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AN ULTRASONIC MOTOR DRIVER USING A RESONANT BOOSTER

Li Huafeng — Zhao Chunsheng *

According to the capacitive characteristic of the ultrasonic motor, a non-transformer driver scheme for ultrasonic motor using LC resonant is proposed in this paper. The circuit is theoretically analyzed and verified by simulation. The relationships of the amplitudes and energy efficiency of the harmonic wave for the output voltage with the driving duty ratio and resonant cycle number are analyzed in detail. Based on this, the design criteria of the circuit are established. The circuit is applied to a 5 mm ultrasonic motor. The output voltage is above 200 V ($V_{\rm p-p}$), the motor works well. It is proved that this circuit is both feasible and reliable for the drive of small-power USM, which makes it easier for the driver to realize integration.

K e y w o r d s: ultrasonic motor, driver,resonant, miniature

1 INTRODUCTION

Novel UltraSonic Motors (USM) exhibit advantages over conventional electromagnetic motors. For example, USM can produce a relatively high torque at a low speed with high efficiency, and the torque produced per unit weight is high. These features are useful for utilizing as gearless actuators or direct servo drives. The motors have recently been applied as direct drive actuators for articulated robots, actuators for control valves and a positioning table of machine tools because they require quick response and precise position control of actuators. Some experts even predict that USMs will replace micro electromagnetic motors in certain special areas in the future.

But in order to drive the USM, a special driver is required, which has been an obstacle for replacement of traditional motors by USMs. If the driver has a big volume, the promotion of USMs would be more difficult. Therefore, on the premise of meeting the basic requirements, the volume of the driver must be reduced to the greatest extent, so as to exploit the particular advantages of USMs in more areas.

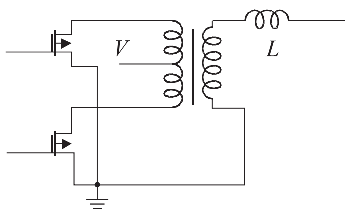

Fig. 1. Push-pull transformer circuit for USM.

Since the motor needs a high voltage of at least 100 V ($V_{\rm p-p}$) to drive, most current drivers use push-pull transformer to set-up, shown as Fig. 1. However, the existence of the transformer leads to the big volume of the driver, and makes a big obstacle to the promotion of such a kind of motor. In this paper, a booster using LC resonant is introduced to get the required high voltage, which reduces the driver's volume greatly, fulfils the demand of practicability for general engineering.

2 SYSTEM ANALYSES

Near the resonant frequency, the ultrasonic motor can be represented by an equivalent circuit, shown as Fig. 2(a), where C_d is the static capacitance of the piezoelectric ceramics, L_m is the equivalent inductance corresponding to the motor's mass effect, C_m is the equivalent capacitance corresponding to the motor's elastic effect, R_m is the equivalent resistance related to the stator's mechanical loss. With the condition that the external characteristics of the circuit do not change, the equivalent circuit of the motor can be transformed to an RC parallel circuit, shown in Fig. 2(C). The transformation relations of the parameters are derived as:

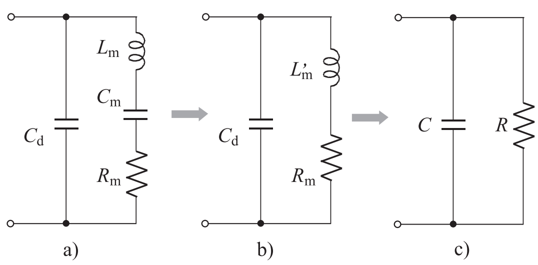

Fig. 2. Transformation of USM equivalent circuit.

$$L'_m = L_m - \frac{1}{\omega^2 C_m}\,,$$

$$C = C_d - \frac{L'_m}{R_m^2 + (\omega L'_m)^2}\,,$$

* Research Center of Ultrasonic Motor, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China. E-mail: lihuaf45@163.com

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$$R = R_m + \frac{(\omega L'_m)^2}{R_m} \, .$$

Since the motor usually works between its resonant and anti-resonant frequencies, the resistance on the series arm is very big, which leads to omitting of R in Fig. 2(c).

The main booster circuit using LC resonant technology is shown in Fig. 3, where L is the series couple inductance, K is a switch, D is an ultra fast recovery diode, and the ultrasonic motor is represented by C.

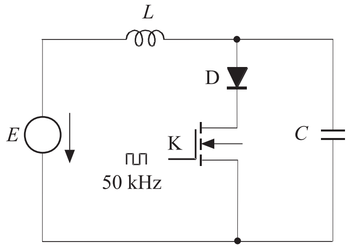

Fig. 3. The non-transformer driving circuit for USM.

The working principle of this circuit is explained as follows: when the switch K turns on, the DC power E accumulates energy to L; when the switch turns off, the inductance L delivers its energy to C and resonates with it, the whole circuit forms an LC series resonant circuit with initial condition. In Fig. 3, the switch K is MOSFET that can bear a high voltage. Since the MOSFET has a body diode anti-paralleled with it, if without D, the capacitance C will discharge through this body diode when its voltage reverses, which makes the output voltage only a half-wave. In order to get entire oscillation to get a high output voltage, as shown in Fig. 4, an ultra fast recovery diode D is in series with MOSFET.

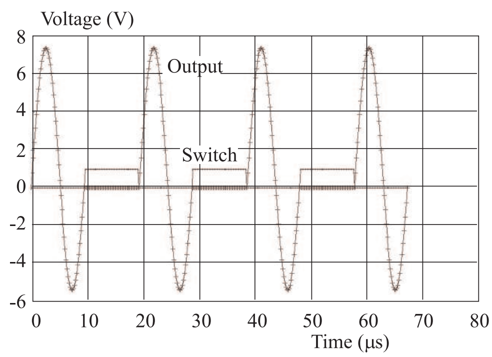

Fig. 4. Simulation of the voltage waveform for the LC resonant circuit.

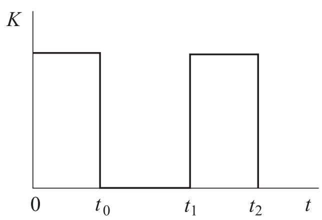

Fig. 5. The wave form of the switch signal.

The detailed working process is as follows: Suppose the waveform of the switch K is as in Fig. 5. When $t = 0$, the switch turns on; at $t = t_0$, the switch turns off, and at $t = t_1$ it turns on again. The on-off cycle $T = t_2 - t_0$, and duty ratio $D = \frac{t_0}{T}$. Assume the resonance between L and C is just one cycle during the switch OFF duration, the inductance L can be estimated by $L = \frac{(1-D)^2 T^2}{(2\pi)^2 C}$.

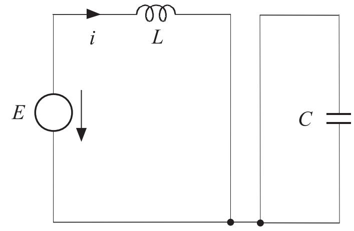

Fig. 6. Equivalent circuit when switch is ON.

Stage I (Switch turns on):

At $t = 0$, the switch turns on, the original circuit can be transformed to Fig. 6. The C is shorted by the switch, and the power and L make-up a loop through the switch. The current i increases linearly: $i = i_0 + \frac{Et}{L}$. When the current is not continuous, $i = \frac{Et}{L}$.

Stage II (Switch turns off):

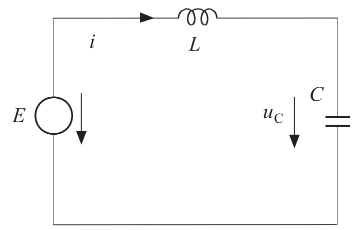

Fig. 7. Equivalent circuit when switch is OFF.

At $t = t_0$, the switch K turns off, L and C constructed resonant circuit, the original circuit can be transformed to Fig. 7. The corresponding state equations are

$$\begin{aligned} C\frac{\mathrm{d}u_c}{\mathrm{d}t} &= i \, , \\ L\frac{\mathrm{d}i}{\mathrm{d}t} &= E - u_c \, . \end{aligned} \tag{1}$$

When the current is discontinuous, the initial conditions of these equations are $i(t_1) = \frac{EDT}{L}$ and $u_c(t_1) = 0$, then the voltage $u_c(t)$ and the current $i(t)$ at the resonant stage can be derived as

$$\begin{aligned} u_c &= E\left[1 - \cos\omega(t-t_0) + DT\omega\sin\omega(t-t_0)\right] , \\ i &= EC\omega\left[\sin\omega(t-t_0) + DT\omega\cos\omega(t-t_0)\right] \end{aligned} \tag{2}$$

where $\omega = \frac{2\pi}{(1-D)T} = \frac{1}{\sqrt{LC}}$ is the resonant angular frequency.

Let $\frac{\mathrm{d}u_c}{\mathrm{d}t} = 0$, then the maximum of u_c is

$$u_c(t)_{\max} = E\big(1 + \sqrt{1 + (DT\omega)^2}\big)\,. \qquad (3)$$

The above analyses are derived on the assumption that the L and C only resonate one cycle at the OFF stage. In fact, we can choose different L so as to let them resonate k ($k = 1,2,3\dots$) cycles at the OFF stage, and the inductance should be decided by

$$L = \frac{(1-D)^2T^2}{(2\pi k)^2C} \qquad (4)$$

and the angular frequency is

$$\omega = \frac{2\pi k}{(1-D)T}\,. \qquad (5)$$

Substitute it into Eqn. (3):

$$u_c(t)_{\max} = E\left(1 + \sqrt{1 + \left(\frac{2\pi kD}{1-D}\right)^2}\right). \qquad (6)$$

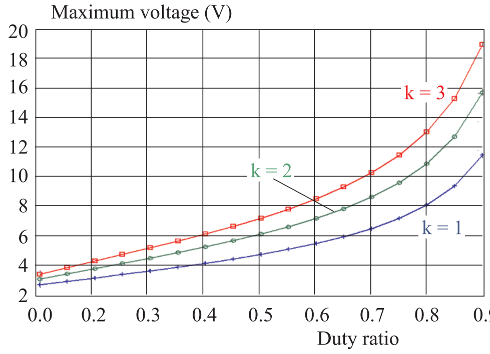

Fig. 8. Maximum voltage under different resonant cycles.

Then we can get the relations between maximum voltage $u_{c\,\max}$ and duty ratio under different resonant cycles k, shown in Fig. 8. It can be seen from this figure that the maximum voltage increases with k under the same duty ratio. Therefore, we should choose high k to get a sufficiently high output voltage. And, at the same k, the $u_{c\,\max}$ increases with the duty ratio.

However, the voltage applied to the motor is not an ideal sine wave, as shown in Fig. 4, which contains abundant harmonic waves. In order to drive the motor efficiently, we should choose a suitable harmonic wave. Therefore, it is necessary to analyze the output voltage using Fourier analyses.

The output voltage can be rewritten as the Fourier series

$$u_c = a_0 + \sum_{k=1}^{\infty}(a_k \cos kt + b_k \sin kt)$$

$$= a_0 + \sum_{k=1}^{\infty} c_k \sin(kt+\beta) = a_0 + \sum_{k=1}^{\infty} f_k(t)\,. \qquad (7)$$

Let $n = \frac{\omega T}{2\pi}$, $m = DT\omega$, $\alpha = (1-D)2\pi$. Then the parameters in Eqn. (7) are:

$$a_k = \frac{1}{\pi}\int_0^{2\pi} u_c \cos kx\mathrm{d}x = \frac{E}{\pi}\Big\{\frac{1}{k}\sin k\alpha - \frac{(n+k)\alpha}{2(n+k)} - \frac{(n-k)\alpha}{2(n-k)} + \frac{m}{2}\Big[\frac{1-\cos(n+k)\alpha}{n+k} + \frac{1-\cos(n-k)\alpha}{n-k}\Big]\Big\},$$

$$b_k = \frac{1}{\pi}\int_0^{2\pi} u_c \sin kx\mathrm{d}x = \frac{E}{\pi}\Big\{\frac{1-\cos k\alpha}{k} + \frac{1-\cos(n+k)\alpha}{2(n+k)} - \frac{1-\cos(n-k)\alpha}{2(n-k)} + \frac{m}{2}\Big[\frac{\sin(n+k)\alpha}{n+k} - \frac{\sin(n-k)\alpha}{n-k}\Big]\Big\},$$

$$c_k = \sqrt{a_k^2 + b_k^2}\,.$$

Therefore, the amplitudes of every harmonic wave under different duty ratio can be derived, shown in Figs. 9 and 10.

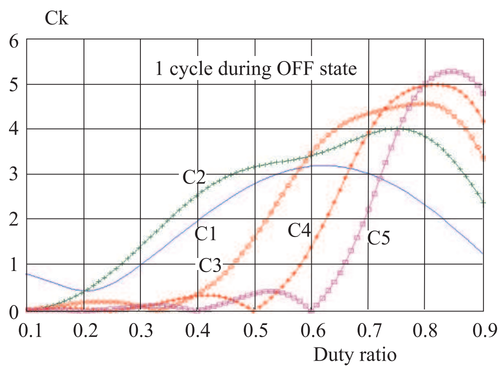

Fig. 9. Relations of amplitudes of harmonic waves with driving duty ratio (1 resonant cycle when switch is OFF

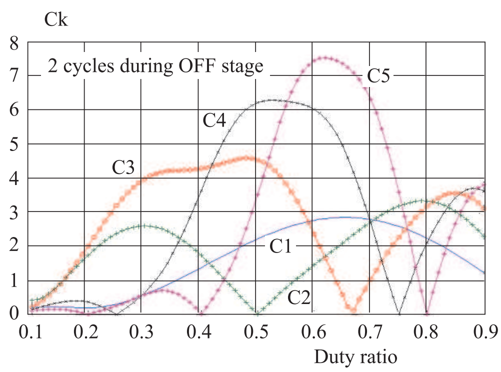

Fig. 10. Relations of amplitudes of harmonic waves with driving duty ratio (2 resonant cycles when switch is OFF).

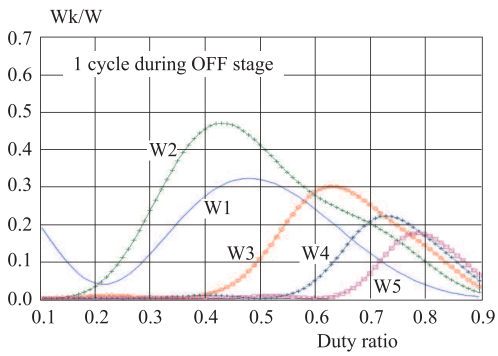

Fig. 11. Relations of energy efficiency of harmonic waves with driving duty ratio (1 resonant cycle when switch is OFF).

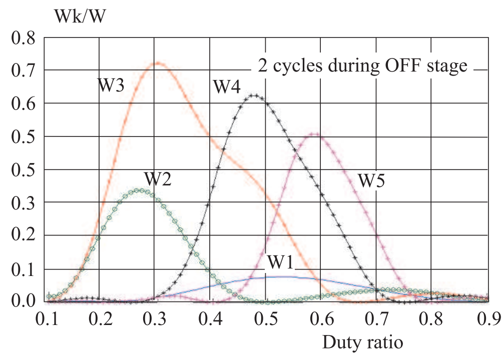

Fig. 12. Relations of energy efficiency of harmonic waves with driving duty ratio (2 resonant cycles when switch is OFF).

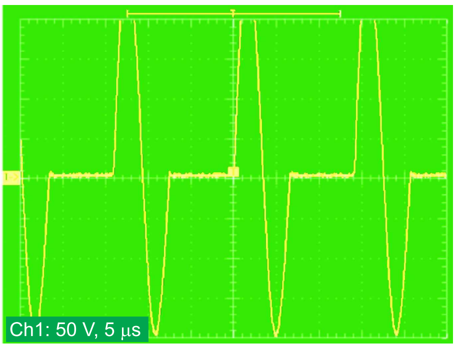

Fig. 13. Actual waveform (1 resonant cycle when switch is OFF).

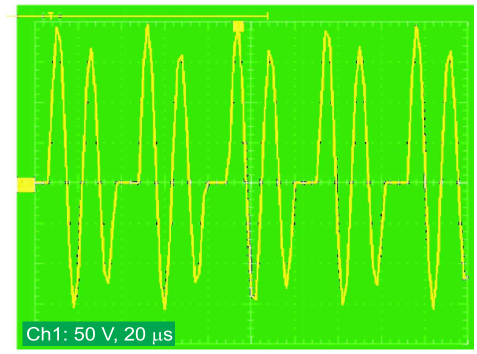

Fig. 14. Actual waveform (2 resonant cycles when switch is OFF).

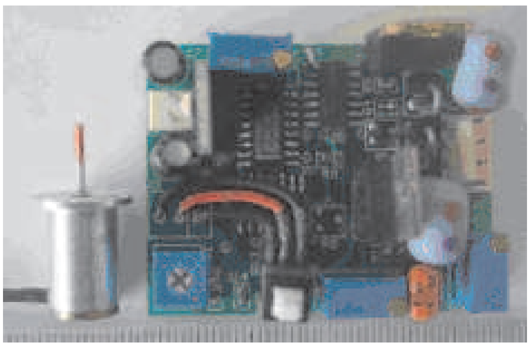

Fig. 15. The driver and the ultrasonic motor.

We can see from the above figures that, with different resonant cycles during OFF stage, the amplitudes of harmonic waves are very different. For choosing suitable circuit parameters, further analysis of the output voltage is required.

Since the components of harmonic waves are very complex, their proportions among the output voltage are very different. However, only the harmonic wave whose frequency equals to the motor's working frequency is active to drive the motor, other harmonic waves are consumed as heat. In order to select an appropriate harmonic wave to drive the motor highly actively, we should know the relations of energy between every harmonic wave and the output voltage.

The energy of the output voltage can be written as

$$W = \int_0^{\alpha} u_c^2 \mathrm{d}x = \int_0^{\alpha} (1 - \cos nx + DT\omega nx)^2 \tag{8}$$

and that of the harmonic wave is

$$W_k = \int_{-\pi}^{\pi} f_k^2(x) \mathrm{d}x = (a_k^2 + b_k^2)\pi \,. \tag{9}$$

Therefore, the energy efficiency R can be defined as

$$R = \frac{W_k}{W} \,.$$

Figures 11 and 12 are the relations between R and D under different resonant cycles.

These figures indicate that when the resonant cycle is 1 during OFF stage, the 2^{nd} harmonic wave with $D = 0.4$ is suitable to drive the motor, for its amplitude and energy efficiency is relatively high. While when $k = 2$, we should choose the 3^{rd} harmonic wave with $D = 0.3$, for its amplitude is relatively high and the energy efficiency is the highest among the harmonic waves.

3 EXPERIMENTAL RESULTS

To verify the rationality of the proposed scheme, an ultrasonic motor with a diameter of 5 mm is used in this study. Its static capacitance is 0.56 nF; driving frequency is about 75 kHz, and the coupling inductance L is selected as 2.7 mH. The whole system and the experimental results are shown in Figs. 13 to 15. The amplitude of the output voltage can reach 200 V (V_{p-p}), the motor works well, which prove this scheme is valid and feasible.

4 CONCLUSION

A new USM non-transformer driver based on LC resonance is proposed in this paper. Choosing different inductance and duty ratio, different harmonic waves can be selected to drive the motor to achieve high energy-efficiency. The proposed scheme has the features of simple construction, high energy-efficiency and easy maintenance, which fulfils the demand of practicability for general engineering.

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Li Huafeng, Associate Professor at Nanjing University of Aeronautics and Astronautics, Nanjing, China. He was born in 1974 and obtained his Bachelor's Degree and Doctor's Degree of Engineering at HUST, June 1997 and June 2002 respectively. His research field is ultrasonic motor and its control system.

Zhao Chunsheng, Professor, University of Aeronautics And Astronautics, Nanjing, China. He was born in 1938. He received the bachelor degree in Aerodynamics from the Nanjing University of Aeronautics and Astronautics, China, in 1961, and the Doctor of Engineering from the "Ecole Nationale Superieure d'Art et Métiers-Paris", France, in 1984. He is a senior member of the Review Committee for the Division of Materials and Engineering of the National Natural Science Foundation of China. He also is the Vice-president of the University Association of Mechanical Engineering Measurement Technologies and the chief editor of the Journal of Vibration, Measurement & Diagnosis. His research interests are in the USM techniques and their applications.