Loudspeaker systems for low-frequency radiation driven by rotational piezoelectric ultrasonic motors

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Abstract: The authors are developing a completely new direct-radiator loudspeaker as an alternative to the conventional electrodynamic loudspeaker. It is driven by the continuous revolution of piezoelectric ultrasonic motors, and is useful for the radiation of very low-frequency signals because it shows almost flat phase-frequency characteristics in the low-frequency region. A preliminary model, named the dual-motor, de-spin (DMDS) model, includes two coaxial ultrasonic motors. The stator of one motor is fixed to the base and that of the other is connected to the cone radiator. Velocity modulation of either motor induces driving force to the cone radiator. The low-frequency sound (for example, 30–120 Hz) output by this model was excellent because it has no significant resonance in this frequency region. However, the output sound was occasionally poor. In this paper, a highly improved model, named the quad-motor, de-spin (QMDS) model, is presented. It is based in two coaxial DMDS mechanisms. The experimental model has a cone radiator of 46 cm diameter and an enclosure volume of 268 l. Its working frequency range is the same as that of the DMDS model. Harmonic distortions included in the output signal are improved to be less than 10 percent of DMDS. Its sound quality is excellent.

Keywords: Audio system, Loudspeaker, Woofer, Ultrasonic motor, Piezoelectric ceramics

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1. INTRODUCTION

Conventional electrodynamic loudspeakers were developed first in the 1930s [1,2]. High-performance permanent magnets developed in the 1940s were a key material in their success. Theoretical analyses of the electrodynamic direct-radiator loudspeakers were carried out in the 1950s by many researchers. In particular, contributions from Tohoku University, Japan, were excellent [3]. They even used a preliminary digital computer system developed by NTT Laboratories for the numerical analysis of the dynamic deformation of cone radiators. A textbook of technology for loudspeaker manufacturers was published by the Japanese government, with contributions from these research engineers [4]. It led to the vigorous activity of many loudspeaker manufacturers. These theoretical design methods gave rise to the industries of very small loudspeakers for transistor radios and heavy-duty loudspeakers for audio instruments in the 1960s. The electrodynamic loudspeakers now seem almighty, but these loudspeakers

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have some limitations in their performance, especially in their characteristics in the very low frequency region. Ordinary direct-radiator loudspeaker diaphragms show resonance at a frequency called $f_0$. The phase of output sound around this resonance frequency varies in a range of 180 deg. This phenomenon results in signal distortion.

To avoid the above defect, the use of an electro-mechanical transducer with large mechanical impedance as the driver is necessary. However, the electrodynamic transducers for the conventional loudspeakers do not have satisfactorily high driving impedance because its driving force is induced indirectly via an air gap.

Solid-state transducers, for example, those of piezoelectric materials, show higher driving mechanical impedance. The theory of piezoelectric ceramic transducers for audio devices was studied beginning in the 1960s and has been completed [5]. Some of its successful applications were piezoelectric microphones and earphones for electronic telephones [6,7]. Piezoelectric sounders and buzzers for alarms are also suitable applications. However, the application of piezoelectric ceramics to direct-radiator loudspeakers was not successful, because the ceramic material is too hard and too frail to withstand the large-displacement vibration necessary for full-range loudspeakers.

A solution to the above problem may be to use a flexible piezoelectric polymer film, for example, the elongated PVDF film studied in the 1970s. Various structures using a single PVDF film were tested and a few commercially available audio devices were developed [8]. However, the lowest resonant frequencies of loudspeakers fabricated using a polymer film were not sufficiently low. One of the authors proposed a full-range piezoelectric loudspeaker fabricated using a piezoelectric bimorph film of two PVDF sheets folded to be a zigzag shape [8]. Its experimental sample achieved a lowest resonant frequency less than 100 dB loudspeakers. However, this loudspeaker still includes distortion due to the resonance, similar to conventional one.

The authors’ group is developing completely new loudspeaker structures using piezoelectric ultrasonic motors as the driver. The ultrasonic motor (USM) is characterized by very high driving mechanical impedance because its rotor is in tight contact with its stator. In this paper, we describe the evolution of the experimental model loudspeakers and propose a practical construction for ultrasonic motors.

2. LOUDSPEAKER IN LOW-FREQUENCY REGION

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

$$P = j\omega \rho \frac{V S}{4\pi d} e^{-jkd},$$  \hspace{1cm} (1)$$

where $\omega$ is the signal angular frequency, $\rho$ is the density of air, $S$ and $V$ are respectively the effective area and the vibrating velocity of the diaphragm, $d$ is the distance between the radiator and the measured point, and $k$ is a wave constant determined as the ratio of $\omega$ to sound velocity. We note that $V S$ is the volume velocity of the source. This formula shows that the acceleration of the diaphragm, $j\omega V$ should be constant against the frequency of the flat response. The diaphragm velocity is given by

$$V = \frac{F}{z} = \frac{F}{j\omega m + r + \frac{s}{j\omega}},$$  \hspace{1cm} (2)$$

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

$$V \approx \frac{F}{j\omega m}$$

gives the constant acceleration condition. This region is described as being mass controlled. Its lower limit is given by the resonant frequency of the diaphragm. Therefore, ordinary direct-radiator loudspeakers cannot effectively radiate signals with frequencies lower than the diaphragm resonant frequency. This means that the resonant frequency should be as low as possible to satisfactorily radiate low-frequency signals.

Therefore greater diaphragm mass or lower support stiffness is necessary. However, a heavy radiator is difficult to support with low stiffness. Moreover, a loudspeaker for the low-frequency region requires a large volume displacement because it is inversely proportional to the frequency. The authors undertake to overcome these limitations.

3. PIEZOELECTRIC ULTRASONIC MOTOR

The commercially available piezoelectric ultrasonic motors are divided into two classes: rotational motors and linear motors. The loudspeaker proposed in this paper utilizes rotational motors.

3.1. Construction

Figure 1 shows a cutaway model of a traveling-wave-type ultrasonic motor, USR60, invented and developed by T. Sashida [9]. It consists of a circular metal ring rotor and a nicked metal ring stator. The stator is laminated with a thin piezoelectric ceramic ring. The weight of this motor is 260 g and its size is $67 \times 67 \times 26.5$ mm, except for the shaft.

Figure 2 illustrates the relationship between the rotor and the stator. They are held in tight contact with each other by a disc-shaped spring. The stator consists of a piezoelectric unimorph transducer. Circumferential defor-
information of the piezoelectric ceramic ring induces stator bending. The nicked shape of the metal stator ring produces an upper surface displacement larger than that at the bottom.

Figure 3 illustrates the principle of the traveling-wave-type ultrasonic motor motion. The piezoelectric ceramic layer driven by two sinusoidal signals with the same amplitude and the same frequency but a 90° phase difference induces a traveling wave on the stator. The rotor and the stator contact each other for driving in this structure. Therefore, the driving mechanical impedance of the ultrasonic motors is extremely large compared with that of the electrodynamic actuators. It is also suitable for high-amplitude operation because its structure accommodates infinite rotation.

### 3.2. Input-Output Characteristics

The rotational velocity of the ultrasonic motor is controlled by the signal frequency applied to each piezoelectric ceramic part of the stator. Figure 4 shows the relationship between the measured rotational velocity and the driving signal frequency of three commercially available samples of USR60. The velocity is controlled from 30 to 100 revolutions per minute by varying the input signal frequency from 43.6 to 42 kHz.

The authors used one voltage-controlled sinusoidal-signal-generating circuit for one motor. It produces the signal frequency variation mentioned above by varying the input voltage from 1 to 3 V. In the following sections, input audio signal voltage will be given as V rms, where the bias voltage will be about 2 V dc.

According to Fig. 4, it is necessary to consider the deviation when designing the loudspeaker.

### 4. DMDS MODEL

After the examination of a few experimental models, the authors developed a structure that is not too heavy or too fragile to function as a practical loudspeaker system it included two coaxial ultrasonic motors.

#### 4.1. Construction of DMDS Model

Figure 5 shows the model with two piezoelectric ultrasonic motors. The arrows show the rotation directions. A fixed motor and a floating motor, are connected by a
common shaft. Therefore, the rotors of both motors rotate at the same velocity. The stator of the former is fixed to the base and that of the latter is connected to the paper cone radiator by the connecting rod. Velocity modulation of either motor, or both motors in the opposite phase, induces driving force to the cone radiator. The authors call this construction as dual-motor, de-spin (DMDS).

Figure 6 shows a mechanical circuit of the DMDS model. \( z_{M1} \) and \( z_{M2} \) are the driving mechanical impedances of the two ultrasonic motors. It is not infinitely large because the stator and rotor may slip against each other. \( m, s, \) and \( r \) are the effective mass, stiffness, and mechanical resistance of the cone diaphragm. \( \omega \) is the signal angular frequency. \( l \) is the distance between the motor shaft center and the joint of the connecting rod. Two dc components of motor revolution velocity, \( \Omega_{dc1} \) and \( \Omega_{dc2} \), compensate for each other. The velocity component of the audio signal \( \Omega_{sig} \), which is the summation of the two ac components \( \Omega_1 \) and \( \Omega_2 \), is applied to the cone radiator.

4.2. Input-Output Characteristics

An experimental DMDS loudspeaker system was constructed using two USR60 motors. The radiator was a paper cone of 46 cm diameter and enclosure volume of 268 \( l \). The enclosure was not completely closed to avoid too large a stiffness load against the cone radiator.

Figure 7 shows an example of the measured output sound pressure level of DMDS for 400 mV input at a point 1 m away from the DMDS. The working frequency range of this loudspeaker is up to 300 Hz. As shown in this figure, the maximum distortion level to overall output level is less than \( \sim 10 \) dB.

The most important problem in the DMDS construction was that induced driving force was still insufficient. We should increase the driving force by improving of the driving mechanism by modifying this construction.

5. QMDS MODEL

The authors developed an improved construction as a thorough solution to increasing the driving force. It is an expanded model of the DMDS system and including four ultrasonic motors [10].

5.1. Construction of QMDS Model

Figure 8 shows the structure of the four-motor model, where we changed the position of the connecting rod from
the left side to the right side in order to look at the inside clearly. Figure 9 shows a diagram of the mechanism of this model. It is actuated by cooperation of two DMDS drivers with one common shaft. The authors call this construction quad-motor, de-spin (QMDS).

Figure 10 shows a mechanical circuit of the QMDS model. The driver is described as a “two-story” shape of the DMDS circuits.

By this chart, we see that the four dc velocity components should satisfy the following relationship to compensate continuous revolution:

\[ \Omega_{dc11} = \Omega_{dc12} = \Omega_{dc21} = \Omega_{dc22}. \]  

(4)

The ac components should also satisfy the following to avoid slip between rotors and stators:

\[ \Omega_1 = \Omega_2 \equiv \Omega_1, \]  

(5)

\[ \Omega_{21} = \Omega_{22} \equiv \Omega_2. \]  

(6)

The loudspeaker radiates audio sound even when \( \Omega_1 \) or \( \Omega_2 \) is zero, i.e., velocity modulation by the audio signal can be applied to the fixed motors or the floating motors only. When the sound pressure level of 100 dB at a frequency of 100 Hz is measured at a distance of 1 m from the loudspeaker, the displacement of the loudspeaker cone is approximately 0.3 mm. Defining the angle of the inclination of the arm as \( \theta \), \( \sin \theta \) is approximately equal to \( \theta \), because the loudspeaker cone displacement is 0.3 mm compared with \( l \) of 66 mm.

Figure 11 shows the driving circuit configuration of QMDS. The motordriver D6060 dedicated to driving one USR60 has the velocity modulation function with respect to input signal. When D6060 inputs an audio signal, QMDS radiates sound. It doubles the rotating velocity difference between the motor modulated by the audio signal and at least one motor, and the paired motors are modulated inversely. The bias circuit absorbs the individual differences.

Figure 12 shows bias and inverse circuits of one DMDS driver. All the electronic circuits comprised operational amplifiers and analog calculation ICs. Four USR60 motors, i.e., serial numbers from No. 11694 to No. 11697, were used for our experimental loudspeaker.

Figure 13 shows rotational velocity versus command voltage of these motors. The command voltages of Nos. 11694, 11695, 11696, and 11697 were set to 2.2, 2.2, 1.9, and 2.1 V, respectively, for a constant rotational velocity of 80 rpm.
5.2. Input-Output Characteristics

An experimental QMDS loudspeaker system was constructed. The radiator used was a paper cone of 46 cm diameter and enclosure volume of 268 L, similarly to the experimental DMDS model. The enclosure was not completely closed to avoid too large a stiffness load against the cone radiator.

Figures 14(a) and 14(b) show the measured output sound pressure levels of a QMDS model for two input voltages at a point 1 m away from the QMDS. We see that this model operates in a wider frequency range than the former models, up to about 200 Hz, because distortion levels relative to the overall output level are decreased to about $-20\, \text{dB}$ in the either measured frequency range. Dynamic range is also extended. The sample works linearly at the frequency of as less as 30 Hz. However, distortion levels are not increased remarkably.

A remaining problem for this kind of loudspeaker may be its life time of continuous operation. The life of the conventional ultrasonic motors may be satisfactory for consumer equipment. It is, however, insufficient for professional requirements, for example, continuous operation for 10 years.

6. CONCLUSION

The authors’ team developed completely new direct-radiator loudspeakers [11]. The loudspeaker structures presented here, which utilize continuous revolution of piezoelectric ultrasonic motors, yielded the most practical results up to now.

The lowest signal-frequency limit of a conventional electrodynamic direct-radiator loudspeaker is given by the lowest resonant frequency $f_0$. The output signal phase varies by about 180 deg around the resonant frequency. This causes signal distortion that may generate audible signal distortion.

This defect can be avoided by using a stiff diaphragm driven by a powerful driver with a high mechanical impedance, excepting conventional electrodynamic transducers. The authors proposed the use of piezoelectric...
ultrasonic motors as the loudspeaker driver. The ultrasonic motor is characterized by very high driving mechanical impedance because its rotor is in tight contact with its stator. A paper cone loudspeaker driven by the ultrasonic motors is expected to operate with large amplitude in the low-frequency region.

After the examination of some structures, the authors invented a highly improved structure named the quad-motor, de-spin (QMDS) model. It uses four coaxial ultrasonic motors. An experimental model with a cone radiator of 46 cm diameter in an enclosure volume of 268 l shows low distortion and simple phase variation in the low-frequency region, for example, from 20 to 300 Hz.

The authors propose this QMDS model as a new practical direct-radiator-loudspeaker structure suitable for radiation in a low-frequency range.

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