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MODELLING OF HYDROPHONE BASED ON A DFB FIBER LASER

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Summary This paper deals with modeling of a DFB fiber laser based hydrophone. Both an analytical and a finite element model are developed to describe the acoustic response of the hydrophone. Particularly, the calculated hydrophone sensitivity using the finite element model is compared to the analytical result.

INTRODUCTION

Hydrophones based on distributed feedback (DFB) fiber lasers [1] are examined using both an analytical and a finite element model. The small dimensions (length 3-6 cm) and low frequency noise of DFB fiber lasers make them useful as hydrophones. Even extremely small changes in fiber laser cavity length yield measurable laser frequency signals. Generally, an acoustic pressure field will result in a deformation of the DFB fiber laser and a change of its length. The effect is small when a bare fiber laser is placed directly in water (sensitivity $\epsilon/p = 3.2 \cdot 10^{-12}\ 1/Pa$). If desired the ambient pressure sensitivity can be modified by using a mechanical mounting. Typically for underwater surveillance applications an amplification of the sensitivity of about 400 times is required to approach the noise level in the sea.

The hydrophone design shown in fig.1 changes the loading of the fiber laser from hydrostatic to axial. The outer cylinder is rigid. In each end of the cylinder an end-plate is placed which can move in the axial direction thus straining the laser. The surface area of the end-plates can be increased to obtain the necessary sensitivity. To avoid buckling the fiber laser is strained before being glued to the end-plates. The soft-material in the center maintain this pre-stain.

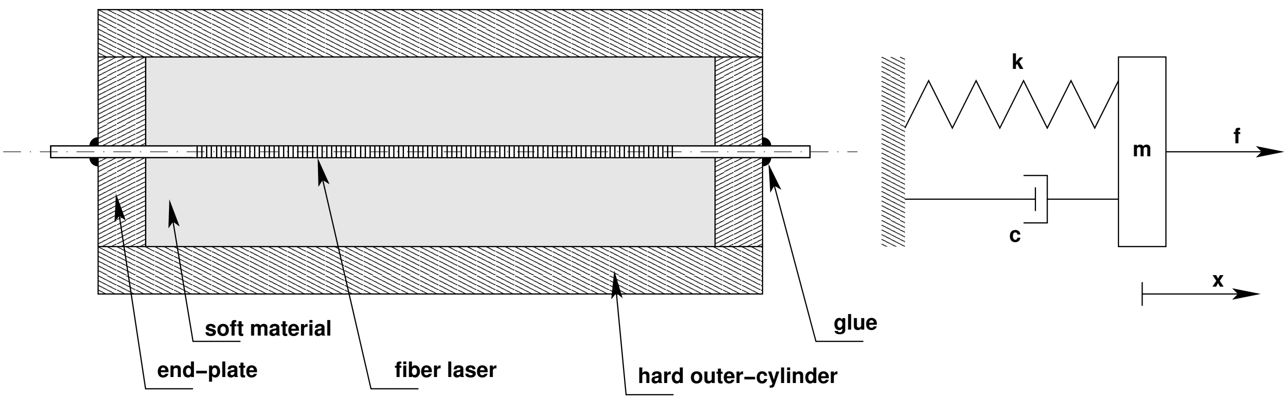

Figure 1. Left: Sketch of hydrophone based on a DFB fiber laser. Right: Damped force oscillator used to model hydrophone with symmetric loading.

HARMONIC RESPONSE ANALYSIS

The hydrophone is assumed to be small compared to the wavelength of the incoming acoustic wave. Moreover, the pressure is assumed to be the same at the two end-plates such that symmetry can be used to model only half of the hydrophone. Under certain conditions a damped forced oscillator, see fig. 1, will sufficiently well describe the mechanical properties of the hydrophone. The harmonic response is described by

$$-m\omega^2 x + ic\omega x + kx = f, \tag{1}$$

where ω is the frequency and x is the complex displacement amplitude of the end-plate of mass m. The acoustic force f acting on the end-plate is found using equation

$$f = Sp - Z_{rad} i\omega x, \tag{2}$$

given in [3] for acoustic receivers. Here S is the surface area of the end-plate, Z_{rad} is the radiation impedance and p is the acoustic pressure in the absence of the hydrophone. The acoustic radiation of the end-plate is modeled as a circular piston [3]

$$Z_{rad} = (\frac{(\hat{k}r)^2}{2} + i\frac{8\hat{k}r}{3\pi})\rho_w c_w S, \tag{3}$$

where the real and imaginary part correspond to frequency dependent damping and added mass respectively. Here $\hat{k}$ is the acoustic wavenumber, r is the end-plate radius, ρ_w and c_w are the density and sound speed of water. The sensitivity of the hydrophone is found from (1), (2), (3) and by using that the axial strain in the fiber laser is given by, $\epsilon = 2x/l$, where l is the fiber laser length. Thus

$$\frac{\epsilon}{p} = \frac{2}{l} \frac{S}{k - \omega^2 \tilde{m} + i\tilde{c}}, \quad (4)$$

where $\tilde{m}$ and $\tilde{c}$ express the total mass and damping including the added terms in (3). For $\omega = 0$ the static sensitivity is obtained as, $\epsilon/p = 2S/lk$. The resonance frequency determining the nominal bandwidth of the hydrophone is $\omega = \sqrt{k/\tilde{m}}$.

FINITE ELEMENT MODELING OF ACOUSTIC FIELD

A Finite Element Model (FEM) of the acoustic field surrounding a fiber laser hydrophone is implemented using FEMLAB. To test the analytical expression derived in (4) The acoustic pressure field p is governed by the three-dimensional Helmholtz equation

$$\nabla^2 p - \hat{k}^2 p = 0. \quad (5)$$

The presence of the hydrophone is taken into account by applying boundary conditions to the acoustic field at the outer surface of the hydrophone. At the domain boundaries we introduce the boundary conditions

$$\mathbf{n} \cdot \nabla p = 0 \qquad \mathbf{n} \cdot \nabla p = -i\omega^2 \rho x \qquad \mathbf{n} \cdot \nabla p = -i\hat{k}p, \quad (6,7,8)$$

where $\mathbf{n}$ is an outward pointing unit vector at the domain boundaries. The B. C. (6) specifies a rigid boundary and is applied to the outer cylinder of the hydrophone. B. C. (7) specifies a moving rigid boundary and is applied at each of the hydrophones end-plates. Finally, B. C. (8) specifies a radiative boundary condition which is applied to all exterior boundaries. The displacement amplitude x depends on the pressure at the end-plate surface and on the mechanical system. If the symmetric assumption is used, as in the previous section, x can be obtained from (1) using that the acoustic force is $f = \int_S p \, dS$.

NUMERICAL EXAMPLE

A hydrophone with aluminum end-plates having a radius of $r = 2mm$ and a thickness of $t = 2mm$ is used as an example. The DFB fiber laser has a length of $l = 6cm$ and is made from a fiber, similar to standard single mode optical fiber, with a radius of $65\mu m$ and a Young modulus of $72GPa$, giving a fiber stiffness of $k = 31.8kN/m$. A stiffness of $4kN/m$ for the soft center material is added to this. The end-plate mass is $m = 0.08g$ and the fiber mass is neglected. The computed sensitivities are shown in fig. 2. Apparently a lower resonance frequency is obtained using the FEM model. This indicates a larger added acoustic mass than the one obtained from (3), giving the hydrophone a lower bandwidth. The sensitivity below resonance is $1.17 \cdot 10^{-8}\ 1/Pa$, almost a factor of 10 higher than required for typical underwater surveillance applications, and therefore the hydrophone is potentially usable.

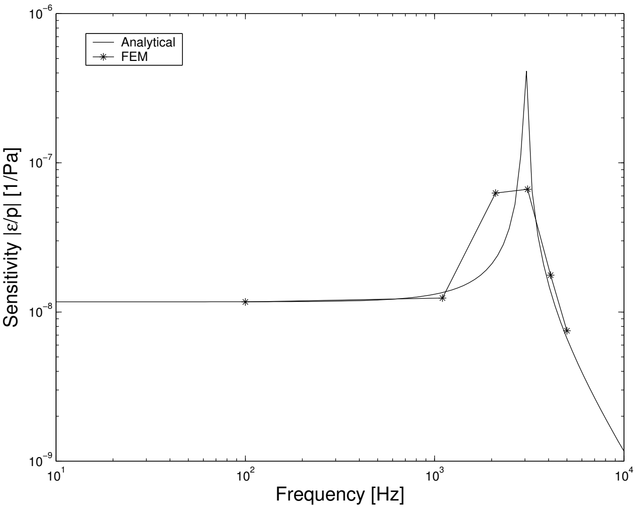

Figure 2. Hydrophone sensitivity.

References

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[2] J. A. Bucaro, H. D. Dardy, E. Carome, "Fiber optic hydrophone", *J. Acoust. Soc. Amer.*, vol. 62, pp. 1302-1304, 1977.
[3] L. E. Kinsler, A. R. Frey, A. B Coppens and J. V. Sanders, "Fundamentals of Acoustics", 4th ed. John Wiley & Sons Inc., 2000.