Indian Journal of Geo Marine Sciences
Vol. 40(2), April 2011, pp. 176-180

Response estimation of micro-acoustic transducer for underwater applications using finite element method

Mohd Ikhwan Hadi Yaacob, Mohd Rizal Arshad & Asrulnizam Abd. Manaf
Underwater Robotic Research Group, School of Electrical & Electronic Engineering,
Universiti Sains Malaysia Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia
[E-mail: mohdikhwanhadi@yahoo.com.my]

Received 23 March 2011, revised 28 April 2011

Present study proposed a modeling method to estimate the responses of micro-acoustic transducer and new design of micro acoustic transducer with nickel aluminum bronze encapsulation. Proposed method utilizes finite element analysis by combining the piezoelectric and modal harmonic analyses of micro-structured acoustic transducer. First, novel design of piezoelectric micro-acoustic transducer with nickel aluminum bronze encapsulation was discussed. It was design specifically for sonar applications with resonance frequency at 122 kHz. Next, transmit and receive responses of the transducer was determined using proposed method with reference to underwater acoustic parameter. Finally, the estimation method was validated using existing calibrated transducers by reverse-engineering approach. As the result responses of micro-acoustic transducers were successfully estimated as a function of frequency. New transducer design with nickel aluminum bronze encapsulation has transmit response at 123 dB re 1µPa/V and receive response at -75 dB re 1V/µPa. Validation of the method reveals the average percentage error at 18.97%. Proposed method is useful for micro-acoustic transducer designer to determine responses before entering fabrication process.

[Keywords: Acoustic transducer, Finite element analysis, Transmitting response, Receiving response]

Introduction

Micro acoustic transducers have gained a lot of attentions lately and the summary of the arousing design challenges, issues and potential can be found in several recent reviews[1-2]. Micro acoustic transducer consists of several layers of different material for specific purposes. For piezoelectric-based acoustic transducer, at least a layer of piezoelectric film is required as a sensing part where the electrostriction process occur. Piezoelectric film is usually sandwiched between two electrodes. Additional layers can also be found such as substrate layer, buffer layer, adhesion layer and protection or encapsulation layer[3-5]. Receiving response of acoustic transducer represent how much voltage will be produced by the transducer corresponds to every micro-Pascal (µPa) of sound pressure received at the surface of the transducer, as given in equation (1). In contrast, transmitting response, as given in equation (2) represent how much sound pressure level (SPL) generated in correspond to each volt of drive voltage, 1 meter away from the transducer as a standard calibration for underwater:

$$S_R \text{ (dB)} = 10 \log (V/V_{ref}) \text{ ; } V_{ref} = 1 \text{ V} \quad \dots (1)$$

$$S_T \text{ (dB @ 1m)} = 20 \log (P/P_{ref}) \text{ ; } P_{ref} = 1 \ \mu\text{Pa} \quad \dots (2)$$

Where S_R is receiving response and S_T is transmitting response.

Both responses are presented in decibel (dB) and can only be determined during calibration process after device's fabrication. The method to determine sensitivity as a function of frequency was demonstrated previously[6] using a special water tank with several other equipments such as ultrasonic source, function generator, preamplifier (receive and transmit) as well as oscilloscope.

This work was motivated from the difficulties to estimate device responses before fabrication process take place. In order to obtain desired responses, one should complete the whole development cycle. Hence, a method to estimate receiving and transmitting responses was proposed. It allows responses estimation during design or pre-fabrication phase, thus offers greater flexibility to sensor designer to achieve specific sensitivity within design constrain in a shorter time. Proposed method used finite element method; combining and interpolating data from piezoelectric and modal harmonic analyses. It was then validated by comparing with experimental data from previous works by other researchers[6-7]. From the comparison, percentage error was then determined.

Materials and Methods

Proposed Transducer Design

Proposed micro acoustic transducer design utilized zinc oxide (ZnO) as piezo active material layer. ZnO was one of the earliest piezo materials being discovered and yet still gaining popularity for its superior piezoelectricity[8] and cheaper method of film deposition compare to other piezo-active thin films[9]. With lower dielectric constant compare to other piezoelectric materials such as lead zirconate titanate (PZT) and aluminium nitride (AlN), ZnO offers better sensitivity. Wide selections of materials are available today to be used as connector and electrodes in micro fabricated devices such as platinum, gold, copper and titanium, each one offers different performance. Previously, we have proposed and theoretically characterized[10] micro-acoustic transducer with nickel aluminium bronze ($CuAl_{10}Ni_5Fe_4$) as electrodes, taking advantage of its good electrical conductivity property at 5.21×10^{12} pS/µm. in addition, nickel aluminium bronze was known to endure longer in extreme corrosion environment and has been widely used in marine applications replacing conventional stainless steel. In this study, aluminium was employed as electrodes, sandwiching the ZnO thin film. Aluminium was introduced as the cheaper alternative for nickel aluminium bronze alloy. Furthermore, well documentation for deposition and etching processes of aluminium is another factor why it was chosen in our proposed design.

The model was built virtually using Process Editor™ within Coventor™ 2008 software package. All material layers were deposited on the silicon substrate. First, 0.5 micron of aluminium film was sputtered on the silicon substrate followed by 40 micron of ZnO. Top aluminium electrode finally was partially sputtered on top of the ZnO film, also with 0.5 micron thickness. Next, silicon substrate was assumed to be etched leaving the thickness of the vibrating diaphragm at 10 micron. Finally, 5 micron encapsulation layer of nickel aluminium bronze was deposited on the 1 micron silicon nitrite protective and insulation layer on the top of the sensor module. Cross-sectional figure of the transducer is illustrated in Fig. 1.

Modeling Method

All analyses and characterizations were done using Analyzer tools package within Coventor™ software. First, two designs were selected[6-7] based on previous

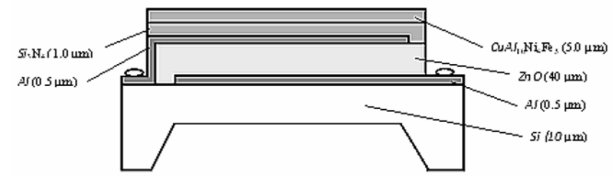

Figure 1—Proposed micro-acoustic transducer for sonar with nickel aluminium bronze encapsulation

works by other researcher. Both transducer designs have been fabricated, tested and calibrated for transmitting and receiving responses. The experimental data from those analyses were taken as a reference value for comparison with the generated data from proposed method. Next, both transducers were rebuilt and the test condition was remodeled for simulation and theoretical characterization using proposed method. The assumption of the models to be a multilayered plate with all outer surface clamped at the fix edge has been demonstrated throughout this work[11]. For finite element meshing, all models were simplified with only the vibrating part left as shown in Fig. 2.

There were five important surfaces on every transducer models. First is the outer edge of the model, S_{fix}. Next surface is on the top of the model, S_{top} whom will receive inbound acoustic signal. Another two surfaces located on top and bottom of piezoelectric layer and being in contact with top and bottom electrodes, denoted with S_{pzt} and S_{pzb} respectively and lastly the lowest surface which the bottom part of the diaphragm, S_{bottom}. These simplified models were then split into two separate regions with different mesh setting. Both regions however have undergone the same linear tetrahedron meshing. Similar meshing method for a square shaped micro ultrasonic transducer using PZT as a piezoelectric layer has been validated elsewhere by others[12]. Piezoelectric coefficients of all material were set to be zero except for ZnO as piezo active material. Young's modulus, E and Poisson's ratio, υ were taken as the measure of elastic coefficients of all isotropic materials as in Table 1.

Once the existing transducers were successfully remodeled, a series of modal and piezoelectric harmonic analyses were conducted. The value of the transmitting and receiving responses from the simulation was then compared with the experimental value claimed by both previous researchers[6-7]. From the comparison, percentage error for utilizing this method can be calculated for validation. Average error value is finally calculated and concluded.

Figure 2—Simplified model with five surfaces for finite element analysis

Table 1—Material Properties

Material	ρ (10^{-15} kg/μm^3)	E (10^4 MPa)	υ
Si_3N_4	2.70	2.22	0.27
Si	2.50	16.90	0.30
Al	2.30	7.70	0.30
$CuAl_{10}Ni_5Fe_4$	7.58	11.50	0.33

Estimation Procedures

This section describes each procedure taken for the estimation of transmitting and receiving responses of micro acoustic transducer. In piezoelectric analysis, three boundary conditions involved. Drive voltage was applied at S_{pzt} and S_{pzb} surfaces which were in contact with the electrodes while S_{fix} surface was fixed mechanically and neutral electrically. To simulate the transmit process; S_{pzt} was supplied with drive voltage while S_{pzb} was kept as reference with 0 V of supply voltage. Then, produced charge on top and bottom part of the ZnO, and the upward deformation of diaphragm were observed. To simulate the receive mode, voltage was across S_{pzb} surface and S_{pzt} surface with S_{pzt} as reference, while deflection of diaphragm on –Z axis direction was observed.

In modal analysis, series of pressure were applied at S_{top} and S_{bottom} surfaces, deflecting the diaphragm upward and downward, mimicking the deflection when supply voltages were applied. During receiving mode, sinusoidal pressure was applied on top of the transducer, and minimum deflection on –Z axis direction as well as generated voltage across two electrodes were observed. When simulating transmitting mode in modal analysis, sinusoidal pressure was applied at the bottom of the transducer and this time maximum deflection on the +Z axis direction and negative voltage produced between electrodes were observed. In both piezoelectric and modal harmonic analysis, same boundary conditions applied to minimize the calculation errors. Finally, to estimate transducers' responses as a function of frequency, both curves from piezoelectric and modal analyses were plotted where maximum response occurs at the interception point between these two curves.

Results and Discussion

Based on the proposed estimation method on existing calibrated transducer, percentage errors at 19.75% and 18.18% were determined as shown in Table 2. With 18.97% of average error, several possibilities can be appointed as its origin. Piezoelectric material was set to have material damping in all analyses while for other layer, it was left as zero. During reconstruction of existing design by Ito *et al*[6] for FEM analysis, adhesion layer was neglected for simplification. This action was suspected to reduce the total vibrating diaphragm mass thus affecting its fundamental frequency and vibration behavior. Finally, estimated SPL from Wygant *et al*[7] was accomplished at the surface of the transducer while original work was suspected to report the value at 1 m from the transducer, taking consideration of standard practice. These three factors were suspected in the contribution of the slightly higher percentage error values.

Receiving response of the proposed model is estimated. Again, receiving response can be defined as output voltage generated by the transducer per 1 µPa of sound pressure at the surface of the transducer. In this analysis, sound pressure was replaced with the harmonic sinusoidal pressure at S_{top} surface as a function of frequency. In modal analysis, the pressure was directed downward so that minimum displacement of the diaphragm occurs which is in the negative direction of the Z axis. While keeping the amplitude of the pressure constant at the reference value of 1 µPa, the frequency was varied and the minimum displacement at the center of the diaphragm was observed.

The modal curve from this analysis in Fig. 3 shows that the minimum displacement at the center of the diaphragm is 1.03×10^{-10} µm. Then, piezoelectric analysis was conducted on the model. At 50 nV of supply voltage when the frequency reached 127 kHz, piezo curve intercepts the modal curve which indicate the maximum point of receiving response. In other words, it takes 50 nV peak to peak of supply voltage at 127 kHz of frequency to produce the same magnitude of deflection at the center of the diaphragm which correspond to the 1 µPa harmonic pressure at

Table 2—Method validation and percentage errors

Transducer Model	Experimental	Estimated	Error (%)
Ito *et al*	-243 dB re 1V/ µPa	-195 dB re 1V/ µPa	19.75
Wygant *et al.*	152 dB max SPL @ 1m	-124 dB @ Surface	18.18

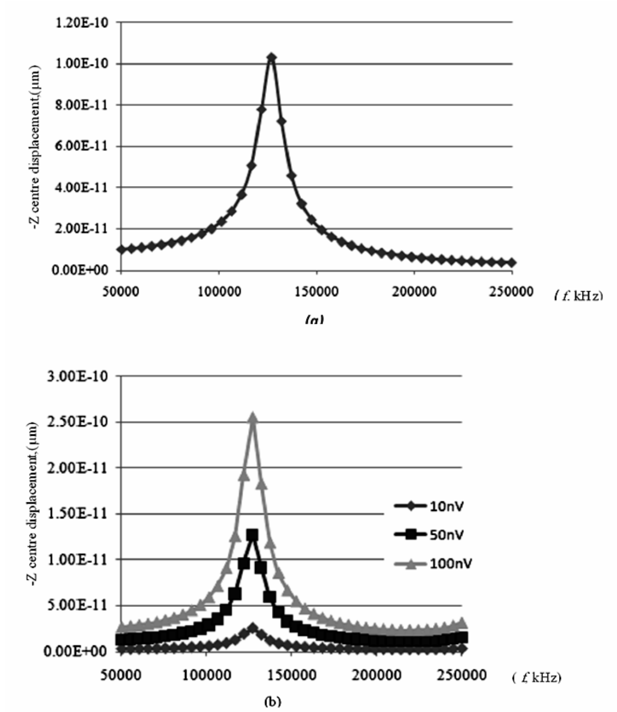

Figure 3—Receiving response curve (a)Modal curve at 1µPa reference SPL (b) Piezo curve at various supply voltage

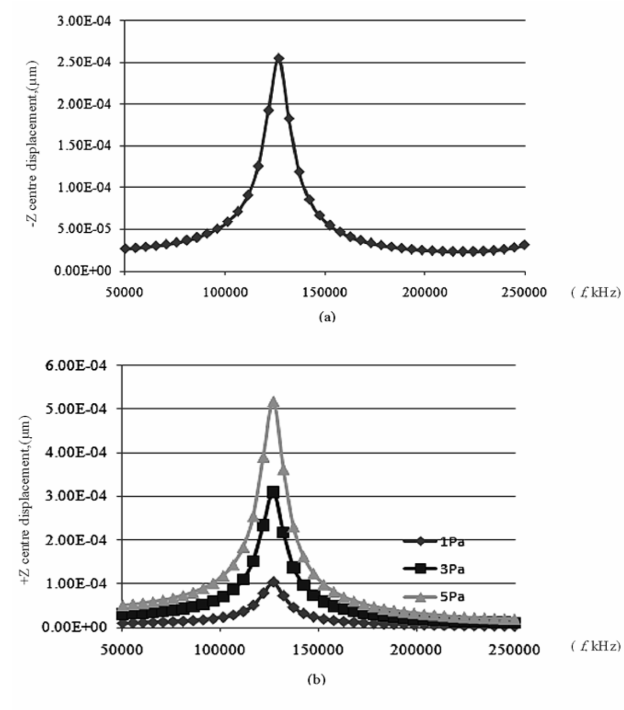

Figure 4—Transmitting response curve (a) Piezo curve at 1V of supply voltage (b) Modal curve at various sound pressure level

the same frequency. 50 nV of peak to peak sinusoid supply voltage is equivalent to 35.4 nV rms, or-74.52 dB re 1V. Thus, receiving response of the model is -74.52 dB re 1V/ µPa.

After that, transmitting response of the proposed model was observed. This quantity measures the amount of generated SPL, 1 m from the transducer for every volt of supply voltage. However, it was almost impossible to model the generated SPL 1 m away from the transducer. Hence, transmitting voltage response in this analysis is estimated at the surface of the transducer. In piezoelectric analysis, 1 V of harmonic sinusoidal supply voltage was supplied across the electrodes with bottom electrode as a reference. Maximum displacement was then observed, which is in the positive direction of the Z axis. From piezoelectric analysis curve in Fig. 4, 1V of supply voltage was able to deflect the diaphragm upward with 1.83×10^{-4} µm of deflection. After that, modal analysis was conducted on the model and various magnitude of harmonic pressure was applied on the S_{bottom} surface within the same frequency range. At 3.0 Pa of pressure, the modal curve intercepts the piezoelectric analysis curve at 137 kHz of frequency, which is equivalent to 2.12 Pa rms or 126.53 dB re 1 µPa. Thus, transmitting response of the model is estimated at 126.53 dB re 1 µPa/V at 137 kHz of frequency on the surface of the transducer model. Transmitting response curve is shown in Fig. 4.

Compare with our previous design[9], newly proposed transducer have simpler structure from fabrication point of view. Most importantly, this study was successfully discovered a method to estimate the responses of the micro acoustic transducer with exceptional percentage errors margin. However, for estimation of the transmitting voltage response, it is very important to take note that the standard measurement of SPL is usually done 1 m away from the transducer. Actual performance of the transducer might be lower from the projected value since the estimation is done on the surface of the device.

Conclusion

In conclusion, a method for estimation of transmitting and receiving responses of micro acoustic transducer has been proposed. Proposed method was found to carry average percentage error at 18.97%. Furthermore, responses of circular shaped micro acoustic transducer having ZnO as piezoelectric layer and nickel aluminum bronze as the encapsulation have been successfully studied. The results obtained were comparable to several previous works by others[10-15] by utilizing different materials and approach of analysis. By using nickel aluminium bronze as encapsulation and aluminium as electrodes, the outcome is theoretically as good as the usage of other expensive conductors such as gold and platinum. Plus, having the thin-film based encapsulation layer might possibly increase the impedance matching between the transducer and water load. The analysis to predict the acoustic impedance matching will be included in our future study. Near the future, we were looking forward to proceed with device fabrication using our proposed design so that further validation within the scope of this paper can be accomplished.

Acknowledgement

This work was supported and funded by several parties namely Ministry of Science, Technology and Innovation Malaysia, through the National Oceanographic Directorate and Universiti Sains Malaysia (USM) as short term research grant (304/ELECT/60310023) and postgraduate research grant scheme (1001/PELECT/8043071). The authors would like to thank all fellows and members of Underwater Robotic Research Group (URRG) and CEDEC, for their consistent support, cooperation and assistance throughout the work.

References

1 Foote K.G., Underwater acoustic technology: Review of some recent developments, *Proc. MTS/IEEE Oceans*, (2008).

2 Arshad M.R., Recent advancement in sensor technology for underwater applications, *Indian J. Mar. Sci.*, 38(3)(2009) 267-273.

3 Muralt P., Recent Progress in Materials Issues for Piezoelectric MEMS, *J. Am. Ceram. Soc.*, 9(5)(2008) 1385-1396.

4 Choi S., Lee H. & Moon W., A micro-machined piezoelectric hydrophone with hydrostatically balanced air-backing, *Sens. Actuator A-Phys.*, 150(2010) 1-55.

5 Akasheh F., Fraser J.D., Bose S. & Banyopadhyay A., Piezoelectric micromachined ultrasonic transducers: Modeling the influence of structural parameters on device performance, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 52(3)(2005) 455-468.

6 Ito M., Okada N., Takabe M., Otonari M., Akai D., Sawada K. & Ishida M., High sensitivity ultrasonic sensor for hydrophone applications, using an epitaxial Pb(Zr,Ti)O_3 film grown on $SrRuO_3$/Pt/γ-Al_2O_3/Si, *Sens. Actuator A-Phys.*, 145-146(2008) 278-282.

7 Wygant I.O., Kupnik M., Khuri-Yakub B.T., Wochner M.S., Wright W.M. & Hamilton M.F., The design and characterization of capacitive micromachined ultrasonic transducers (cMUTs) for generating high intensity ultrasound for transmission of directional audio, *IEEE Proc. on Ultrason. Symp.*, (2008) 2100-2102.

8 Yoon S.H. & Kim D.J., Fabrication of piezoelectric ZnO and PZT films for FPW device, *Proc. Mat. Research Soc. Symp.*, (2007).

9 Akasheh F., Myers T., Fraser J.D., Bose S. & Bandyopadhyay A., Development of a piezoelectric micromachined ultrasonic transducers, *Sens. Actuator A-Phys.*, 111(2004) 275-287.

10 Yaacob M.I.H., Arshad M.R. & Abd. Manaf A., Modeling of circular piezoelectric micro ultrasonic transducer using $CuAl_{10}Ni_5Fe_4$ on ZnO film for sonar applications, *Acoust. Phys.*, 57(2)(2011) 151-158.

11 Li X., Du H., Xu L., Hu Y. & Xu L., Optimization of a circular thin film piezoelectric actuator lying on a clamp multilayered elastic plate, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 56(7)(2009) 1469-1475.

12 Lam T.Y., Lam K.H. & Chan H.L.W., Micromachined Piezoelectric Polymer Membrane Acoustic Sensor, *Integr. Ferroelectr.*, 76(2005) 31-37.

13 Choi H., Ding J.L., Bandyopadhyay A. & Bose S., Finite element analysis of piezoelectric thin film membrane structures, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 54(10)(2007) 2036-2044.

14 Wang Z., Miao J. & Tan C.W., Acoustic Transducers with a perforated damping backplate based on PZT/silicon wafer bonding technique, *Sens. Actuator A-Phys.*, 149(2009) 277-283.

15 Hong E., McKinstry S.T., Smith R., Krishnaswamy S.V. & Friedhoff B., Vibration of Micromachined Circular Piezoelectric Diaphragms, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 53(4)(2006) 697-705.