) \), \( \mu \) is Poisson ratio of mass block, \( h \) and \( H \) are the thickness of mass block and height of cilia, respectively.
Vector Hydrophone Affected by Sound

Considering that sound pressure acting on the mass block is much less than that of the cilia, the sound pressure acting on the mass block is ignored. Because only half of the cilia are affected by the sound pressure \( p \), the force of cilia is \( F = \pi Hpr \). When the sound in X direction, the bending moment of mass block can be expressed as

\[
M = \frac{\pi prH^2}{2}
\]  

(4)

The analysis of hydrophone under the influence of sound pressure is similar to that under the acceleration effect of X direction. The longitudinal stress on the top surface of beams at location \( x \) of beams B4 and B6 are expressed by Eq. 5 and Eq. 6, respectively.

\[
\sigma_4 = -\frac{3(l^2 + 3bl - 6bx - 3lx)}{2wt^2[6b^2 + 6d^2 + (2 + \varepsilon)l^2 + 6bl]}M - \frac{\pi Hpr}{wt}
\]  

(5)

\[
\sigma_5 = -\frac{9d(l - 2x)}{2wt^2[6b^2 + 6d^2 + (2 + \varepsilon)l^2 + 6bl]}M
\]  

(6)

Summary of Results

It can be seen from Eqs (5) and (6) that the stress of the beam is independent of the thickness of the mass block when the hydrophone is subjected to acoustic pressure. Eq (1) implies that the absolute value of longitudinal stress at location \( x \) equals to that at location \( l-x \) for any thickness of mass block when vibration in Z direction. Eq (2) indicates that the absolute value of longitudinal stress at location \( x \) and \( l-x \) of X-beams is not the same for any thickness of mass block when vibration in X direction. Eq. (3) states clearly that the absolute value of longitudinal stress at location \( x \) and \( l-x \) of Y-beams is the same for any thickness of mass block. Therefore, making \( \sigma_2(x) = -\sigma_2(l-x) \) can suppress the output of hydrophone caused by vibration but does not decrease its output resulted by sound.

FEM Simulation

In order to verify the conclusion obtained from models developed in this paper, FEM Simulation was conducted. The structure parameters of hydrophone for simulation are listed in table 1. The thickness of mass block ranges from 100\( \mu \)m to 300\( \mu \)m stepped by 10\( \mu \)m. The output voltage of hydrophone vs thickness of mass block when 1 Pa sound was applied on it is plotted in Fig.2a. The figure show that the max change of output voltage is 0.261\%. The absolute output voltages vs thickness of mass block of hydrophone is plotted in Fig. 2b. The figure obviously illustrates that the output voltage is minimum when the thickness of mass block is 230\( \mu \)m.

<table>
<thead>
<tr>
<th>Table 1. Structure parameters of sensor.</th>
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<tr>
<td>Parameters</td>
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<tr>
<td>----------------</td>
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<tr>
<td>Beam length</td>
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<tr>
<td>Beam thickness</td>
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<tr>
<td>Proof mass length</td>
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<td>Cilium radius</td>
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Summary

The models of proposed structure of hydrophone were established in this work. Based on the developed models, the method, optimizing the thickness of the mass block, to reduce the output caused by vibration was presented but hardly no influence on the output of hydrophone caused by sound. The FEM simulation results proved the theory we presented. For the designed hydrophone, when the thickness of mass block is 230μm can effectively suppress the output caused by vibration. Out work would boost the engineering application of piezoresistive vector hydrophone.

Acknowledgement

This research was funded by the National Natural Science Foundation for Distinguished Young Scholars of China (Grant No.61525107), NSFC(Grant No.61604134), the Fund for Shanxi ‘1331 Project’ Key Subject Construction (1331KSC), National Natural Science Foundation of China as National Major Scientific Instruments Development Project (Grant No.61727806).

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