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Low-Frequency Pulse Width Modulation Control Methods of Ultrasonic Motor

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Abstract

Because of the serious non-linearity and coupling among state variables caused by the complex energy conversion process in ultrasonic motor, the motion control strategy of ultrasonic motor still need to be studied in detail to obtain better performance. As a kind of special control method, the low-frequency PWM control strategy can make the on-line optimum control easier, and may be an effective means to realize high performance motion control using ultrasonic motor. But this kind of strategy has not been studied in detail until now. This paper analyzes the difference among three low-frequency PWM control methods in details, works out the principle of selection among these methods.

Keywords: *ultrasonic motor, speed control, low-frequency PWM*

1. Introduction

As the operation mechanism of ultrasonic motor (USM) is different from the traditional electromagnetic motors, USM has the energy conversion from electric to mechanical by converse piezoelectric effect of piezoelectric materials. And the mechanical power output is obtained from friction effect between stator and rotor, which convert stator's micro-vibration into rotor's macro-motion in one direction. Because of the serious non-linearity and coupling among state variables caused by the complex energy conversion process in ultrasonic motor, the reasonable and effectual motion control strategy of USM has become a hot research topic in recent years. Almost every control strategy used in electromagnetic motor, including adaptive control, neural network and fuzzy control, have been used in USM as a lot of efforts have been made [1, 2]. But because of the complexity of USM's operation mechanism and the backwardness of its mathematical model, the potentiality of motion control has not been exerted fully, and it still needs to be studied in detail. At present, with the research development of USM's structure and operation mechanism [3-5], the understanding of USM is improved gradually, which provides the basis for the research of motion control strategy.

Due to the specific characteristics of USM's operation mechanism, the design of control strategies should be fit for the USM's non-linearity, with part of it used in electromagnetic motor as reference [1, 2, 4, 5]. Because of the serious time-varying non-linearity of USM, it is observed that the self-adaptive (self-studied) control strategy is reasonable [1, 2]. With the development, the trend of USM's motion control strategy has been changed. It means the full use of control degrees of freedom and the optimum control of performance. Based on optimization objective (as efficiency optimization) and constraint conditions, the USM's online control process is the dynamic selection of optimal working point and routing in control space composed by three different control inputs, namely, voltage amplitude, driving frequency and phase difference. Because of coupling among state variables and the time-varying characteristics, the self-adaptive control process is complication. Meanwhile, considering the requirements of speed and position, the on-line control is more complex. Because of this, the control strategy is simplified in general, that is using single variable or two variables.

As a kind of novel control method, the low-frequency PWM control strategy [6-8] controls speed by input voltage's ON/OFF and switching, rather than by the change of voltage amplitude, driving frequency and phase difference. Therefore, this method can separate speed control from dynamic optimization, as can make the on-line optimum control easier and may be

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an effective means to realize high performance motion control using USM.

Three kinds of low-frequency PWM control strategies [6-8] have received much attention in recent years. However, up to now, there is no study on detail, as to say which one is suitable, and the control performance is unclear. This paper analyzes the principle of low-frequency PWM control, and the experiments have been made by 2-Phase traveling wave USM driving circuit based on DSP and CPLD. And it is also analyzes the difference among three low-frequency PWM control methods in details, works out the principle of selection among these methods, which is helpful to studies and applications.

2. Three Low-Frequency PWM Control Strategies

As there are many kinds of USM, 2-phase traveling wave USM is the main type in applications. Its input-voltage is 2-phase high-frequency (20-100kHz) and high-voltage (peak-peak value is 100-1000V generally) for driving. As the essence of this method, there is a modulation process of driving voltage using lower frequency PWM, to make the input voltage in the control of ON/OFF or switching. The basic low-frequency PWM is ON/OFF PWM [6], which makes driving voltage on or off, as shown in Figure 1. As driving voltage is effective, USM has the energy conversion from electric to mechanical. As driving voltage is ineffective, USM is still rotating depending on its rotor's mechanism inertia and piezoelectric ceramic's piezoelectric inertia. The speed can be controlled by adjusting the pulse width.

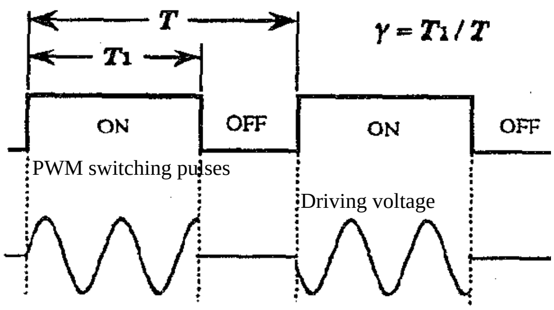

Figure 1. ON/OFF PWM Control Method [6]

The secondary low-frequency control method, namely Forward/Backward (F/B) PWM [7] is shown in Figure 2. The output voltage drives USM rotating in positive while low-frequency PWM control signal turn to high level. Compared with it, output voltage drives USM rotating in negative, as control signal turn to low level. Obviously, the speed can be changed by adjusting the width of control pulses. If the pulse width is 50%, the speed will be zero.

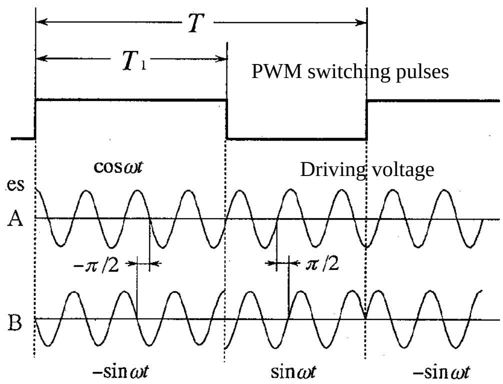

Figure 2. Forward/Backward PWM Control Method [7]

Figure 3 is the third low-frequency PWM control method, which is the combination of the first and the secondary method, as mentioned before. It contains forward, backward and zero voltage in four time stages. As the time of zero voltage is fixed, the speed can be changed by adjusting the working time of forward and backward voltage. This method is called as Forward/Backward/Stop (F/B/S) PWM control method [8].

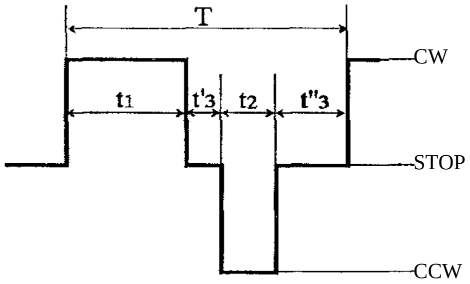

Figure 3. Forward/Backward/Stop PWM Control Method [8]

3. The Realization Methods of Three Low-Frequency PWM Control Strategies

This section gives three low-frequency PWM control strategy implement methods, which combined DSP and CPLD, and validated by experiment.

Low-frequency PWM control have different control modes. Among them, ON/OFF PWM control is the most basic low-frequency PWM control strategy, which makes the driving voltage onoff. By changing the relationship of the driving voltage's phase of the motor input to achieve the low-frequency PWM control of the motor reversing, which is called Forward/Backward PWM control strategy. It is called Forward/Backward/Stop (F/B/S) PWM control strategy, which is the combination of the above two methods. All of the three low-frequency PWM control strategies [6-8] can achieve the control of speed by adjusting the duty cycle of the PWM control signal.

Low frequency is relative to the motor input high frequency driving voltage character. Low frequency PWM control use the PWM signal whose frequency is lower than the frequency of the driving voltage,and input it into the motor to control the motor turn on and off or switch control, so low-frequency PWM control need give adjustable high-frequency and low-frequency PWM control signal at the same time.

3.1. Experimental Device

The experimental device is drive controller which is based on DSP for traveling wave ultrasonic motor, the USM use Shinsei USR30 motor, its resonant frequency is 49kHz. Motor control dedicated DSP56F801 as the master chip of control circuit to adjust the duty cycle of the PWM signal (AM) and phase difference. CPLD EPM7256A, as a symmetrical PWM signal generator [2], it generate four signals whose frequency, amplitude and phase difference can be adjusted. With SPI port the LTC6903 used to control the frequency of the PWM signal. Driver circuit adopts two-phase push-pull configuration and ues the DC12V as power supply, the basic structure shown in Figure 4.

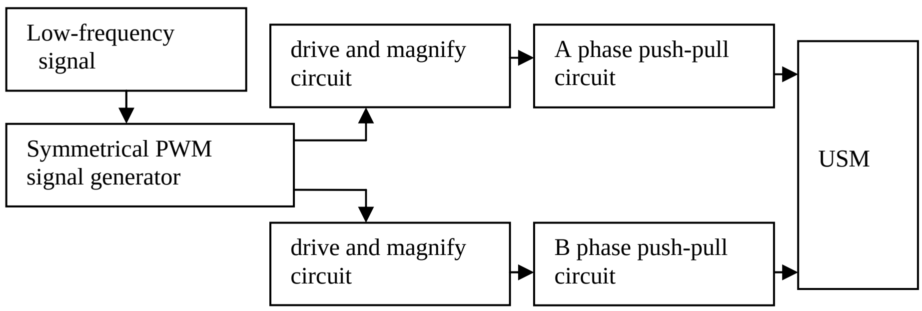

Figure 4. Push-pull driving-circuit

Low-frequency PWM control signal generated by the built-in dedicated PWM module of DSP56801, by controlling the CPLD output symmetric high frequency PWM signal to control the motor input voltage’s ON/OFF or switch control, which effectively control the motor’s speed.

3.2. The Generation of High-Frequency PWM Signals

For two-phase traveling wave ultrasonic motor, you need to input four symmetrical PWM signals whose frequency, amplitude and phase difference can be adjusted, these PWM signals based on the CPLD to implement, and the specific design as shown in Figure 5.

Wherein the comparative value N-bit and the offset N+1-bit by the DSP multi-SPI port communication which based on CPLD, to adjust the duty cycle of the input signal and the phase difference by setting the duty cycle of the word and the phase of word, while using LTC6903 with SPI ports control the frequency of the PWM signal, its design as shown in Figure 6.

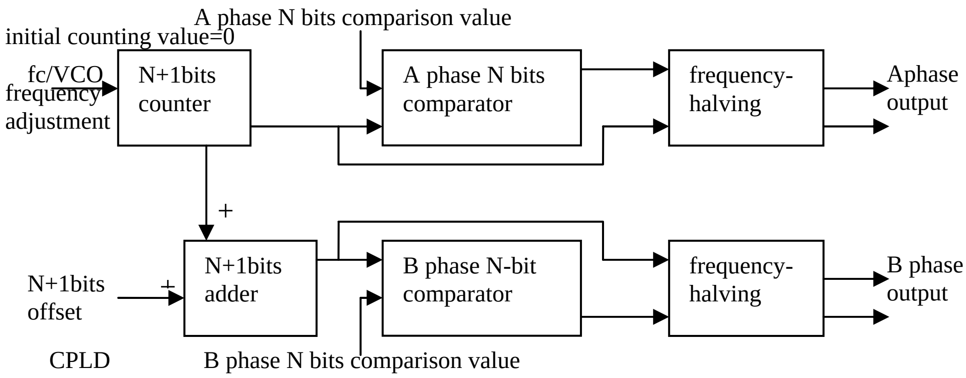

Figure 5. Symmetry PWM Signal Generator

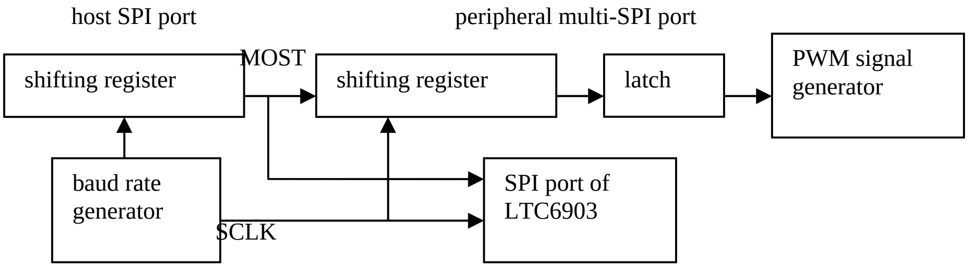

Figure 6. The Design of Multi-SPI Communication

3.3. The Generation of Low-Frequency PWM Signals

DSP internal with pulse-width modulation module PWM, can output PWM wave by setting corresponding register. Low-frequency PWM pulse width of the control signal is determined through the count value register (PWMVAL), the cycle is set through the counting mode register (PWMCM), duty cycle is determined by the two jointly.

The implement of low-frequency PWM based on DSP56801 hardware platforms: When the chip’s maximum operating frequency is 60MHz and the division factor is 1, the value of counting mode register is 3A98 in central alignment way, the output frequency of PWM wave is 1KHz, so we can change the frequency of the PWM wave by adjusting counting mode register value (also we can adjust the output frequency of the PWM wave by adjusting the division coefficient). When the values of counting mode register are fixed, the frequency of PWM is proportional to the prescale factor; on the contrary, when the value of prescale factor is fixed, the frequency of PWM is inversely proportional to the value of counting mode. When the frequency of the PWM wave is fixed, the relationship between the value of the duty cycle and the value of counting value register is linear, regardless of the alignment and prescale factor. If the counting value register is a fixed value whose duty cycle is inversely proportional to the value of counting mode registers, in the frequency 1kHz, when the counting value register's value is 2A80, the duty cycle of the output PWM wave is 80%, when the counting value register value is 1D4C, its the duty cycle of the output PWM wave is 50%.

Since the frequency of the PWM signal is lower than the frequency of the driving voltage, it is called low-frequency PWM, which is used to control the motor input a high-frequency voltage's ON/OFF or switch.

3.3.1. The Realization of ON/OFF PWM Control

ON/OFF PWM control means on the basis of the motor is forward, on the output terminal of CPLD introduce a PWM enable signal A- gain control of it, and the enable signal is a low-frequency PWM signal of the DSP's output. When the A- is a high level, the CPLD output normal signal, in the A- is low CPLD does not output any signal, in order to meet to achieve the control function on the motor input voltage intermittent during one low-frequency PWM cycle. The concrete realization of the design is shown in Figure 7.

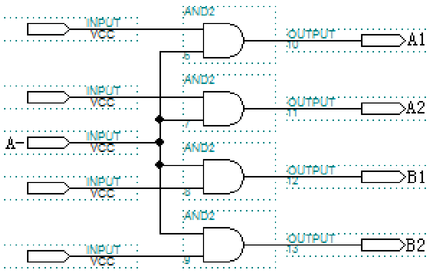

Figure 7. The Design of ON/OFF PWM Control Method

3.3.2. The Realization of Forward/Backward (F/B) PWM Control

To achieve the F/B function of the motor on the basis of the motor is forward, we can keep A, B two phases of one's output signal is normal in a low-frequency PWM control period, it is assumed to be the A phase signal, only control the B-phase signal to change the A, B two phases lead or lag relationship. During the enable signal A- of low-frequency PWM is high level, B phase output normal signal, while enable signal A- is low level, B phase output inverted PWM signal which is opposite to the forward signal, namely the two signals of B phase complementary switching output the high and low level. In this way, it is able to meet the motor's F/B switching function during one low-frequency PWM control cycle, during one high level the signal of B phase ahead of the A-phase 90°, the motor forward, during the low period phase B lag phase A 90°, the motor runs in reverse. The specific design is shown in Figure 8.

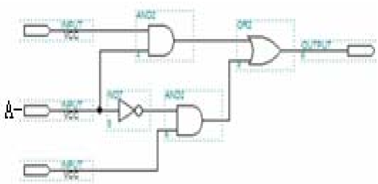

Figure 8. The Signal of Phase B Design to Realize Motor Reverse

3.3.3. The realization of Forward/Backward/Stop (F/B/S) PWM Control

F/B/S PWM control is based on F/B PWM, on the signal output terminal of CPLD reintroduce a PWM enable signal to control it. The enable signal is controlled by the low-frequency PWM signal A, B- of DSP's output, when A same as B- phase, CPLD output the original F/B PWM signal, when A and B- dissimilarity CPLD does not output any signal, the motor does not run, namely through A not exclusive or B- to achieve motor's F/B/S control function during one Low frequency PWM signal cycle. At the same time, set the duty cycle of the enable signal A- of phase B in F/B control between the A and B-duty. The duty cycle of A determines the signal duration of the motor's forward, and the duty cycle of B- determines the signal duration of the motor's backward, the high level action time of B- and the motor backward time is the sum of a low-frequency PWM control cycle. F/B/S based on F/B PWM control design is shown in Figure 9:

3.4. The Analysis of Experimental Results

Figure 10 shows A, B two-phase output voltage waveform of the control circuit CPLD during one cycle and the measured waveform of the motor's input drive voltage, in the three kinds of low-frequency PWM control mode, the frequency of low--frequency PWM was 1 kHz. Figure (a), Figure (b), respectively are the ON/OFF PWM control and the F/B PWM control under the duty cycle is 80%, Figure(c) is F/B/S PWM control in which forward duty cycle is 60%, stop duty cycle is 20%, in order to facilitate comparison study, Figure(d) corresponding to the ON/OFF PWM control of duty cycle is 100%, i.e. one high-frequency PWM waveform which do not use low-frequency PWM control.

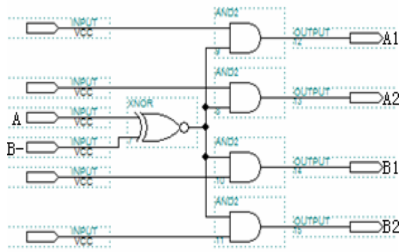

Figure 9. The Design of Forward/Backward/Stop PWM Control Method

Analysis shows the experimental results from Figure 10, when there isn't low-frequency PWM signal, both A and B two-phase output continuous voltage waveform and satisfies the forward condition, corresponding to the motor's input voltage is also continuous. After join the low-frequency PWM control signal of the DSP's output, during one low-frequency PWM cycle, the control terminal the CPLD output signal and the waveform of the motor input terminal appear intermittently or switch.

This section uses a combination of DSP and CPLD design method, making three low-frequency PWM control strategy implement methods on the basis of reasonable division of hardware and software. The experimental results show that the method is simple to realize.

4. Three Low-Frequency PWM Control Strategies Compare

Based on DSP and CPLD, the experiments have been made by 2-Phase traveling wave USM driving circuit. The type of USM used in the test is Shinsei USR30, that is 2-Phase traveling wave USM, and its resonant frequency is 49kHz. The main control chip in control circuit is DSP56F801, as it is the special chip for control. With DC 12V power supply, 2-phase push-pull convertor is used in driving circuit.

4.1. Contrast of USM Stator Traveling Wave Vibration Status

In the test, the surface of stator sticks on piezoelectric ceramic in which single-pole can be used to provide feedback voltage, as the reflection of traveling wave vibration on stator's surface. As the result of energy conversion from electric to mechanical, the traveling wave vibration on stator's surface, which is the reflection of USM's running state, is the driving power for rotating.

Figure 11-Figure 13 show the tested waveforms of PWM control signal with three low-frequency PWM control strategies. As in Figure 11-Figure 13, the top waveform is PWM control signal, and the middle is driving voltage, compared with the bottom is single-pole feedback voltage. In the test, the frequency of every low-frequency PWM control strategy is 1kHz. Figure 11 is the pulse width with 80% using ON/OFF PWM. Figure 12 is the pulse width with 80%

using F/B PWM. Figure 13 is the pulse width with 60% in forward and 20% in backward using F/B/S PWM.

As shown in Figure 11-Figure 13, based on the control of low-frequency PWM, the vibration of traveling wave can be changed by adjusting driving voltage, resulting in the change of speed and torque. However, the traveling wave vibration is not accomplished at the moment of the driving voltage changed, as a process changing in inertial. As the traveling wave vibration's transient changes in periodic, the frictional contact state between stator and rotor, resulting in the influence of energy conversion and torque ripple, is different from it in steady state. With different frequency and width of control signal, the contact stat between stator and rotor may always be different. The speed and efficiency of energy conversion will also be changed. Therefore, changing the frequency and width of PWM control signal can be seen as a method to control speed. Furthermore, this inertial change process shows as the electric field established frequently in electrical characteristics by capacitive piezoelectric materials, so that the reactive power between driving circuit and USM is large.

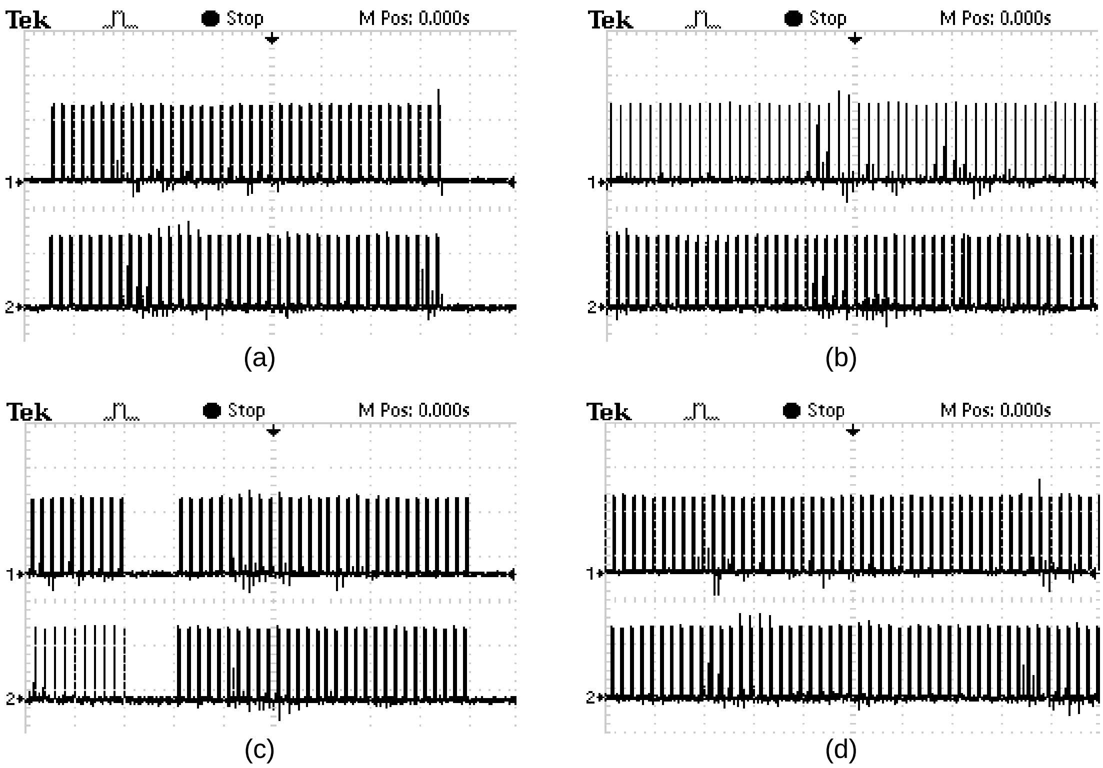

Figure 10. Waveform of Output-voltage of Control Circuit

As the change of traveling wave vibration is an inertial process, in condition of the driving voltage's ON/OFF (or switching)time interval shortened, that is increasing the frequency of low-frequency PWM, vibration amplitude of traveling wave should be able to decrease until the change is unobvious. Therefore, the time constant of inertial process can provide the basis for choosing the PWM frequency. According to the envelope shape of single-pole feedback voltage shown in Figure 11, it is obtained that the time constant of this inertia link is about 0.2ms.

Figure 14 shows the tested waveform of ON/OFF PWM frequency with 20kHz. Using ON/OFF PWM, the voltage value of single-pole feedback maintains constant in general, and this value (means traveling-wave amplitude on the stator surface) is increased by the width increasing of ON/OFF PWM, as shown in Figure 15.

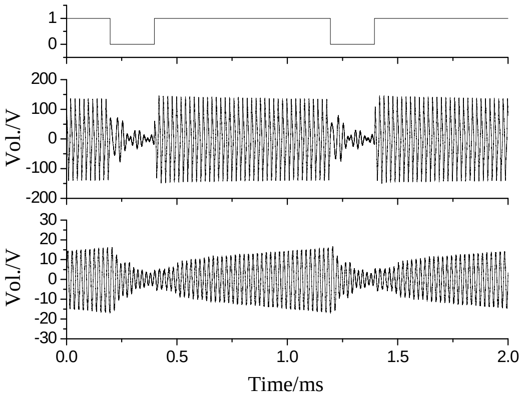

Figure 11. Waveform of Single-Pole Feedback

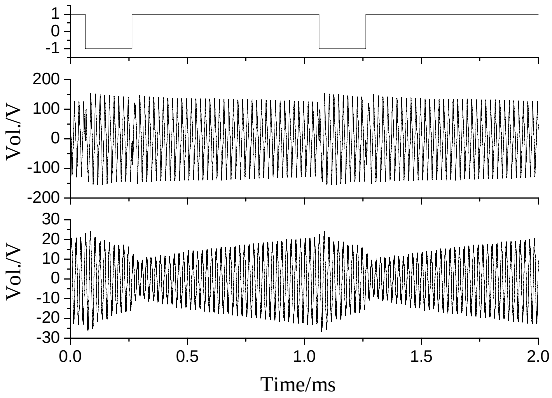

Figure 12. Waveform of Single-Pole Feedback

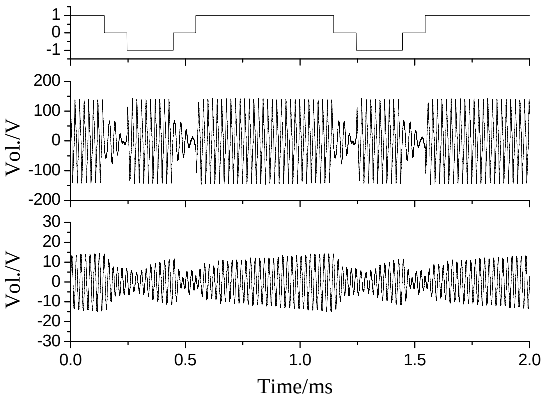

Figure 13. Waveform of Single-Pole Feedback

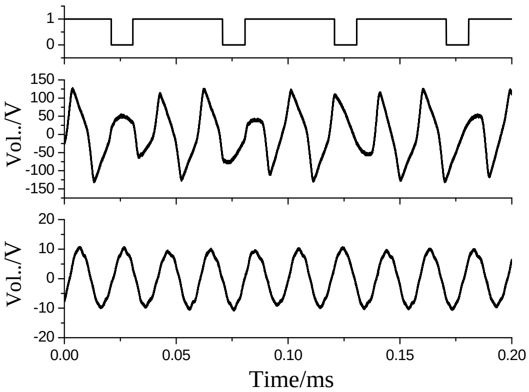

Figure 14. Waveform of single-pole feedback

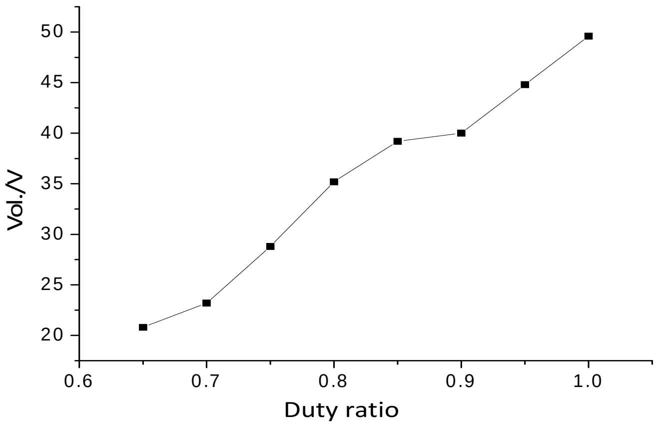

Figure 15. Amplitude Control Characteristic of Single-Pole Feedback

It should be noted that Figure 14-Figure 15 show the waveforms of steady state. With changing the width of PWM control pulse, the traveling wave vibration has the same dynamic inertial process as mentioned before. Therefore, the increasing of PWM control signal frequency is not always means the increasing of control response speed (bandwidth).

4.2. Contrast of USM Speed Control Characteristic

As the low-frequency PWM control strategy is used in speed closed-loop control, adjusting the width of PWM control pulse can be sued to control speed. To design speed controller, it should be known that the relationship between the PWM width and speed is linearity or non-linearity. If the relationship is non-linearity, the style of non-linearity also should be indicated.

Figure 16 is the speed control characteristic of ON/OFF PWM with different frequencies. As the characteristic curves are non-linearity shown in Figure 16, the linearity is the best with 0.8 kHz, which is helpful to the design of speed controller. While the frequency decreases to 0.6 kHz or increases, the linearity goes to bad. With 1-1.5 kHz, the change of characteristic curve is not obvious. With 2 kHz, speed changes slowly before the pulse width reaching 0.85, compared with the leap, which goes against the improvement of dynamic speed control performance as reaching 0.85. As frequency is 20 kHz and width is 0.65, the speed is almost to zero, and the adjusting range of pulse width is decreased obviously.

The speed control characteristic of F/B and F/B/S (the width of stop is 20%) PWM are shown in Figure 17 The common feature is characteristic asymmetry between forward and backward, the same as the open-loop speed control. The control linearity is the best nearby zero-speed (the width is 50%) using F/B PWM. With the width increasing, the speed change rate increases gradually, the same as using ON/OFF PWM. The change of speed control characteristic curve's linearity using F/B/S PWM, is similar to F/B PWM. But, with the same pulse width, the speed is lower than using F/B PWM and ON/OFF PWM, and the adjusting range of speed is also smaller.

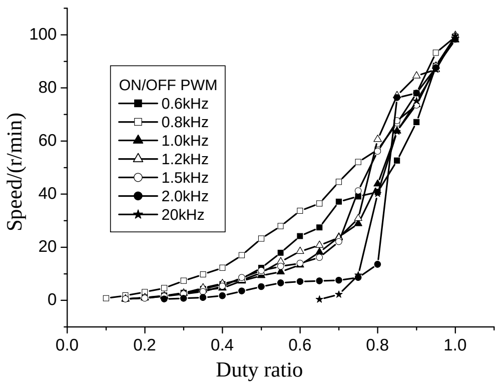

Figure 16. Speed Control Characteristic of ON/OFF PWM Method

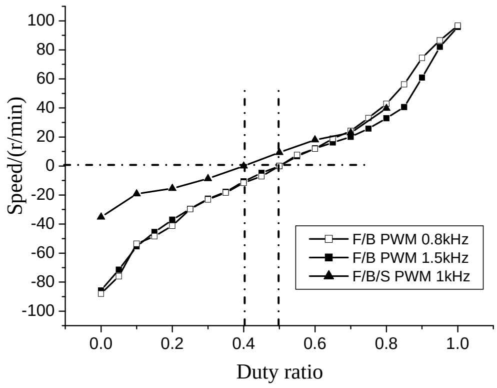

Figure 17. Speed Control Characteristic of F/B and F/B/S PWM Methods

As shown in Figure 16-Figure 17, it is observed that there is a controlling dead zone while the pulse width is nearby 10% using ON/OFF PWM, that is the speed has been decreased to zero nearby 10%. Compared with the others, there is not controlling dead zone around zero-speed (the width is 50% and 40% respectively), which is easier to achieve smooth transition of forward and backward. Because of pre-tightening force, it is well known that USM holding torque is large. Therefore, USM will not rotating until the torque increasing to a certain value, that is the reason of controlling dead zone using ON/OFF PWM. The purpose of forward F/B PWM control method is to improve the starting performance of USM. While the width of control pulse is 50% using F/B PWM, the speed is zero, however, the forward and backward torque is alternately effective in rotor in every low-frequency PWM control period. It means a sliding frication status between stator and rotor. In theory, it can maintain holding torque is zero, as USM is easier to start from zero-speed. As the improvement of F/B PWM, F/B/S PWM can make the required holding torque by adjusting the ratio of stop time, in order to adapt different applications. USM's holding torque is zero while the ratio of stop time is zero, and the holding torque is increased with the increasing of stop time ratio.

As mentioned in 4.1, using F/B PWM and F/B/S PWM, the amplitude change of traveling wave is not obviously by adjusting frequency. Because the traveling wave maintains the driving mode (forward or backward) in every low-frequency PWM control period, there is the only one (as forward or backward torque) effective in rotator. And then, the function of adjusting holding torque is lost. To make the full use of it, it is obtained that the frequency should be low. And it is clear that the frequency should be lower than 2 kHz, as shown in the test.

4.3. Contrast of USM Input Power Characteristic

Though USM have many advantages, for the motion control of USM, the efficiency of energy conversion from electric to mechanical is obviously lower than that of traditional electromagnetic motor. With the development of USM driving control and applications, low efficiency has become one of main problems restricting USM applications. Thus, solving the problem of low efficiency has become a research topic, as control strategy is one of the important aspects.

With the same output mechanical power, the energy conversion efficiency of USM is lower, during the input power is more. Compared with the others, F/B PWM consists of forward and backward driving voltage, as there must be one of these opposite the direction of rotator. That is to say, the input power is more and the efficiency is lower. F/B/S PWM is the combination of ON/OFF PWM and F/B PWM, and its efficiency should be in the middle of them.

Figure 18 to Figure 20 show the input active power characteristics of three low-frequency PWM methods. To make clear, they also show the open-loop input active power characteristics, that is not using low-frequency PWM, as marked “normal” in Figs. As shown in Figure 18, the input active power of ON/OFF PWM is lower than that of nonuse low-frequency PWM. With PWM frequency increased, the input active power increases gradually in lower speed and higher speed, as decreasing in middle speed. As in Figure 19, the input active power of F/B PWM is higher than that of nonuse low-frequency PWM, and the input active power decreases along with the increasing of PWM frequency.

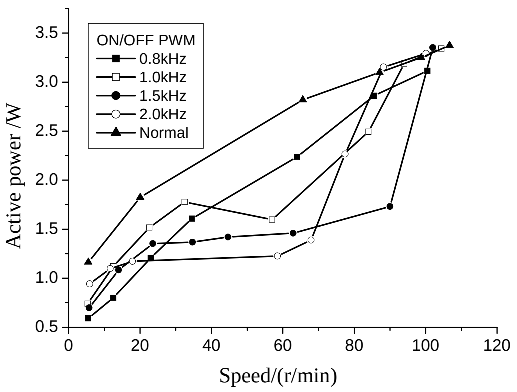

Figure 18. Input Active Power Characteristic of ON/OFF PWM Method

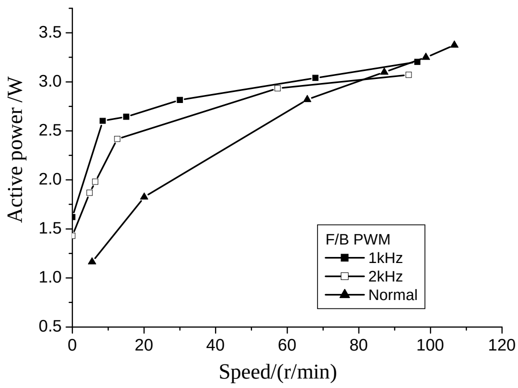

Figure 19. Input Active Power Characteristic of F/B PWM Method

Figure 20 is the input active power characteristics of three low-frequency PWM methods. Obviously, that the power of F/B PWM is the most, compared with that of ON/OFF PWM is the least. Because F/B/S PWM is the combination of ON/OFF PWM and F/B PWM, its power characteristic is in the middle of them.

5. Conclusion

According to the requirement of high performance motion control using 2-phase traveling wave USM, this paper analyzes the difference among three low-frequency PWM control methods in detail. Some conclusions have been worked out:

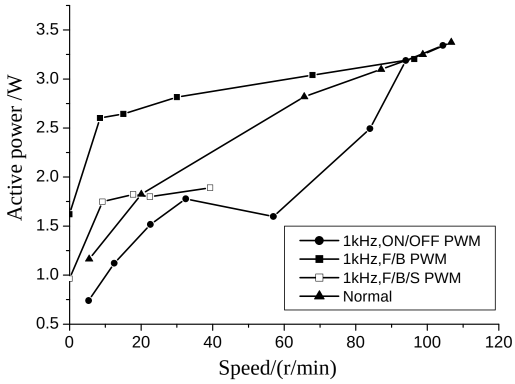

Figure 20. Comparison of Input Active Power Characteristics

1) Low-frequency PWM control strategy can make the speed control easy and effective, without adjusting voltage amplitude, driving frequency and phase difference.

2) As the comparison of three low-frequency PWM control strategies, the comprehensive performance of ON/OFF PWM is the best. F/B PWM or F/B/S PWM can be used to start USM smooth with zero-speed, or to control holding torque.

3) As the important parameter of low-frequency PWM control strategies, the frequency can be increased to enhance the stationarity of traveling wave vibration in the stator surface, and also can improve the response speed of closed-loop control. But with the frequency increasing to a certain extent, there is a leap in the speed control characteristic, that is the restriction of improving dynamic performance of speed control. While the frequency is higher than the half of USM drive voltage frequency, the width adjusting range of low-frequency PWM is decreased obviously. According to USM characteristic and the requirements of control, the frequency of low-frequency PWM is lower than 10% of USM driving voltage frequency, in general. For F/B PWM or F/B/S PWM, the PWM frequency should be no more than 5% of USM driving voltage frequency, to adjust holding torque.

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