CHAPTER 8

Conclusions

For rotating machines with relatively long flexible rotors there may be axial location where small clearances exist between the rotor and stator. If the deflection of the rotor due to vibration exceeds the clearance space then rotor-stator contact will occur and this may lead the machine to malfunction or cause damage. By using active vibration control methods it may be possible to influence dynamic behaviour during rub so that damaging response behaviour is prevented.

8.1 Test Rig and Mathematical Model

A test rig was designed and built to represent a typical rotating machine with flexible rotor and compliant stator in order to investigate response behaviour and implement and evaluate proposed controllers. The design speed range of the rotor was 0-6,000 rpm (0-100 Hz). An active magnetic bearing was used to apply control forces to the rotor, and could also be used to excite vibration of the rotor. A rotor-stator interaction mechanism was placed in a separate plane and involved a circular surround supported by four thin horizontal rods, the length of which could be varied in order to change the support stiffness. The system was designed to reproduce both rotor-stator coupled whirl response behaviour with and without influence of friction at the location of contact. The control approaches investigated in this research need a device which can measure rotor-stator contact forces and so an interaction force sensing device was designed and fitted within the stator unit.

A dynamic model of the rotor was identified using an identification method known as peak-picking. The stator model parameters were obtained by measuring the free vibration due to impact force. A full state space model of the system was constructed involving a combination of linear dynamic models of the rotor and stator parts. A non-linear interaction model was considered in the form

$$\mathbf{f} = -\kappa(\|\mathbf{q}\|)\mathbf{q} \tag{8.1}$$

where **f** is the rotor-stator interaction force, **q** is the contact penetration and κ is an effective stiffness coefficient, the value of which can vary with the degree of penetration, thereby allowing for non-linear compliance effects.

8.2 Rotor-Stator Coupled Whirl without Significant Friction

Rotor-stator interaction on the test system was found to lead to a coupled whirl vibration that persisted over a wide interval of rotational speeds even for low excitation from unbalance. Within this interval, jump transitions between alternative low amplitude contact-free and high amplitude response involving continuous rub were possible.

Two vibration stability prediction approaches, which are Nyquist stability approach and Lyapunov based approach, were investigated. The Nyquist stability approach is based on the frequency response function of the rotor-stator structure. Another approach is a Lyapunov based approach which leads to stability conditions in the form of LMI constraints. The Lyapunov stability condition must be combined with other constraints that relate to the characteristics of the interaction model (8.1). In order to treat the nonlinear function within this LMI-based stability analysis the stiffness κ was assumed to be bounded according to $0 \leq \kappa(\|\mathbf{q}\|) < k$. Using this approach, parametric boundaries for a contact-free orbit solution to be globally stable can be obtained.

An active vibration control method was proposed involving dynamic force feedback. The input signals to the controller were the measured rotor-stator interaction forces while the output signals were the forces applied to the rotor through the magnetic bearing. The controller dynamics were accounted for in a synthesis method based on a closed loop system model and a global stability condition for a contact-free orbit. Controller solutions were obtained by using a standard LMI solver in Matlab. The controller was implemented and shown to be successful in preventing amplitude jump behaviour i.e. preventing transgression of a contact free orbit to one involving persistent rotor-stator rub interaction.

8.3 Rotor-Stator Coupled Whirl with Friction Influence

Another possibility following rotor-stator contact is a backward whirl response. Physically, this is only possible if friction force is sufficient to drive the whirl in the direction opposite to the direction of rotation. In this research, friction effects were included in the system model using a Coulomb friction model, which is a typical model for friction between two bodies with dry surfaces in contact, with friction coefficient μ. Simulation results were obtained to investigate the influence of the friction on the rotor vibration response. With sufficiently low friction, the rotor whirl exhibited a limit-cycle orbit involving bouncing motions within the clearance space. With high friction, the rotor whirl transgresses to a friction-driven full backward whirl instability with a perpetual growth in vibration amplitude. Simulation results also showed that the stable forward whirl could be preserved by the dynamic force feedback control method when friction effects are accounted for within the controller design.

The experiments for rotor-stator coupled whirl with friction were undertaken at an operating frequency below the first natural frequency of the combined rotor-stator system in order to avoid the aforementioned amplitude jump phenomena. It was found that a thin sheet of abrasive paper attached to the inner surface of the contact ring was necessary to increase the friction coefficient to levels where backward whirl motions occurred. Although, the vibration patterns in experiment did not exactly match those in the simulation results, the experimental results did indicate that an initial bouncing phase of backward whirl could be alleviated by the controller.

8.4 Discussion

A model-based control design method based on dynamic feedback of measured rotor-stator interaction forces has been shown to be effective in preventing jump response modes in a non-linear rotordynamic system. The control method was shown to be capable of stabilizing a contact-free forward whirl response even when friction has significant influence. The control design approach is general enough to be applied to machine structures with other forms of actuator and it is also able to deal with a number of complicating system features including flexible multi-mode dynamics, non-collocation of actuators and sensors, and limited actuator capacity/bandwidth. The necessity to be able to measure rotor-stator interaction force is a possible limitation for which new design solutions may be required. For industrial application, there are still some issues that would need to be addressed, particularly, how best to integrate sensors in a real machine structure so that rotor-stator interaction forces can be measured for use by controller. If a number of sensing locations can be incorporated in a stator structure then the controller could deal with multiple potential interaction planes. Such capability may prove to be useful for improving safety and performance of industrial machines.