Drive Circuit for a Mode Conversion Rotary Ultrasonic Motor

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Abstract **– A mode conversion rotary ultrasonic motor (USM) has potential applications in miniature robotics. However, its electrical drive circuit presents some unique challenges, particularly in producing a high frequency (~40kHz), high voltage (~200V peak-to-peak) signal into a low impedance (~100Ω) capacitive motor, while achieving high efficiency. This paper describes the design of such a drive circuit, intended for use with a 12V battery. The drive circuit consists of a switch-mode power converter driving the USM via a step-up planar transformer. Compensation and resonant elements are added to improve the power efficiency. While the peak efficiency of this circuit is 45%, in practice the equivalent impedance of the USM changes with mechanical load and temperature, resulting in an average efficiency of 16%. The admittance vs. frequency characteristic and the equivalent electrical model for a USM prototype are also presented in this paper. The circuit simulations and loaded testing of a full-bridge DC-AC resonant converter with DC-offset module were performed. A load-adapted frequency tracking method has also been proposed to improve the efficiency and stability of the drive circuit.**

I. INTRODUCTION

Piezoelectric ultrasonic motors (USMs) are resonating displacement devices, in which the alternating strain is excited by an AC electrical field, preferably operating at the mechanical resonance frequency [1]. USMs received wide attentions due to their specific advantages over the electromagnetic motors, such as: low speed and high torque for direct mechanical driving, simple structure and compact size, high power/weight ratio, and high efficiency [1]. However, there are some disadvantages for USMs, such as: the requirement of high frequency & high voltage power drive, and high wear rates for both stator and rotor.

There are two types of USMs: standing-wave USM and traveling-wave USM, which are distinguished by their vibration mechanisms. Each type of USM can be sub-divided into categories either linear motor or rotary motor [1]. A mode conversion rotary ultrasonic motor is a rotary standing-wave USM, and is also called a Kumada motor. It transfers the longitudinal vibration generated by the piezoelectric ceramic cylinder or disk into torsional vibration by using a longitudinal-torsional (L/T) coupler [2].

Shown in Fig. 1 is a prototype of a mode conversion USM, developed at North Carolina State University, which includes a stator assembly and a rotor assembly [3]. The resonator and the L/T coupler comprise the stator assembly. The rotor and the pre-load assembly comprise the rotor assembly. The resonator produces longitudinal resonant vibrations which are converted to elliptical displacements at the tips of the L/T coupler. Then the rotor is driven by the elliptical displacements and coupling friction; thereby, producing useful torque [3].

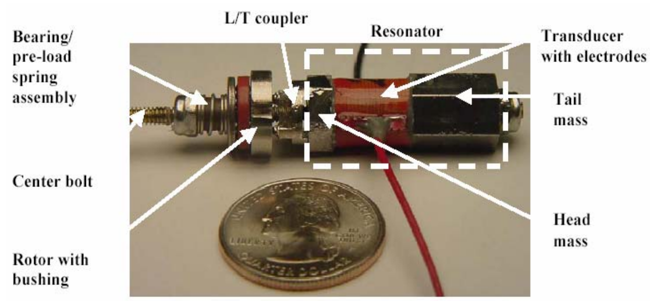

Fig. 1. A prototype of mode conversion USM developed at North Carolina State University [3].

USMs are expected to be used in mobile devices such as miniature robotics. A battery is the power supply for such a device; therefore, the design of a high efficiency and small size power drive for the USM is a critical issue. Compared with publications on drive circuit design for traveling-wave USMs, less research have been done in the area of drive circuit design for standing-wave USMs. Crivii and Jufer designed a half-bridge topology DC-AC resonant converter with a step-up transformer to drive a rotary standing-wave USM. Their circuit was proposed to drive a USM with a disk piezoelectric ceramic transducer having relatively small static capacitance (~2.5nF) [4].

This prototype of a mode conversion USM used a multilayer Lead-Zirconate-Titanate (PZT) ceramic stack transducer [3]. Compared with a cylinder or disk ceramic transducer, the multilayer ceramic stack transducer has much larger electrode area and is much thinner; hence, it has much larger static capacitance (~40nF). Since this USM presents a large capacitive load and requires a high operating frequency (e.g. 40kHz), its equivalent impedance could be as low as 100Ω. This USM also requires a high drive voltage (e.g. 200V peak-to-peak), which leads to a very large drive current (e.g. 2A peak-to-peak). In the testing for USM prototypes, a function generator and a voltage amplifier are used as the drive source [5]. To drive this USM, a generic voltage amplifier cannot guarantee output linearity and can even be pulled into overload. Beside these issues, this multilayer stack transducer needs a negative DC-offset for polarization, and the amplitude of the DC-offset is expected to be half of peak-to-peak AC voltage. The design of the drive circuit is a key for developing a successful USM system.

The large equivalent capacitance of the multilayer ceramic stack transducer introduces some unique challenges

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to the drive circuit design. In this paper, the design of a high voltage, high frequency and small size power drive for a mode conversion USM is presented. For a USM prototype, the admittance vs. frequency characteristic and the equivalent electrical model at the operating conditions are also presented. The circuit simulations and loaded testing of a full-bridge DC-AC resonant power drive with polarization DC-offset were performed. A load-adapted frequency tracking method has also been proposed to improve the efficiency and stability of the drive circuit.

II. CHARACTERIZATION AND MODELLING

A. Admittance Characterization

To design a high efficiency drive circuit for a USM, the impedance matching between the output impedance of the drive circuit and the equivalent impedance of the USM should be considered, and the impedance (or admittance) of the USM needs be clearly known. The admittance of a USM not only depends on the operation frequency but also changes with the applied voltage. An impedance analyzer works in a low voltage range (e.g. 1V) and can only measure the static impedance vs. frequency characteristic of a USM. To measure the dynamic admittance vs. frequency characteristic for a USM, a test system, which includes a function generator, a high voltage amplifier and an oscilloscope, was used and shown in Fig. 2.

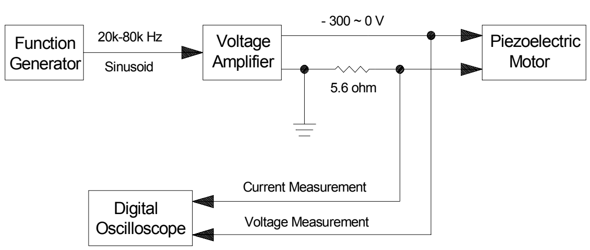


Fig. 2. A test system for characterization of a USM

At different frequencies, between 20 kHz and 80 kHz, the voltage (V_m) applied on the USM, the current (I_m) flowing through the USM, and the phase differential (θ) between them were measured. At a specific frequency, the admittance of a USM can be evaluated by: $Y_m = I_m / V_m$, $Y_m = Y_m \angle \varphi$, $I_m = I_m \angle \theta$, $V_m = V_m \angle 0$, where Y_m is the amplitude of admittance and $\angle \varphi$ is the phase angle of admittance. Although at some specific frequencies the output of voltage amplifier cannot maintain a constant value because of the small impedance of USM. The peak-to-peak value of output voltage was higher than 100V and had a -100V DC offset. The measurement results represent the characteristics under typical operating conditions.

By observing the measured admittance vs. frequency characteristic, shown in Fig. 3, there are three frequency points (around 33kHz, 44kHz and 64kHz) at which the amplitude of admittance presents pole point. This means that the mechanical system resonates at these frequencies. By interpreting the phase vs. frequency curve, the USM acts as a capacitive device across most of the frequency range, though it also shows inductive behavior at particular frequencies.

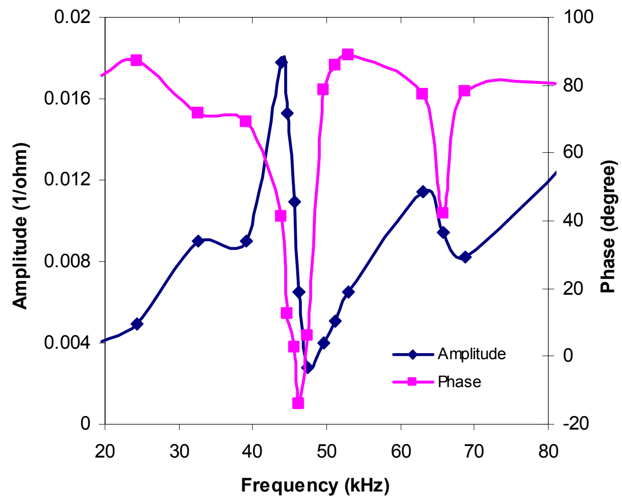


Fig. 3. The admittance vs. frequency characteristic of a USM

B. Equivalent Model

To understand the interaction between the electrical drive and the mechanical system, which includes the USM and its output load, an electrical equivalent model for the USM needs be abstracted. A general equivalent model for a USM is shown in Fig. 4a. If a USM is operated at its mechanical resonant frequency, the equivalent circuit can be simplified as shown in Fig. 4b [6].

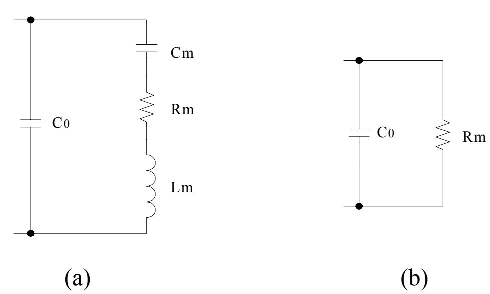


Fig. 4. An electrical equivalent model of a USM, (a) a general equivalent model; (b) a simplified equivalent model

For the general equivalent model, the admittance of a USM can be expressed as the following equations:

$$Y_m = j\omega C_0 + \frac{1}{R_m + j\omega L_m + 1/j\omega C_m}$$

$$Y_m = \frac{(1 + C_0/C_m - \omega^2 C_0 L_m) + j\omega C_0 R_m}{R_m + j(\omega L_m - 1/\omega C_m)}$$

Where $\omega=2\pi f$, C_0 represents the static capacitance of piezoelectric elements; R_m represents the dynamic resistance correspond to mechanical damping; C_m represents the dynamic capacitance correspond to mechanical stiffness; L_m represents the dynamic inductance correspond to mechanical mass [7].

If the operating frequency equals the series resonant frequency (f_s), the admittance reaches a maximum; if the operating frequency equals the parallel resonant frequency (f_p), the admittance reaches a minimum. f_s and f_p can be calculated by the following equations:

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{L_m C_m}}$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{C_m + C_0}{L_m C_m C_0}}$$

$$\frac{f_p}{f_s} = \sqrt{1 + \frac{C_m}{C_0}}$$

For the measured admittance amplitude vs. frequency curves, shown in Fig. 3, a maximum appears at ~43.9 kHz and a minimum appears at ~47.5 kHz, corresponding to f_s and f_p respectively. The following values were calculated: C_0=42.6nF, R_m=75.1Ω, C_m=7.03nF, L_m=307.6μH, and were used in the simulations below.

III. DRIVE CIRCUIT DESIGN

A. Design Goals

The operation of a mode conversion USM is based on the torque generated by piezoelectric ultrasonic vibrations. An optimal supply voltage for the USM is a sinusoidal voltage with frequency near the mechanical resonance frequency of the stator-rotor assembly. To polarize the PZT stack, a positive or negative DC-offset voltage is required. For instance, to operate this USM prototype**,** a high frequency (20~80 kHz) and high voltage (200~300 V, peak-to-peak) AC power drive is required. If the supplied voltage has a quasi-sinusoidal waveform and negative DC offset (-200V), optimal operations can be obtained. The goals for drive circuit design are to satisfy these requirements, as well as achieve high power efficiency and small size.

B. Circuit Schematic

The proposed drive circuit, shown in Fig. 5, is a full-bridge resonant DC-AC converter. It includes:

Vpower:	12V DC battery;
Voffset:	DC-DC converter module;
S_1-S_4:	N-channel Power-Mosfet;
T:	Planar transformer (ratio=1:20);
Lr1, Lr2:	Resonant inductor;
Cr1, Cr2:	Parallel capacitor;
C_1:	Bypass capacitor.

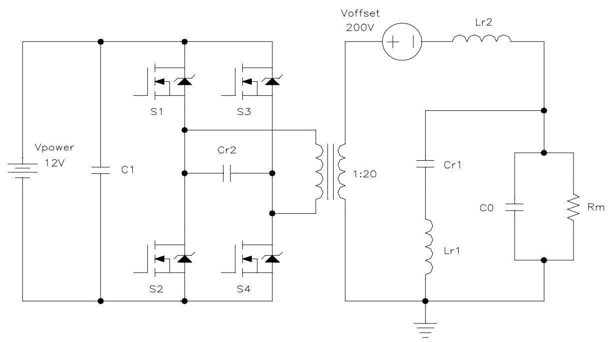


Fig. 5. A full-bridge resonant converter circuit

The drive circuit is supplied by a 12V battery. A full-bridge (H-bridge) switching circuit, which includes Power-Mosfets S_1~S_4, is used to convert a DC voltage into a high frequency AC voltage. A planar transformer which features high efficiency, small size and light weight was chosen to isolate and step up that high frequency AC voltage.

A voltage-mode regulating pulse-width-modulated (PWM) controller IC was used to drive the gates of Power-Mosfets. The controller has dual complementary channels, which output square-wave control signals with opposite phase to each other. S_1 and S_4 share one control channel and turn on/off simultaneously; S_2 and S_3 share another control channel and also turn on/off simultaneously. By adjusting the oscillator cycle of the PWM, the operation frequency of switching can be changed.

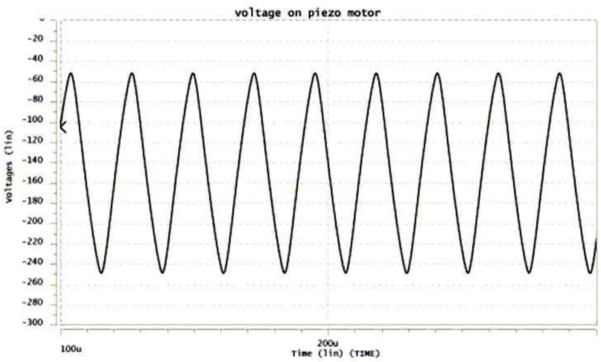
The additional inductors, Lr_1 and Lr_2, and capacitors, Cr_1 and Cr_2, together with the transformer and the USM compose a complex LC circuit. Through proper selection of Lr_1, Lr_2, Cr_1 and Cr_2, the entire resonant converter circuit and load, can be tuned so that the electrical elements and electrical equivalents of the mechanical system form a circuit that resonates at the USM mechanical resonance frequency. This complete resonant circuit produces a quasi-sinusoidal drive voltage across the USM, instead of the harmonic rich output of a genetic full-bridge drive circuit.

C. Simulation Approach

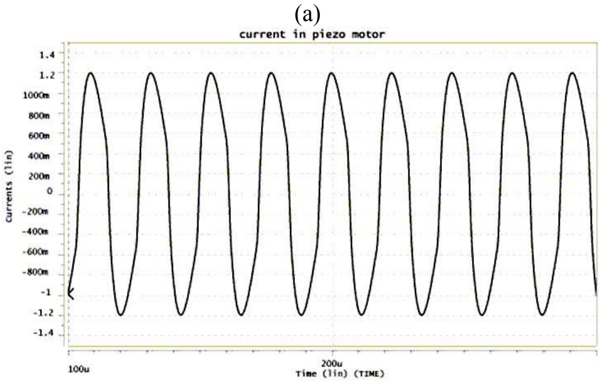
To optimize the circuit structure and component parameters, Hspice was used to simulate the drive circuit. For a specific operating frequency, sweep simulations were performed with different values of Lr_1, Lr_2, Cr_1 and Cr_2, and a set of resonant parameters were acquired. For the simulation results of the applied voltage and flowing current of the USM, shown in Fig. 6, the quasi-sinusoidal waveforms have been observed.

D. Experiment Results

A prototype of the power drive for a mode conversion USM was built and tested. For the experiment results, shown in Fig. 7, the lower curve represents the voltage applied on the USM, and it is a sinusoidal waveform (222V peak-to-peak) with -195V DC offset, which is an optimal source to transfer electrical energy to mechanical energy for the USM. The upper curve represents the voltage cross a series resistor (5.6Ω) and is used to measure the current flowing through the USM, which has a quasi-sinusoidal waveform. The rms value of voltage is 78.5V and the rms value of current is 0.5A. The phase differential between the voltage and the current is 66.2°, while the output power is 15.8W. The DC power consumption is about 98.2W, and the average efficiency of this power drive is 16%.



(a)



(b)

Fig. 6. The simulation results, (a) voltage on a USM, 200V peak-to-peak, -150V offset; (b) current in a USM, 2.4A peak-to-peak.

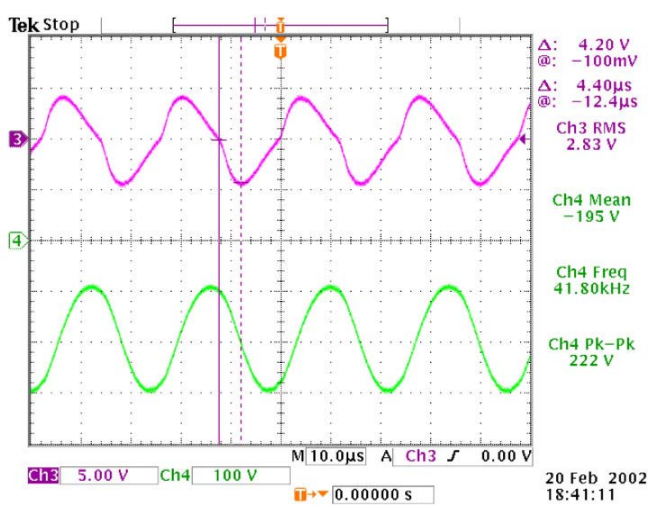


Fig. 7. Experimental waveforms: the upper curve -- voltage cross a serial resistor; the lower curve -- voltage applied on a USM.

The operation frequency is 41.8 kHz, which is slightly different from the resonant frequency in the experiments on admittance measurement. This difference is due to the additional mechanical load, causing a shift in mechanical resonant frequency.

IV. DISCUSSION

There were two main challenges in the design of this drive circuit. First, the current flowing through this USM is large (~2A peak-to-peak) due to the large static capacitance (~40nF) of the ceramic stack. Second, the operation of this drive circuit may not stable due to the mechanical resonant frequency shifting with the output load and the temperature of USM.

The large current in the USM, w.r.t. the high voltage side of the transformer, would result in a very large current (~14A rms) on the low voltage side of the transformer, introducing high heat loss in the switchers and low power efficiency. To resolve this problem, a bypass inductor L_{r1} was applied to compensate the large capacitance of the USM, and an additional capacitor C_{r1} was also included to block DC current from flowing through that inductor.

The measured peak efficiency of this electrical drive was as high as 45% when the output impedance of drive and the equivalent impedance of USM well matched. However, they did not match under common conditions and this mismatching degraded the average efficiency. A proposed load-adapted frequency tracking circuit by using phase-lock-loop (PLL), shown in Fig. 8, could improve the stability as well as the power efficiency [8]. The voltage and the current of the USM are feed back to a phase detector (PD). The output of the PD, which depends on the phase differential (θi) between the voltage and the current, feeds into a voltage-control-oscillator (VCO) and controls the operating frequency. By approaching θi to a target value θs could track variations of the mechanical resonant frequency and would keep the drive circuit stable.

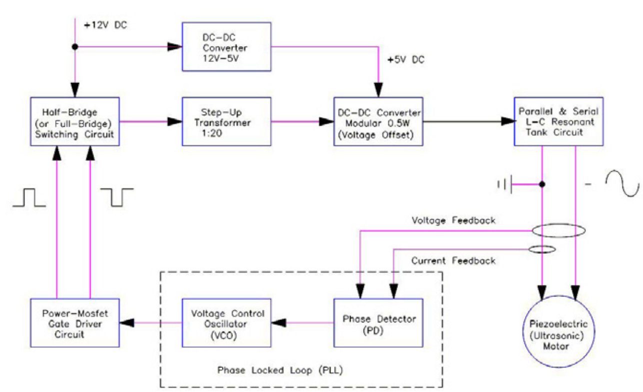


Fig. 8. Block diagram of a frequency tracking circuit

V. CONCLUSION

USMs are potentially interesting for a number of emerging applications, such as miniature robotics. Their electrical drive circuits present some unique challenges, particularly in producing a several hundred volts and tens of kilohertz signal into a low impedance capacitive motor, while achieving high efficiency. This paper describes the design of such a drive circuit, intended for use with a 12V battery. The circuit consists of a switch-mode power converter, driving the USM via a planar step-up transformer. A LC circuit was introduced to prevent the large current, leading by the low input impedance of the USM, in the transformer primary; Another LC circuit was used to produce a resonant driver. While the peak efficiency of this circuit is 45%, in practice the equivalent impedance of the USM changes with load and temperature, resulting in an average efficiency of 16%. A feedback circuit is proposed to compensate this issue.

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