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Analysis for microstructure of MEMS bionic vector hydrophone*

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Abstract: The MEMS bionic vector hydrophone, which has advantages of high sensitivity, broad frequency band, vector and high Signal to Noise Ratio(SNR), is one kind of underwater acoustic signal detection device integrating piezoelectricity and MEMS technology. However, to make a further step in improving the predictive accuracy and the resonant frequency of underwater acoustic signal, optimization design of the MEMS hydrophone bionic microstructure is performed with finite element method in this paper. Firstly, it can be learned from theoretical formulas of natural frequency and stress that the natural frequency of bionic microstructure is inversely-proportional to the height of bionic cilia and the beam length, at the same time, is proportional to the beam width and thickness; Instead, the sensitivity is proportional to the bionic cilia height and beam length, and is inversely-proportional to the beam width and thickness. Based on the theoretical analysis, maximum stress curves and resonance frequency curves of sensor under different structural parameters are drawn. Secondly, a static analysis was done with ANSYS software and a response curve of natural frequency and stress was drawn. Finally, the simulation results show that a better performance of high sensitivity and broad frequency band for MEMS hydrophones can be obtained by designing beam length, width, thickness and bionic cilia height and radius as 400, 80, 50, 1000 and 80 μm respectively. The simulation results and the theoretical analysis are compared, and the differences between them are analyzed.

Key words: MEMS; ANSYS; hydrophone; sensitivity; frequency band

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With the development of underwater acoustic detection technology, the study of bionic vector hydrophone has been a research focus both at home and abroad[1]. As the frequency of underwater acoustic detection is expanding to high frequency, the study of underwater imaging, underwater target detection and underwater noise measurement urgently needs hydrophone with high frequency of hundreds of kHz or higher[2-4]. Thus the development of high frequency hydrophone has received widespread and extensive attention.

Bionic, which is studied systematically using biological methods and designed engineering systems, is one discipline imitating the sensitive characteristics of bionics. A large number of data show that the fish lateral line sense organ is highly sensitive to especially low frequency acoustic stimulation, which provides a new design-idea in the development of low frequency vector hydrophone[5-7]. With the development of M/NEMS technology, it has become a reality to develop nano-scale sensor[8], which provides technical support in imitating fish lateral line sense organs to develop good performance hydrophones.

Combining with piezoelectricity and bionic theory, vector hydrophone based on MEMS technology has performance features of vector, high frequency, small size and passive work. The vector hydrophone microstructure consists of two parts: high precision four - beam microstructure and bionic cilia. However, as the

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acoustic coupling characteristics of hydrophone have a lot to do with inherent mechanical properties of cantilever beam and bionic cilia[9], the inherent properties of microstructure will directly affect the accuracy of acoustic signal detected by hydrophone. To make a further step in improving the predictive accuracy of underwater acoustic signal and the natural frequency, firstly we analyze the relationship between structural performance and sizes of MEMS hydrophone bionic microstructure in theory, and then do optimization design with ANSYS finite element method. Thus, acoustic signal with a higher sensitivity and broader frequency band can be detected.

1 Theoretical analysis

Combining with piezoelectricity and bionic theory, vector hydrophone based on MEMS technology consists of two parts: high precision four-beam microstructure and bionic cilia. A bionic cilia is fixed in the center of the four-beam microstructure and the piezoelectric film on the beam. Underwater acoustic signal in transition will cause the vibration of water particles and the bionic cilia will swing under the force of water particles, thereby transmitting this force to the sensitive beam. Thus piezoelectric film will output charge on the act of water particle power. So long as underwater acoustic signal can be got by the bionic cilia, piezoelectric film would detect the signal.

1.1 Sensitivity analysis

The static characteristic of MEMS hydrophone bionic microstructure is mainly decided by the rigidity of bionic cilia and four cantilever beams. When force is loaded onto the bionic cilia, it will lean on the force and will be transmitted to the center connector who will rotate with it until the reacting force from four-beam cilia is balanced with the acting force from the cilia. The bionic microstructure is shown in Fig. 1 and its mechanical analysis model is shown in Fig. 2.

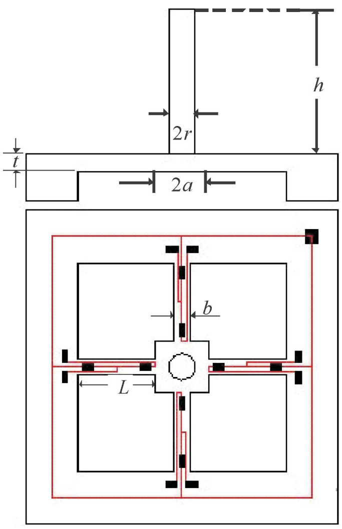


Fig. 1 MEMS bionic microstructure

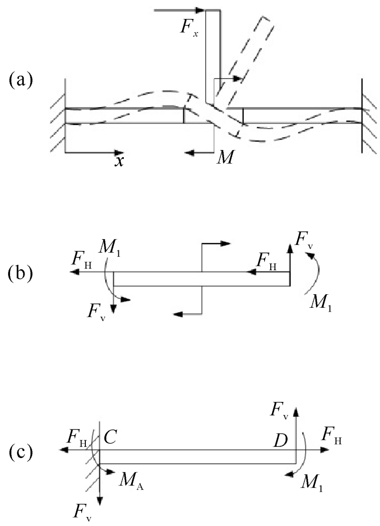


Fig. 2 Mechanical analysis model

According to reference[10], the stress under the action of bending moment (M) and horizontal force (F) on cantilever beam of any point can be expressed as follows

$$\sigma_{(x)} = \pm \frac{L^2 + 3aL - 3x(a+L)}{\frac{2}{3}bt^2(L^2 + 3aL + 3a^2)} M \pm \frac{F_{\mathrm{H}}}{bt} \tag{1}$$

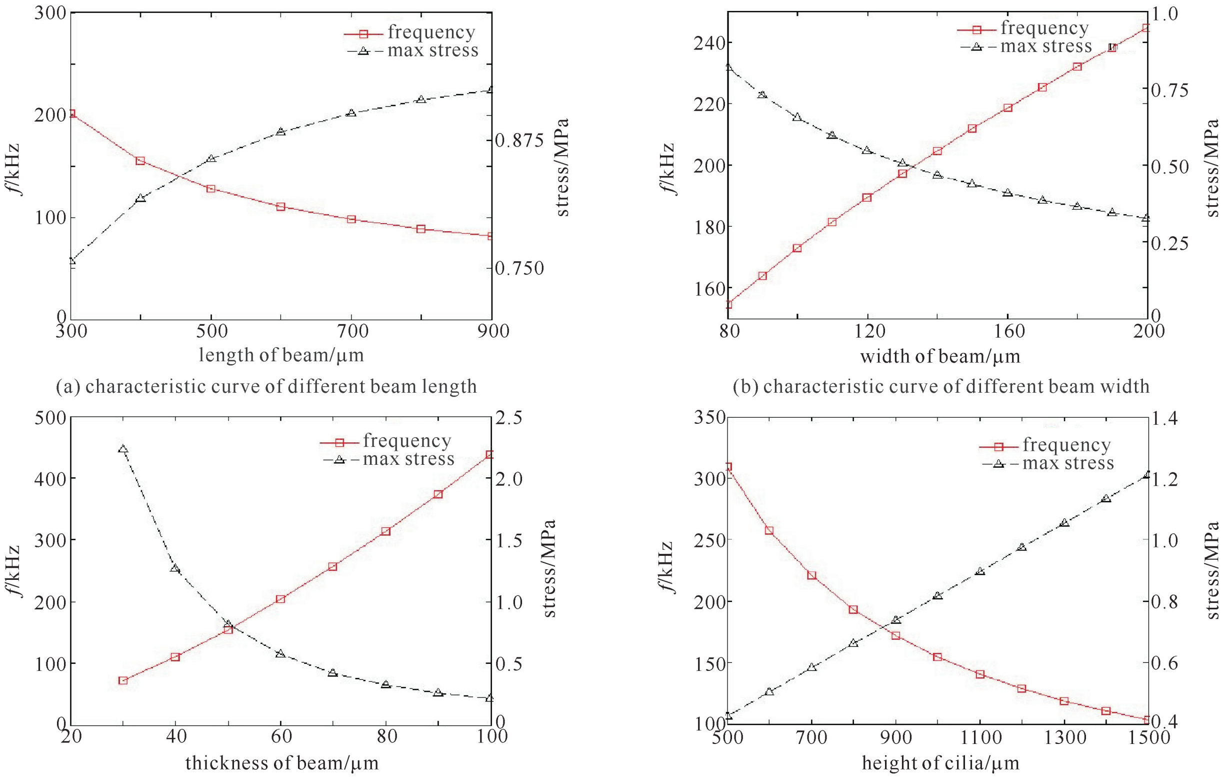
where $F_{\mathrm{H}} = mg$, and m is the mass of bionic cilia, L, b and t are the length, width and thickness of cantilever beam respectively, $2a$ is the side length of the centre connector and M is the bending moment on the centre connector. Because the maximum stress on beam is proportional to the sensitivity of bionic microstructure, different maximum stresses on the beam can be got by choosing different sizes of the beam and bionic cilia.

1.2 Resonance frequency analysis

According to reference[10], the resonance frequency of bionic microstructure can be expressed as follows

$$f=\frac{1}{2\pi}\sqrt{\frac{K}{m}}=\frac{1}{2\pi}\sqrt{2\,\frac{Ebt^3}{mLh^2}\left(\frac{a^2}{L^2}+\frac{a}{L}+\frac{1}{3}\right)} \tag{2}$$

where h is the height of bionic cilia and E is a constant. It's easy to find that the resonance frequency of microstructure is closely related to its size, different natural frequency of microstructure can be got by choosing different sizes of the beam and bionic cilia. Fig. 3 shows the maximum stress on beam and natural frequency in different sizes of bionic microstructure.



(a) characteristic curve of different beam length

(b) characteristic curve of different beam width

(c) characteristic curve of different beam thickness

(d) characteristic curve of different cilia height

Fig. 3 Characteristic curves of different microstructure sizes

These figures show that the natural frequency of bionic microstructure is inversely-proportional to the height of bionic cilia and the beam length, at the same time, it is proportional to the beam width and thickness; Instead, the sensitivity is proportional to the bionic cilia height and beam length, and is inversely-proportional to the beam width and thickness. However, in the practical application, high sensitivity and broad frequency band are hoped at the same time. Considering the high frequency characteristic of piezoelectricity, the response frequency is set as 120 kHz around where there is good linearity. Finally the preferred microstructure parameters are designed as the length, width and thickness of cantilever beam are 300, 50 and 40 μm respectively, and the height of bionic cilia is 1000 μm.

2 Finite element analysis

ANSYS is applied to analyze the effect of the cantilever beam and the bionic cilia on the MEMS bionic vector hydrophone. First, establish the finite element model of sensitive structure, and then do static analysis and modal analysis. The finite element model of MEMS microstructure is shown as Fig. 4.

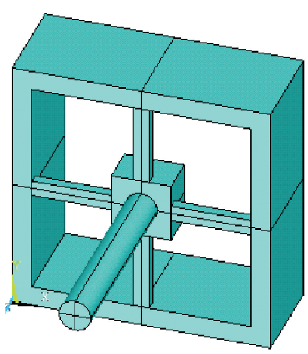
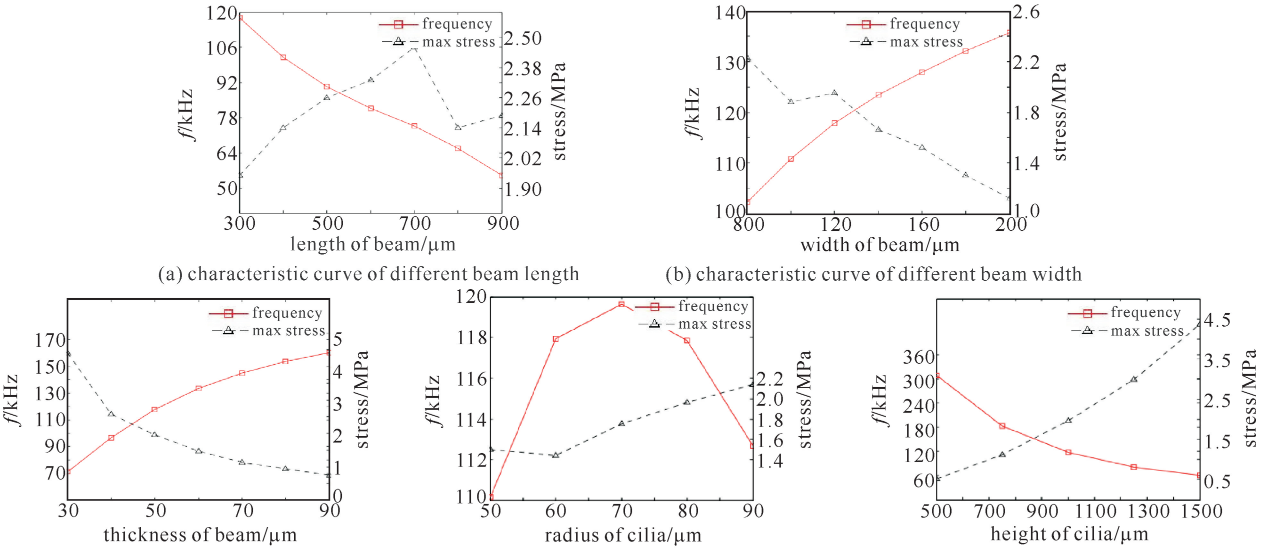


Fig. 4 Finite element model of microstructure

Static analysis of structure is used to calculate the response, such as displacements, strains and stresses, in a certain fixed power, namely analyzing the structural changed by the force. Modal analysis of structure is generally used to analyze the vibration performance of designed structure, that is to say, the structural frequency response and modal can be acknowledged by modal analysis.

Consulting the hydrophone bionic microstructure and its structural parameters mentioned above, we do static analysis and modal analysis using finite element software. Maximum stress and resonance frequency curves of microstructure under different parameters are drawn as Fig. 5.

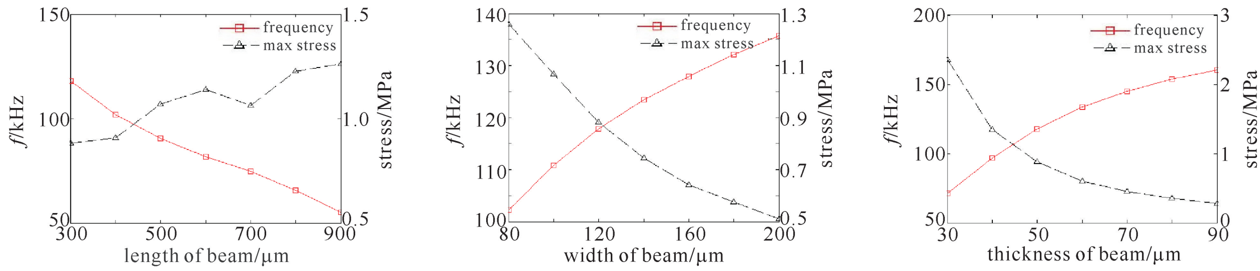


(a) characteristic curve of different beam length (b) characteristic curve of different beam width (c) characteristic curve of different beam thickness (d) characteristic curve of different cilia radius (e) characteristic curve of different cilia height

Fig. 5 Characteristic curves of different microstructure sizes

It's obvious that with different structural parameters, the maximum stress and natural frequency of microstructure show the opposite trends, which is consistent with theoretical analysis. By analyzing Fig. 5, the preferred microstructure parameters are designed with the radius and height of bionic cilia being 80 and 1000 μm respectively. But the optimal values of length, width and thickness of cantilever beam can't be got simply, however it can be learned that they are around 300, 70 and 50 μm respectively.

To make a further step in confirming structural parameters, we do static analysis based on updating the maximum sizes combining with control variate method and draw response curves of natural-frequency and stress which are shown in Fig. 6.



(a) characteristic curve of different beam length (b) characteristic curve of different beam width (c) characteristic curve of different beam thickness

Fig. 6 Characteristic curves of different cantilever beam sizes

From Fig. 6, considering the sensitivity among a certain frequency band, a better performance of high sensitivity and broad frequency band for MEMS hydrophones can be obtained by designing beam length, width, thickness and bionic cilia height and radius as 400, 80, 50, 1000 and 80 μm respectively.

By comparing the results of simulation and of theoretical analysis, it will be found that the natural frequency of theory is higher than the simulation value. In the formula of natural frequency of bionic microstructure, it can be known that resonance frequency is inversely-proportional to its effective mass. But considering that the mass of four-beam is much lighter than that of bionic cilia, four-beam mass is ignored in applications. So there are some differences between them. For all these, the results of theoretical analysis and finite element analysis show consistency in the whole trend, which confirms the validity of theory formulas of microstructure maximum stress and natural frequency.

3 Conclusion

According to the four-beam microstructure of MEMS bionic vector hydrophone developed by North University of China, the relationship between structural performance and structural sizes of four beams and bionic cilia is analyzed in theory. Modeling and simulation of MEMS hydrophone bionic microstructure in different sizes have been done with ANSYS. By comparison, optimum structure sizes of four-beam microstructure are accepted. At the same time the correctness of the theoretical analysis is verified. Optimization design of MEMS hydrophone bionic microstructure makes for the realization of higher sensitivity and broader frequency band in underwater acoustic detection.

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MEMS 仿生矢量水听器微结构的有限元分析

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摘 要： 结合压电原理和仿生学理论，利用 MEMS 工艺制作的仿生矢量水听器，具有高灵敏度、宽频带、矢量性及高信噪比等特点。为了进一步提高水听器预测水下环境中声学特性的准确性并提高其固有频率，利用有限元方法对 MEMS 水听器仿生微结构进行优化分析。首先，对仿生微结构固有频率和灵敏度与其结构尺寸关系作了理论分析并画出不同微结构尺寸下的固有频率和最大应力曲线。其次，运用 ANSYS 软件对仿生微结构进行有限元仿真并画出固有频率和最大应力响应曲线。对比分析理论与仿真结果，得出当悬臂梁长、宽、厚及仿生纤毛的高度和半径分别为 400，80，50，1000 和 80 μm 时，MEMS 矢量水听器的性能得到最优化，同时对理论与仿真结果的差异进行了分析。

关键词： MEMS； ANSYS； 矢量水听器； 灵敏度； 频带