CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 328

Research on the Active Permanent Magnet Torsional Vibration Control Technology for ICE

System Integration & Hybridization

Zhou Yan, Shanghai Marine Diesel Engine Research Institute

ABSTRACT

Under the background of "carbon peak, carbon neutral", intelligent, clean and efficient internal combustion engine and hybrid power system are developing rapidly. At the same time, the permanent magnet motor and new energy power technology are developing quickly. This paper studies the method of identifying the amplitude and phase of the main harmonic angular acceleration, generating theelectromagnetic torque to suppress the torsional response of the crankshaft and the shaft of internal combustion engine by the closed-loop vector control method; establishing the theoretical calculation model and test stand of diesel engine shaft system, analyze and verify the control effect of active permanent magnet torsional vibration. Through the measurement analysis, it shows that the active permanent magnetic torsional vibration control method can effectively control the torsional vibration of the internal combustion engine.

1 INTRODUCTION

Under the background of "Carbon peak, Carbon neutral", the main development goal of internal combustion engine (ICE) and power plant is "clean, efficient, intelligent, integration and comfort". The energy saving, emission reduction, intelligent control technologies of internal combustion engine develop rapidly. Gas and dual fuel engine are widely used, which can burn various clean fuels such as natural gas, methanol, ammonia and so on. Integrated power propulsion system, new energy hybrid transmission system and shaft motor (PTO/PTI) device are widely utilized[1]. In order to ensure the reliability and comfort of vehicle and marine internal combustion engine, it is necessary to configure various types of torsional vibration dampers, such as being made of rubber, silicone oil, sleeve spring, plate spring, spiral spring, etc.[2]

Hao Z.Y. et al. adopted the modified DC motor and torque control method to use the DC(Direct Current) motor as a torsional vibration damper and installed at the free end of crankshaft for 6130 type diesel engine to realize the active torsional vibration control of the internal combustion engine[3]. Zhang D.J. et al. adopted the motor torque compensation control strategy to inhibit the fluctuation of engine and the vibration of the vehicle, improve the comfort of hybrid vehicle[4]. Zhou Y. et al. adopted active harmonic control technology, tracked the main harmonic frequency of torsional vibration of power system in real time, and superposed reverse excitation torque on the shaft generator rotor which installed on the middle shaft of the roll-on ship. The calculation verification showed that the torsional vibration response decreased significantly when the phase difference was 180 deg, then the shaft generator can be used as the active torsional vibration damper of the internal combustion engine shafting system[5].

As the rapid development of intelligent power plant technology, the measurable, adjustable, controllable and optimal technology of torsional vibration could be improving further by optimizing the working parameters of engine and power plant. Shafting torsional vibration monitoring, fault diagnosis and active control technology are constantly innovating [6].

With the enforcement of the International Maritime Organization(IMO) MARPOL VI-amendment since January 1st, 2023, shaft generator has high performance cost ratio, significant emission reduction effect and simple system architecture, that means it can be applied to the current or new building ships to achieve energy saving and emission reduction and reduce operating costs. Modern permanent magnet synchronous motor (PMSM) technology is developing rapidly with the advantages of high efficiency, high power density, accurate control, low noise and vibration and long lifetime [7], can be used as marine shaft motor, and becomes a technical way for the active torsional vibration control of internal combustion engine and power plant shafting.

This paper investigates and analyzes the control strategy of permanent magnet synchronous motor in the internal combustion engine and hybrid power system; applies the online shafting torsional vibration monitoring technology, identifies the amplitude and phase of a number of main harmonic torsional angular velocity vectors of the crankshaft and shaft system (the phase difference with the ignition of internal combustion engine); studies on the active torsional vibration control method of permanent magnet synchronous motor, applies one or several reversed moments on the motor rotor for the one or several major harmonics. Its harmonic phase deviates from the excitation phase by 180 deg, in order to suppress the torsional vibration response of engine shafting; establishes the theoretical calculation model and test verification bench of TBD234V8 diesel engine shafting equipped with permanent magnet synchronous motor, analyzes the torsional vibration properties of this shafting model, and verifies the actual effect of active permanent magnet torsional vibration control by test. Therefore, some useful exploration and research have been done in the study of the active torsional vibration control and the active torsional vibration damper of the permanent magnet synchronous motor.

2 CONTROL STRATEGY OF PMSM

Permanent magnet synchronous motor(PMSM) has the properties of small size, light weight, high efficiency, its torque with the characteristics of convenient adjustment and control, a wide range of speed regulation, good dynamic response, due to use high-performance permanent magnet materials as magnetic poles. The permanent magnet motor system is mainly composed of permanent magnet rotor, coil winding stator and controller, whose structure form as shown in Figure 1.

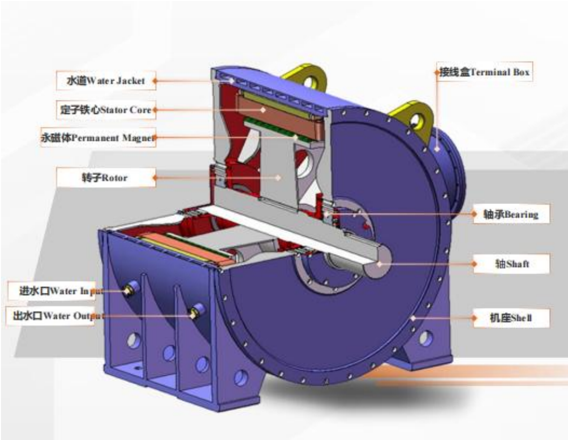


Figure 1. Structure view of PMSM

Three coordinate systems are usually used in the control of PMSM, namely A-B-C coordinate system (three-phase stator, namely three-phase AC winding), α - β coordinate system (two-phase stator) and d-q coordinate system (two-phase rotor), which can be converted to each other, shown as Figure 3 and Equation (1).

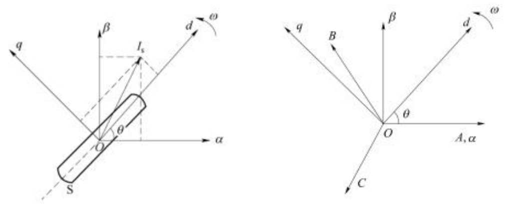


Figure 2 Diagram of three kinds of coordinate systems and the Park transformation

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (1)$$

Assume θ=ωt+θ_0 (θ_0 -- initial angle), get by Park transformation:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (2)$$

The voltage equation in the d-q coordinate system is given as follows

$$\begin{cases} U_d = RI_d + \dfrac{d(L_d I_d + \psi_f)}{dt} - p\omega L_q I_q \\ U_q = RI_q + \dfrac{d(L_q I_q)}{dt} + p\omega(L_d I_d + \psi_f) \end{cases} \quad (3)$$

Electromagnetic torque:

$$T_e = 1.5 p \psi_f I_q \quad (4)$$

Mechanical torque of motor by the dynamic equation:

$$T_L = T_e - J\frac{d\omega}{dt} - B\omega = 1.5p\psi_f \cdot I_q - J\frac{d\omega}{dt} - B\omega \quad (5)$$

Where I_a, I_b, I_c--stator current in A-B-C axis (A), I_α and I_β --stator current in α - β axis (A), I_d and I_q---stator current in d - q axis (A), U_d and U_q--stator voltage in d-q axis (V), R--stator coil resistance (Ω), ψ_f-- rotor magnetic chain(Wb), ω--angular speed of motor (rad/s), p--pole pairs of motor, J--inertia of rotor(kgm^2), B--rotation friction damping coefficient (Nms/rad), L_d and L_q--inductance in d-q axis (H).

The basic process of vector control strategy of PMSM is shown in Figure 2. The current of d axis is often set to 0 (no excitation for permanent magnet motor), the speed is regulated by the current of q axis which is adjusted by the voltage, and the d-q axis voltage command is converted to the α - β axis through the six-switch space vector pulse width modulation(Space Vector Pulse Width Modulation--SVPWM) strategy , and the sensor collects the motor current and speed signals as the feedback of vector control, forming a closed loop control.

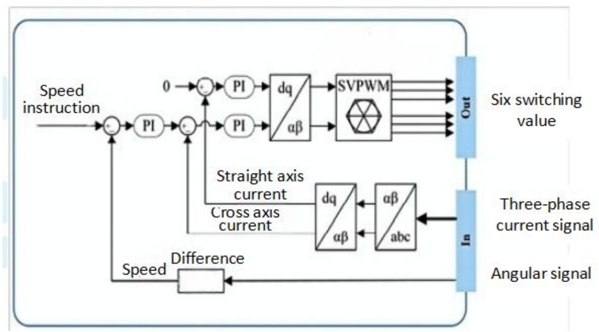


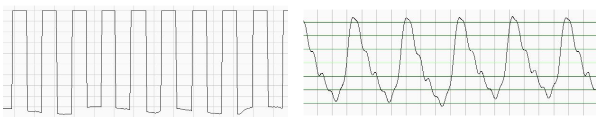
Figure 2 Vector control strategy of PMSM

It can be seen that the magnitude of electromagnetic torque or mechanical torque depends on the magnitude of the stator's current of q-axis from the torque equation of PMSM. Applying the similar principle of harmonic control method to suppress harmonic oscillation, PID (Proportional Integral Derivative) control method is adopted to adjust the current and phase of main harmonic of q-axis stator, and generate the reverse phase mechanical torque of main harmonic, so as to suppress main harmonic response amplitude of torsional vibration of the internal combustion engine and shaft system.

3 STUDY ON ONLINE MONITORING METHOD OF TORSIONAL VIBRATION

The speed pulse waveform of rotating shaft can be obtained on the shaft system of the internal combustion engine, using the torsional sensors, such as electromagnetic and magneto-electric sensor, optical electric and magnetic pole sensor, which installed on the free end of crankshaft, flywheel, coupling, torsional vibration damper, shaft surface, gearbox, generator, the number of pulses per rotation depends on the desired torsional vibration analysis accuracy.

The lossless digital signal of rotation speed pulses by the high signal acquisition card are filtered, shaped, demodulated and analyzed to obtain the torsional vibration angular velocity (rad/s) of the tested shaft system, which can also be converted into angular acceleration (rad/s^2) and angular displacement (rad), see Figure 4.



Speed pulse signal   Torsional angular curve

Figure 4 Brief diagram of torsional vibration monitoring analysis

4 RESEARCH ON ACTIVE PERMANENT MAGNET CONTROL TECHNOLOGY

Using closed-loop vector control method, the amplitude and phase of torsional angular velocity in the shaft system (main harmonic) obtained by real-time monitoring and analysis, and used as input signal of the controller to set up the amplitude and phase of the current of main harmonic to the motor, and consequently, the reverse phase torque (main harmonic) from the ICE excitation harmonic through the pulse width modulation (PWM), frequency modulation and voltage regulation, in order to suppress the torsional vibration response of ICE shafting, shown as Figure 5.

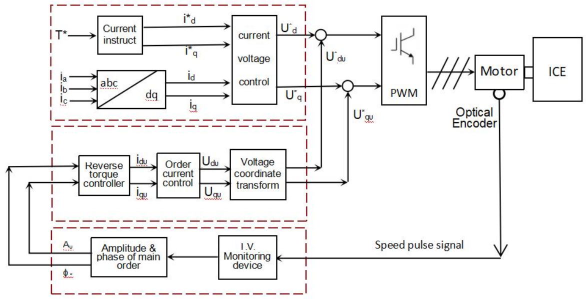


Figure 5 Diagram of the active permanent magnet control analysis

5 STUDY ON ACTIVE PERMANENT MAGNET TORSIONAL VIBRATION DAMPER OF INTERNAL COMBUSTION ENGINE

When the permanent magnet synchronous motor is installed at the free end of the internal combustion engine crankshaft, working as a shaft generator, while monitoring the torsion vibration of internal combustion engine, producing reverse magnet torque of main harmonic to suppress the torsional vibration of internal combustion engine's crankshaft, and protect the crankshaft from torsional vibration damage, the permanent magnet synchronous motor can play the role of torsional torsional vibration damper, so called Active Permanent Magnet Torsional Vibration Damper (APM-TVD).

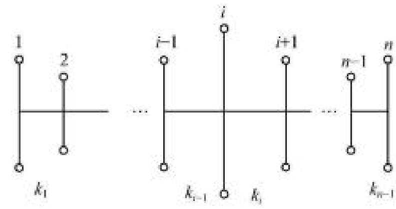


Figure 6 Mass-elastic system diagram

For the internal combustion engine which is installed PMSM at the free end of crankshaft, the mass-elastic system composed of n masses and n-1 shafts, its movement equation of torsional vibration:

$$[J]\{\ddot{\varphi}\} + [B]\{\dot{\varphi}\} + [C]\{\varphi\} = \{T_{ICE}\} + \{T_L\} \quad (6)$$

Where [J]--Mass matrix(n×n, kgm^2), [B]--Damping matrix(n × n, Nms/rad), [C]--Torsional stiffness matrix(n×n, Nm/rad), $\{T_{ICE}\}$--Excitation torque of ICE(n × n, Nm), $\{T_L\}$--Excitation torque of active PMSM(n × n, Nm), $\{\varphi\},\{\dot{\varphi}\},\{\ddot{\varphi}\}$ -- Angular displacement array(n × 1, rad), angular velocity array(n×1, rad/s), angular acceleration array(n×1, rad/s^2) respectively.

The excitation moment {T_{ICE}} of internal combustion engine is the torsional vibration excitation moment generated by the gas pressure in the cylinder. The excitation torque {T_L} of the active PMSM is the phase reverse excitation torque superimposed on the motor rotor, which can be decomposed in a series of harmonic:

$$\mathrm{T_L} = \sum_{\upsilon}^{q} T_{L\upsilon} = \sum_{\upsilon}^{q} t_{L\upsilon} \sin(\upsilon\omega t + \theta_{\upsilon}) \quad (7)$$

Let the angular displacement of the k-th mass:

$$\varphi_k(t) = \sum_{\upsilon} [\varphi_k(t)]_{\upsilon} = \sum_{\upsilon} \mathrm{A}_{k\upsilon} \sin(\upsilon\omega t + \phi_{k\upsilon}) \quad (8)$$

Where ω-- Angular velocity (rad/s), q-- Number of harmonic orders, $T_{L\upsilon}$ -- Excitation torque vector of motor for υ order (Nm), $t_{L\upsilon}$ -- Amplitude of excitation torque of motor for υ order (Nm), θ_{υ} -- Phase of excitation torque of motor for υ order (rad), υ-- Harmonic order, usually υ=1,2,3,...,24 for 2-stroke ICE, υ=0.5,1.0,1.5,2.0,...,12.0 for 4-stroke ICE, $[\varphi_k(t)]_{\upsilon}$ -- Angular displacement vector of k-th mass for υ order (rad), $A_{k\upsilon}$-- Amplitude of angular displacement of k-th mass for υ order (rad), $\varphi_{k\upsilon}$-- Phase of angular displacement $[\varphi_k(t)]_{\upsilon}$ of k-th mass for υ order (rad).

Take equation (7) and equation (8) into equation (6) to solve the equation sets and get the torsional vibration response result of the internal combustion engine shaft system after active control, including amplitude and phase of sine terms, cosine terms of main harmonic orders, and comprehensive values.

We can also set up the objective function, and further use equation (6) to establish the control strategy of {T_L}, and the robust controller parameters.

6 TEST BENCH AND VERIFICATION RESULTS ANALYSIS

The internal combustion engine test bench is composed of TPYE4-180M-4 type permanent magnet synchronous motor -- TBD234V8 type diesel engine, as shown in Figure 7. The parameters of PMSM include: rated power / rated speed: 22kW / 3000 r/min. The Parameters of diesel engine include: rated power / rated speed: 296 kW / 1800 r/min, cylinder diameter / stroke: 128 mm / 140 mm, ignition interval angle between column: 420 deg, single cylinder reciprocating mass: 5.105 kg.

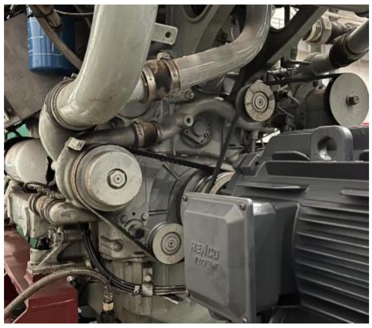


Figure 7 ICE test bench equipped with active PMSM

6.1 Analysis results of torsional vibration without active excitation of PMSM

After installing the PMSM (replacing the original silicon oil torsional vibration damper), the diesel engine runs up with no load and unactive excitation of PMSM, from 800 r/min to 1800 r/min continuously, the torsional vibration amplitude and phase of main harmonic at the free end of crankshaft, shown as Figure 8. The 1st mass is the motor rotor, the No.2 to No.5 mass are the cylinders (A + B column) of diesel engine, and the 6th mass is the flywheel (as shown in Figure 6).

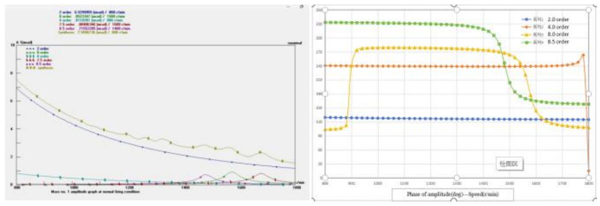


Figure 8 Calculation results of torsional amplitude and phase of diesel engine shaft of with no-load for main orders (no motor excitation)

Figure 8 shows that the 2.0 and 4.0 harmonic amplitudes are node-free forced response, and the phases are basically stable, while the 7.5, 8.0 and 8.5 harmonic amplitude curves have the corresponding resonance speed, and the phases have a large steep drop near the resonance speed. This provides the direction of adjustment for the subsequent active control.

6.2 Measurement results of torsional vibration with active excitation of PMSM

The diesel engine with no-load operates at 1000 r/min, 1200 r/min and 1400 r/min respectively, with active and unactive motor excitation. Using the speed pulse signal generated by the built-in encoder of motor, the main harmonic torsional amplitude at the free end of the crankshaft is analyzed, which listed in Table 1.

Table 1 The amplitude comparison at free end of diesel engine with active and unactive PMSM

Speed /r/min	Order	Motor mode		
		Unactive /±deg	Active /±deg/±Nm	Reduction ratio
700	2.0	0.72	0.66/14	8.3%
			0.51/28	29.2%
			0.44/42	38.9%
800		0.51	0.35/42	31.4%
900		0.27	0.19/42	29.6%

Table 1 shows that the active reverse excitation torque applied by the permanent magnet synchronous motor can play a good torsional vibration reduction effect, and the amplitude reduction is not less than 20%.

7 CONCLUSIONS

7.1 Under the background of "Carbon peak, Carbon neutral", the vehicle and marine hybrid power system has been widely used, through the installation of shaft motor and controller. It is necessary to further improve comfort and reliability while improving energy efficiency and reducing emissions.

7.2 Permanent magnet synchronous motor (PMSM) is widely used in new energy vehicles, including the active noise reduction technology. At the same time, the application of PMSM is gradually expanded in the marine field, due to its high efficiency, wide speed regulation range and good dynamic response.

7.3 The on-line torsional vibration monitoring technology is adopted to identify the torsional angular velocity vector (amplitude and phase) in real time. Simultaneously, the active permanent magnet control technology using a set of reverse phase torque to the motor rotor installed on the shaft of ICE, and real-time feedback closed loop control method, so that it is possible to suppress the torsional vibration response of internal combustion engine.

7.4 Diesel engine test bench was established for calculation and measurement, which verified the good vibration reduction effect of active permanent magnet control. Therefore, the permanent magnet synchronous motor has the possibility to be an active permanent magnet torsional vibration damper (APM-TVD) for the internal combustion engine.

7.5 This paper has only made some useful exploration, and if possible, the design feasibility of active permanent magnet torsional vibration damper will be further studied.

8 REFERENCES AND BIBLIOGRAPHY

[1] Zhou Y. 2023. V*ibration control of power plant shafting*, Shanghai science and technology press, Shanghai, China P.R.

[2] Zhou Y. et al. 2024. Study on the type selection and performance optimization design method of torsional vibration damper for internal combustion engine. *Diesel engine*, (2):1-5.

[3] HAO Z.Y.1994. Study on active control system of internal combustion engine. *Journal of Vibration Engineering*, 9: 209-216.

[4] Zhang D.J. et al. 2014. Analysis and control of torsional vibration in HEV. *Drive system technology*, 12: 3-8.

[5] Zhou Y. et al. 2023. Research on the torsional vibration characteristics and control technology of vehicle-marine hybrid power system shafting. *The 15th National Conference on Vibration Theory and Application*, Chengdu, China P.R.

[6] Zhou Y. et al. 2024. Development and research on the torsional vibration control technology of internal combustion engine shafting system. *Diesel engine*, 1:1-7.

[7] Qiu G.P. 2020. *Experimental design and application technology of permanent magnet synchronous moto*r. Shanghai science and technology press, Shanghai, China P.R.

[8] Liu J. et al. 2018. *Application of electric vehicle power electronic technology*. Beijing Jiaotong University Press, Beijing, China P.R.

[9] Wu Z.Q. 2021. Harmonics close-loop transmission mechanism and torsional Vibration suppression in permanent magnet synchronous motor[D]. South china university of technology,.Guangzhou, China P.R.

[10] Nestorides E.J. 1958. *A Handbook on Torsional Vibration*. Cambridge University Press, London, England.

[11] Wilson W.K. 1968. *Practical solution of torsional vibration problem*. Chapman & Hall Ltd., London, England.