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중형급 고속 터보차저의 로터다이나믹 안정성 및 비선형 거동 특성

Rotordynamic Stability and Nonlinear Behavior Characteristics of a Mid-Class High-Speed Turbocharger

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1. INTRODUCTION

A turbocharger is a rather simple but sophisticated class of turbomachine. It is often found as an engine component in diesel and gas engines, which are used as prime movers in marine and land transportation applications. Its rotordynamic reliability and aerodynamic performance designs are very sophisticated and often challenging as it runs far over 2 times of its first whirl natural frequencies and a customer requires a world-class higher overall efficiency for the maximum engine output and the lowest fuel consumption. Johnson [1] reported survey results of the market place for the turbochargers of the 1990s for two to four-cycle engines in 600 to 13,000 kW ranges and set up some design objectives such as the improved overall efficiency, high reliability and others. Pettinato and DeChoudhury [2] discussed the redesign of a high-speed turbocharger for diesel locomotives, especially, for improved bearing life and rotordynamic stability. They redesigned the two journal bearings by changing from an original 3-axial groove bearing design to a 3-lobe bearing design and used the linear LogDec (logarithmic decrement) evaluation method [3] to check the stability of turbocharger rotor-bearing system. Sahay and LaRue [4, 1996] discussed their experience, showing that turbochargers can run satisfactorily with a limited amount of bearing instability provided that the whirl orbit of rotor-bearing system, the limit cycle, does not exceed a certain percentage of the bearing clearance space. San Andres et al. [5] applied the nonlinear analysis method, incorporating complete nonlinear bearing forces and a time-marching numerical integration scheme. In this study rotordynamic linear and nonlinear stability characteristics of a medium-size high-speed turbocharger are analyzed, especially, to evaluate the effects of journal bearing design variables. The rotor of radial turbine and compressor impellers, having the rated speed of 40,500 rpm and maximum continuous speed of 45,000 rpm, is supported by two 3-lobe journal bearings.

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2. ANANYSIS RESULTS AND DISCUSSIONS

2.1 Models and conditions

Figure 1 shows an outline and equivalent FE rotordynamic model of a medium-size 1,500 kW class turbocharger rotor for diesel engines, having a total mass of about 20 kg. The supporting 3-lobe journal bearing whose reference design variable values are a machined clearance of 50 μm and a preload of 0.5. The lubricating oil is SAE 10W-50, having about VI 120 and its inlet temperature is 40°C.

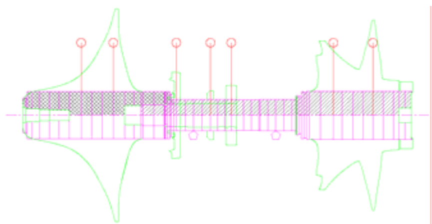


Fig. 1 Outline and equivalent FE rotordynamic analysis model of a medium-size 1,500 kW class turbocharger rotor for diesel engine applications

2.2 Basic analysis

For the reference bearing design, Campbell diagram of the rotor-bearing system, obtained by applying the linear dynamic coefficients of the bearings. The rotor has practically one critical speed at 18,359 rpm whose LogDec is 0.51 as the other has a LogDec of 3.21. Besides, at the rated speed of 40,500 rpm, the rotor has the first whirl natural frequency of 16,182 rpm. Thus, the rated speed is higher than 2 × the first whirl natural frequency. Unbalance response of the rotor-bearing system, calculated with a total of G5.0 unbalance (30% attached at the compressor impeller and 70% at the turbine impeller). The vibration levels are very minimal at the rated speed as they are all less than 1 μm (Pk.-Pk.), where they are designated by nodes #27 and #39 in the figure. On the other hand, stability diagram of the rotor-bearing system is shown in Fig. 2 as a function of rotating speed. It is observed that the first whirl natural frequency starts to have a negative LogDec at about 30,000 rpm and has a LogDec of -0.41 at the rated speed, which is relatively high and more than worrisome.

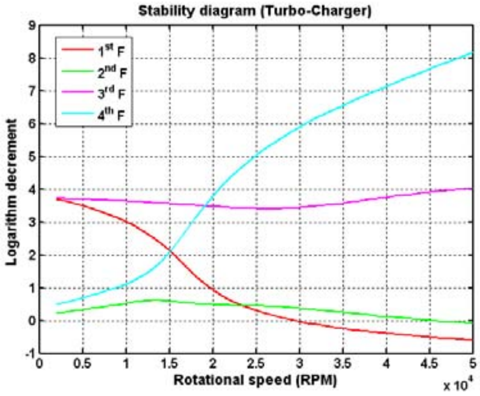
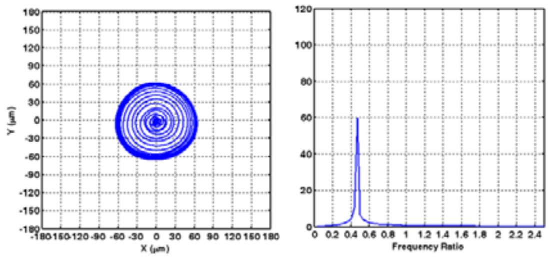


Fig. 2 Stability diagram of the turbocharger rotor for the reference bearing design

From the above, the separation margin of critical speed and unbalance responses of the rotor-bearing system are quite satisfactory. But the linear stability analysis shows that the rotor system may fall into unstable and unsatisfactory run at much earlier than the rated speed. Therefore, the dedicated design efforts to make the rotor system more stable in the linear sense and the nonlinear analysis approach to predict and check the rotor behavior supported by the journal bearings with nonlinear characteristics should be performed.

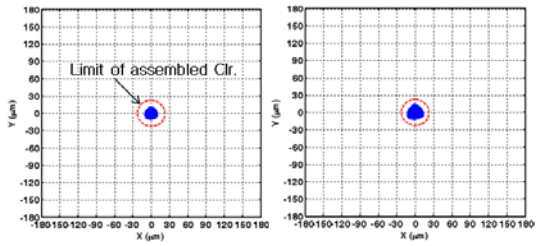
2.3 Nonlinear stability analysis

Analysis results with a machined bearing clearance of 45 μm and a preload of 0.5 - the case identified as unstable with a LogDec of -0.29 by the linear analysis. The transient response, calculated at the rated speed of 40,500 rpm with a total of G5.0 unbalance (30% attached at the compressor impeller and 70% at the turbine impeller), are discussed first. The response at the turbine impeller position, which grows from 0 to the limit cycle with a radial magnitude of around 60 μm, is shown in Fig. 3(a) while the frequency ratio, with respect to a rotating speed, of the limit cycle is shown in Fig. 3(b). The frequency ratio is a little less than 0.5, which indicates the bearing-induced instability, i.e., oil whip. And the responses at the compressor and turbine bearing positions are shown in Fig. 4(a, b). Their limit cycle magnitudes are 48.7 and 63.2 %, respectively, with respect to an assembled bearing clearance, whose frequency ratios are all the same as that at the turbine impeller position, of course. It should be mentioned that noticeably the shapes of the limit cycles resemble the contour shape of the 3-lobe bearing.



(a) **(b)**

Fig. 3 (a) Transient response at the turbine impeller position at the rated speed with G5.0 unbalance and (b) frequency ratio of the limit cycle: the unstable case



(a) **(b)**

Fig. 4 Transient responses (a) at the compressor bearing and (b) the turbine bearing positions at the rated speed with G5.0 unbalance: the unstable case

3. CONCLUSIONS

In this study rotordynamic linear and nonlinear stability characteristics of a medium-size high-speed turbocharger have been analyzed to evaluate the effects of journal bearing design variables, where the rotor is supported by two 3-lobe journal bearings. The nonlinear analysis results have shown that as the instability thresholds are far less than the rated speed, the limit cycles at the rated and maximum continuous speeds are not different too much and also that when the system instability is large enough, the limit cycle is independent on an amount of unbalance applied. For the turbocharger rotor-bearing system considered, the 3-lobe journal bearing design with a smaller assembled clearance and a larger preload, e.g., 45 μm and 0.6, have been analyzed as preferred for the stable response. More importantly, since it has been found that there exists a good correlation between the linear and nonlinear stability analysis results, it is concluded that firstly the linear stability analysis method may be applied to screen quickly the ranges of bearing designs for stable or least unstable solutions and then, finally the nonlinear stability analysis method may be deployed to check an absolute motion stability in terms of the limit cycle.