Study on Vibration Suppression Control for Rotary Compressor

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Recently, permanent magnet synchronous motor (PMSM) drive systems without the rotor position sensor are widely used as actuators in many applications. However, in the case of a pulsating load such as the compressors, the rotational speed of the motors is fluctuated and the drive system is vibrated due to the pulsating load torque. In this paper, we propose a new method to reduce the rotational speed pulsation. This method can seamlessly change the vibration suppression control and the high efficiency control. The simulation results indicate that the proposed method is very effective and practical.

Keywords: rotary compressor, vibration suppression, high efficiency, seamless

1. Introduction

Inverters have increasingly been incorporated in motor drive devices in recent years. Among these, the permanent magnet synchronous motor has high efficiency compared to induction motors, so most household appliances have become inverter drive devices which use a permanent magnet synchronous motor. These devices have also been driven by sine waves with the objective of improving their efficiency and noise reduction⁽¹⁾.

Therefore, driving the permanent magnet synchronous motor with sine waves at a high level of performance requires accurate detection of the rotor position, but methods which use high-resolution position sensors or motor current sensors are expensive and difficult to apply in household appliances. There has thus been progress in the development of sensor-less control methods which do not use such expensive motor current sensors or position sensors, and these have currently been applied to various household appliances.

The authors have also proposed a motor current sensor-less/position sensor-less sine wave vector control method that reproduces the motor current from the DC bus current (less & less method)^{(2)–(4)}. Furthermore, the cascade vector control method⁽⁵⁾ which serves as the basis for this vector control uses the extended induced voltage method⁽⁶⁾ to achieve sensor-less control, as well as combines the inverse model of the d-q axis interference term of the motor with current control to achieve ideal current control characteristics. Stable

current control even under low-period calculations is a feature of this method.

Meanwhile, there have been investigations on reducing the compressor rotational speed in devices which use cooling cycles (e.g., air conditioners, refrigerators) in order to save energy and reduce noise. However, the rotary compressor has periodic fluctuations in load torque (periodic torque disturbance) due to the suction of refrigerants and the compression stroke. Vibrations are generated according to differences from the motor output torque, so this hampers further decreases in the compressor rotational speed.

Various countermeasures have been proposed against such periodic torque resistance, including a method which sets the output torque pattern of the motor in advance, reads out the output torque patterns according to the rotational speed or average torque, and controls the motor output torque; or methods which control the motor output torque by introducing repeated control or Fourier transformations^{(7)–(12)}. The authors have also used the square wave drive method to propose a periodic torque resistance suppression control which uses repeated control and applied this to compressor drive devices for room air conditioners^{(13)–(16)}.

A periodic torque resistance suppression control has also been previously proposed in the sine wave vector control method⁽¹⁷⁾. This method estimates the pulsating component of the torque from the axis error estimated value, which is the error between the control axis and the actual axis. This estimated value is then compensated with a periodic torque resistance compensator which uses simple Fourier transforms and inverse transforms to match the load torque and motor output torque, suppressing the vibrations caused by load torque fluctuations.

As described above, vibration suppression control suppresses rotational speed fluctuations and reduces compressor vibration by matching the load torque and motor output torque. However, system efficiency decreases because the peak motor current value fluctuates greatly according to the

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motor output torque.

Therefore, methods which increase vibration by controlling the motor output torque to a constant level according to the air conditioning operation conditions, but which increase system efficiency by setting the peak motor current value as a constant have been used⁽¹⁸⁾.

This article proposes a vibration suppression control which suppresses the rotational speed fluctuations due to periodic torque resistance by using a controller that uses sine wave transfer functions (referred to as an S controller)⁽¹⁹⁾⁽²⁰⁾, as well as a control configuration which can seamlessly change high-efficiency control which increases system efficiency by maintaining the motor output torque at a constant level (referred to as seamless torque control).

Specifically, we introduce a motor drive system for air conditioners, and report on vibration suppression effects from simulation results and actual devices after explaining the system torque control configuration and the S controller.

2. Motor Drive System for Air Conditioners

2.1 Outline of Motor Drive System Figure 1 shows a simplified configuration diagram of the motor drive system. The motor drive system for air conditioners is primarily composed of a diode rectifier, smoothing capacitor and inverter, and a control micro-computer. Furthermore, a one-shunt current detection method which reproduced a three-phase motor current from the DC bus current was used for reducing costs. A high-efficiency permanent magnet synchronous motor (PMSM) was also used for the motor.

2.2 Position Sensor-less/Motor Current Sensor-less Cascade Vector Control Figure 2 shows a block diagram of the motor control. A position sensor-less control that used extended induced voltage⁽⁶⁾ was adopted in order to drive the motor that was built inside the compressor, and

Fig. 1. Drive system used in air-conditioner

Fig. 2. Motor control configuration used in air-conditioner

this is a method which uses PLL to adjust the speed ω_r so that the axis error $\Delta\theta$ would be zero.

The current control (ACR) also adopts the previously proposed cascade vector control⁽⁵⁾. Using this control enables a stable current control without setting the ACR calculation cycle early.

The currently proposed seamless torque control is achieved by adding to the speed control (ASR) configuration. Details of the seamless torque control are explained below.

3. Seamless Torque Control

3.1 Overall Configuration Figure 3 shows a block diagram of seamless torque control. S controller 1 is a vibration suppression controller which outputs the pulsating torque current command I_{qsin}^* so that the frequency component of the periodic torque resistance included in the rotational speed deviation $\Delta\omega_r$ would be zero, from which the period disturbance torque and motor output torque are matched to suppress vibration.

S controller 2 is a high-efficiency controller which outputs the speed deviation correction value $\Delta\omega_{rsin}^*$ so that the frequency component of the periodic torque resistance included in the torque current command I_{q0}^* output from ASR is zero, after which the SDR speed deviation $\Delta\omega_{r0}$ is corrected to control the peak motor current value to a constant value and reduce conduction loss.

As shown in Fig. 3, S controller 1 (vibration suppression

Fig. 3. Proposed seamless torque control configuration

controller) was connected to ASR in parallel, and S controller 2 (high-efficiency controller) is connected in antiparallel.

Here, there is an adjustment method for calculating the S controller error value E_{rr} by using the rotational speed fluctuation width command value $\Delta\omega_r^*$ in order to adjust the effectiveness of the vibration suppression and high-efficiency control.

Figure 4 shows a block diagram of the adjustment method. This adjustment method calculates the error value E_{rr} by using the integral control from the deviation between the rotational speed fluctuation width command value $\Delta\omega_r^*$ and amplitude of the rotational speed fluctuation value $\Delta\omega_r$.

The error value E_{rr1} is input into S controller whereas E_{rr2} ($= 1 - E_{rr1}$) is input into S controller 2 so that the effectiveness of S controller 1 (vibration suppression controller) and S controller 2 (high-efficiency controller) are opposite. Here, the rotational speed fluctuation width command value $\Delta\omega_r^*$, integral gain K , and the S controller control gain K_s (discussed later) were determined with air conditioner system experiments.

3.2 Outline of Seamless Torque Control Operation

Figure 5 shows an image of the seamless torque operation. This figure is an image of the rotational speed fluctuation width command value $\Delta\omega_r^*$ operation, with the rotational speed on the horizontal axis and the rotational speed when the rotational speed fluctuation width command value $\Delta\omega_r^*$ was taken on the vertical axis.

As shown in this figure, the low-speed region (below 1500 min^{-1}) switches to the vibration suppression control, the moderate speed region (3000 min^{-1} to 4500 min^{-1}) switches to the high-efficiency control, and the high-speed region (over 4500 min^{-1}) switches to the normal control.

Here, vibrations due to periodic torque resistance also decrease in the intermediate region between the low speed and moderate speed regions (1500 min^{-1} to 3000 min^{-1}), so the need for complete vibration suppression control also decreases. In other words, operations which increase efficiency

while suppressing vibration are desired.

Therefore, it is decided that this region is operated using seamless torque control (i.e., change the rotational speed fluctuation width command value $\Delta\omega_r^*$).

3.3 S Controller The S controller uses the transfer function of Eq. (1) and has the feature of having an extremely large gain with respect to a specified frequency (ω_0).

$$G_c(s) = K_s \frac{s}{s^2 + T_a s + \omega_0^2} \dots \dots \dots (1)$$

Here, K_s is the control gain, T_a is the damping constant, and ω_0 is the central frequency. The rotational speed command ω_r^* is set when ω_0 is this control.

Here, the damping constant T_a is as shown in Eq. (2).

$$T_a = K_s \left\{ \frac{E_{rr}}{(1 - E_{rr})} \right\} \dots \dots \dots (2)$$

The damping constant T_a is calculated as shown in Eq. (2). As shown in Fig. 4, the effectiveness of the S controller was also adjusted by calculating the E_{rr} value.

Figure 6 shows an example of a Bode diagram of the S controller ($K_s = 314 \text{ rad/s}$, $T_a = 0$, $\omega_0 = 100 \text{ Hz}$). Figure 7 shows a block diagram of the S controller.

Fig. 6. Bode diagram of S controller

Fig. 7. Block diagram of S controller

Fig. 4. Block diagram of the adjuster

Fig. 5. Image of operation of seamless torque control

Fig. 8. Simulation waveform for seamless torque control at 3000 min⁻¹

Fig. 9. Simulation waveform of seamless torque control at 3000 min⁻¹ (sudden change)

4. Simulation Results

4.1 Overall Waveform Figure 8 shows the overall waveform of the torque, rotational speed, and motor current when the effectiveness of the vibration suppression control was changed in four stages. The rotational speed command ω_r^* was 3000 min⁻¹. The waveforms shown are the load torque and motor output torque, rotational speed, and motor current (three-phase), from top to bottom.

Time 2 s–4 s shows the operation waveform at a vibration suppression control of 100% (rotational speed fluctuation width command value $\Delta\omega_r^* = 0$ min⁻¹), and time 8 s–10 s shows the operation waveform at a high-efficiency control of 100% (rotational speed fluctuation width command value $\Delta\omega_r^* = 300$ min⁻¹). The intermediate times of 4 s–6 s and 6 s–8 s show the operation waveforms with rotational speed fluctuation width command value $\Delta\omega_r^* = 40$ min⁻¹ and rotational speed fluctuation command value $\Delta\omega_r^* = 70$ min⁻¹, respectively.

Figure 9 also shows the operation waveform when rapidly changed from the vibration suppression control to the high-efficiency control (rotational speed fluctuation width $\Delta\omega_r^* = 0$ min⁻¹ → $\Delta\omega_r^* = 300$ min⁻¹). The rotational speed command ω_r^* was 3000 min⁻¹.

Table 1 shows the motor constant and control gain K_s used in simulations. Furthermore, the load torque waveform was set as a sine wave, and the amplitude was set as 1 Nm.

Both figures show that the switches were conducted seamlessly, and stable control was possible even when suddenly changing from vibration suppression control to

Table 1. Motor constant and control gain (K_s)

K_e	0.2Vpeak/(rad/s)
L_d	10mH
L_q	10mH
R	0.5Ω
Poles	4
J_m	0.00038kg·m ²
K_s (S controller 1)	879.2rad/s
K_s (S controller 2)	1884rad/s
Rotation speed command	3000min ⁻¹

high-efficiency control.

4.2 Time-expanded Waveform Figure 10 shows the time-expanded waveform (3.8 s–3.9 s, 5.8 s–5.9 s, 7.8 s–7.9 s, and 9.8 s–9.9 s) of the waveforms shown in Fig. 8.

The waveform at 3.8 s–3.9 s in Fig. 10(a) was the operation at a vibration suppression control of 100%, so the load torque and motor output torque were matched, and the rotational speed fluctuations were almost constant. However, the peak value of the motor current waveform was large. In contrast, the waveform at 9.8 s–9.9 s in Fig. 10(d) was the operation at a high-efficiency control of 100%, so the motor output torque was constant, and the peak motor current value was also constant. However, in contrast to the waveform in Fig. 10(a), rotational speed fluctuations of 100 min⁻¹ were generated.

Here, the rotational speed fluctuation width command value $\Delta\omega_r^*$ was 300 min⁻¹, but the actual rotational speed fluctuations were 100 min⁻¹. This signifies that the rotational speed fluctuation width only reaches a value of 100 min⁻¹ when under load torque (amplitude 1 Nm) and a rotational speed of 3000 min⁻¹ in this motor.

Figure 10(b) and Fig. 10(c) each show the operation waveforms according to each rotational speed fluctuation command value $\Delta\omega_r^*$. From the above, it can be seen that a seamless operation was possible.

5. Experimental Results

Figures 11 and 12 show vibration measurement results of the actual compressor. These results are experimental results using a single-cylinder rotary compressor. Here, Table 2 shows the motor constant and load torque waveform (estimated waveform) of the compressor used in experiments, and Table 3 shows the experimental conditions (compressor pressure conditions and rotational speed fluctuation width command value $\Delta\omega_r^*$) in Fig. 12.

Figure 11 shows the results of comparing the primary vibrations of the compressor where the vibration suppression control was at 100% (proposed method and conventional method⁽¹⁷⁾) and when the vibration suppression control was absent (vibration value with no control is set as 1). The measured rotational speed was 1000 min⁻¹. Results confirmed that a vibration reduction effect identical to the conventional method was obtained.

Figure 12 shows the experimental results of the compressor primary vibration when the rotational speed fluctuation command value $\Delta\omega_r^*$ was changed (vibration at 3000 min⁻¹ was set as 1). Results confirmed the seamless control of the compressor vibration according to the rotational speed

Fig. 10. Simulation waveform of seamless torque control at 3000 min⁻¹ (time-expanded waveform)

fluctuation command value $\Delta\omega_r^*$. Here, the reason why the compression vibration did not become zero even below 1500, when the rotational speed fluctuation command value $\Delta\omega_r^*$ was 0 min⁻¹, was because the torque command value output by the S controller was a sine wave (motor output torque was sine wave), whereas the actual load torque was a waveform that included many high-frequency components, as shown in

Fig. 11. Experimental results of compressor vibration suppression effect at 1000 min⁻¹

Fig. 12. Experimental results of compressor vibration in response to rotational speed fluctuation command

Table 2. Motor constant and load torque waveform at the time of experiment

Ke	0.18Vpeak/(rad/s)
Ld	8.1mH
Lq	13.6mH
R	0.59Ω
Poles	4
Jm	0.00038kg·m ²
Load torque with respect to mechanical angle (Pd/Ps: 2.3MPa/1.4MPa)	

Pd: Discharge pressure, Ps: Suction pressure

Table 2. Therefore, differences were present between the motor output torque and load torque, and the rotational speed fluctuation could not be controlled completely to 0 min⁻¹.

In other words, further reductions in vibration require the addition of higher-order components of motor output torque (i.e., S controller corresponding to higher-order components).

6. Conclusions

In this paper, the S controller was used to propose a vibration suppression control which suppressed rotational speed fluctuations based on periodic torque resistance, as well as a control configuration which was capable of seamlessly

Table 3. Experimental conditions for seamless torque control

Rotational speed (min ⁻¹)	Pd/Ps (MPa)	$\Delta \omega$ r* (min ⁻¹)
600	1.8/1.4	0
1000	2.3/1.35	0
2000	2.8/1.35	50
2500	3.0/1.25	75
3000	3.4/1.2	100

Pd: Discharge pressure, Ps: Suction pressure

changing high-efficiency control, which sets motor output torque at a constant level to improve system efficiency.

The validity of the proposed method was confirmed with simulations and actual devices. Suppression effects of vibration suppression control and increased efficiency can be freely changed by using this control.

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