Inverter Design and Electrical Analysis of an Ultrasonic Clutch Module

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Abstract--This paper investigates the electrical characteristics of an ultrasonic clutch module, comprised of two piezoelectric vibrators, a frictional control unit and others. The clutch module interposed between a motor and a load is employed to control the connection or disconnection between the motor and the load. Then, an equivalent circuit of a piezoelectric vibrator is used to derive both steady-state responses induced by a sinusoidal voltage and a voltage transient response determined by the initial conditions. Also, the transient response involves an AC component and a DC component. Meanwhile, both the DC response time and the AC response time are derived according to the derived transient response, and a parallel resistor is used to reduce the DC response time. As anticipated, the transient response can be induced at electrical terminals of the vibrator immediately after an AC voltage applied to the vibrator is switched off. Moreover, a DC-to-AC resonant inverter is constructed to generate sinusoidal voltages existing at the electrical terminals. Furthermore, the relationships between the rotational speed of the driven shaft and the motional current of the vibrator energized electrically are measured and discussed, and the electrical characteristics of the clutch module are also measured and discussed.

KEYWORDS: Ultrasonic clutch module, piezoelectric vibrator, inverter design, electrical analysis, motional current

I. Introduction

Many magnetic clutches have been used to transfer the torque of a driving motor to a driven load. [1] For a magnetic-powder type clutch, a high enough DC current existing in a coil is required to induce strong magnetic links in magnetic powders enclosed by the coil, and to cause the effect of high electromagnetic interference (EMI) on adjacent electronic devices. In order to cancel the effect of EMI, an ultrasonic clutch module mounted between a driving motor and a driven load is used to control the connection or disconnection between the motor and the load, and thus transfer the torque of the motor to the load. This clutch module comprises two piezoelectric vibrators, a frictional control unit and others. Then, the motional current of the vibrator energized electrically is employed to govern the joint or separation of radiation surfaces of the vibrators in the clutch module. This motional current is linearly proportional to the velocity of vibration in the vibrator. [2] Notably, a transient response with high enough voltage is induced immediately after an AC voltage applied to at least one of the vibrators is switched off. Additionally, the motional current has been used to govern the speed of a transportation system driven using near-field acoustic levitation. [3]

Regarding the transient response analysis of a piezoelectric vibrator, a short-circuit current transient response has been induced at electrical terminals of a piezoelectric vibrator immediately after an AC voltage applied to the vibrator is switched off and both electrical terminals were short-circuited. [4] This current transient response contains an only AC component. Also, the equivalent resistance concerning the mechanical loss of the vibrator is calculated using both a decay rate of the current transient response and a force factor of the motional current to the velocity of vibration measured by an expensive Doppler vibrometer. Recently, an open-circuit voltage transient response with high enough voltage, involving a DC component and an AC component, has been induced at electrical terminals of a piezoelectric vibrator immediately after an AC voltage applied to the vibrator under resonance operation is switched off. [5] This high-voltage transient response is employed to cause an electric shock for users of the vibrators and a great damage for associated electronic instruments.

II. Description of Ultrasonic Clutch Module

From Fig. 1, an ultrasonic clutch module comprises two piezoelectric vibrators, a frictional control unit, a carbon brush unit, and others. For both vibrators, one is used as a driving frictional member connected to a driving motor via a connector, and the other is as a driven frictional member connected to a driven load via another connector. Also, each of the vibrators is implemented using a bolt-clamped Langevin transducer (INCREASE-MORE, BLT-45282H), and comprised of two adjoining piezoelectric ceramic elements, two non-
adjoining cylindrical aluminum-alloy blocks and a bolt. Meanwhile, both aluminum-alloy blocks are mutually engaged using the bolt. The frictional control unit includes a ring-wave type steel spring and a frictional control regulator applied to govern the frictional force between radiation surfaces of the vibrators. The carbon brush unit comprises four carbon brushes, four springs, four screws, and others. Thus, the AC electrical power is applied to the vibrators through the carbon brush unit.

Next, according to Fig. 2, the clutch module interposed between a driving motor and a driven load. The motor is implemented using a DC servo motor (SANYO DENKI, U508T-012WL8), and the load is implemented using a magnetic clutch (OGURA (SANYO DENKI, U508T-012WL8)), and the load is implemented using a relay circuit depicted in Fig. 4. This relay circuit includes a DC relay (DC12V, JZC-6F, 4098) and a MOSFET device (IRF840), respectively. Additionally, an equivalent circuit of an oscilloscope (YOKOGAWA, DL1520) and a resistor module (AMERICAN RELIANCE, FG-506). In an operation of the chopper, a sinusoidal voltage, $v_1$, occurs at the output side of the chopper, and a square voltage, $v_{sw}$, occurs at the output side of the tank or the input side of the vibrator. Meanwhile, amplitudes of both $v_{sw}$ and $v_1$ are controlled by a DC power supply (AMERICAN RELIANCE, LPS-305), and frequencies of them are determined by a function generator (AMERICAN RELIANCE, FG-506). In an operation of the chopper, according to Fig. 4, $v_{sw} = v_1$, if $S_1$ and $S_4$ are ON.

and $S_2$ and $S_3$ are OFF; $v_{sw} = -V_x$, if $S_1$ and $S_4$ are OFF, and $S_2$ and $S_3$ are ON. The switches, $S_1$ through $S_4$, are implemented using MOSFET devices (IRF840), and driven by rectangular voltages, $v_{gw}$, through $v_{gw+}$, with an on-duty cycle of 50%. Finally, a control switch, $SW_1$ or $SW_2$, displayed in Fig. 2 is implemented using a relay circuit depicted in Fig. 4. This relay circuit includes a DC relay (DC12V, IZC-6F; 4098) and a MOSFET device (IRF840), $S_{sw}$, driven by a rectangular voltage, $v_{sw}$. If $v_{sw} = 0V$, then $S_{sw}$ is OFF and $SW_1$ (or $SW_2$) is OFF. If $v_{sw} = 12V$, then $S_{sw}$ is ON and $SW_1$ (or $SW_2$) is ON. Thereby, the switch, such as $SW_1$ or $SW_2$, is electrically controlled using the voltage, $v_{sw}$.

**IV. Electrical Analysis**

### 4.1 Description of equivalent circuit

An equivalent circuit of the vibrator shown in Fig. 5 is expressed as follows: $R_e$, $L_e$ and $C_e$ represent the equivalent resistance, the equivalent inductance and the equivalent capacitance, respectively; $R_f$ and $C_f$ represent the dielectric resistance and the damped capacitance, respectively. Additionally, an equivalent circuit of an oscilloscope (YOKOGAWA, DL1520) with its associated probe, including $R_{scope}$ and $C_{scope}$, is considered to exactly derive electrical responses of the vibrator. Here, $R_{scope}$ and $C_{scope}$ represent the parallel resistance and parallel capacitance, respectively. The oscilloscope and its associated probe are used to measure electrical responses of the clutch module. Next,
using an impedance analyzer (HP4194A), one obtains following parameters of the equivalent circuits:

\[ R_m \approx 102.2 \Omega, \quad L_m \approx 157.2 \, \text{mH}, \quad C_m \approx 0.1877 \, \text{nF}, \quad C_{sv} \approx 3.475 \, \text{nF}, \quad f_s \approx 29.30 \, \text{kHz} \quad \text{and} \quad f_v \approx 30.08 \, \text{kHz} \]

for the vibrator; \[ \approx 12.7 \, \text{M} \Omega \quad \text{and} \quad \approx 3.8 \, \text{pF} \]

for the oscilloscope.

4.2 Derivation of steady-state responses

In Fig. 6, an AC voltage, \( v_s \), is given by

\[ v_s = V_v \sin \omega_f t \]  

(1)

where \( \omega_f = 2nf_s \), and \( f_s \) is a switching frequency of the chopper depicted in Figs. 3 or 4. Then, a motional current, \( i_m \), through \( mL \) is

\[ i_m = I_m(\omega_f) \sin(\omega_f t - \theta_m(\omega_f)) \]  

(2)

where

\[ I_m(\omega_f) = \frac{V_v}{\sqrt{R_m^2 + (\omega_f L_m - 1/\omega_f C_m)^2}}. \]

A capacitor voltage, \( v_{cm} \), across \( mC \) is

\[ v_{cm}(\omega_f) = V_c \sin(\omega_f t - \theta_m(\omega_f) - \pi/2) \]  

(3)

where

\[ v_{cm}(\omega_f) = \frac{V_c}{\omega_f C_m \sqrt{R_m^2 + (\omega_f L_m - 1/\omega_f C_m)^2}}. \]

And, a terminal current, \( i_t \), is

\[ i_t = I_t(\omega_f) \sin(\omega_f t - \theta_t(\omega_f)) \]  

(4)

where

\[ I_t(\omega_f) = \frac{V_v}{\sqrt{R_t^2 + (1/\omega_f C_m)/(R_t + 1)(\omega_f L_m - 1/\omega_f C_m)}}. \]

At resonance, i.e., \( \omega_r = \omega_o = 1/\sqrt{L_mC_m} \), \( i_t \approx i_m \), determined by Eqs. (2) and (4), and waveforms of derived steady-state responses, including \( v_s \), \( i_m \) and \( v_{cm} \), are shown in Fig. 7. Notably, the terminal current is used as the motional current at resonance.

4.3 Derivation of transient response

From Fig. 6, a transient response, \( v_{oc} \), is induced by the initial conditions, such as \( V_{ov}, \quad V_{om} \quad \text{and} \quad I_c \). Also, according to K.-T. Chang et al. [5], an equation for the transient response, \( v_{oc} \), is

\[ v_{oc} \equiv A e^{-t\tau_{oc}} + B e^{-t\tau_{oc}} \cos(\beta t - \delta) \]  

(5)

where

\[ \tau_{oc} = R_s C_v ; \quad \tau_{ac} = 2L_m / R_m ; \]

\[ A \equiv V_{ov} + (C_m / C_v)(\alpha_d - \alpha_w) L_m I_o + V_{cm} ; \quad B = \sqrt{C^2 + D^2} ; \]

\[ \delta = \arctan(D / C) ; \quad C = -(C_v / C_m) \alpha_d L_m I_o + V_{cm} ; \]

\[ D \equiv [C_m (\alpha_d - \alpha_w) V_{cm} - I_o] \beta C_v ; \]

\[ \beta \equiv 1/\sqrt{L_mC_v (C_m + C_v)}. \]

Here, \( R_s = R_s || R_p || R_{scope} \), \( C_v = C_{scope} + C_d \). The derived transient response, \( v_{oc} \), is plotted in Fig. 8. Using Eq. (5), the DC term, \( A e^{-t\tau_{oc}} \), approaches zero at \( t = t_{dc} = 5\tau_{oc} \), where \( \tau_{dc} \) and \( \tau_{oc} \) represent the DC time constant and the DC response time, respectively. Similarly, the AC term, \( B e^{-t\tau_{oc}} \cos(\beta t - \delta) \), approaches zero at \( t = t_{ac} = 5\tau_{ac} \), where \( \tau_{ac} \) and \( \tau_{ac} \) represent the AC time constant and the AC response time, respectively. Meanwhile, amplitude of the DC term is about 0.368A at \( t = t_{dc} \), and amplitude of the AC term is about 0.368B at \( t = t_{ac} \). Also, a parallel resistance, \( R_p \), is adopted to reduce both the DC time constant and the DC response time.
VI. Conclusions

When at least one of the vibrators in the clutch module is energized electrically at resonance, the rotational speed of the driven shaft decreases as the motional current of the energized vibrator increases. Then, the motional current increases and the resonant frequency decreases as the driving voltage increases. Moreover, a high-voltage transient response is induced at both electrical terminals of the vibrator immediately after an AC voltage applied to the vibrator is switched off. Also, the AC response time decreases as the motional current increases, and both the DC response time and the DC response time decrease as the parallel resistance decreases.

References: