Control of Underwater Sound Propagation using PVDF and Negative Capacitance Circuit

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ABSTRACT

Electrical control of underwater sound propagation using piezoelectric polyvinylidene fluoride (PVDF) film was undertaken. A curved PVDF film was installed between a sound generator and a sound detector in water. The sound pressure transmitted through the film was measured by the detector. The PVDF film was connected to a negative capacitance circuit. The apparent elastic constant of the film was altered by changing the ratio of capacitances of the circuit and the film. The intensity of sound passed through the film first decreased about 20 dB to a minimum, and then increased with opposite phase as large as 40 dB with the increase of feedback. The experimental data were well represented by the theoretical curve for Young’s modulus of the PVDF film calculated by Date’s equation using the values of the circuit elements.

Keywords: Underwater sound propagation, PVDF, Electrical control, Negative capacitance circuit
INTRODUCTION

The reflection and transmission of sound have been investigated by many methods. One of the recent unique techniques is to use the piezoelectric materials coupled with a special electrical circuit. The elasticity and viscosity of piezoelectric materials can be altered by the negative capacitance circuit (NCC). Sound pressure applied to a piezoelectric film produces the electric voltage, which is fed back to the electrode of the film, which causes the change of the effective viscoelasticity of the film. Many papers [1, 2, 3, 4, 5, and 6] have already proved that the reflection and transmission of air-borne sound can be controlled by the piezoelectric film or plate coupled with a NCC. However, the reflection and transmission of sound in water have not been investigated so far. This study is the first preliminary attempt to see how this technique of combination of piezoelectric film and NCC will work for the underwater sound. As a piezoelectric material, we have used a film of polyvinylidene fluoride (PVDF), which shows the high piezoelectric activity.

EXPERIMENTAL SETUP

The principle of the experiment is depicted in Fig.1. An acoustic tube is constructed using circular acrylic resin with a diameter of 43 mm and a length of 800 mm. Circular unimorph actuators made of PZT are installed at both ends of the tube.

In the middle of the tube, a curved PVDF film with the thickness of 100μm is installed. All operations were made by hand in laboratory. The tube with both ends unclosed was immersed in a large water bath. After the water filled the tube, both ends of the tube were tightly closed in the water bath. Then the water in the bath was drained. The water proof of the PVDF film and PZT actuators for electrical insulation was carefully confirmed.

Electrical output voltage from the function generator excites the PZT transmitter and the underwater sound is generated. The sound produces the in-plane vibration in the curved plane of the PVDF film. In order to control the vibration of PVDF, a negative capacitance circuit is connected to the electrodes of the film. The schematic diagram of the experimental setup is given in Fig. 1.

Fig. 1: Acoustic tube experiment for underwater sound propagation
**A NEGATIVE CAPACITANCE CIRCUIT (NCC)**

The negative capacitance circuit including the PVDF film is represented in Fig. 2. It is essentially a feedback circuit using an operational amplifier with a gain as large as 50 dB. The capacitance of the PVDF film is denoted as $C_s^*$, a complex quantity. Ignoring the series resistance $R_s$, the effective capacitance of the circuit $C_c^*$ is also given as a complex quantity.

$$C_c^* = -\frac{R_2}{R_1}(C_0 - i/\omega R_p)$$  \hspace{1cm} (1)

where $R_0$, $R_1$, $R_2$, $R_3$, $R_4$ and $R_s$ are the resistance shown in Fig. 2. $C_0$ is the capacitance, $\omega$ the angular frequency and

$$R_p = (1+R_4/R_3)R_0.$$  \hspace{1cm} (2)

It has been known that if NCC is connected to any piezoelectric material under applied stress, the apparent elastic constant of the material is changed due to the feedback reaction of NCC. In the present case, we excite the in-plane vibration of the PVDF film and the vibration of the film produce the sound detected. The curved plane was purposely created to use the high value of $d_{31}$ piezoelectric constant of the PVDF. We expect that the control of Young’s modulus of PVDF by NCC will give the influence on the sound pressure detected.

The equation between the Young’s modulus $Y$ and the parameters of NCC is given by Date [1],

$$\frac{Y}{Y_0} = 1/(1 - k^2/(1 + C_c^*/C_s^*))$$  \hspace{1cm} (3)

where $Y_0$ is the Young’s modulus without NCC. $k$ is the electromechanical coupling coefficient. The quantities $Y_0$, $k$ and $C_s^*$ are constants. $C_c^*$ is the complex capacitance given by Eq.(1) and involves the values of several resistances. The imaginary part of $C_c^*$ is determined by the angular frequency of sound $\omega$ and $R_p$. The value of $R_4/R_3$ is determined to suppress the self-oscillation of the circuit. The variable parameter used in experiments is only a ratio $R_2/R_1$. 

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**Fig. 2:** Negative capacitance circuit
TRANSMISSION OF UNDERWATER SOUND THROUGH PVDF FILM

In the apparatus shown in Fig. 1, the sound with constant amplitude was produced from the PZT actuator at the left side and the amplitude of sound passed through PVDF film was detected by the PZT actuator at the right side. The variable resistance (R1+R2) was changed and the variation of sound pressure at the right side was observed.

Fig. 3 shows the variation of the received pressure P plotted against the change of resistance R1/(R1+R2). Po is the pressure of received sound when the NCC was disconnected. The frequency used was 4, 8, 10 and 20 kHz. The range of frequency was limited by the gain decay of the operational amplifier at higher frequencies.

At each frequency, with the increase of R1, the received pressure P gradually decreased, reached a minimum and then sharply increased. At the minimum, the decrease of P was near -20 dB. The later increase of P was more than 20 dB.

The effect of NCC is remarkable. We speculate that with increasing R1, the Young’s modulus of PVDF gradually decreases resulting in the increase of reflection of sound. As R1 comes to a critical point, the phase of sound is reversed. Then the amplitude of the vibration of PVDF film increases causing the increase of detected sound pressure.

Fig. 3: The plot of P/P0 against R1/(R1 + R2)

Fig. 3 shows that NCC gives the interesting effect for the penetration of underwater sound through the curved PVDF film. The change should be caused by the alteration of elastic properties of PVDF due to the feedback from NCC. We simply assume that the output sound pressure is determined by the dynamic stress of PVDF, which is excited by the input sound. Then the pressure of output sound should be proportional to the Young’s modulus of PVDF.
Since the value of the element in the circuit is known, using Eq. (3) we can calculate the Young’s modulus $Y$ as a function of $R_1/(R_1 + R_2)$. Fig. 4 shows an example of comparison of such calculation and experimental data at 20 kHz. For this case, $C_0 = 2.95 \text{nF}$, $R_o = 100\Omega$, $(R_3 + R_4) = 100 \text{k}\Omega$, $(R_1 + R_2) = 100 \text{k}\Omega$, $k = 0.25$ were used. The curve fitting is improved if slight modification is given to these values. Some unexpected error such as stray capacity and resistance could be corrected. The overall agreement between the calculated and measured values is better than expected.

The reflection and absorption of air-borne sound in the acoustic tube have been already published [2]. The sound shield by the PVDF film combined with NCC is significant. However, the type of NCC was different. Young’s modulus increases with increasing feedback, so that the PVDF film becomes harder. For the case of underwater sound, the feedback by NCC decreases the Young’s modulus and the film becomes softer. The details of NCC are described in reference [1].

Fig.4: Comparison of received sound pressure $P$ and Young’s modulus $Y$ of PVDF connected to NCC calculated by Eq. (3)

**CONCLUSION**

A circular acoustic tube was filled with water. In the middle of the tube a curved PVDF piezoelectric film connected with a negative capacitance circuit NCC was installed. Sounds with a fixed frequency were introduced to the tube by a PZT actuator and received at the other end of the tube by another PZT actuator.

With the increasing feedback of NCC to PVDF, the received sound pressure first decreased to about 20 dB and increased with the opposite phase as large as 40 dB. The behavior was well represented by the theoretical curve derived from Date’s equation.
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