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主 論 文 の 要 旨

論文題目　**Nonlinear Rotordynamics Investigation on Self-Excited Vibration of Rotors Supported by Fixed Profile and Tilting Pad Journal Bearings**
(固定形状およびティルティングパッドジャーナル軸受で支持されたロータの自励振動の非線形ロータダイナミクス解析)

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論 文 内 容 の 要 旨

As an increasing trend in a high-efficiency rotating machine, the rotor of the rotating machine has been designed to be more slender and operated at a higher speed. These design and operating parameters make the rotor supported by journal bearings (JBs) susceptible to self-excited vibration caused by JB's nonlinearity. When this self-excited vibration occurs, the rotor at the stable equilibrium starts to whirl at the Hopf bifurcation point. The rotor will whirl with subsynchronous frequency in either a bounded limit cycle (supercritical Hopf bifurcation) or unbounded limit cycles (subcritical Hopf bifurcation), which can cause damage from the rubbing between the rotor and stator. Furthermore, the rotor at speed below the Hopf bifurcation point can also become unstable if perturbed sufficiently in subcritical Hopf bifurcation. Hence, the identification of the Hopf bifurcation type is essential, particularly in the design stage. However, the linear analysis, which is still the industry's norm in rotordynamics analysis (RDA), cannot capture critical behavior such as limit cycles and Hopf bifurcation types. As a result, the nonlinear RDA is an essential tool for the designer to predict the nonlinear behavior, especially when the rotor becomes linearly unstable or perturbed by unforeseen excitation, such as earthquake and loss of rotating mass.

Nevertheless, the nonlinear RDA requires considerably more computational time than the linear RDA. Hence, it is limited to the relatively simple rotor and bearing models, which have simplified mathematical expressions. However, these models might not correctly represent the real machine's behaviors. In this aspect, the numerically efficient nonlinear RDA of the complex rotor and bearing system that better represents the real machine is advantageous in understanding the rotor and bearing system's dynamic behavior. Even several research papers dealt with this kind of nonlinear RDA, the research on nonlinear self-excitation of a rotor supported by the JB with complex rotor-bearing geometries and operating condition representing the real rotating machine is still limited.

In this thesis, a time-efficient nonlinear vibration analysis program for the autonomous, self-excitation problem of the rotor supported by the JB based on the shooting method with parallel computing and arclength continuation is developed. It is used to determine the solution branch originated from the Hopf bifurcation point and its stability, which is later used to identify the Hopf bifurcation type. The bearing forces in the program are numerically determined from the Reynolds equation in every time step, so the applicable range of the analysis is not restricted to a small orbit amplitude as in the analyses based on linear or nonlinear dynamics coefficients. The analysis program can accommodate the models of fixed profile JB and the JB with movable pads, such as tilting pad journal bearing (TPJB) and flexure pivot tilting pad journal bearing (FPTPJB). Also, the turbulence effect can be readily included in the Reynolds equation. The rotor model used in the analysis can be a rigid or flexible rotor model constructed from the beam’s finite element (FE), which the latter model can generally represent the rotor of the real machine. The degrees of freedom (DOF) of the flexible rotor model can be reduced to those subjected to the nonlinear forces by model reduction schemes, such as modified Guyan reduction and component mode synthesis (CMS) to increase the calculation speed. The analysis program is employed to investigate the effects of the selected rotor and bearing parameters on the nonlinear vibration. The numerical results are verified by the experiment.

The outline of this paper is described below.

In Chapter 2, the mathematical models and equation of motion (EOM) of the rotor (rigid and flexible) and JB of various profiles are expressed. Then, the numerical method for solving the JB force calculation and rotor model reduction are described. Later, the proposed numerical procedures for nonlinear RDA, which is the combination of the shooting method, parallel computing, arclength continuation, and Floquet multiplier analysis, are presented. Lastly, the Hopf bifurcation is described, and type classification criteria are given.

In Chapter 3, the critical parameters of the test rotors and bearings are presented. Also, essential settings of the test rig used for experimental verification are described. Lastly, the instrumentation settings and signal processing are explained.

In Chapter 4, the effects of turbulence on the nonlinear vibration of a rigid rotor supported by two identical bearings are examined. The investigated parameters are bearing length-to-diameter (L/D) ratios, profiles, and type of turbulence model (Constantinescu and Ng-Pan-Elrod). The results are compared to those obtained from the laminar bearing model. It is found that the bearing with preload always gives supercritical Hopf bifurcation regardless of the L/D ratio and turbulence model. In contrast, the Hopf bifurcation type of the bearing without preload shifts to the subcritical Hopf bifurcation at a longer L/D ratio. It is also observed that the L/D ratio that the Hopf bifurcation changed from supercritical to subcritical of both turbulence models is lower than that of the laminar model. The discrepancies between preloaded and non-preloaded bearings are caused by the downward force from the upper pad of the preloaded bearing, which becomes more pronounced as the preload is increased and further reinforced by the additional viscosity of the turbulence models. Lastly, the Hopf bifurcation point obtained from the Ng-Pan-Elrod turbulence model is always higher than that of the Constantinescu model. Hence, the findings suggest that the journal bearings operated in the turbulent regime should have a high pad preload and L/D ratio to obtain the higher onset speed of instability (OSI) and supercritical Hopf bifurcation with a lower limit cycle's growth rate. Furthermore, the Ng-Pan-Elrod model is considered more conservative than the Constantinescu model in predicting the OSI in all investigated bearing configurations.

In Chapter 5, the importance of considering the journal's angular whirling motion for correctly predicting the Hopf bifurcation type of the highly slender rotor supported by JB is investigated. The applicable range of the bearing model that considers and does not consider this motion of the highly slender rotor is examined. Besides, the effects of rotor and bearing parameters on the Hopf bifurcation type are studied. The calculation results are compared with the experimental results. It can be concluded that considering the journal's angular whirling motion is essential in the cases of long JB's L/D ratio with the main rotor mass located close to JB. Apart from these cases, the model that does not consider the journal's angular whirling motion is sufficient. Hence, this model is preferable in the remaining cases because it uses about half the calculation time due to the axial symmetry. Moreover, the supercritical bifurcation is likely to occur when JB has preload and short L/D ratio, and the main rotor mass is located near the journal bearing.

In Chapter 6, the effect of load orientation: load-on-pad (LOP) and load-between-pad (LBP), on nonlinear vibration of a flexible rotor supported by a 4-lobe flexure pivot tilting pad journal bearing (FPTPJB) is numerically investigated along with the first critical speed and OSI. Each pad is modelled as a rigid body allowed to move in radial, tangential, and tilting directions relative to the pivot's axis and constrained by linear stiffnesses of the flexure pivot. The investigation is extended to the tilting pad journal bearing (TPJB) and fixed profile journal bearing (JB) of the same pad geometry for comparison. The calculation results show that FPTPJB and the fixed profile JB give subcritical Hopf bifurcation in both orientations, where FPTPJB gives considerably higher OSI than the fixed profile JB of the same orientation. In contrast, the rotor supported by TPJB remained stable in the rotational speed range considered in this thesis. Besides, FPTPJB in LOP orientation yields considerably higher OSI than the LBP one, whereas the OSI of the fixed profile JB in LOP orientation is substantially higher than the LBP counterpart. Below OSI, the FPTPJB in LOP orientation produces the largest stable region encircled by the unstable limit cycle, whereas the fixed profile JB in LBP configuration yields the smallest one. The calculation results are verified by the experiment, in which good agreement in shaft centerline, the first critical speed, OSI, and Hopf bifurcation type are observed in the most case except the cases of TPJB in both orientations and FPTPJB in LOP orientation, in which the OSI and Hopf bifurcation type could not be verified due to the test rig's speed limit.

In Chapter 7, the summary of each chapter, contributions, future perspectives and recommendations for future work are given.

By using the proposed efficient calculation method, the nonlinear RDA of complex rotor and bearing can be performed for parametric study in more cases in the same amount of time, which is advantageous for studying the nonlinear behavior in the rotor-bearing system, especially in the design stage. With the proper bearing force model, the proposed calculation method yields a good agreement in Hopf bifurcation type with the experiment.