As the technical requirements from the market are getting severer, the analysis of shaft systems including the bearing, shaft, housing and peripheral structures has become important. JTEKT has developed its own system analysis software that engineers can utilize in daily design work. While used mainly for static rigidity analysis and bearing life calculation, this software may also be used for power transmission calculation, vibration analysis, bearing rotational torque calculation, and thermal analysis. Combined calculation and analyses are also possible with this software. This report presents the analysis capability of this analysis software for the shaft systems as well as analysis examples.

Key Words: shaft system, thermal analysis, vibration analysis, static analysis, combined analysis

1. Introduction

CAE (Computer Aided Engineering) is an indispensable tool for product design and widely used in every sector of the industry. In research & development and design of bearings and bearing related products, CAE has contributed to upgrading the level of analysis and shortening the lead time of the product development process.

As the requirements from the market become increasingly severe and more sophisticated, the conventional method of analysis of the bearing itself can no longer provide sufficient results and data, and therefore the analysis needs to cover the total shaft system including bearing and housing. FEM analysis software available in the market can analyze a detailed model of the shaft system, but it needs professional skills for making the analysis model and a long time for analyzing itself because a lot of non-linear contacts exist inside rolling bearings. Therefore, engineers specialized in analysis are in charge of such work.

In view of this situation, new analysis software for single shaft systems that combines the elastic contact theory of bearing and FEM beam element has been developed and used for analyses in automotive and industrial applications. Even design engineers can operate this software as a daily tool for shaft system analysis. In addition, exclusive GUI (Graphical User Interface) has recently been developed. This interface makes it possible to easily analyze multiple shaft systems and is now available to all design engineers at JTEKT and its affiliated companies.

This software is used mainly for analyzing static rigidity and calculating bearing fatigue life. But it also contains a series of programs developed by JTEKT for calculation of power transmission, vibration analysis, calculation of bearing rotational torque, thermal analysis, and calculation of contact pressure distribution on the surfaces of rollers and raceways. This software makes it possible to select any of the analyses and calculations and to combine them (Fig. 1). If properties of the housing or the shaft of the FEM analysis model are compressed into the necessary nodal point only, for example, the position of bearings by FEM, the housing or the shaft can be used as a FEM analysis model in this analysis software for shaft systems and the analysis can be made within an allowable time frame.

This report presents the structure of this analysis software for shaft systems and examples of the analyses.

Fig. 1 Structure of analysis software for shaft systems
2. Analysis of Static Rigidity and Calculation of Bearing Fatigue Life

Automotive and industrial transmissions tend to be designed, aimed at lightweight, compactness and high efficiency for less fuel consumption. Variable speed units such as dual clutch transmission (Fig. 2) that have a more complicated structure than conventional transmission is becoming more common. For bearings mounted in such a new transmission unit (especially where the bearings are mounted on multiple shafts), it is important to analyze the system rigidity; the above-mentioned analysis software for shaft systems works effectively to this end. With transmissions, it is necessary to make analyses on multiple loading patterns for different power transmission paths and for different rotational directions of the input shafts. This shaft system analysis software can analyze the static rigidity for each of the loading patterns at once so as to determine the loading state of each bearing, resulting in an immediate calculation of the bearing life. This leads to the best selection of bearings for the customer’s requirements, thus contributing to reduction in size and weight of the unit. If the lubrication conditions are given, it is also possible to calculate the thickness of the EHL oil film between rolling elements and raceways; bearing rotational torque under loaded condition as well as adjusted fatigue life of bearings after taking into consideration the life adjustment factors, \(a_{23}\) and \(a_{\text{ISO}}\). Furthermore, upgrading the accuracy of bearing life prediction and predicting the torque loss attributable to the bearings in the system units will contribute to compactness, lightweight and less torque loss for designing bearings and system units lighter.

3. Vibration Analysis

When the natural frequency corresponds to the rotational speed of a shaft system, resonance occurs and the vibration amplitude increases. Consequently, it is important in this sense to accurately predict the relationship between the natural frequency and the rotational speed. Another important thing is to accurately predict response vibration displacement and loads when unbalanced load and forced vibration from the outside occur.

Bearing stiffness is generally not linear to shaft rotational speed and displacement. The analysis software for shaft systems calculates the equilibrium state through the static rigidity analysis, turns it into a linear form, and thus deals with micro vibrations close to the equilibrium state.
Combined Analysis of Temperature, Rigidity and Vibration in Shaft System

As methods of vibration analysis, within the scope of linear form, there are a transmission matrix method and a finite element method. Here used is the finite element method to calculate dynamic characteristics of the shaft system. Figure 3 is an example of vibration analysis under unbalanced load applied to the compressor and turbine blade of turbocharger. Figure 3 (b) shows the relationship between the rotational speeds and the natural frequencies; their overlap indicates critical speeds. Figure 3 (c) shows the response vibrations at the point of measurement on the housing as well as at the gravitational centers of the turbine and compressor blade under the unbalanced load of rotor. This suggests that the gravitational center of the turbine blade and the response vibrations at the point of measurement on the housing peaks when the rotor speed ranges between 1 600 Hz and 1 850 Hz.

4. Thermal Analysis

Friction exists at contact areas between mechanical components like bearings. When relative movements occur between these components, heat is generated, causing temperature rise of the system units where the components are used. The temperature varies more widely as load and/or rotational speed increase, which has significant influence on the system units, especially for machinery requiring high rotational accuracy like machine tools.

Thermal speed rating has been adopted as a new international standard defining the rated rotational speed of bearings. It defines the rotational speeds at which the temperature of the bearings reaches 70°C under specified running conditions as the thermal rated rotational speeds.

The necessity of thermal analysis is now self-explanatory. Based on the thermal analysis method described in the document by Harris5, JTEKT has developed a new thermal analysis program for the system units, which is incorporated in the analysis software. It has simplified the configuration of housings and shafts used in the analysis software for shaft systems.

An example of the thermal analysis applied to the test equipment is shown in Fig. 4. Figure 4 (b) shows the measured temperatures, and Fig. 4 (c) shows the calculated temperature values. The calculated values show that the difference in temperature between the points of measurements is small. The errors were about 15% at the housing points and less than 10% at the other points. This is a simple model of analysis but it provides sufficient data for having a rough idea of the temperature distribution.
5. Combined Analysis of Temperature, Rigidity and Vibration

By using the method described in the previous section, heat generation of the bearings, heat radiation from peripheral components and heat conduction/heat transfer in the system units can be defined. Then, by analyzing the heat balance, the temperature at each of the points can be known. But as the temperature varies, the dynamic viscosity of the lubricant and the pre-load of the bearings also vary, resulting in a change in heat generation (bearing rotational torque). With the analysis software for shaft systems, a group of analysis programs has been controlled to calculate temperature distribution of the system units and bearing rotational torque by repeating thermal analysis, static rigidity analysis and calculation of bearing rotational torque. This analysis software also makes it possible to make a vibration analysis using the rigidity calculation results of the shaft systems in the given temperature distribution.

Machine tool spindles are required a performance of high rigidity (high accuracy) and of high-speed rotation. For bearings, high pre-load is an answer to high rigidity, but as the pre-load increases, the bearings are likely to generate more heat and this increases the risk of bearing seizure at high rotational speed. By making a combined analysis of temperature, rigidity and vibration as explained above, the best selection of bearings along with optimum pre-load setting can be made, and predicting the critical speeds of the spindles allows the optimum design of the system units.

6. Conclusion

In this report, analysis technology for shaft systems was discussed. Reliable and speedy work is required in current product development, and this technology has supported JTEKT in keeping a high level of technical review at the bearing design stage with a short lead time. Further efforts will be made at JTEKT to improve the prediction accuracy based on the analysis results and to upgrade the level of analysis technology to achieve analysis technology with higher reliability through accumulation of analysis data for various application fields including automotive and other industries.

References

3) ISO281: 2007
4) ISO15312: 2003