Suppression Control Method of Torque Ripple for IPMSM Utilizing Repetitive Control and Fourier Transformer

Satomi Hattori, Muneaki Ishida and Takamasa Hori

Dept. of Electrical and Electronic Eng., Mie University, Mie, JAPAN

Abstract - Recently, many examples of practical applications of the motors with reluctance torque, such as IPMSM, RM, etc. are reported. However, the problems of the torque ripple produced by the IPMSM, are also presented. The main reasons of the torque ripple generation are the structural imperfectness of the IPMSM and its control system, such as the cogging torque of the motor, the dead time of inverter, sensors offset, imbalance and non-linearity, and so on.

In this paper, authors propose a suppression control method of the torque ripple for IPMSM utilizing the repetitive control with the Fourier transformer and a vibration signal detected by an acceleration sensor attached to the motor frame, considering periodicity of the motor torque ripple. An experimental system to simulate the compliant mechanical frame is constructed, and the effectiveness of the proposed method is confirmed by experimental results.

I. INTRODUCTION

Variable speed drive systems of PMSM (Permanent Magnet Synchronous Motor) have been widely used for industry applications, home electric appliances, and so on, due to the progress of the power electronics, and simple structure, easy maintenance, high efficiency, etc. of the motor. Moreover, because the PMSM can realize the same high performance drive as DC motor, it is used in the fields where the quick response and high accuracy control are required. However, structural imperfectness of PMSM and its control system produce torque ripple, which causes mechanical vibration, rotor speed ripple and acoustic noise.

It was well known that the torque ripple could be reduced by addition of particular feedforward compensation current (voltage) to the normal current (voltage) for the control input as shown in Fig.1 [1],[2]. However, how do we obtain the feedforward compensation signals or data? Of course, we can derive the compensation signals by analysis considering the structure of the motors, estimation from the e.m.f. waveshape, etc. approximately, but cannot obtain the accurate signals. Finally for the individual motor, we must make a fine adjustment of the compensation signal in order to suppress the torque ripple sufficiently.

In earlier papers, some methods to reduce the mechanical vibration of the induction motor with the pulsating torque load and the permanent synchronous motor with the torque ripple, such as 3-phase HB-type stepping motor and SPMSM (Surface Permanent Magnet Synchronous Motor), by the repetitive control have been proposed [3]-[6]. The repetitive controller has large loop gain (basically infinity) only for the fundamental repetitive frequency component and its harmonics. The repetitive control system is effective to reduce the vibration due to periodical torque ripples. In order to acquire the compensation signal for reducing torque ripple, the vibration of the motor frame caused by torque ripple is detected by the acceleration sensor attached to the motor frame. The sensor is used only for the acquisition of the feedforward compensation data. However, because the vibration signals detected by the acceleration sensor contain various frequency components and the mechanical system around the motor and load has complicated resonant characteristics, we can not stabilize the repetitive control system and reduce the vibration by directly using the vibration signals from the sensor.

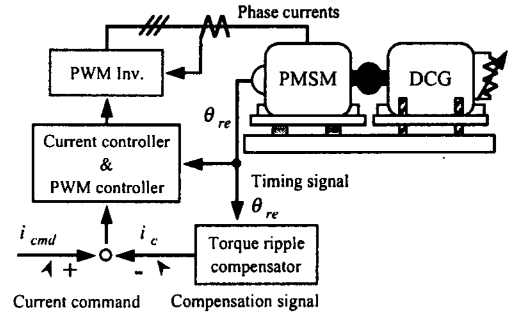


Fig.1 Feedforward compensation control system for suppression of periodical torque ripple

To cope with this problem, we proposed a suppression control method for the torque vibration utilizing the Fourier transformer placed before the input of the repetitive controller [4]-[6]. As a result, only one frequency component of vibration signal from acceleration sensor is inputted to repetitive controller, the stability of the control system can be ensured. In this paper, we propose the vibration suppression control method for IPMSM driven under the maximum torque control. An experimental mechanical system to realize the mechanical vibration is constructed and the effectiveness of the proposed vibration suppression method is confirmed by experimental results. Also, we show that the rotor speed ripple caused by the torque ripple can be suppressed by the vibration suppression control of the motor frame.

II. CONFIGURATION OF CONTROL SYSTEM

Fig.2 shows a block diagram of proposed system using the acceleration sensor, the repetitive controller and the Fourier transformer. Here, *d*-axis coincides with a direction of the magnetic flux vector produced by the PM field of

IPMSM and α_S is the mechanical rotational vibration signal of the motor frame.

IPMSM is controlled by the current control system including the non-interference control [7] and the maximum torque control [8], so the generated motor torque is controlled by the current command i_{qcmd} except the ripple torque τ_{rip} caused by the imperfectness of motor, current sensors (offset, gain unbalance among phases), driving source, and so on when the motor rotates. The rotational speed of the IPMSM is fluctuated due to the ripple torque. At the same time, the ripple torque is applied to the motor frame by a reaction from the rotor and, as a result, causes the vibration of the motor frame. Since the vibration is periodical in phase with the rotation of the motor, the repetitive control can be applied to the reduction of the vibration.

A. Torque Control System

Generally, the dynamic equations of IPMSM are described as follows:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + PL_d & -\omega_{re} L_q \\ \omega_{re} L_d & R_a + PL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_{re} \Phi_a \end{bmatrix} \tag{1}$$

$$T = n_p \Phi_a i_q + n_p (L_d - L_q) i_d i_q \tag{2}$$

where i_d, i_q : d, q-axis component of armature current
v_d, v_q : d, q-axis component of armature voltage
R_a : armature winding resistance
L_d, L_q: d, q-axis component of armature winding self-inductance
ω_{re} : electrical angular speed of the rotor referred to the motor frame
Φ_a : maximum value of PM flux linkage
P : operator d/dt
n_p : number of pole-pairs

From (1), the motor currents (i_d, i_q) are under influence of the electromotive force $\omega_{re}\Phi_a$ and the reactance $\omega_{re}L_d$, $\omega_{re}L_q$. In order to control i_d and i_q exactly by removing these influences, we adopt the non-interference control [7].

In the torque equation (2), the first term in the right side represents the field magnet torque, and the second one does the reluctance torque. In this paper, we suppose IPMSM is operated in low-speed operation region, and the current commands, i_{dcmd} and i_{qcmd}, are given by following equation to realize the maximum torque control.

$$i_{dcmd} = \frac{\Phi_a}{2(L_d - L_q)} - \sqrt{\frac{\Phi_a^2}{4(L_d - L_q)^2} + i_{qcmd}^2} \tag{3}$$

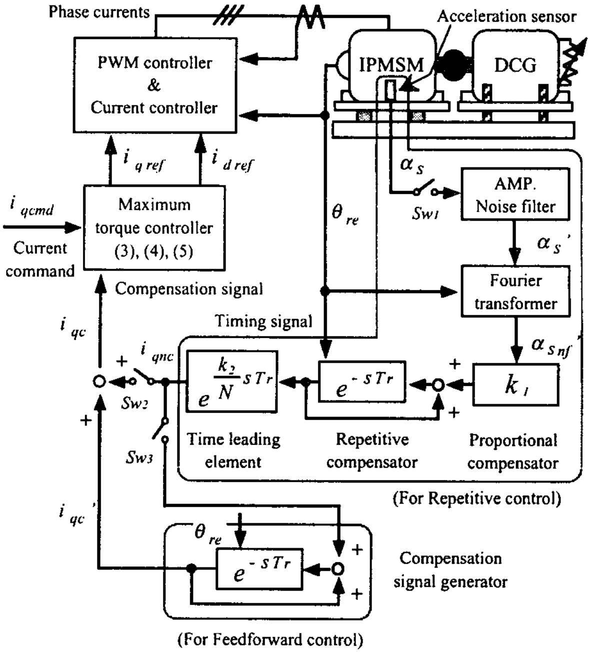


Fig.2 Configuration of vibration suppression control system

B. Acceleration Sensor and Noise Filter

The motor frame vibration due to the ripple torque may occur in any directions depending on the construction and the characteristics of the mechanical system around the motor and load. So the acceleration sensor is attached to the motor frame taking the mechanical characteristics into consideration. Because the acceleration signals detected by the sensor contain the higher frequency sensor noise, we use a low pass filter to cut-off it.

C. Extraction of Specific Component of Vibration by Fourier Transformer

The vibration signal (α_S) detected by the acceleration sensor includes various frequency components. Fourier transformation is applied to the detected vibration signal in order to extract the particular vibration frequency component to be reduced. In this paper , nf($n = N/n_p$, N=1, 2, 3, ... ; n_p : number of pole-pairs) denotes nf frequency component of the vibration (α_{Snf}).

D. Repetitive Controller

The compensation signal i_{qc} for the torque ripple is produced from the vibration signal of the acceleration sensor attached to the motor frame during the repetitive control. Moreover, d-axis component of the compensation signal i_{dc} is calculated by using the relation between i_{dcmd} and i_{qcmd}, obtained by (2) and (3), is expressed as follows :

$$i_{dc} / i_{qc} = i_{dcmd} / i_{qcmd} \tag{4}$$

$$i_{qref} = i_{qcmd} - i_{qc}, \; i_{dref} = i_{dcmd} - i_{dc} \tag{5}$$

The parameter k_1 of the proportional compensator is for adjusting control loop gain, and the time leading element (the parameter : k_2) is that to compensate the phase lag. The parameters k_1 and k_2 are determined so that the repetitive control system becomes stable for the individual vibration frequency component.

E. Compensation Signal Generator

In this proposed system, we use the repetitive compensator (implemented with memories) not only as the repetitive controller to learn a compensation signal but also as the compensation signal generator, which stores the learned compensation signal, and outputs it as a feedforward compensation signal.

During the learning process of the compensation signal when the switch S_{w1} and S_{w2} in Fig.2 close, the repetitive control is carried out for the frequency component of the vibration signal extracted by the Fourier transformer at one operating point of the motor, and at the same time the signal for the torque ripple compensation is renewed by the input signal and restored in the controller. When the selected vibration frequency component is reduced to be negligibly small, the switch S_{w1} opens and the signal input to the repetitive controller stops. After finishing the learning process, the stored signal in the repetitive controller is added to the stored signal in the memories of the compensation signal generator when the switch S_{w3} closes during one period of the repetitive control. Just after that, the switch S_{w2} opens and the compensation signal in the repetitive controller is cleared. By repeating these procedure for all selected frequency components, a feedforward compensation signal is made up in the compensation signal generator. Again, the above procedure is repeated for the other operating points of the motor.

Moreover, by using the acquired compensation signals and the motor operating point data, the feedforward control for the vibration suppression can be realized without the acceleration sensor. In this case, we use an information of the rotor position θ_{re} as a timing signal to output the compensation signal.

III. STABILITY OF REPETITIVE CONTROL SYSTEM

The gain of the repetitive controller becomes infinity at multiple frequency of the repetitive frequency. Therefore the repetitive control system, may become unstable, i.e., the vibration diverges unless the control parameters k_1 and k_2 are set up appropriately [5], [6]. In this paper, the values of k_1 and k_2 are determined by the auto-tuning algorithm [6].

IV. EXPERIMENTAL RESULTS

A. Experimental System

For experiment, a mechanical system is constructed as shown in Fig.3. In this system, the motor base is supported by vibration proof rubbers and the load (DC generator) base is set on the fixed base by bolts.

Fig.4 (a), (b) show the rotor structure, and the waveform of electromotive force of the experimental machine (IPMSM : 2 pole-pairs), respectively. From Fig.4 (b), we can confirm that the waveform of electromotive force contains the higher harmonic components. Since this experimental machine is the trial product, we don't know the detailed rated values, it's stator winding is that of a 5.5[kW] induction motor.

The system parameters for experiment are shown in Table 1. Here, T_c is the control period of the inverter, and we use a rotary encoder in order to detect the rotor position for the Fourier transformation, the current control and the repetitive control.

Fig.5 shows an example of the motor frame vibration

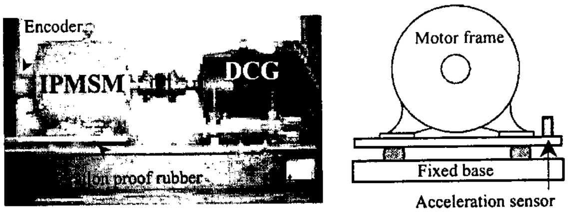
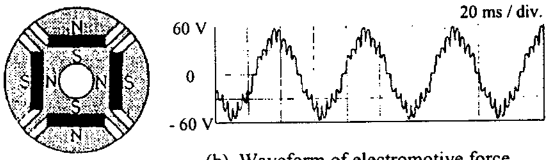


Fig.3 Experimental model of mechanical vibration system



(a) Rotor structure

(b) Waveform of electromotive force (u - v , f = 20[Hz])

Fig.4 Characteristics of experimental machine

Table 1 System parameters for experiment

IPMSM
$R_a = 0.45$ [Ω] , $L_d = 7.4$ [mH] , $L_q = 18.8$ [mH]
$\Phi_a = 0.27$ [V sec / rad] , Number of slots : 18
INV. source : 100[V] , $T_c^* = 100$[μs]
Driving condition
$i_{q\,cmd} = 1.3$ [A] , $i_{d\,cmd} = -0.07$ [A] , $f = 6.0$ [Hz]
Rotary encoder : 4096 [pulses/rev] , control period : T_s =400[μs]
Repetitive controller
$6f$: $k_1 = -0.02$[A/G] , $k_2 = 9$ $18f$: $k_1 = 0.06$[A/G] , $k_2 = 0$
Memory : $N = 420$, control period : $T_r = 2\,T$ ($T = 1/f$)
Resolution of A-D converter : 12[bit]
Input range : -0.51 ~ + 0.51[G] , – 1.25×10^{-4}[G/resolution]

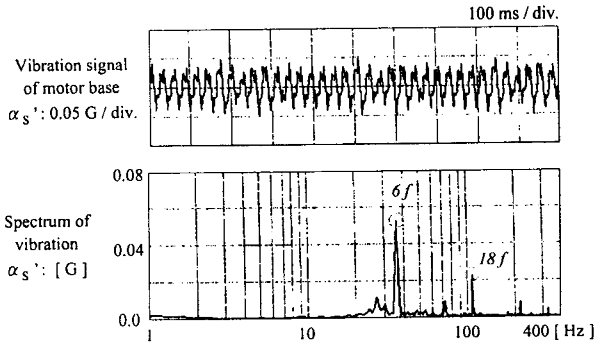


Fig.5 Vibration waveform of motor frame (Without vibration suppression control)

waveform and its FFT spectrum. In this figure, we can see that the main components of the motor frame vibration are *6f* and *18f* ones. Generally, it is considered that *6f* and *18f* components are generated by interaction between the higher harmonic components of the magnetic flux distribution and the number of slots per pole-pairs.

B. Compensation Data Acquisition by Repetitive Control

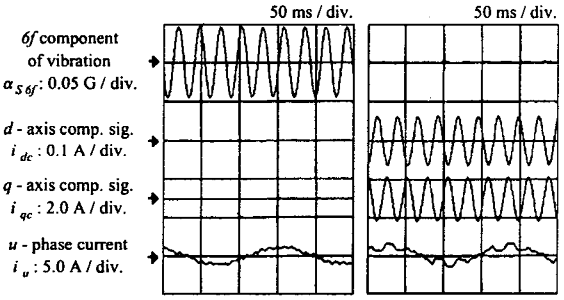
In experiment, the control system shown in Fig.2 is tested. The system parameters are shown in Table 1. Here, parameters k_1 and k_2 are final values determined by the auto-tuning algorithm[6]. The repetitive control is carried out when the switch S_{w1} and S_{w2} in Fig.2 close.

Fig.6 shows experimental results of the repetitive control for *6f* component of the motor frame vibration on-load in steady state. From top, the waveforms of the *6f* component of the motor frame vibration, the *d*-axis compensation signal, the *q*-axis compensation signal and the *u*-phase current are shown. In Fig.6, we can see that the *6f* component of motor frame vibration is considerably reduced and at the same time, *d*-axis and *q*-axis compensation signals are produced.

C. Vibration and Torque Ripple Suppression Control by Feedforward Compensation Control

Fig.7 shows FFT spectrum of the motor frame vibration in the cases without and with the repetitive control, respectively. Fig.8 shows FFT spectrum of the rotational speed signal in the cases without and with the repetitive control, respectively. Comparing Fig.7 and Fig.8, it is indicated that the *6f* component of the rotational speed ripple is considerably reduced, corresponding that the *6f* component of the vibration is decreased by the repetitive control using the motor frame vibration signal.

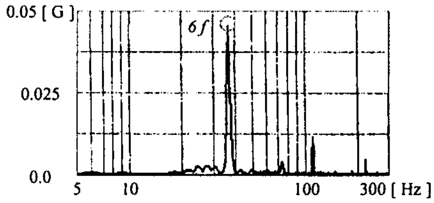
Fig.9 shows the final result of the vibration suppression control where the repetitive control is performed for each of *6f*, *18f* components of the vibration one by one with the acquired compensation data employed as the feedforward control. Comparing with Fig.5 the *6f*, *18f* components of vibration are considerably reduced.



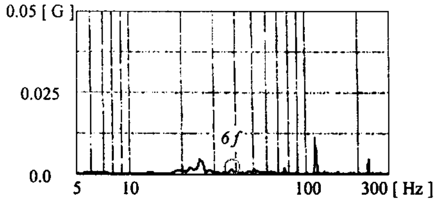
(a) Without control (b) With control

comp. sig. : compensation signal

Fig.6 Experimental results for repetitive control

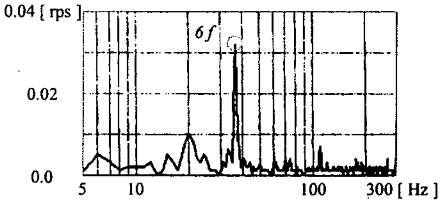


(a) Without repetitive control

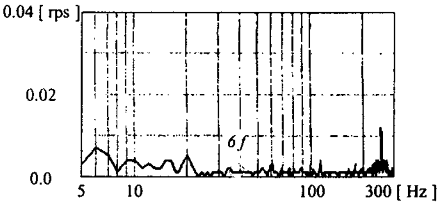


(b) With repetitive control

Fig.7 FFT analysis of motor frame vibration



(a) Without repetitive control



(b) With repetitive control

Fig.8 FFT analysis of rotational speed signal
(Steady state : 2.9 [rps])

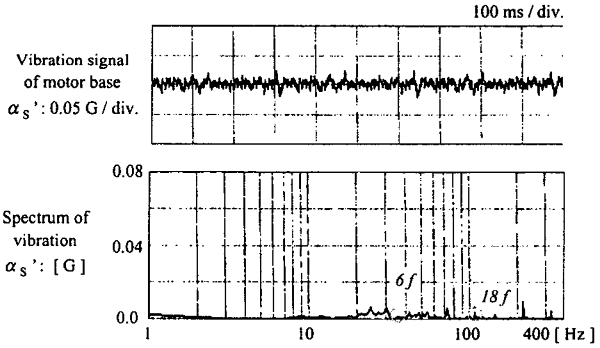


Fig.9 Vibration waveform of motor base
(With vibration suppression control)

D. Comparative Experiment

In order to confirm the effectiveness of the vibration suppression control system using the motor frame vibration signal detected by the acceleration sensor shown in the preceding section, the comparative experiments are performed, where the repetitive control is carried out using the rotational speed signal detected by the rotary encoder

(4096 pulse/rev) as shown in Fig.10. In this experiment, the same system parameters, shown in Table 1 as the preceding experiment are used. The experimental results, are shown in Fig.11 and Fig.12.

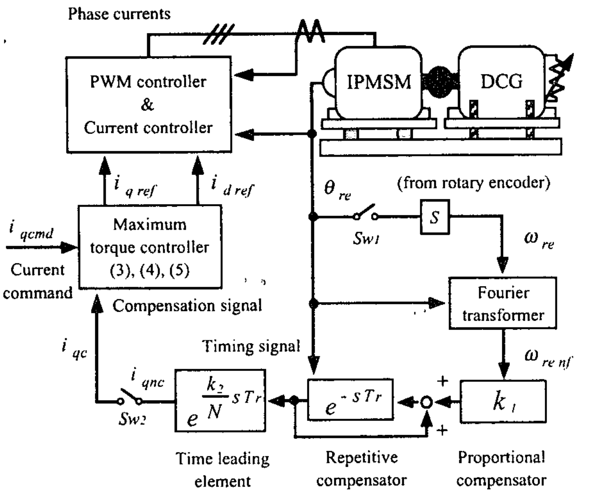
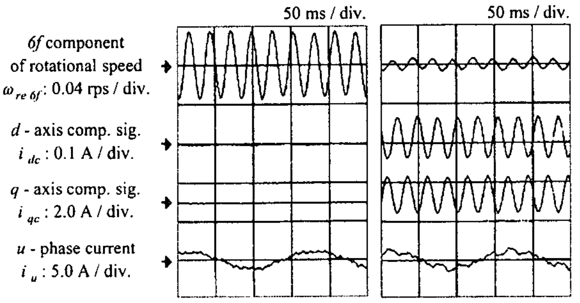


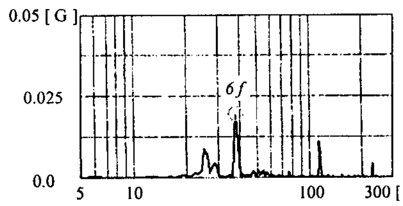
Fig.10 Configuration of comparative experimental system



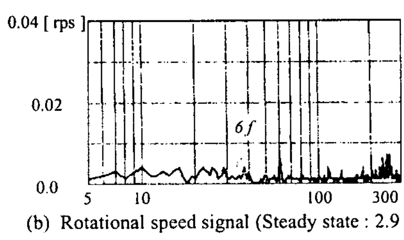
(a) Without control (b) With control

\# comp. sig. : compensation signal

Fig.11 Experimental results for repetitive control
(Compensation signal learns from rotational speed signal)



(a) Vibration signal of motor frame



(b) Rotational speed signal (Steady state : 2.9 [rps])

Fig.12 FFT analysis with repetitive control
(Compensation signal learns from rotational speed signal)

These experimental results indicate that the $6f$ component of the rotational speed ripple is considerably reduced. However, compared with the results shown in Fig.7, we can see that the control effect on the motor frame vibration and the rotational speed ripple is poorer. But this effect may be improved by using higher resolution rotary encoder. Therefore, the vibration suppression control system using the motor frame vibration signal detected by the acceleration sensor is more useful in the system using lower resolution rotary encoder.

V. CONCLUSION

We proposed a suppression control method of torque ripple for IPMSM utilizing feedforward compensation control, and a generation method of compensation signals for the feedforward control by the repetitive control system with the Fourier transformer utilizing a vibration signal detected by an acceleration sensor attached to the motor frame. Usefulness of proposed methods was confirmed by the experimental results.

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