Axial Vibration of a Rotor Observed in a Turbo Pump Considering Compressibility of Fluid

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Summary. It is known that axial vibration of a rotor is excited by the fluid force in a balance piston of a turbo pump used in a liquid rocket engine. The balance piston system is basically stable, however, the vibration problem happened during actual tests under the specific operating condition. Such an unstable phenomenon is supposed to be caused by self-exited vibration or divergence of the balance piston system. To clarify the mechanism of the axial vibration of a rotor induced by swirling leakage flow, we proposed a theoretical model considering the effect of compressibility of fluid.

Introduction

In order to reduce the axial thrust of a turbo pump automatically, a balance piston system is often used. As shown in Fig.1, the balance piston system consists of a gap of the impeller back, a casing, an outside diameter side orifice (orifice1), and an inside diameter side orifice (orifice2), and the gap of two orifices are controlled to reduce unbalanced axial thrust, which is basically stable, but in some rare case, the vibration problem happened during actual running tests. Such an unstable phenomenon is supposed to be caused by self-exited vibration or divergence of the balance piston system, however, the cause of the vibration has not yet clearly understood up to now. The main purpose of this paper is to propose mathematical model which can clarify the mechanism of the axial vibration of a rotor induced by swirling leakage flow. In the analysis, we proposed a model considering the effect of compressibility of fluid, rotational velocity of a rotor and pre-whirl strength of inlet swirling leakage flow. As a result, in the case that whole fluid around the balance piston was treated as compressible gas, it was found that self-exited vibration and divergence can be excited at a particular equilibrium position of the balance piston.

Vibration model

A cross section of a turbo pump is indicated in Fig.1. The fluid boosted by a pump is divided into the flow entering the mainstream and the one entering into a balance piston. In this research, a rotor part of a turbo pump (light-blue part in the Fig.1) is modeled by a single degree of freedom lumped mass, dashpot and spring system which is allowed to move in the axial direction as shown in Fig.2, then the equation of motion around equilibrium point can be described by Eq.(1).

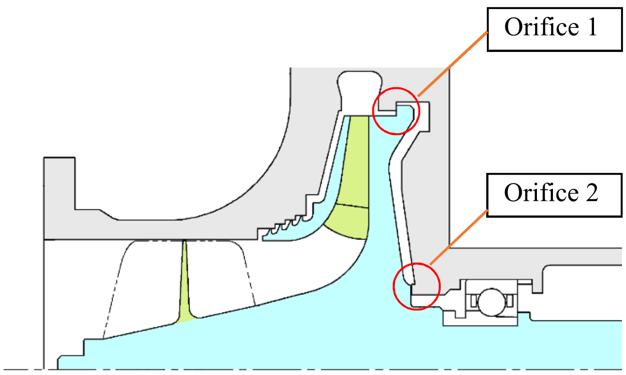

Fig.1 A cross section of rocket turbo pump

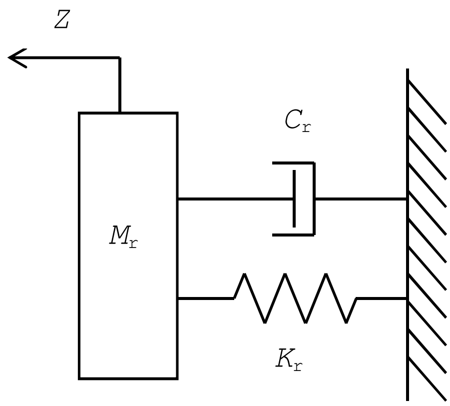

Fig.2 Vibration model

$$M_r\ddot{Z} + C_r\dot{Z} + K_rZ = F_f \qquad (1)$$

where M_r, C_r, K_r denote equivalent mass of the rotor, equivalent damping factor and equivalent stiffness respectively, and F_f is unsteady component of the fluid force.

Flow path model and model of compressibility

Fluid passing through the balance piston goes through a narrow and complicated flow path from an impeller exit to the bearing room and the flow path is divided into 9 segments as shown in Fig.3. The compressibility of working fluid i.e. liquid-hydrogen is considered so that the density of the fluid is described by a function of pressure of the fluid as shown in Fig.4.

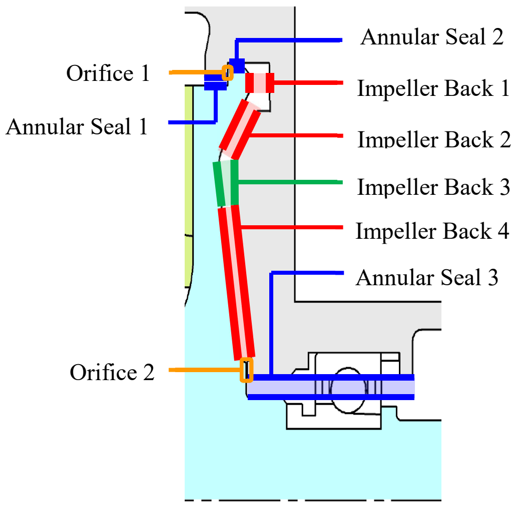

Fig.3 Flow path model

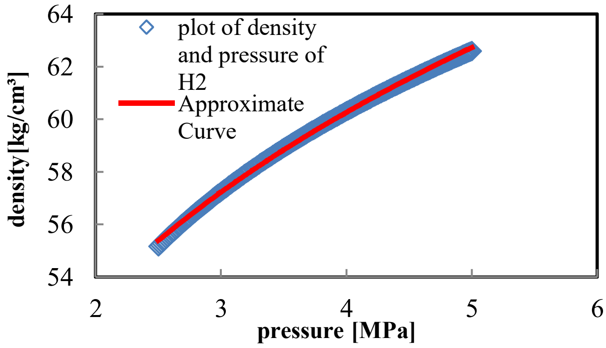

Fig.4 Relationship between density and pressure

Calculated result based on bulk flow model considering flow compressibility

In this research, a model considering the compressibility of the working fluid is introduced into a bulk flow model for an incompressible fluid proposed by Childs [1] together with turbulent lubrication model of Hirs [2] describing the stress component acting on a wall from the working fluid. To apply the bulk-flow model to the complicated flow path of the balance piston, flow path is divided into 9 divided sections. Therefore, flow of each divided sections should be connected by the conservation laws such as mass conservation law, angular momentum conservation law and must satisfy Bernoulli's principle. Detail derivation process and assumptions are described by Onishi [3]. In Fig.5 and Fig.6, calculated added fluid force and calculated added damping are shown.

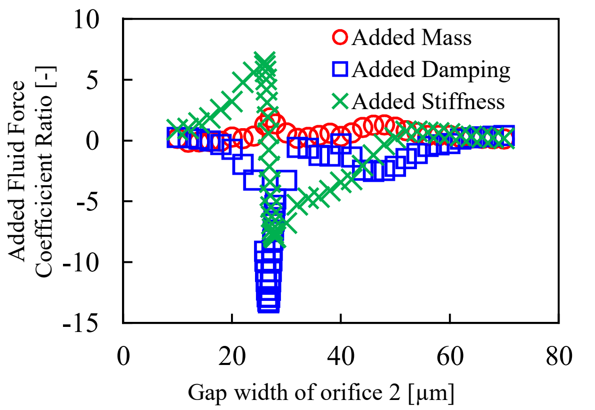

Fig.5 Calculated added fluid force coefficient ratio

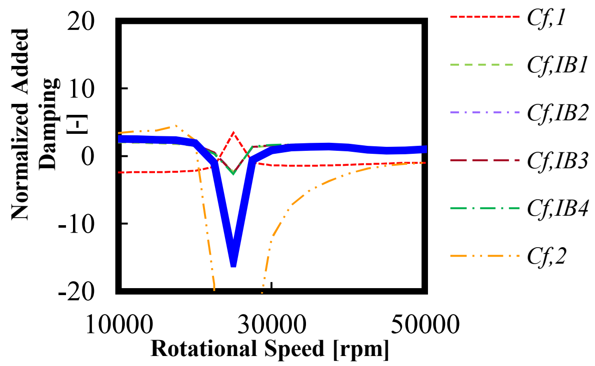

Fig.6 Calculated added damping

Conclusions

Dynamic characteristics of the fluid force acting on the balance piston by considering the effect of compressibility of the flow is shown. In the case that whole fluid around the balance piston was treated compressible, it was found that self-exited vibration can be excited at a particular equilibrium position of the balance piston. Moreover, we analyzed some cases by changing the rotational speed and found a possibility of self-exited vibration in axial direction.

References

[1] Childs, D.W., "Fluid-Structure Interaction Forces at Pump-Impeller-Shroud Surfaces for Axial Vibration Analysis," *Journal of Vibration, Acoustics, Stress, and Reliability in Design*, Vol. 111 (1989), pp. 216-225.

[2] Hirs, G.G., "A Bulk-Flow Theory for Turbulence in Lubricant Film", *Journal of Lubrication Technology*, Vol. 95, No. 2 (1973), pp. 137-145.

[3] Onishi, I and Kaneko, S., "Development of Model for Axial Vibration of a Rotor Observed in Turbo Pump Considering Compressibility of Fluid", *International Gas Turbine Congress 2015*, Tokyo, Nov.15-20, (2015)