MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Coupling analysis of torsional vibration, Speed control system and advanced injection angle of low speed diesel engine

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ABSTRACT

For general simulation and evaluation of torsional vibration of low speed diesel engines, the parameters of PID controller and advanced injection angle are always assumed to be constant. The influences of PID controller and advanced injection angle on torsional vibration of low speed diesel engines are always not considered. However, both of these two factors would affect the excitations of torsional vibration directly. Also correspondingly, once severe torsional vibration occurred, transient rotating speed would be varied and then affect the speed control system. For studying such coupling effect of engine shafting system and control system, in this paper, a coupled crankshaft torsional vibration simulation model with both speed control system and advanced injection angle considered are established. The influences of different parameters of PID controller and advanced injection angle on both excitations and torsional vibration of the shafting system are analyzed and illustrated. The results indicated that the PID controller and advanced injection angle have a significant influence on the combustion performance and the

excitation torque applied upon the shafting.
Keywords: Torsional vibration, Speed control system, Advanced injection angle, Coupling
I-INCE Classification of Subject Number: 40

1. INTRODUCTION

Low speed diesel engines are widely used in shipping transportation. With the improvement of the safety standards of diesel engine, the problem of the torsional vibration of crankshaft is receiving more attentions. The major factors of torsional vibration are caused by elastic shaft, large inertia and periodic torque.

On the torsional vibration by coupling model, H. Y. [1] studied on the influencing mechanism of the fuel injection vector on torsional vibration based on the lumped mass method. Results show that the amplitude of torsional vibration can be reduced by adjusting the different injection vectors. A. P. Carlucci [2] established a closed loop system to control the cylinder pressure taking the instantaneous speed of crankshaft as feedback. S. W. Y. [3] established a coupling model between torsional vibration and PID controller of diesel engine and analyzed the effect of control parameters on torsional vibration. X. L. T. [4] established a novel simplified torsional vibration model to study the torsional vibration characteristics of a planetary hybrid propulsion system and accurately described the low-frequency vibration based on the simplified model. The real-time performance of the coupling model can be confirmed. Y. B.G. [5] proposed a coupled simulation model by combining deformable shaft torsional vibration to solve the problems of coupling oscillation in diesel engine. A.P. Carlucci [6] analyzed the reliable relationship between the injection parameter and block vibration based on the signal processing. This study proved the influence of injection parameters on vibration can't be ignored. C. D. L. [7] established a close-loop system using the response of crankshaft to calculate the torsional vibration during the active control of shaft vibration.

In this paper, a coupling model of the low speed diesel engine is established. The influences of different advanced injection angle are analyzed.

2. COUPLING MODEL

2.1 Shafting model

The shaft systems of low speed diesel engine researched in this paper consist of crankshaft, rigid coupling and hydraulic dynamometer. According to the principle of keeping the vibration characteristics unchanged based on lumped parameter method, the shaft system can be instead by a lumped parameter model with 13 inertias and 11 elastic shaft segments. It is shown in Fig.1. The parameters of shaft system are shown in Table 1.

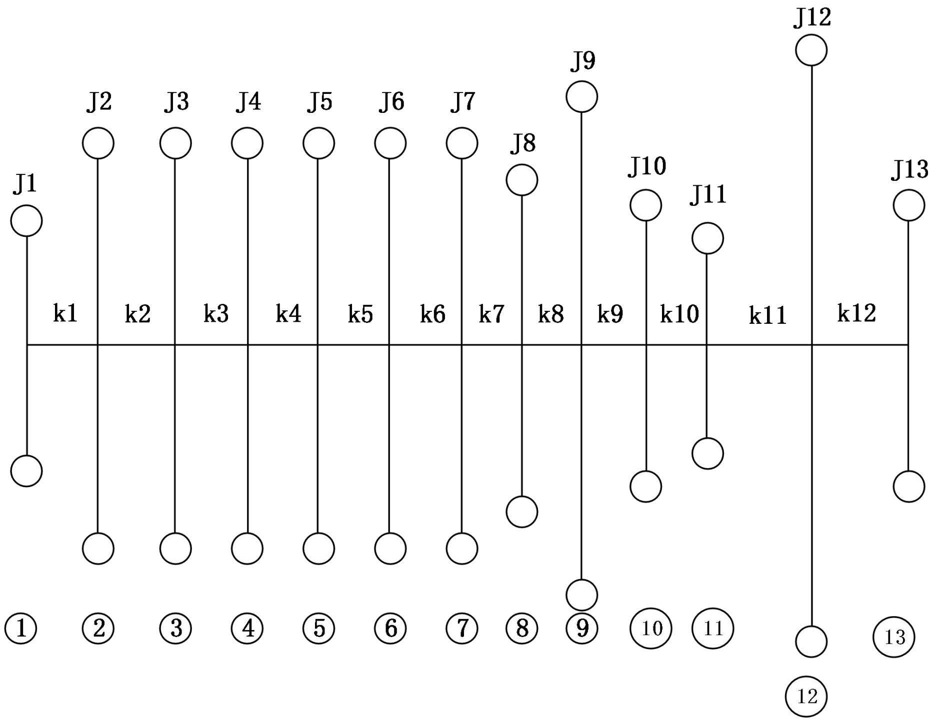

Fig.1 Equivalent shaft system of Low speed diesel engine

Table 1 Parameters of equivalent shaft system

No.	Moment of inertia ($kg \cdot m^2$)	Flexibility($MN \cdot m/rad$)
Inertia J1	1.77E+01	
Stiffness K1		2.3094E-09
Inertia J2	1.1069E+03	
Stiffness K2		3.9682E-09
Inertia J3	1.1061E+03	
Stiffness K3		3.9682E-09
Inertia J4	1.1061E+03	
Stiffness K4		3.9682E-09
Inertia J5	1.1061E+03	
Stiffness K5		3.9682E-09
Inertia J6	1.1061E+03	
Stiffness K6		3.9682E-09
Inertia J7	1.107E+03	
Stiffness K7		2.3149E-09
Inertia J8	2.108E+02	
Stiffness K8		1.1013E-09
Inertia J9	5.8803E+02	
Stiffness K9		1E-12
Inertia J10	9.3587E+01	
Stiffness K10		3.0559E-09
Inertia J11	5.6134E+03	
Stiffness K11		3.4364E-09
Inertia J12	5.0755E+03	

Stiffness K12		3.4364E-09
Inertia J13	4.7575E+02	

In the Fig.2, The No.1 inertia represent flange plate. The inertias from No.2 to No.7 represent the cylinders. No.8 represent the gear system. No.9 represent flywheel and No.10 represent coupling. No.11 to No.13 represent the hydraulic dynamometer.

The equation of free torsional vibration is given as:

$$[J]\{\ddot{\theta}\}+[K]\{\theta\}=0 \tag{1}$$

The form of the solution of the Eq. (1) can be written as:

$$\{\theta\}=\{A\}\cos(\omega t) \tag{2}$$

Substituting the Eq. (2) to Eq. (1), the equation can be expressed as follows:

$$[K]\{A\}=\omega_n{}^2[J]\{A\} \tag{3}$$

Where $[J]$ is inertia matrix, $[K]$ is stiffness matrix, $\{\theta\}$ is instantaneous angular displacement vector of torsional vibration. $\{A\}$ is the static angular displacement vector of torsional vibration. ω_n is the natural frequency of crankshaft.

Using the Eq. (3), the natural frequencies of crankshaft are calculated. The comparison of natural frequencies between test and simulation is shown in Table 2.

Table 2 Comparison of natural frequencies between test and simulation

No.	1	2
Calculating values (Hz)	21.22	46.67
Testing values (Hz)	22.095	47.311
Differences (%)	3.96%	1.35%

The calculation frequencies of the first order and second order agree with the test very well and the differences between them are within 5%. By and large, the natural frequencies of equivalent shaft system and the test natural frequencies are in good agreement. The model of equivalent shaft system is acceptable to be used in the simulation analysis later on.

2.2 Analysis of crankshaft system stability

Due to the simulation model of the shafting system which is a liner multi-input and multi-output system, it is necessary to analyze the crankshaft system stability. According to the theories of state-space method, the state equation shown as follow:

$$\begin{aligned}\dot{x}&=Ax+Bu\\ y&=Cx+Du\end{aligned} \tag{2}$$

Where $A=\begin{bmatrix}0 & 1\\ -J^{-1}K & -J^{-1}C\end{bmatrix}_{26\times 26}$ is system matrix reflecting characteristics of the crankshaft system. $B=\begin{bmatrix}0\\J^{-1}\end{bmatrix}_{26\times13}$ is the input matrix. $C=\begin{bmatrix}I & 0\end{bmatrix}_{13\times13}$ is the output matrix. $D=\begin{bmatrix}0\end{bmatrix}_{13\times13}$ is the directed effect matrix of system. x is the state variable. u is the input variable. y is the output variable. According to the theories of the modern control, the eigenvalues of system matrix having negative real parts, the system is stable; otherwise, the system is unstable. The eigenvalues of the system matrix shown as Fig.2.

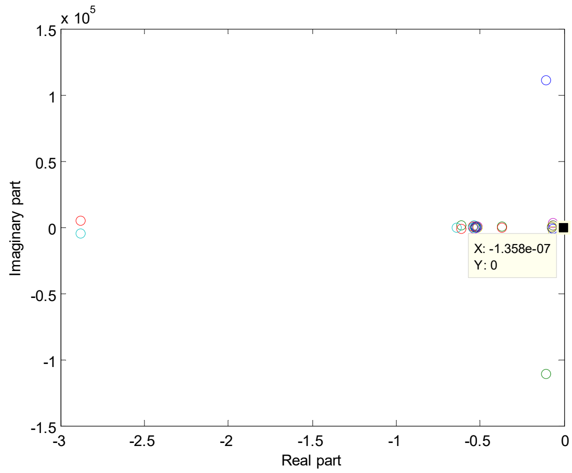

Fig. 2 The eigenvalues of the system matrix

From Fig. 2, all the eigenvalues of the system matrix of low speed diesel engine have negative real parts. It is proves that the system is stable.

2.3 Coupling model of the crankshaft and PID controller

At traditional control model, researchers only considered the influence of PID controller. The flow diagram of the traditional control model shown as Fig.3.

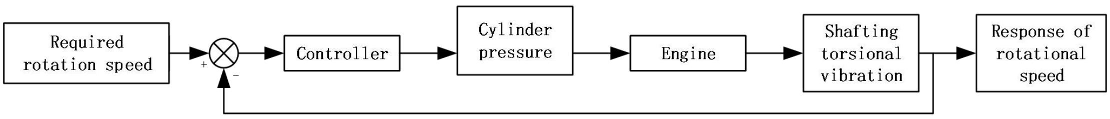

Fig.3 Coupling model of PID controller and crankshaft system

In this research, the influence of advanced injection angle is considered. The flow diagram is shown as Fig. 4.

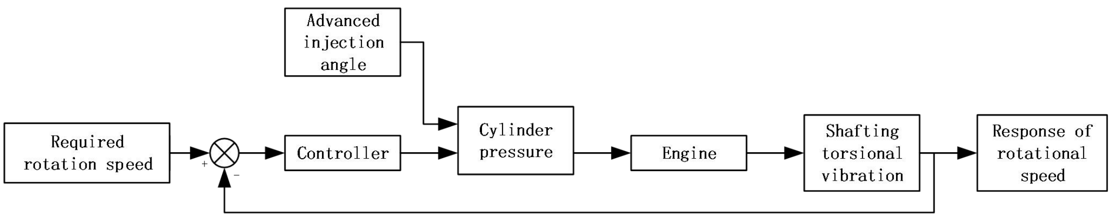

Fig. 4 Structure of considering advanced injection angle system

The coupling is composed of the following parts: PID controller module, cylinder pressure selection module, calculation module of the excitation of torsional vibration and flexible shaft module, which are shown in Fig. 5 to Fig. 8.

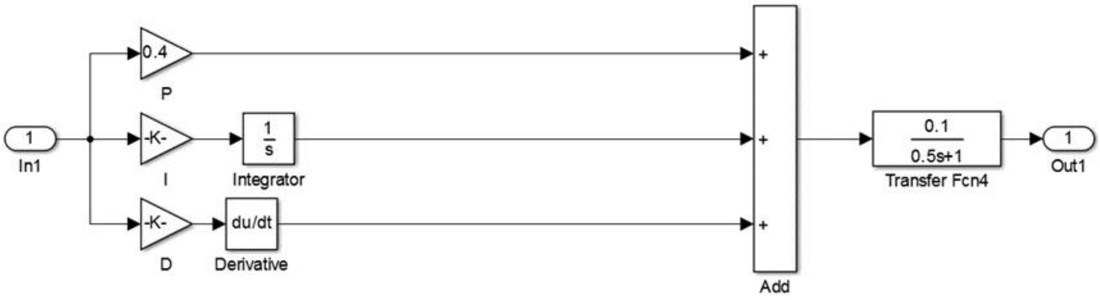

Fig. 4 PID controller module

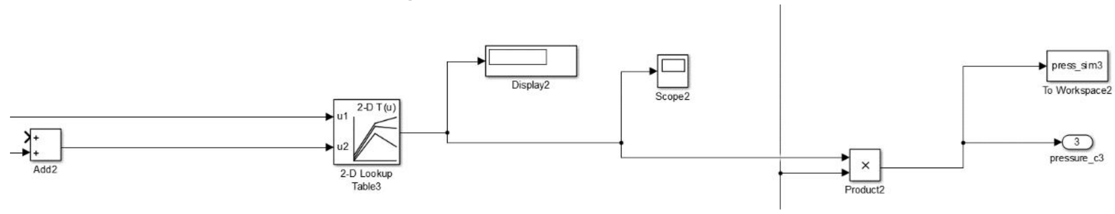

Fig. 5 Cylinder pressure section module

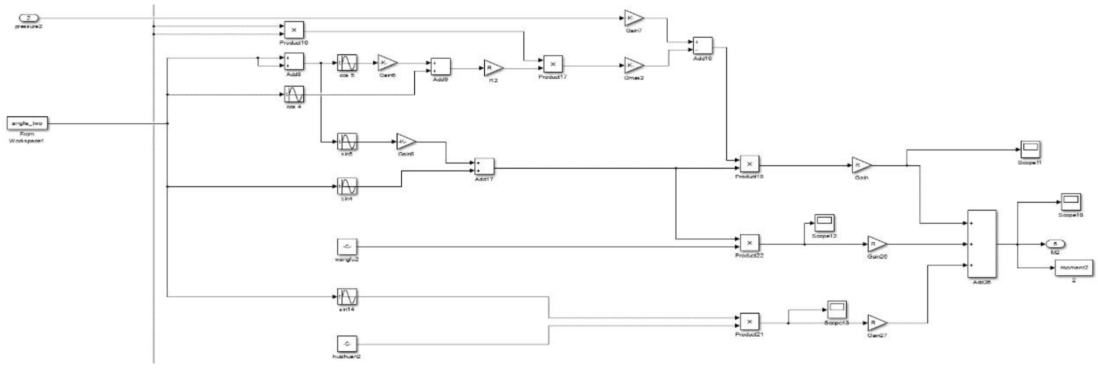

Fig. 6 Calculation module of the moment of torsional vibration

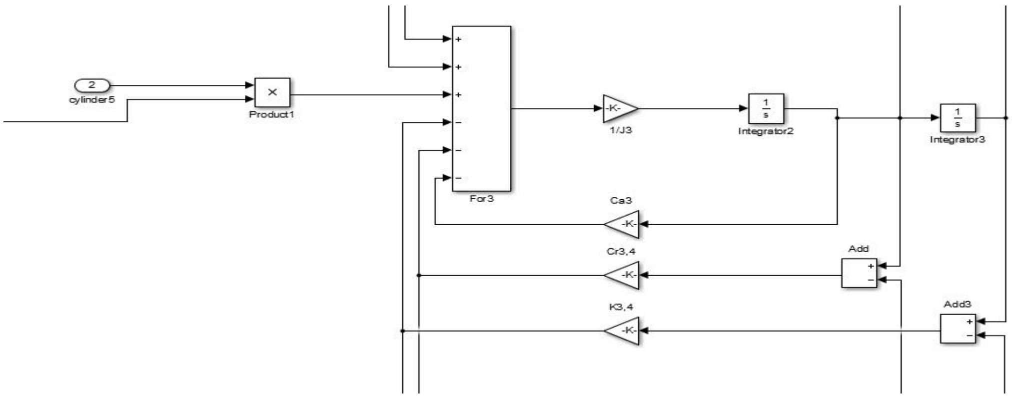

Fig. 7 Calculation module of shaft system

The simulation system process is that torsional vibration and PID controller form a closed-loop calculation system. That is, the signals collected by the speed sensors and passed to the PID controller are actually the derivatives of the angle responses of the elastic shafting torsional vibration. Meanwhile, excitations of torsional vibration affected by advanced injection angle.The new working form shown in Fig. 8.

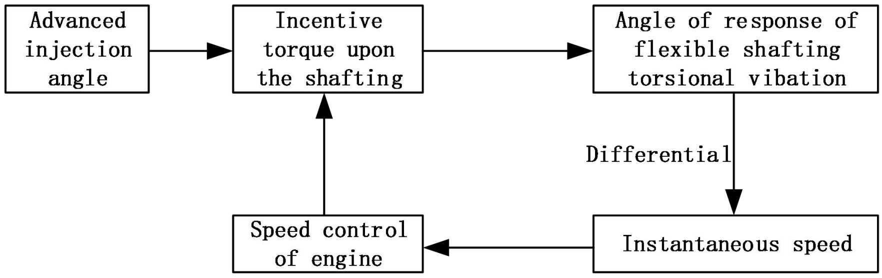

Fig. 8 The process of coupling model

3. COUPLING ANALYSIS

3.1 Initial condition

The rotational speed of the propulsion system with the PID controller parameter and advanced injection angle shown in table 3. The output speed of the engine tend to be stable under self-regulation. Some simulation results are presented, taking inertia 9 (flywheel) as an example, the relative speed is shown in Fig. 9.

Table 3 Initial parameter of the controller

	P	I	D	Advanced injection angle
Values	0.32	0.26	1.54	0

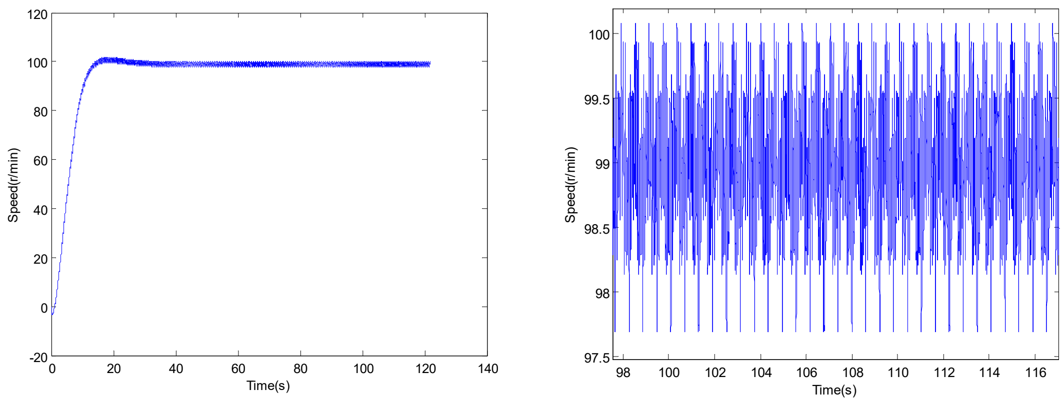

Fig. 9 The relative speed of initial condition

Comparison with the results of test and simulation, the different of amplitude of torsional of 1st order and 2nd order are within 5% which meets the engineering requirement. Hence, the coupled model of crankshaft, PID controller and advanced injection angle is acceptable to be used in the simulation analysis later on. The results shown in Fig. 10.

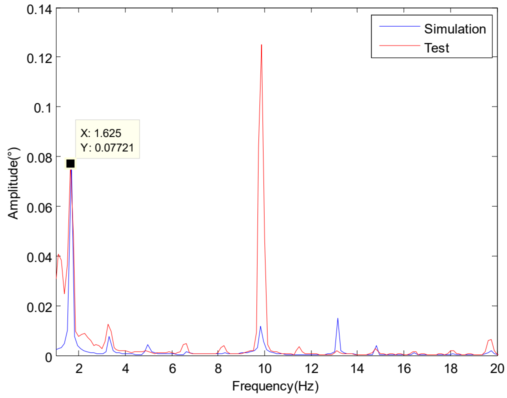

Fig. 10. Comparison with test and simulation of torsional vibration

3.2 Effect of advanced injection angle

3.2.1 The stabilization time of the instantaneous speed

Under the adjustment of the advanced injection angle parameters as Table 4, the varieties of the instantaneous speed are shown in Fig. 11.

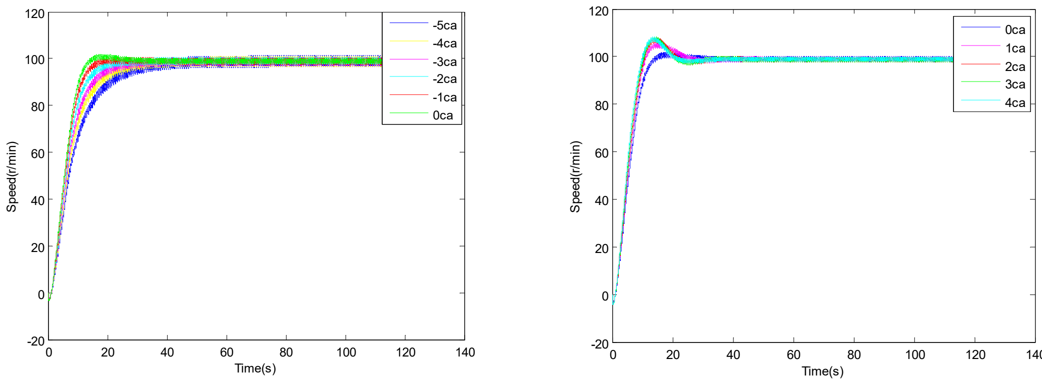

Fig. 11 The instantaneous speed

With the increase of the advanced injection angle, the over control of the instantaneous speed of the crankshaft is showing a trend of increasing. It is expressed that the exaction of the torque changed by advanced injection angle effect on the coupling model. Thus, the stabilization time of the instantaneous speed of the low speed diesel engine can changed by the advanced injection angle and thus changed the torsional vibration of the crankshaft.

3.2.2 Statistical rhythm

The mathematical expectation and the kurtosis of the instantaneous speed of the variety advanced injection angle are shown in Fig. 12 and Fig. 13.

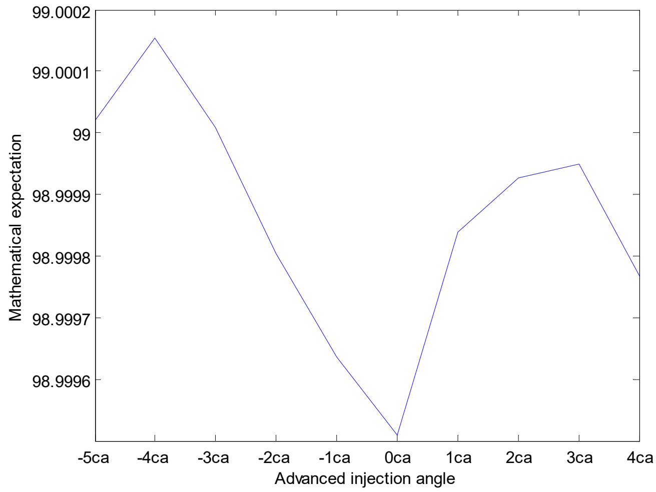

Fig. 12 The mathematical expectation of the instantaneous speed

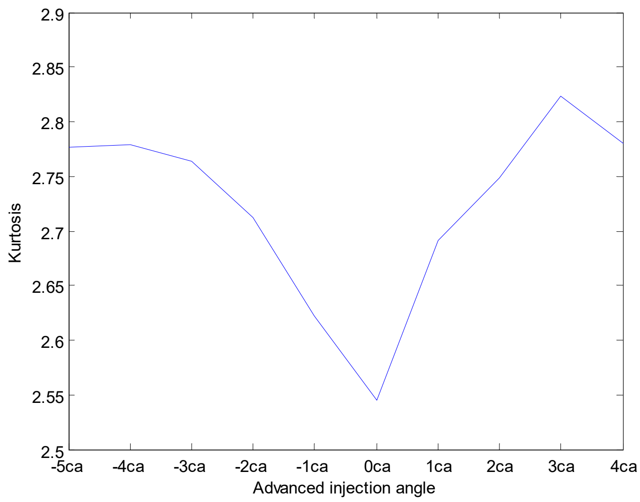

Fig. 13 The kurtosis of the instantaneous speed

From the result varieties of the mathematical expectation and the kurtosis of the instantaneous speed of the crankshaft, the average value and the degree of the data offset is showing a trend of decreasing first and then increasing and the result is optimal at the initial condition.

4. CONCLUSIONS

For analyzing the shafting rotating speed oscillation phenomenon in real engineering, a rotational speed control system model considering the torsional vibration and the advanced injection angle is established in this research.

By analyzing instantaneous speed simulation results of the coupling model under different advanced injection angle, the stable arrival time of the instantaneous speed is optimized.

Researching the statistical rhythm of the results of the coupling model under the different advanced injection angle, there are the optimized value of average value and data offset.

In conclusion, The advanced injection angle should be taken into the coupling model between the speed control system and the torsional vibration of the shafting system during the design of the control system of a low speed diesel engine. How to choose appropriate advanced injection is a vital importance for making sure that the system would safe and stable.

5. ACKNOWLEDGEMENTS

This research was supported by Marine Low-Speed Engine Project-Phase I and National Natural Science Foundation of China (Grant No. 51805106).

6. REFERENCE

[1] Y.H, *Influencing mechanism of fuel injection vector on diesel engine torsional vibration.* Transactions of CSICE. 1000-0909(2012)01-0062-05.

[2] A.P. Carlucci, D. Laforgia, S. Motz, R. Saracino, S.P. Wenzel, *Advanced closed loop combustion control of a LTC diesel engine based on in-cylinder pressure signals*, Energy Convers. Manag. 77 (2014) 193–207.

[3] S. Yu, Y. Liu, X. Han, M. Chen, W. Li, *Coupling analysis of torsional vibration and engine rotational speed control system of marine propulsion shafting*, Internoise 2014. (2014) 1–8.

[4] X. Tang, W. Yang, X. Hu, D. Zhang, *A novel simplified model for torsional vibration analysis of a series-parallel hybrid electric vehicle*, Mech. Syst. Signal Process. 85 (2017) 329–338.

[5] Y. Guo, W. Li, S. Yu, X. Han, Y. Yuan, Z. Wang, X. Ma, *Diesel engine torsional vibration control coupling with speed control system*, Mech. Syst. Signal Process. 94 (2017) 1–13.

[6] A.P. Carlucci, F.F. Chiara, D. Laforgia, *Analysis of the relation between injection parameter variation and block vibration of an internal combustion diesel engine*, J. Sound Vib. 295 (2006) 141–164.

[7] C. Lu, M. Wu, X. Chen, W. Cao, C. Gan, J. She, *Torsional vibration control of drill-string systems with time-varying measurement delays*, Inf. Sci. (Ny). 467 (2018) 528–548.