Vibration damage mechanism analysis on rotor of diesel generating set with rigid coupling

Bing Yan[1], Weizhen Shi, Chunrong Hua, Jingming Liu, Dawei Dong and Jun Chen

College of Mechanical Engineering, Southwest Jiaotong University, China

E-mail: yanbingwd@163.com

Abstract. The crankshaft output end is generally connected with generator rotor through the coupling in diesel generating set. When using rigid coupling, the attachments and connecting parts of generator rotor (especially at larger gyration radius) are vulnerable to fatigue damage even if the vibration level of the generating set does not exceed the acceptable “usual value”. In order to investigate the reasons, the torsional vibration of the rotor in the diesel generating set was calculated and measured in this paper, which shows that using high rigidity coupling would result in large torsional vibration on the generator rotor, and that the linear vibration (the tangential vibration) value induced by torsional vibration at larger gyration radius of generator motor is almost the same as the vibration level of the generating set. Then, the vibration level of generating set was obtained, and the maximum vibration velocities of the generator are below the permissible value regulated by ISO 8528-9. But the velocities of synthetic vibration of the generating set vibration and the linear vibration induced by torsional vibration at larger gyration radius are much higher than permissible value 2(28mm/s) regulated by ISO 8528-9, which may be the reason of the mechanical damage of the attachments and connecting parts at larger gyration radius of generator motor caused by exceeded vibration.

1. Introduction

As the power unit of much mechanical equipment, diesel generating set is widely used in industrial production, traffic and other fields. Therefore the failure of diesel generating set threatens the normal operation of equipment and personnel safety significantly.

There are various generator faults including stator fault, rotor fault , bearing fault and so on [1][2],

[1] No.111, North 1st Section of Second Ring Road, Chengdu, Sichuan province, China

among which the rotor fault is the main fault type[3]. Rotor broken bar and the fracture of end ring are general rotor faults, which will make the generator emitting heat during operation, and lead the guide bar and end ring to suffer cyclic thermal stress and deformation, resulting in further expansion of the fault. The reasons of the generator rotor faults include unbalanced rotor mass, uneven temperature and unbalanced electromagnetic force, which will cause rotor's bending vibration and generator vibration; there are many studies in these areas [4-6]. Diesel generating set has its particularity of uneven tangential torque acting on the engine crankshaft, which may produce obvious torsional vibration on rotor. This can be the reason that the vibration level of a generating set does not exceed the acceptable "usual value", but the fatigue failure of the attachments and connecting parts on generator rotor (especially at larger gyration radius) often occurs, and especially when the output end of the crankshaft is coupled rigidly with the generator rotor in the generating set, generator rotor is more vulnerable to fatigue damage. Therefore in this paper the torsional vibration of the generator rotor in the generating set and its linear vibration characteristics were studied, and its effect on structure vibration of the rotor was investigated combining with examples.

2. Dynamic characteristics analysis of generator rotor torsional vibration for typical generating set

Generally speaking, with the increasing of the number of the cylinders and the length of the crankshaft in diesel engine, the crankshaft stiffness decreases, thereby the crankshaft modal (the nodes are in the crankshaft) frequency decreases, and vice versa. The above two kinds of crankshaft torsional vibration modal characteristics are distinctly different, and the modal natural characteristics and vibration response characteristic of shafting torsional vibration are also different when different stiffness couplings are used to connect the generator, but they all have the generality of larger rotor torsional vibration induced by high rigidity coupling (such as metal diaphragm coupling) in generating set shafting.

2.1. Larger crankshaft rigidity

With the decreasing of the number of the cylinders and the length of the crankshaft in diesel engine, the crankshaft stiffness increases, thereby the crankshaft modal frequency increases. Taking a generating set with a 6-cylinder diesel used in a diesel multiple units of railway locomotive as an example, the engine speed ranges from 900r/min to 1800r/min. The equivalent system diagram of the generating set shafting is shown in Figure 1.

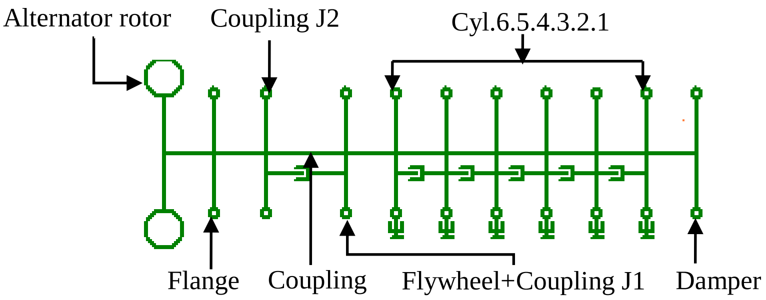

Figure 1. The equivalent system diagram of 6-cylinder engine shafting.

Figure 2 is the curves of the maximum synthesized torsional vibration displacement amplitude (hereinafter referred to as Syn) at crankshaft free end, generator rotor and crankshaft flywheel changing against coupling stiffness. It shows that when using highly elastic coupling (for example, below 0.031 MNm/rad), the torsional vibration amplitude of the generator is small (below 0.066°), and the torsional vibration amplitude of the flywheel and the crankshaft free end is large (about 0.6°).

When using large stiffness coupling, the generator rotor is rigidly connected with the crankshaft, and the torsional vibration response characteristics are mainly determined by roll-vibration [7]. In low speed condition, compared with highly elastic coupling, the main harmonic torsional vibration amplitude of the crankshaft is reduced obviously and that of the generator rotor is increased evidently. It is shown from Figure 2 that the maximum Syn at crankshaft free end decreases significantly (slightly larger than 0.2°) and that of the generator rotor increases greatly (about 0.19°), when using larger stiffness coupling (Supposing the stiffness of the diaphragm coupling is 92.7 MNm/rad), therefore the ability to bear torsional vibration and the induced tangential vibration of the generator rotor should be taken into consideration. The maximum Syn of the generator rotor reaches 0.19°, which means that the larger tangential vibration amplitude may exist at larger gyration radius of the generator rotor. For example, the tangential vibration amplitude induced by torsional vibration may reach 0.83mm at gyration radius of 250mm of the generator rotor, and the effective value of tangential vibration velocity is approximately 166 mm/s, which is significantly larger than usual vibration velocity permissible value of the generator. Therefore the vibration velocity of the generator rotor caused by torsional vibration is relatively larger in this circumstance, and may result in strong excitation on rotor parts, which may possibly make the generator rotor generate strong structural vibration.

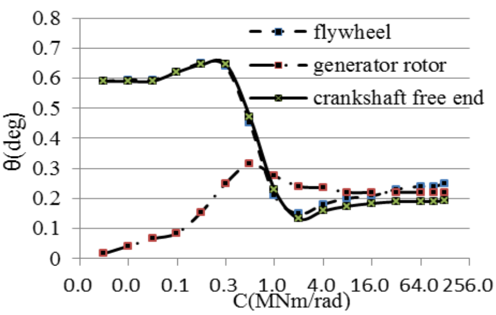

Figure 2. The curves of maximum Syn changing against coupling stiffness.

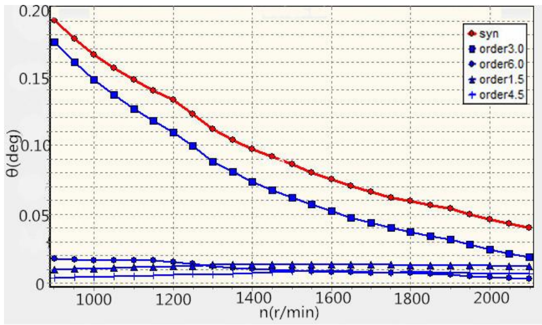

Figure 3. The torsional vibration amplitude of generator rotor changing against speed.

2.2. *Smaller stiffness crankshaft*

For diesel engine with more cylinders and longer crankshaft, the crankshaft stiffness is relatively small, and the effect of using the above two kinds of coupling on torsional vibration characteristic of the shafting is not as obvious as the larger rigidity crankshaft mentioned above, but the natural frequency and response characteristic of torsional vibration coupled modal for crankshaft and generator rotor are affected apparently.

Taking the 3150kW diesel generating set used in railway locomotive as an example, the shafting

Journal of Physics: Conference Series **628** (2015) 012071 doi:10.1088/1742-6596/628/1/012071

mass-elastic system model is shown in Figure 4. A measurement and calculation is carried out for the torsional vibration of the shafting.

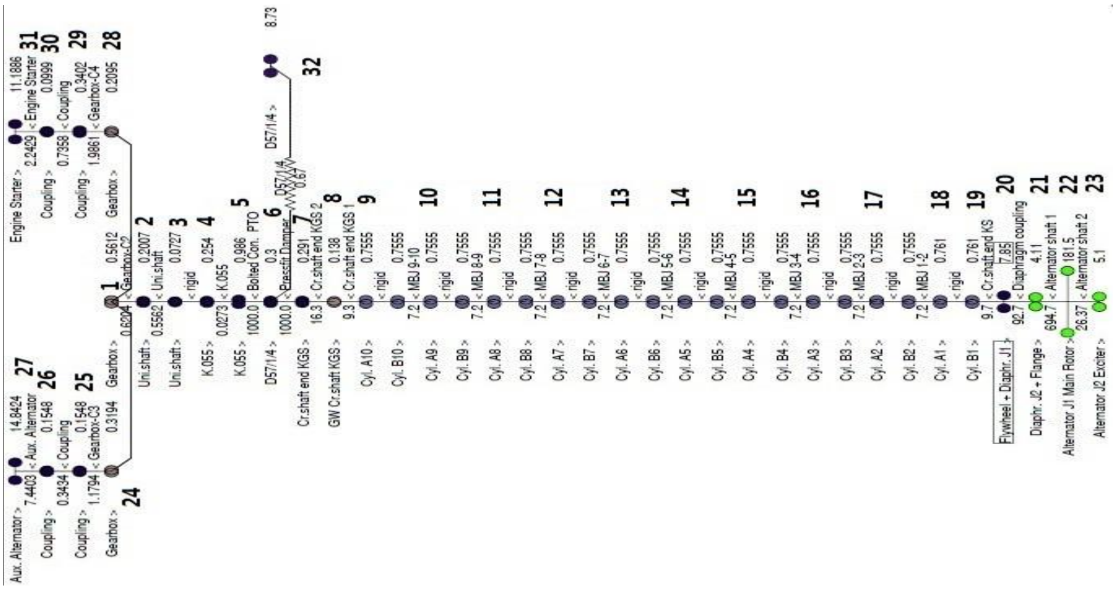

Figure 4. The mass-elastic system diagram of crankshaft for a locomotive generating set.

Figure 5 is the resonance speed diagram of the shafting using higher stiffness diaphragm coupling (the stiffness of the diaphragm coupling is 92.7 MNm/rad). Calculations and analysis for the shafting show that the third order modal is the coupled modal between the crankshaft and the generator rotor through diaphragm coupling. The resonance speed of the 2.5 order and 1.5 order engine excitations corresponding to the third order modal (1757/60=29.3Hz) of the shafting is 703r/min and 1171r/min respectively. Figure 6 is the measurement results of torsional vibration at the generator end, which shows that the resonance arising from the interaction of the 2.5 and 1.5 order engine excitations and the third order modal of the shafting appears apparently on the generator rotor.

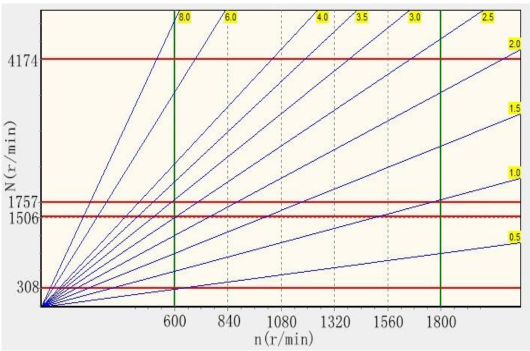

Figure 5. The resonance speed diagram connected with diaphragm coupling.

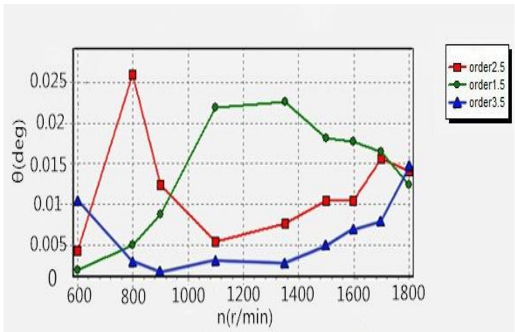

Figure 6. The measurement results of torsional vibration at the generator.

The maximum Syn at crankshaft free end, generator rotor and crankshaft flywheel changing against the coupling stiffness could be obtained from further calculation for the torsional vibration (as shown in Figure 7). The figure shows that the vibration amplitude of the generator rotor is large when using high stiffness coupling (above 1.44 MNm/rad). The torsional vibration amplitude of the generator rotor will reduce along with the decreasing of coupling stiffness (below 1.44 MNm/rad).

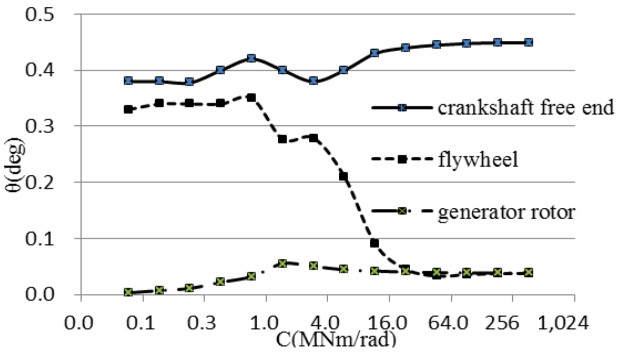

Figure 7. The curves of maximum Syn changing against coupling stiffness.

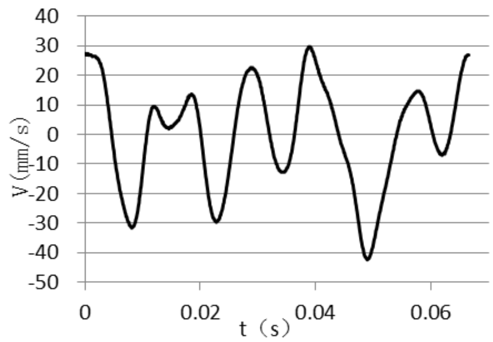

Figure 8. The linear vibration curve induced by torsional vibration in radial 250mm position of generator rotor.

Selecting the maximum torsional vibration working condition from Figure 6 and calculating the generator vibration, the linear vibration induced by torsional vibration in radial 250mm position of generator rotor is shown in Figure 8, in which the effective value is 18.0mm/s, almost the same vibration level with the generating set.

In summary, although the torsional vibration modal characteristics of the shafting is different, it is a general character that using large stiffness coupling may lead to large torsional vibration on rotor and the linear vibration (tangential vibration) induced by the torsional vibration at larger gyration radius of generator rotor reaches the same level with the vibration of the generating set.

3. Vibration analysis for the generating set

3.1. The measured results

The 3150kW diesel generating set used in diesel locomotive comprises a 20-cylinder diesel engine (20V4000R53) and a generator (CDJF201L), and the generating set is connected with the locomotive body through eight rubber isolators, among which six isolators are on the diesel engine and two are on the generator. The structure of the generating set is shown in Figure 9,

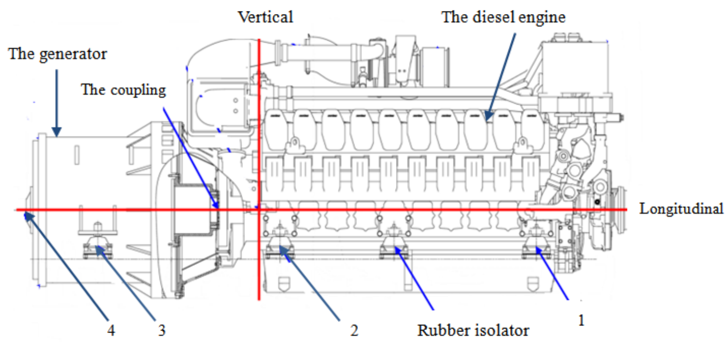

Figure 9. The structure schematic of the generating set.

The experimental results show that the vibration value of the generating set reaches the maximum in the condition of 1800r/min and 3150kW. The number and the position of measuring points are shown in Figure 9 and the effective values of three-dimensional vibration velocities are shown in Table 1. The experimental results above are provided by the MTU Company.

Table 1. The measured vibration velocity of the generating set.

NO.	Measuring Point	Effective Value of Vibration Velocity（mm/s）		
		Vertical	Transverse	Lateral
1	Upper Edge of Crankshaft Free End Bearing	21	15	21
2	Upper Edge of Drive End Bearing	15	15	17
3	Upper Edge of Generator Bearing	21	15	18
4	Back End of Generator Stator	21	16	13

It can be seen from Table 1 that the effective values of vibration velocity of measuring points on the generator are below the permissible value 2 (28mm/s) regulated by ISO 8528-9.

3.2. The calculated vibration results of the generating set

The calculated vibration results of the generating set in the condition of 1800r/min and 3150kW through a six degree-of-freedom model of the generating set with eight isolators are in consistent with the measurement results. The calculated effective values of lateral and vertical vibration velocity of the measuring points on the generator are below the permissible value 2 (28mm/s) regulated by ISO 8528-9.

4. The synthesized results of the generating set vibration and linear vibration induced by torsional vibration

From above measurement and calculation results, we know that the vibration level of the generating set meets the standards, but the attachments and connecting parts at larger gyration radius of generator rotor are locations where structural damage initiates in practical operation, which may be caused by the combination action of the generating set vibration and the linear vibration induced by torsional vibration. Therefore the following paper synthesizes the vibration of the generating set and the linear vibration induced by torsional vibration in radial 250mm of generator rotor, and analyzes its actual vibration condition(as shown in Figure 10).

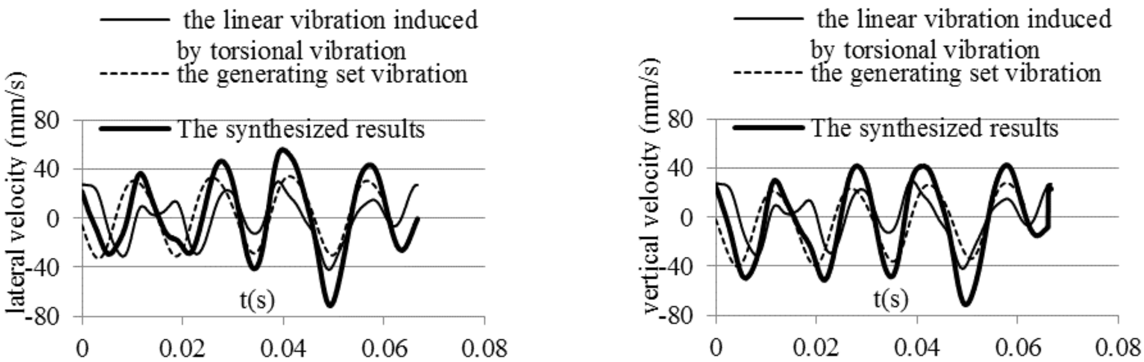

Figure 10. The synthesized results of the generating set vibration and the linear vibration induced by torsional vibration in in radial 250mm of generator rotor.

The calculation results show that the effective values of lateral vibration velocity at gyration radius of 250mm of the rotor is 30.98mm/s, the effective value of vertical vibration velocity is 32.05mm/s, exceeding the maximum vibration velocity value 2(28mm/s) regulated by ISO 8528-9, which will make the generator rotor and connecting parts be subjected to excessive vibration and appear structural failure; the normal operation of generator will be affected, accordingly.

5. Torsional vibration control of the generating set rotor

From the analysis mentioned above, we know that the structural damage commonly initiates at the attachments and connecting parts where the gyration radius of generator rotor is larger, which is possibly caused by the combined action of the generating set vibration and the linear vibration induced by torsional vibration. Under the condition that the generating set vibration is difficult to be reduced further, it is another method to reduce the structural damage of generator rotor through controlling torsional vibration on generator rotor of the generating set for the purpose of reducing the influence of torsional vibration on the rotor.

From Figure 7, we can see the reduction of coupling stiffness (below 1.44 MNm/rad) is apparently favorable for the decreasing torsional vibration amplitude of the generator rotor. On the premise of ensuring transmitting required torque for the generating set shafting, the coupling is replaced with a Geislinger elastic coupling (its stiffness is 0.51MNm/rad). Results show that the natural frequency of coupled modal of the crankshaft and generator rotor is obviously decreased with the high elastic coupling; the resonance speed diagram of the first four modal is shown in Figure 11. Further calculations and analysis show that the second order modal is the coupled modal between the crankshaft and generator rotor through diaphragm coupling. The resonance speed of the 1.5 and 1.0 order engine excitations corresponding to the second order modal (1104/60=18.4Hz) of the crankshaft is 736r/min and 1104r/min respectively. The measurement results of torsional vibration are in accordance with the above calculation on the aspect of general rules. The Figure 12 shows that the resonance arising from the interaction of the 1.5 and 1.0 order engine excitations and the second order modal of the shafting appears on the generator rotor.

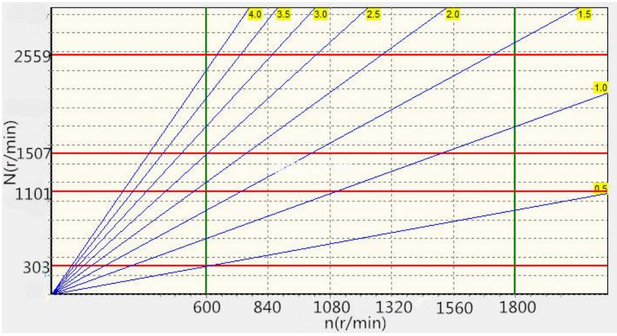

Figure 11. The resonance speed diagram with high elastic coupling.

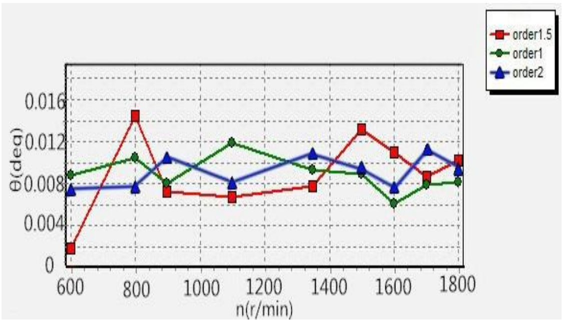

Figure 12. The measurement results of torsional vibration at the generator.

Selecting the condition of maximum torsional vibration from Figure 12 to calculate, the effective value of the linear vibration caused by torsional vibration in radial 250mm position of generator rotor is decreased to 7.5mm/s, and by 58.3% compared to the unimproved structure.

When the shafting are connected by highly elastic coupling, through synthesizing the linear vibration caused by torsional vibration (tangential vibration) at radial 250mm position of generator rotor and the generating set vibration, it can be calculated that the effective value of lateral vibration velocity at gyration radius of 250mm is 23.21mm/s, and the effective value of vertical vibration velocity is 24.24mm/s, falling in between the value 1 (20mm/s) and 2 (28mm/s) regulated by the ISO

8528-9, satisfying the standard demands. When using highly elastic coupling, the fault rate of the generator rotor decreases in practical engineering application.

6. Conclusion

Combining with the examples, this paper studied the characteristic of the torsional vibration and linear vibration of generator rotor when the generating set uses rigid coupling, and discussed the influence on the structure vibration of the rotor. Conclusions which have a certain guidance and reference value for coupling selection for the generating set and the strength design for accessories and the connecting parts on generator rotor, are as follows:

1) Although different types of diesel engine crankshafts have markedly different torsional vibration modal characteristics, but they all have the generality that using high rigidity coupling would result in large torsional vibration on the generator rotor.
2) When using high rigidity coupling, the linear vibration (tangential vibration) value caused by torsional vibration at larger gyration radius of the generator rotor is equivalent to the vibration level of the generating set. The synthesized vibration of the generating set vibration and the linear vibration caused by torsional vibration maybe the mechanical damage reason of the attachments and connecting parts at larger gyration radius of generator motor because of the exceeded vibration.
3) Under the condition that the vibration of the generating set is difficult to further reduced, through controlling the torsional vibration of the generator rotor to reduce the influence of the torsional vibration on the generator rotor, it is a feasible method to reduce the structure damage to the generator rotor.

References

[1] Iasmotor Reliabitity Working Group. 1985 Report of Large Motor Reliability Survey of Industrial and Commercail Installations-Part I [J].IEEE Trans on Ind.App Ⅰ. 21(1):853-64
[2] Subhasis N, Hamid A. T and Xiaodong Li. 2005 Condition Monitoring and Fault Diagnosis of Electrical Motors—A Review[C]. IEEE Transactions On Energy Conversion, 719-729
[3] Tongguang Yang and Xinhua Jiang. 2010 Research and Development Trends of Induction Motor Fault Diagnosis[J]. *Micromotors Servo Technique*,43(4) 68-69
[4] Lijuan Zhang,Xinhua Yang,Chengxia Ma and Hongwei Wang. 2009 Remedy on Vibration of Turbogenerator Due to Thermal-caused Bending of Rotor[J]. *Large Electric Machine and Hydraulic Turbine*, 4(4)
[5] Xueshi Yao and Chunlong Zheng. 2014 Research on Bending Vibration of a Rotor Based on Spin Softening[J]. *Turbine Technology*, (2)
[6] Xiongqing Li,Shi Liu,Yongxin Feng,Xiaowen Deng,Fei Wang and Weimin Que. 2011 Diagnosison on Vibration Problem of Generator with Bending Rotor[J]. *Journal of Vibration,Measurement & Diagnosis*, 31(2)
[7] Bing Yan,Meiyun Sun,Yumei Li,Xiao Li and Chunrong Hua. 2006 The Single Order Quasi Rigid Body Model of Torsional Vibration Diagnosis for ICE Crankshaft[J]. *Chinese Internal Combustion Engine Engineering*, 27(4)： 62-65