Reduction Method of Stopping Vibration for Compressor in Home Appliances

Taisuke Shioi, Takahiro Kumagai, Keisuke Kusaka, Jun-ichi, Itoh
Nagaoka University of Technology
1603-1, Kamitomioka-machi, Nagaoka, Niigata, JAPAN
Tel., Fax: +81 / (258) – 47.9533.
E-Mail: s183135@stn.nagaokaut.ac.jp
URL: http://itohserver01.nagaokaut.ac.jp/itohlab/en/index.html

Keywords

«Permanent magnet motor», «Vibration suppression», «Three-phase motor drive», «Sensor-less control»

Abstract

This paper proposes a low-vibration stopping method by switching the free-run mode and the short-circuit braking mode for compressors. The vibration is generated by the bounce of the rotor caused by the fluctuation of the load torque. The proposed method suppresses the rotor bounce by stopping the motor during the suction process because the compressor does not generate large torque in the suction process. In order to stop the motor during the suction process, the proposed method switches the operation mode form the free-run mode to the short-circuit braking mode at the Top Dead Center, which is starting point of the suction process. Furthermore, the inrush current during the a short-circuit braking mode is suppressed by a hysteresis current controller. The vibration is evaluated under four pressure conditions with the conventional method and the proposed method. As the result, the proposed method achieved more than 58% reduction of the amplitude of the vibration at all four pressure conditions. Notably, the proposed method reduced the amplitude of the vibration by 71% under the high-pressure condition.

Introduction

Recently, permanent magnet synchronous motors (PMSMs) are being increasingly employed to home appliances thanks to its distinct advantages of high power density and high efficiency [1]-[9]. The operation with low acoustic noise and low vibration is required since the home appliances such as refrigerators and air conditioners are built into a living environment. The compressor in the home appliances repeats the cycle of (suction) => (compression) => (ejection) for a heat exchange. These repeated operations lead to a large load torque fluctuation and a large speed ripple of the motor. In addition, a speed sensor and a position sensor cannot be attached on the compressor motor because the inside of the compressor is the high temperature and the high pressure. Furthermore, there is a limit to the processing speed of the microcomputer from an aspect of the product cost.

Automatic start-stop control is applied in order to control the pressure of the compressor. This control leads the reduction of the power consumption. On the other hand, the frequency of the start/stop operation more increase than general purpose motors. Therefore, it is important for the compressor motor to reduce the vibration not only under steady state but also under start and stop.

Under the steady state, some literatures have achieved to reduce the vibration by suppressing the speed ripple due to the load torque fluctuation[10],[11]. The effect of the suppression method for vibration depends on the accuracy of the estimated position because the most of these methods adopt the sensor-less field oriented control (FOC). Generally, a back electromotive force (EMF) based position estimation method is employed in the medium and the high speed region [12],[13]. However, the accuracy of the estimated position deteriorates in the low speed region because the back EMF becomes small[14]. Therefore, the effect of the reduction method of vibration based on the back EMF become worse under the start and the stop. In addition, the sensor-less FOC requires expensive microcomputers for the complex calculations. Thus, it is not suitable for home appliances which adopts cheap microcomputers in order to save the cost.

During the start, the three-steps starting method is employed [15]. This method consists of the preposition, the open-loop operation, and the sensor-less control. The motor outputs the torque which is larger than the load torque by the open-loop operation and sensor-less control. However, the vibration of the compressor is generated by the load torque fluctuation because the period of the open-loop operations cannot control the motor torque. Under the start, the load torque fluctuation is small because the pressure of the ejection valve agrees with the suction valve in the compressor. Thus, the vibration due to the load torque fluctuation is small. On the other hand, under the stop, the vibration due to the load torque fluctuation becomes large because the pressure of the ejection valve is higher than the suction valve. Therefore, this paper focus on the stop which has the large vibration.

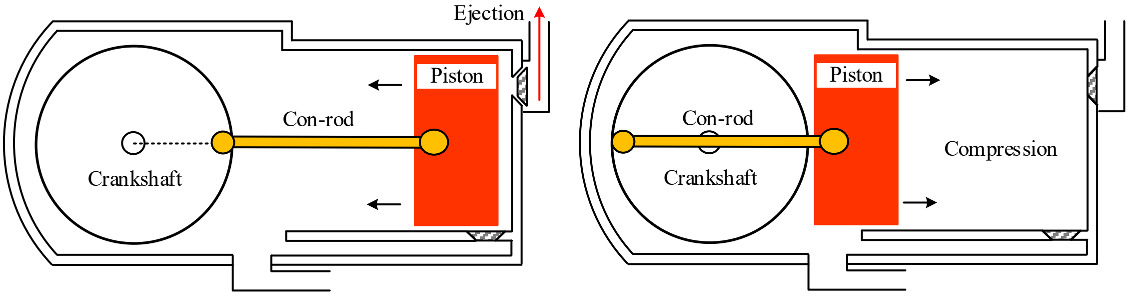
During the stop, the free-run method in which all switching devices are tern-off state is known as one of the simplest stopping methods. In this method, the motor is stopped only by the load torque including the mechanical loss because the output torque of the motor becomes zero. The free-run method leads to the vibration of the compressor due to the speed ripple caused by the load torque fluctuation. In the [16], the vibration is reduced by changing switching pattern to the free-run mode after decelerating the rotation speed. This method sets a delay time between receiving the stop signal and changing the switching pattern to free-run mode. In the delay time, the motor is decelerated at the maximum acceleration using the motor torque. In this method, the optimize delay time for the reduction of the vibration depends on the rotation speed and pressure of the compressor. Thus, when the rotation speed and pressure are changed, this method cannot suppress the vibration. Therefore, the low-vibration stopping method that is independent of the rotation speed and the pressure is necessary in order to reduced the vibration at stop.

This paper proposes a low-vibration stopping method, which is independent of the rotation speed and pressure condition. The originality of this paper is that the vibration is reduced by stopping the motor during the suction process which does not generate the large torque. This method combines (i) the deceleration mode using the free-run method and (ii) the stopping mode using the short-circuit braking. In addition, the inrush current during the short-circuit braking is suppressed by a hysteresis current controller. Furthermore, the proposed method is implemented with a cheap microcontroller because it does not require the complex calculation. Therefore, the proposed method is suitable for the home appliances.

This paper is organized as follows: firstly, the lord torque characteristics of the compressor is described. Secondly, the cause of the vibration with conventional method is investigated. Next, the detail of the proposed low-vibration stopping method is explained. Finally, the vibration is compared between the conventional method using free-run mode and the proposed method in the experiment.

Lord torque characteristics of compressor

Figure 1 shows the scheme drawings of the reciprocating compressor. The reciprocating compressor compresses the refrigerants by repeating the reciprocating motion of a piston which connected to a rotor. As shown in figure 1, the point where the operation of the compressor changes from the ejection to the suction is defined as Top Dead Center (TDC). In addition, the point where the operation changes from the suction to compression is defined as Bottom Dead Center (BDC). This paper defines TDC as 0 degree of the crank angle and BDC as 180 degree of the crank angle.



(a) Top dead center (TDC)　　(b)Bottom dead center (BDC)

Fig.1. scheme drawings of reciprocating compressor.

Figure 2 shows the torque characteristics of the compressor, where P_d denotes the pressure of the ejection valve and P_s denotes the pressure of the suction valve. As shown in the figure 2(a), the torque is small during the suction process and it becomes large during the compression and the ejection. As shown in the figure 2(b), the torque varies depending on the pressure of the compressor.

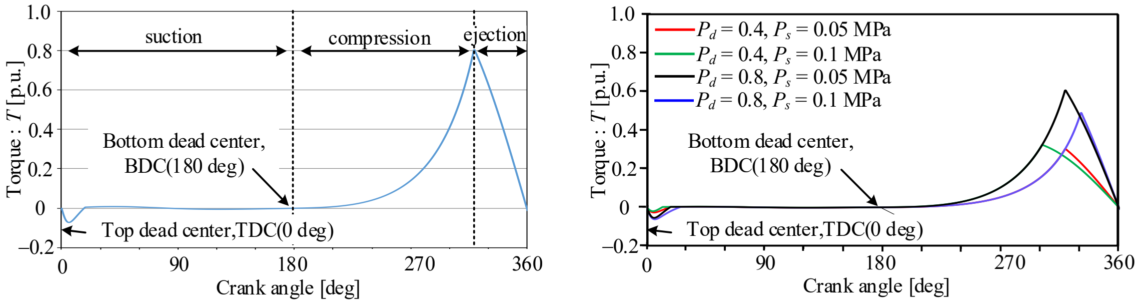
Investigation result of the vibration with conventional stopping method

Experimental conditions

This paper evaluates the vibration of the motor during the stop with the free-run method and proposed stopping method. Firstly, this paper evaluates the vibration of the motor stops with the free-run method in order to clarify the causes of the vibration.

Figure 3 shows the switching pattern of the inverter during the free-run mode in which all switch of the inverter is off. Thus, the motor does not generate torque. Therefore, the motor is decelerated by only the load torque. Note that the voltage of the output of the inverter agrees with the back EMF of the motor in the free-run mode.

Table 1 shows the parameters of the inverter and the motor. The pressure condition influences to the torque characteristics of the compressor. It is necessary to measure the vibration at same pressure conditions in order to compare the vibration at stop using the free-run method and the proposed method. Thus, in this experiment, the motor is driven until the pressure in the compressor becomes constant in this experiment. After that, the motor is stopped and the vibration is measured with an acceleration sensor attached to the compressor. The pressure in the compressor and the rotation speed are determined from the operation characteristics of the household refrigerators.



(a) Pressure characteristics of compressor. (b) Pressure characteristics in each pressure conditions.

Fig.2. Pressure characteristics of compressor.

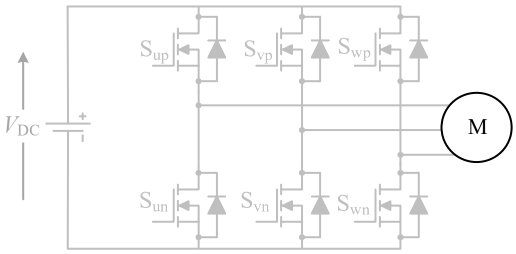


Fig.3. switching pattern of free-run

Table 1. Experimental conditions.

Parameter	Symbol	Value
Rating rotation speed	ω_n	80 rps
Rating torque	T_n	0.237 N•m
Polar logarithmic	P	3
Winding resistance	R	6.2 Ω
d-axis inductace	L_d	76.3 mH
q-axis inductace	L_q	136 mH
DC-link voltage	V_{dc}	280 V
Switching frequency	f_{sw}	16 kHz
Dead time	T_d	0.5 μs

Investigation result of the vibration using free-run method

Figure 4 shows the output waveform of the acceleration sensor and the estimated rotation speed when the motor is stopped with the free-run method. The rotation speed is estimated from the back EMF because the compressor does not be hanged the speed sensor. The rotation speed is decreased by the load torque in the free-run method. Therefore, a periodical change of the rotation speed is caused by the load torque shown in Figure 2. The rotation speed is sharply reduced during the compression and the ejection process because the compressor generates a large torque in this period. The direction of the rotation is reversed because the rotor bounces due to the load torque as shown in figure 4. In addition, the output of the acceleration sensor becomes large after the rotation speed sharply reduced. As the result of the figure 4, the vibration occurs due to the speed ripple and the rotor bounce caused by the load torque fluctuation. In particular, the large vibration is generated after the rotor bounce. This paper proposes the reduction method of the vibration by suppressing the rotor bounce which is main cause of the vibration.

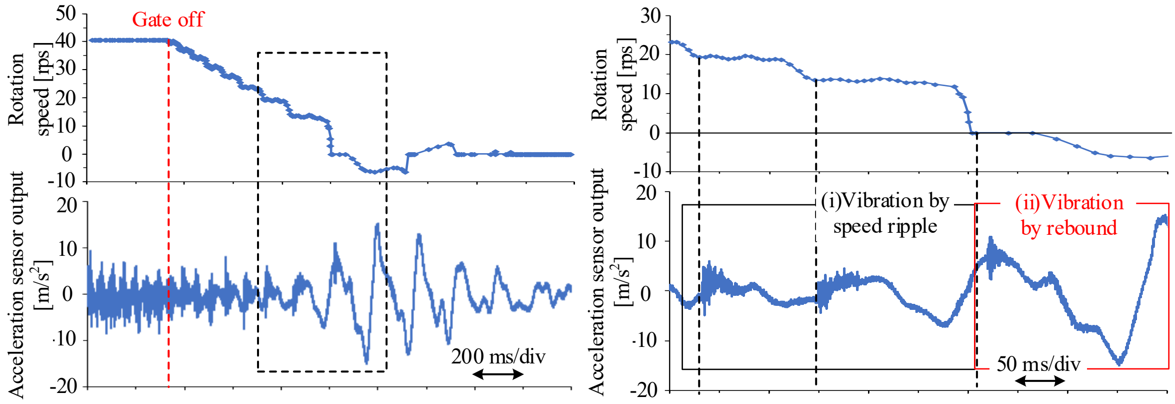
Proposed low-vibration stopping method

This paper proposes a low-vibration stopping method with switching the operation mode to the free-run mode and the short-circuit breaking. The proposed method suppresses the rotor bounce, which causes the large vibration by stopping the motor during the suction process. In order to stop the motor during the suction process, the proposed method generates the brake torque with the short-circuit braking.

Figure 5 shows the main circuit configuration for the proposed method. This system requires three voltage sensors in order to estimate the rotation speed and mechanical position. In addition, this system requires three current sensors in order to control the amplitude of the current.

Figure 6 shows the switching pattern of the inverter during the short-circuit braking. In the short-circuit braking, the output voltage of the inverter becomes zero. The motor is rapidly stopped by converting the rotation energy of the motor into heat energy at the wire resistance. Note that in the short-circuit braking, the motor may be damaged by an overcurrent due to the back EMF. Therefore, it is necessary to control the motor current in order to prevent the over current of the inverter.

The proposed method has two operation modes which are (i) the deceleration mode and (ii) the stopping mode. During (i) the deceleration mode, the motor is decelerated with the free-run state and estimates



(a) Rotation speed and acceleration sensor output. (b) Enlarged view at the rotor bounce point.

Fig.4. Rotation speed and acceleration sensor output when the motor is stopped with the free-run.

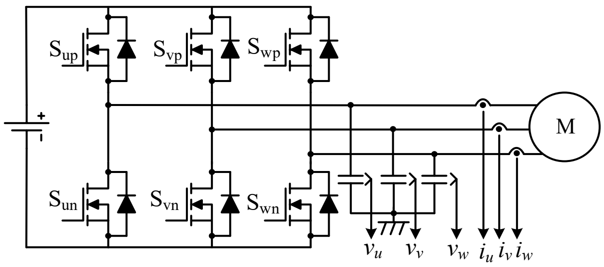


Fig.5. Main circuit configuration for proposed method.

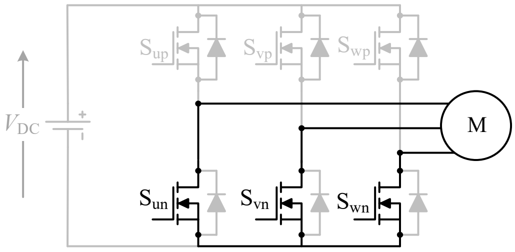


Fig.6. Switching pattern of short circuit braking.

the rotation speed and TDC from the back EMF and the acceleration of the motor. When the rotation speed becomes under the threshold value and rotor position agrees with TDC, the operation mode change to (ii) the stopping mode. During (ii) the stopping mode, the motor is stopped with the short-circuit braking.

Figure 7 shows the control block diagram of the proposed method. The proposed method consists of the V/f control part for the steady state operation, the speed estimator, the operation mode selector, the current controller, and the switching pattern selector. In the deceleration mode, the rotation speed and TDC are estimated with the speed estimator and the operation mode selector. The operation mode is changed according to the signal from the operation mode selector and the current controller.

Estimation method of the rotation speed and TDC

The proposed method estimates TDC from the acceleration and the phase of the motor. As shown in figure 3, the rotation speed sharply reduces only compression and ejection process in the free-run mode. Thus, the acceleration becomes large during the compression and ejection process. Therefore, the mechanical angle is estimated from the acceleration of the motor.

Figure 8 shows the block diagram of the rotation speed and the acceleration estimator. The proposed method requires to estimate the rotation speed in order to change the operation mode from the (i) the deceleration mode to (ii) the stopping mode. The rotation speed is estimated from the back EMF under (ii) the deceleration mode with the free-run mode. The electric angle θ_r of the motor is given by (1).

$$\theta_r = \tan^{-1}\left(-\frac{v_\alpha}{v_b}\right) \quad \text{...} (1)$$

where, v_α is the α-axis voltage, v_β is the β-axis voltage. The rotation speed is given by differentiation of the electric angle from (1). The acceleration is estimated from the second derivative of the phase calculated by (1). Note that the accuracy of the acceleration estimator is deteriorated due to the detection noise. Thus, this method uses the filter that has derivative characteristics under the rated frequency and cut off characteristics above the rated frequency.

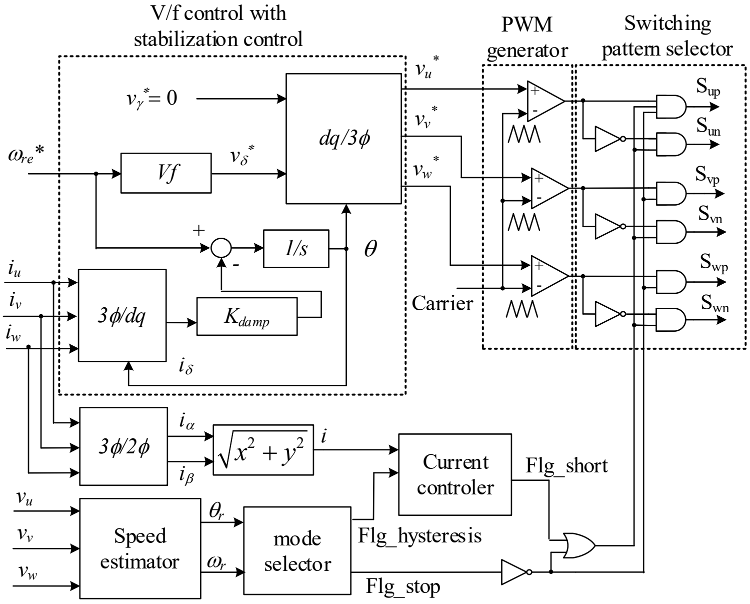


Fig.7. Control brock of the proposed method.

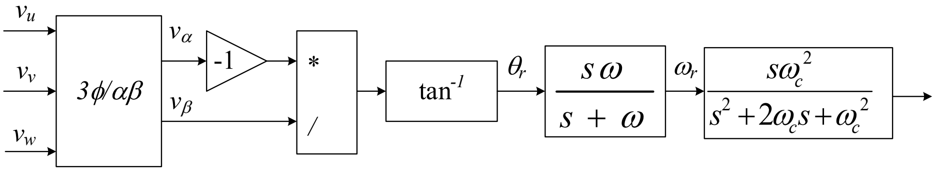


Fig.8. Block diagram of the speed and acceleration estimator.

The proposed method switches operation mode to (ii) the stopping mode at TDC in order to stop the motor during the suction process. Therefore, it is necessary to the estimate TDC during (i) the deceleration mode.

Figure 9 shows the control flowchart of the proposed method. The operation mode is switched in the order of (i) the deceleration mode with the free-run method, and (ii) the stopping mode with the short-circuit braking.

Figure 10 shows the phase, the rotation speed, and the acceleration waveform during (i) the deceleration mode using the free-run method. As shown in figure 10, TDC is the point when the acceleration a_r becomes the small value after the rotation speed is sharply reduced due to the load torque.

Current control method using free-run mode and short-circuit braking

Figure 11 shows the amplitude of the current vector with the hysteresis current control under (ii) the stopping mode. The short-circuit braking causes an overcurrent, which may damage the motor. Therefore, it is necessary to control the motor current in order to prevent the over current. In (ii) the stopping mode, the stator current is controlled by switching the short-circuit braking and the gate block with the current controller shown as "current controller" in figure 7. The operation mode switches to the gate block, in which all switching device are turn-off, when the current amplitude is more than the upper

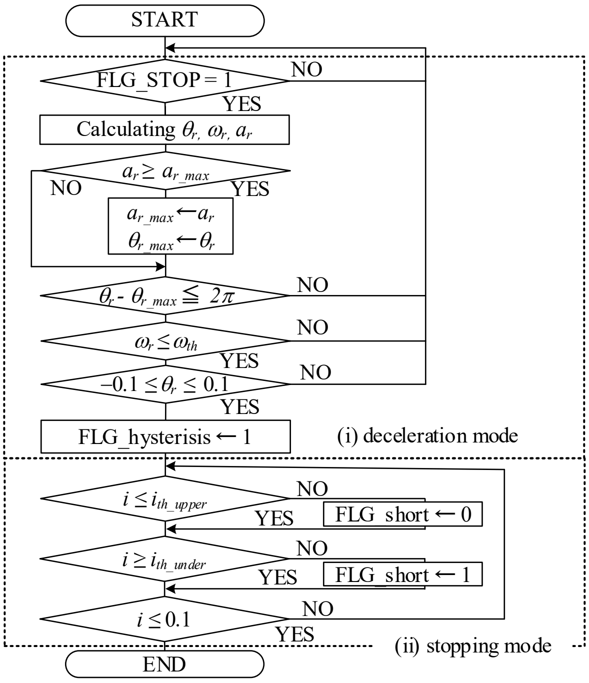


Fig.9. The control flowchart of the proposed method.

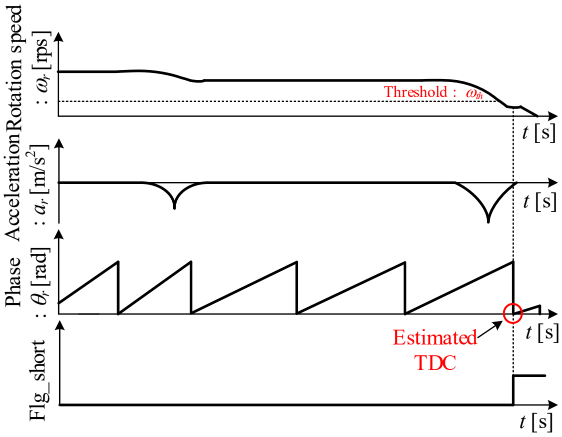


Fig.10. Phase, rotation speed, and acceleration waveform.

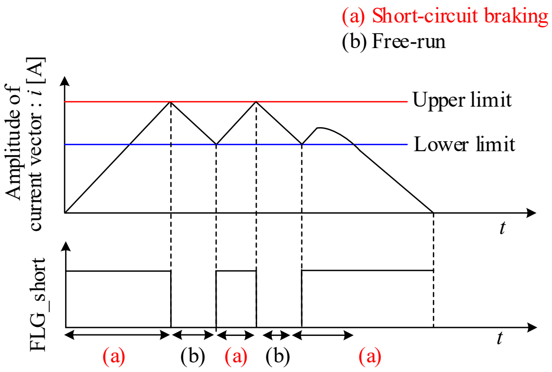


Fig.11. Amplitude of the current vector under the (iii) stopping mode

threshold. On the other hand, all lower switches of the inverter turn on when the current amplitude is less than the lower threshold. The stator current decreases as the rotation speed decreases because the current depends on the back EMF during the short-circuit braking.

Experimental result with proposed method

This experiment evaluates the vibration with the proposed stopping method. The experimental conditions are same as the experiment using the free-run method. When the threshold value ω_{th} which is threshold value in order to change the operation mode to (ii) the stopping mode is low, the rotor bounce is happened during (i) the deceleration mode. Thus, in order to avoid the rotor bounce during the (i) the deceleration mode, the threshold value is set to 15 r/s, which means the 20% of the rated rotation speed. The upper limit of the hysteresis control is 1 A, which means the 20% of the demagnetizing current. In addition, the lower limit is 0.9 A in order to set the current ripple rate to 10%.

Figure 12 shows the waveforms of the estimated rotation speed and the estimated acceleration at the switch point to (ii) the stopping mode from (i) the deceleration mode. Note that the phase, the rotation speed, and the acceleration cannot be estimated during the short-circuit braking because EMF is not detected. As shown in the figure 11, the proposed method detects TDC and switches to the short-circuit braking at TDC.

Figure 13 shows the current waveform of the motor during (ii) the stopping mode. As shown in figure 13(a), the peak value of the motor current is approximately 1.9 A when the current control is not enabled. On the other hand, the peak value of the motor current is suppressed to less than 1 A by the current control as shown in figure 13(b). Therefore, the proposed prevent the damage of the motor due to the short-circuit braking.

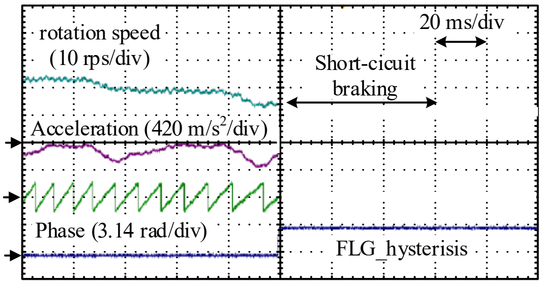
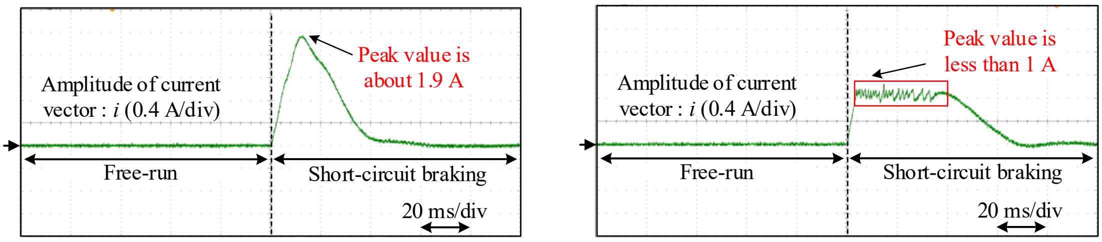
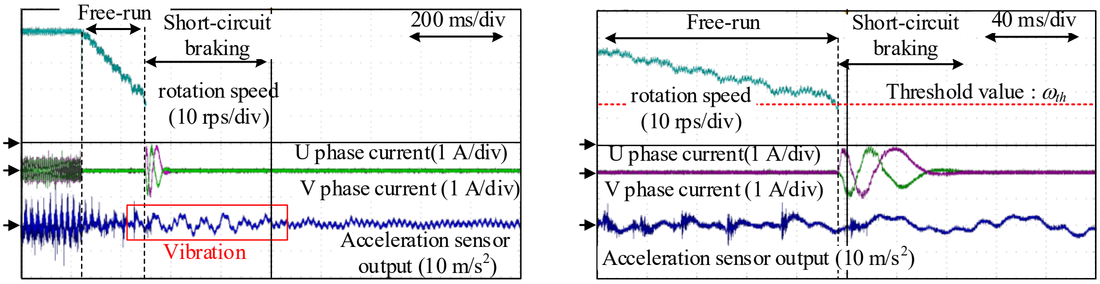


Fig. 12. Output waveforms of rotation speed and acceleration estimator.



(a) Without hysteresis current control. (b) With hysteresis current control.

Fig.13. Motor current waveform in the (iii) stopping mode.



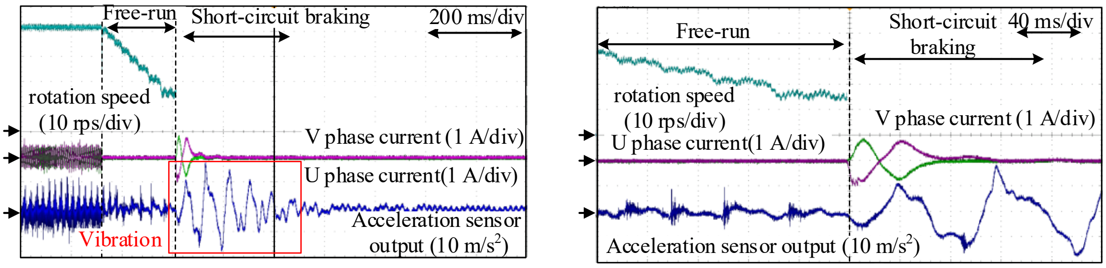
(a) Estimated speed and acceleration sensor output. (b) Enlarged view of the waveform at switching point.

Fig.14. Deceleration operation waveforms with the proposed method when the motor stops during the suction process.

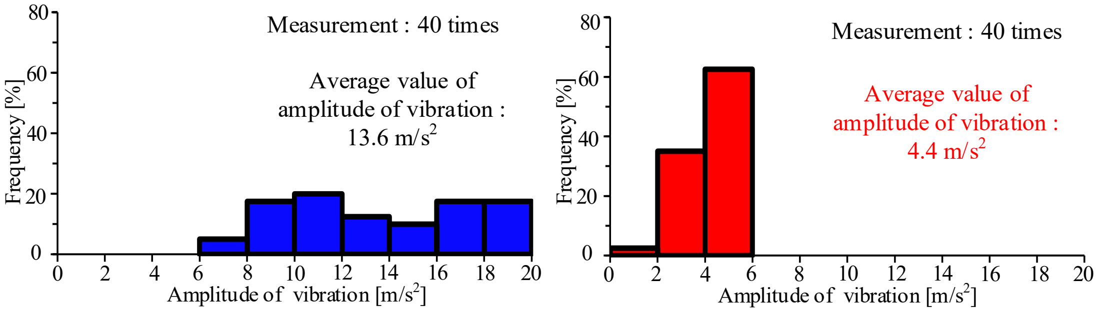
Figure 14 shows the estimated rotation speed, the waveform of the U and V phase current, and the output waveform of the acceleration sensor with the proposed stopping method. Figure 14(b) shows the waveforms at around the changing point from (i) the deceleration mode to (ii) the stopping mode. As shown in figure 14(a), The rotation speed was decreased until less than the threshold value by (i) the deceleration mode. After that, the motor stopped during the suction process by changing to (ii) the stopping mode at TDC. As shown in figure 14(a), the proposed method reduced the vibration at the motor stop compared to the conventional method using the free-run mode shown in figure 4.

Figure 15 shows the estimated rotation speed, the waveform of U and V phase current, and the output waveform of the acceleration sensor when the operation mode is changed to (ii) the stopping mode at BDC. When operation mode switches to (ii) the stopping mode at BDC, the motor stops during the compression process, which generates the large torque. As shown in figure 15, the large vibration occurs compared to figure 14. This result indicates that the large torque due to the compression leads to the vibration. Thus, it is necessary to stop the motor during the suction process in order to reduce the vibration.

Figure 16 shows the amplitude of the vibration when the conventional and the proposed stopping method are applied. As shown in figure 15, the proposed method reduced the average amplitude of the vibration by 67% compared to that of the conventional method using the free-run mode. In the free-run mode, the amplitude of the vibration had large variability because the free-run mode cannot control the stopping position of the motor. On the other hand, the proposed method controls the stopping position. Thus, the variability of the amplitude of the vibration when the proposed method was applied was small.



(a) Estimated speed and acceleration sensor output. (b) Enlarged view of the waveform at switching point.
Fig.15. Deceleration operation waveforms when the motor stops during



(a) Conventional method (free-run) (b) Proposed method
Fig.16. Amplitude of vibration with conventional and proposed stopping method.

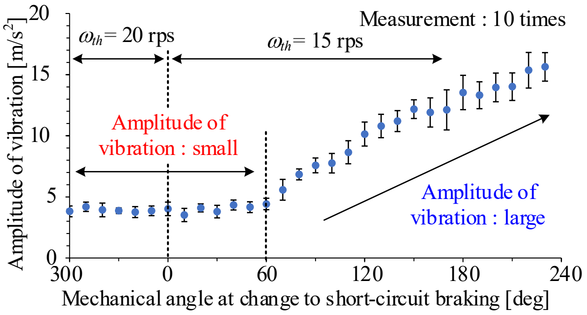


Fig.17. Peak value of vibration when operation mode switched to (ii) stopping mode at each mechanical angle.

Figure 17 shows the amplitude of the vibration when the operation mode is switched to (ii) the stopping mode at each mechanical angle. when the threshold value of the rotation speed was 15 r/s, the rotor bounce occurred at the mechanical angle of 300 to 350 degree. Thus, the threshold value was changed to 20 r/s from 15 r/s, in this period. As shown in figure 17, the proposed method reduced the amplitude of the vibration by 67% or more compare to the conventional method in the condition of the switching operation mode to (ii) the stopping mode at the mechanical angle of 0 to 60 degree. Therefore, the proposed method reduces the vibration at stop even when the estimated mechanical angle has error of approximately 60 degree due to delay of detection of voltage and detection noise.

Figure 18 shows the amplitude of the vibration at the different pressure conditions. As shown in figure 18, in the conventional method using the free-run mode, the amplitude of the vibration increased when the pressure inside the cylinder was high because the amplitude of the load torque was large. On the other hand, the proposed method reduced the vibration by 58% or more compare to the conventional method in all four pressure conditions.

Table 2 shows the amplitude of the vibration and the reduction ration of the vibration compare to the conventional method. As shown in the table 2, the proposed method achieved the reduction of the vibration by 71 % at P_d = 0.65 MPa and P_s = 0.05 MPa.

Conclusion

This paper proposed the low-vibration stopping method, which changes (i) the deceleration mode using the free-run mode and (ii) the stopping mode using the short-circuit braking. The proposed method reduced the vibration by stopping the motor during the suction process of the compressor because the compressor generates the lower torque in this process. This method achieved the stopping the motor during the suction process by switching the operation mode to (ii) the stopping mode from (i) the deceleration mode at TDC. As the experimental result, the proposed method reduced the amplitude of the vibration by 67% compare to that of the conventional method using the free-run mode. In addition, the proposed method reduced the vibration by 58% or more compare to free-run mode in all four considered pressure conditions.

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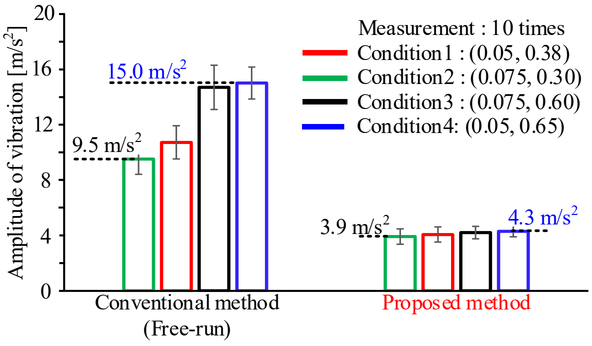

Fig.18. Peak value of vibration in terms of pressure conditions.

Table 2. Comparison results of vibration at stop.

		Average value [m/s²]		Reduction rate [%]
		Free-run	Proposed method	
Pressure condition [MPa]	1	9.5	3.9	58.9
	2	10.7	4.1	61.7
	3	14.7	4.2	71.4
	4	15.1	4.3	71.5

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