Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

New construction of loudspeaker for low frequency range by rotational type ultrasonic motor

Ryousuke SUZUKI(1), Gen TAKRDA(1), Hirokazu NEGISHI(2)
Juro OHGA(2)/(3),Ikuo OOHIRA(4),Maeda MAEDA(5),Hajime KUBOTA(1)

(1) Chiba IT, Narashinoshi, Japan(2) MIX Acous Lab,Yokosukashi, Japan(3) Shibaura IT, Tokyo, Japan
(4)self-owned business, Yokohamashi, Japan(5) TOA.Ltd., Koubeshi, Japan

PACS: 43.38.Ar, 43.38.Ja

ABSTRACT

This work gives a new loudspeaker construction which is completely different from the conventional electrodynamic loudspeakers. Direct-radiator-loudspeaker is required a large diaphragm displacement and low resonant frequency for satisfactory performance at a low frequency range. The conventional electrodynamic transducer is, however practical, not ideal for for this sort of loudspeakers because motion of the voice coil driven through an air gap cannot be controlled perfectly and its resonance peak with high Q-factor may result a long group delay time. The authors proposed an improved driving construction by using revolution of ultrasonic motors for direct-radiator-loudspeakers. It is suitable for radiate a high sound pressure at a low signal frequency. The piezoelectric ultrasonic motor is characterized by excellent motion controllability and high driving mechanical impedance because its rotor contacts its stator tightly. Therefore, the loudspeaker driven by ultrasonic motors expected to operate with large amplitude and high-fidelity in low frequency region even by a heavy diaphragm. However, continuous revolution of ultrasonic motor cannot induce reciprocal motion of the diaphragm directly. The important invention by the authors was the mechanism for generation of a vibration by revolution of an ultrasonic motor. It was given by use of an ultrasonic motor with a heavy metal block on its shaft. The preliminary model with this construction radiated a satisfactorily large sound. However, use of large metal block prevents reduction of loudspeaker size as well as weight. The authors reduced the heavy ring by using revolution of two ultrasonic motors with a common shaft. A loudspeaker using a driver of this construction, called as DMDS (Dual-Motor-De-Spin) model, shows a satisfactory performance for a direct-radiator-loudspeaker at a frequency range of 30 to 200 Hz.

1 INTRODUCTION

The lowest frequency of sound signal from a direct radiator loudspeaker is limited by the lowest resonant frequency (so-called f-zsro). The vibration displacement of its diaphragm is inversely proportional to the square of signal frequency. Therefore, size of a loudspeaker diaphragm for radiation of low frequency signal shall be large and its amplitude shall also be large.

To construct a diaphragm of large and completely controlled vibration, we showld use an electrically controllable diaphragm driver with high driving mechanical impedance. The electro-dynamic transucers for conventional loudspeakers, however, does not have so high driving impedance, because its driving force is induced via an air gap.

The authors proposed a loudspeaker driven by continuous revolution of a piezoelectric ultrasonic motor[1][2]. This solt of motors is known for use for precise positioning apparatus in IC manufacturing plants. It is characterized by very high driving mechanical impedance because its rotor contacts its stator tightly. This type of loudspeaker is expected to operate with large amplitude in low frequency region.

2 LOUDSPEAKER IN LOW FREQUENCY REGION

The simplest form for output sound pressure of an omnidirectional direct radiator loudspeaker is given by the following formula:

$$P = j\omega\rho \frac{VS}{4\pi l} e^{-jkl} \tag{1}$$

where, ω is signal angular frequency, ρ is density of air, S and V are effective area and vibrating velocity of the diaphragm, l is distance between radiator and measuring point and k is wave constant, ratio of ω and sound velocity. We notice VS is volume velocity of the source. This formula, therefore, shows that the acceleration of diaphragm $j\omega V$ should be constant against frequency for a flat frequency response. The diaphragm velocity is given by the following formula:

$$V = \frac{F}{z} = \frac{F}{j\omega m + r + \frac{s}{j\omega}} \tag{2}$$

where, F is driving force. z, m, r and s are mechanical impedance, effective mass, mechanical resistance and stiffness of the diaphragm. We see that only the region where:

$$V \approx \frac{F}{j\omega m} \quad (3)$$

meets the constant acceleration condition . This is called as *mass controlled region*. Its lower limit is given by resonant frequency of the diaphragm. Therefore, ordinary direct radiator loudspeakers cannot radiate the signal whose frequency is lower than the diaphragm resonant frequency effectively. This means the diaphragm resonant frequency shall be as low as possible to radiate satisfactorily low frequency signal.
It results that larger diaphragm mass or smaller support.stiffness is necessary. But, a heavy radiator is difficult to be supported by a soft stiffness. Moreover, a loudspeaker for low frequency region requires a large volume displacement, because it must be inversely proportional the frequency.

It is the authors' proposal to utilize the piezoelectric ultrasonic motors as a driver of a loudspeaker for low frequency reproduction, exploiting its high mechanical impedance. Introduction of ultrasonic motor seems to overcome common shortcomings of ordinary electrodynamic loudspeakers.
This report covers results of the authors' recent measurements and evaluation of our most recent prototype..

3 THE ULTRASONIC MOTOR

The revolution type piezoelectric ultrasonic motors (USM) are commertialy avairable by a few makers for components of office-automation equipment etc[3].
The authors used a mid-sized model USR60E3 by Shinsei Kogyo. Figure 1 shows the cut view. We see the location of piezoelectric actuator, teethed stator and metallic rotor.

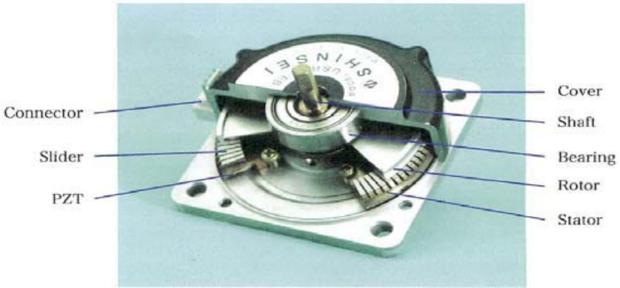

Figure 1 Ultrasonic motor USR60E

3.1 Driving principle

Figure 2 describes principle of piezoelectric ultrasonic motor. The stator is laminated by a thin piezoelectric ceramic ring. Two 40-45 kHz sinusoidal waves, with same frequency and with phase difference of 90 degree, are applied to the piezoelectric ceramic to generate a progressive wave [3].
The revolution velocity of the motor is varied by changing the amplitude of the progressive wave on stator surface. It can be done by adjustment of amplitude, frequency, or phase difference of the two sine waves. In order to reverse the direction of rotation, the phase difference between the two input signals simply has to be reversed.

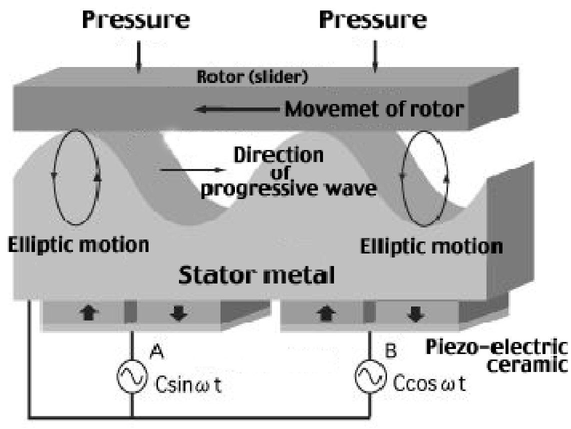

Figure 2 Driving principle

3.2 Rotational characteristics of ultrasonic motor

Rotational velocity of USR60E3 used here is controled by adjusting frequency of the sinusoidal signals applied to the piezoelectric ceramic. The frequency is controlled by the input voltage of a voltage-controlled oscillator in the driving circuit. Figure 3 shows the relationship between the input voltage and the driving frequency.

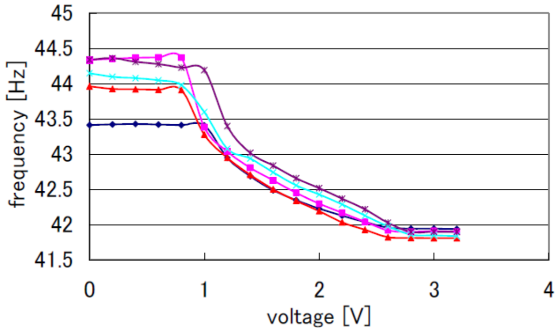

Figure 3 Relation between instruction voltage and driving frequency

Figure 4 shows the relationship between the input voltage and the rotational velocity. The loudspeaker models can be designed by using this reratiomship.

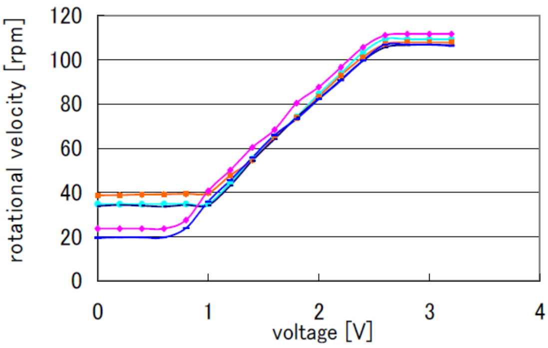

Figure 4 Relation between instruction voltage and rotational speed

4 DETAILS OF INERTIA-DRIVEN DIRECT RADIATOR MODEL

4.1 Preriminary model

Figure 5 shows construction of the preriminary model constructed at first.
It is an ordinary direct radiator loudspeaker with a cone diaphragm mounted in a boxy enclosure. The driving mechanism including one USM was installed in the enclosure. A coupling rod connects center shaft of the USM to the cone radiator via an elastic joint to mitigate stress by difference between circular and linear motions. "Funnel" means central part of the cone radiator. A steel ring (we call as inertia ring) of a few kilograms in weight is installed to outside of the stator of the motor to rotate together. The stator with the inertia ring rotates continuously by electrical input applied via slip ring contacts. The rotor does not move because it is connected to the cone.
The revolution velocity of the inertia ring is still kept constant because its ineatia is satisfactorily large. Therefore, when the revolution velocity of the motor is modulated by the input audio signal, driving force to the cone diaphragm is induced by the rotor then sound is radiated by vibration of the cone.

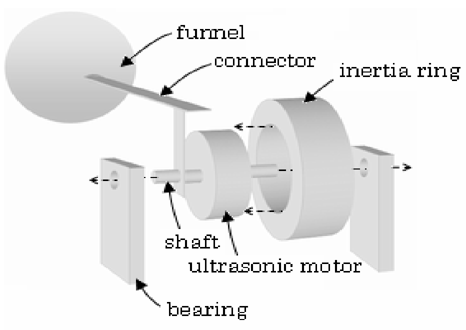

Figure 5 Structure of inertia-driven direct radiator model

The experimental model constructed by the authors used a paper cone radiator of 25 cm in diameter installed to an enclosure of 33.5 X 58.5 X 31.5 cms. Length of the conneting rod was 50 mm and the ring mass was about 5 kg. Resonant frequency was calculated to be about 10 Hz. Therefore, diaphragm was in mass-controlled region in the working frequency range. Frequency characteristic of output sound pressure is expected to be flat because constant driving force results constant acceleration in mass-controlled range. Output sound pressure was estimated to be about 100 dB at the point 1 m distant by assuming 30 gram of diaphragm effective mass and no energy loss. These expectations confirmed by experiments.

4.2 Improved model

Then, the authors constructed a new improved inertia-driven direct radiator model loudspeaker. Figure 6 shows the structure of the improved model loudspeaker. Functions of the stator and the rotor were inversed in this model to remove a slip-ring contactor. Two inertia rings were installed to the rotor via the shaft, and the corn radiator was connected to the stator.

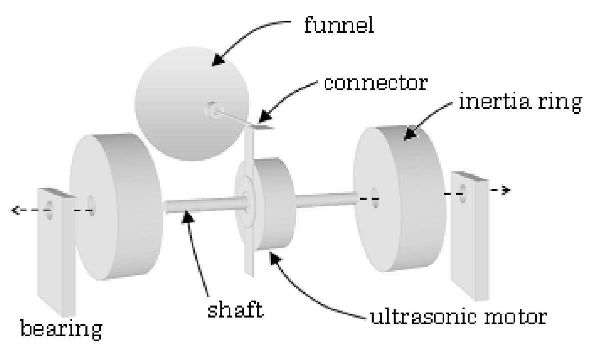

Figure 6 Improved model

Driving principle of the model is similar to the former model. The rotor and the inertia rings maintain a continuous rotation. When the velocity of the motor is modulated by the applied acoustic signal, the stator shows a reciprocal motion by the velocity modulation. It causes vibration of the corn diaphragm.

5 DMDS (Dual-moter-de-spin) model

Unfortunately, the model with heavy rings was not practical because it was too heavy. This problem was solved by the next generation model by using co-axial two ultrasonic motors.
Figure 7 shows the dual motor model. Two motors are introduced to achieve linear modulation and cone type radiator is connected to give reciprocal motion. Frequency modulation is chosen to control the motor.
Stator of one motor to give bias rotation is fixed to a solid base and its shaft is connected to the shaft of the other motor. Stator of the second motor is linked to the cone radiator by a rod. The second motor is counter driven at the same speed as the first motor to keep the cone stationary. When either or both motor(s) is(are) modulated by audio signal, the driving force to the cone is induced. This construction is named as the dual motor de-spin (DMDS) model.

Figure.8 shows the photo of the DMDS model. We can see two co-axial motors.

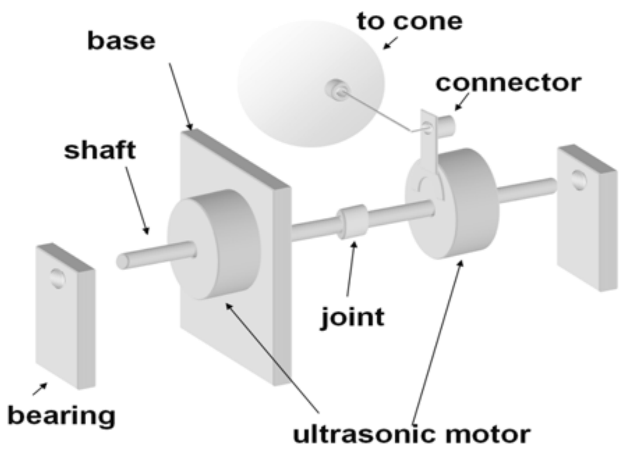

Figure 7 DMDS (Dual-motor-de-spin) model

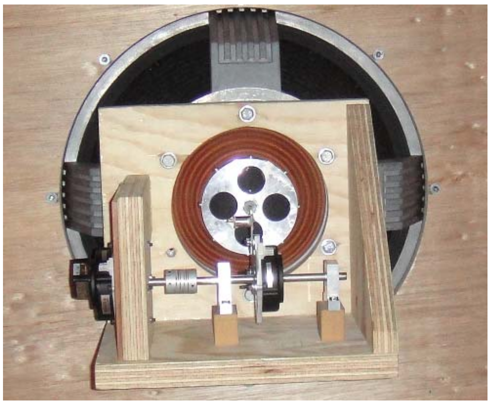

Figure 8 Photograph DMDS model

5.1 Experiment procedure

Frequency responses of the DMDS model were measured in an anechoic room. Distance between the microphone and the loudspeaker was 1000 mm. The input voltage of 1.45V was loaded to the driving circuit. A vented box of 125 litter was used. An air damper, a bundle of small tubes, was inserted in the duct..

5.2 Experimental results

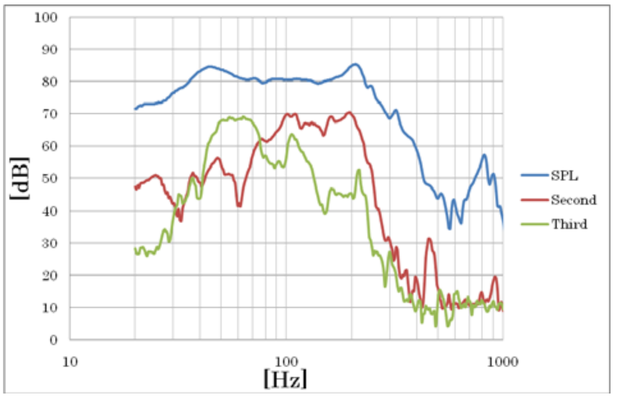

Figure 9 Output sound pressure frequency response

Measurement results are shown in Figure 9. We see the output sound is almost flat up to 200 Hz. Still the response under 20 Hz cannot be seen by limitation of measuring system, very low frequency signal can be radiated by this loudspeaker.

Muximum signal distortion is about 30 per cent which is higher than it of the conventional electrodynamic loudspeakers. This is a problem to be solved at the next examination

6 CONCLUSION

The loudspeaker using continuous revolution of an ultrasonic motor (USM) is proposed. This is suitable to radiate sound of very low frequency, because USM includes high driving mechanical impedance. After a few experiments by single-motor model with heavy ineatia rings, an improved model by co-axial two motors without any heavy rings, the dual motor de-spin (DMDS) model, was invented. The experimental models show satisfactorily large output sound pressure in low frequency region.

This new loudspeaker is expected not only for ordinary audio set use, but also for a radiator of the active noise cancelling system.

Further study will be carried out in order to improve performance by control of driving part to reduce signal distortion.

ACKNOULEDGEMENT

The authors wish to thank Mr.Matsumoto in TOA Corp.for their valuable contributions and advices.

REFERENCES

1. J. Ohga, H. Negishi, T. Sashida, K. Maeda: "A loudspeaker utilizing ultrasonic motor", JASJ Vol.62, No.11. pp. 813-818 (2006)
2 J. Ohga, H. Negishi, K. Maeda: "Louspeaker for low frequency by two ultrasonic motors", AES Japan Section Conference, Osaka, Japan (July, 2008-07)
3 T. Kenjo, T. Sashida: "An Introduction to Ultrasonic Motor",(Sogo Denshi Pub. Co, Tokyo, 1991) [in Japanese, English version was published by Oxford Press]
4 T. Adachi,R Suzuki,G takeda,J. Ohga,I .Ohira,H. Negishi, K . Maeda and H. Kubota: "Improving travel wave type ultrasonic motor driven loudspeaker", 3-P-17, Spring Meeting of The Acoustical Society of Japan (March, 2010)
5 J. Ohga: "Variety of electroacoustical devices by piezoelectric materials" Fundamentals Review, Institute of Electronics, Information and Communication Engineers. Vol. 1, No. 4, pp. 46-61 (April, 2008)