

FLUID FORCE AND MOMENT ON CENTRIFUGAL IMPELLERS IN PRECESSION MOTION

H. Ohashi, H. Imai, and T. Tsuchihashi
Department of Mechanical Engineering
University of Tokyo
Tokyo, Japan

Abstract

In the past decade studies of the fluid force acting on centrifugal impellers in whirling motion have been conducted. Present study deals with the case in which centrifugal impellers oscillate in a tilting or precession mode. A test apparatus is built and the fluid force and moment acting on impellers in a forced precession motion are measured.

The result indicates that fluid moment induced by precession exerts destabilizing effect on the vibrating shaft at low precession/rotational speed ratio. A centrifugal impeller mounted at the end of an overhung shaft receives moment-induced fluid excitation at rotational speed higher than twice its critical speed.

Introduction

Fluid force and moment acting on centrifugal impellers of a rotating shaft play an important role for the rotordynamic stability of the shaft system. The motion of a rotating centrifugal impeller on a vibrating shaft is different according to the bearing and shaft configuration. Figure 1 (a) and (b) illustrate two typical cases. In the former case the impeller is mounted at the center of a shaft supported by two bearings at each shaft end, while in the latter the impeller is mounted overhung at the end of a shaft supported by a pair of bearings.

The vibration of mid-bearings impeller (a) is called whirling motion, in which the impeller shaft rotates and whirls on an orbit while keeping its direction parallel. The vibration of overhung impeller (b) is more complex and can be considered as the superposition of whirling motion and tilting motion in which the inclination of the shaft also oscillates.

The vibration of a rotating impeller (rotational speed ω) can be dissolved into two fundamental modes; whirling with a constant eccentricity ϵ (circular orbit) and precession with a constant inclination α , as illustrated in Figure 2 (a) and (b). In the illustrated precession, the center of the impeller, G, does not move but the direction of shaft inclination rotates with a constant speed Ω .

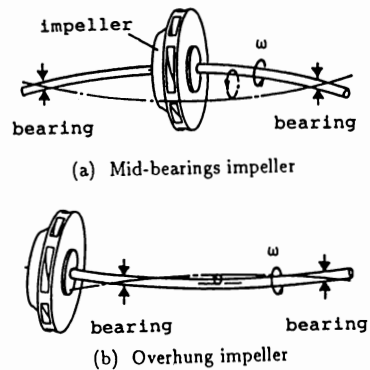


Figure 1 Motion of a centrifugal impeller on a vibrating shaft

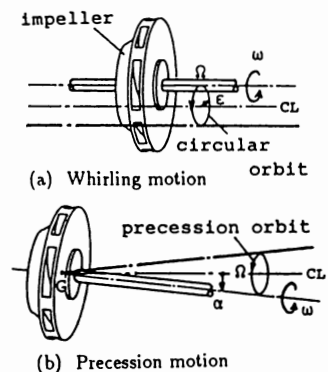


Figure 2 Two fundamental vibration modes of an impeller

In the past decade studies of the fluid force acting on whirling centrifugal impellers have been conducted by several researchers [1-5], experimentally as well as theoretically, and the nature of the whirl-oriented fluid force has been made clear to a considerable extent. It was found that the fluid force on whirling impeller exerts destabilizing effect on the shaft in positive whirl with low whirl/rotational speed ratio, $\Omega/\omega < 0.5$.

The present paper deals with the fluid force and moment acting on impellers in a precession motion. In contrary to the case of whirling motion, the moment plays a predominant role for the stability of rotating shaft in precession. The test apparatus is so designed that the rotating test impeller is forced into a precession with a constant inclination and an arbitrary precession speed.

The induced fluid force and moment are measured by four-axis force sensor attached to the shaft end and are then divided into two components parallel and normal to the precession motion. Normalized force and moment components are plotted against precession/rotational speed ratio for various flow rate of the impeller. The presentation of precession-oriented force and moment in terms of mass, damping and stiffness matrices can be done by performing best-fitting of the above plottings to parabolic curves, see [1].

Test Apparatus

The coordinate system and the prescribed precession motion of the test impeller are illustrated in Figure 3. The center of the impeller, G, is defined in this case as the intersection of discharge center plane (center of exit width) and the shaft center. Impeller center G locates on the absolute center axis, O-z, and does not move. The rotating shaft with rotational speed ω is inclined to the absolute axis with a constant angle α and makes a precession motion with a constant angular velocity Ω . When the precession is in the same direction as that of the impeller rotation, the motion is called positive precession ($\Omega > 0$). The radial and tangential direction of the motion is defined in the figure and the components of force and moment applied by the surrounding fluid to the impeller are denoted by F_r , F_t , M_r and M_t , respectively.

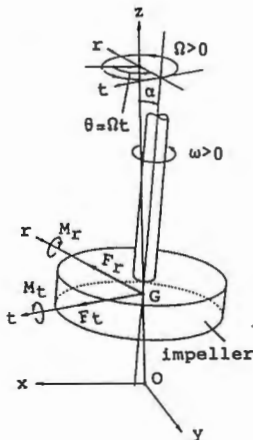


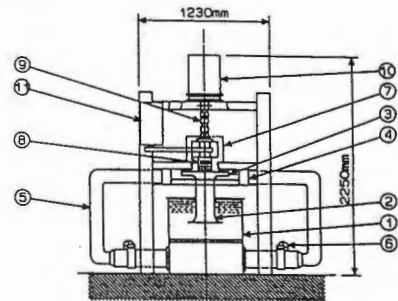
Figure 3 Coordinate system and components of force and moment

The test apparatus is designed to materialize the prescribed motion. The overall setup is shown in Figure 4. It is virtually a single-stage vertical-shaft centrifugal pump and is composed of test impeller in a matching diffuser, force and moment balance, precession generator and water recirculating loop. Figure 5 illustrates shaft layout and attached precession generator. The pump shaft is supported by two (double-row spherical roller) bearings, whose eccentricities can be adjusted independently. When two eccentricities are the same in length and phase, a pure whirling motion with a given eccentricity can be materialized. In the present case of pure precession motion, two eccentricities are so adjusted that the center of the impeller G locates on the absolute axis and the inclination agrees with the prescribed value (1 degree in the present case).

The test impeller is a model of a boiler feed pump and has outer diameter of 350 mm, made of aluminum casting to reduce inertia force. The impeller is connected to the pump shaft via rotating balance (parallel plate structure, four-axis force sensor) as illustrated in Figure 6. The transfer matrices which convert four strain outputs to four components, F_r , F_t , M_r , M_t , are determined by a series of dynamic calibration tests.

Force and moment are measured twice, that is, in air and in water at the same test condition. The former represents merely inertia force and moment of the impeller due to the precession motion and, therefore, the fluid-induced force and moment can be obtained by subtracting the former from the latter.

During the test, the pump rotational speed is kept constant ($\omega = 530$ rpm) and the precession speed is varied from positive to negative to cover the precession/rotational speed ratio of $\Omega/\omega = -1.2 \sim +1.2$. Flow rate of the impeller is varied from zero (shut-off) to the maximum by adjusting the discharge valve.



- ① settling tank
- ② suction pipe
- ③ test impeller
- ④ vaned diffuser with wire gauze at exit
- ⑤ return pipe (x2)
- ⑥ butterfly valve (x2)
- ⑦ eccentric drive mechanism
- ⑧ four axis force sensor
- ⑨ universal joint
- ⑩ main drive motor
- ⑪ eccentric drive motor

Figure 4 Overall setup of test apparatus

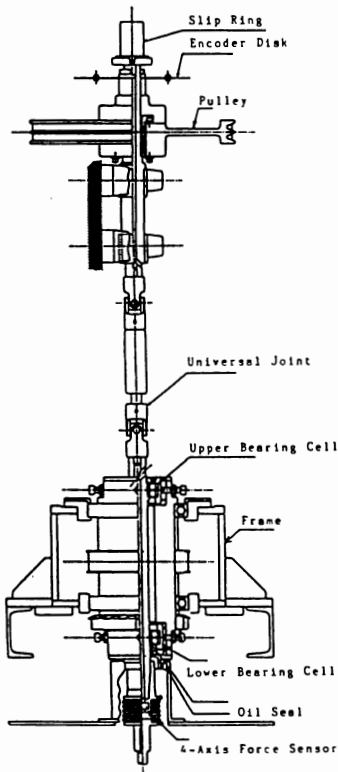


Figure 5 Shaft layout and precession generator

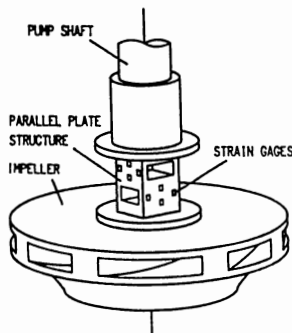


Figure 6 Test impeller and rotating four-axis force sensor

Test Result

Measured force and moment are averaged over one cycle of precession. These average values, F_r, F_t, M_r, M_t , are normalized as:

$$f_r = F_r/F_0, \quad f_t = F_t/F_0$$

$$m_r = M_r/M_0, \quad m_t = M_t/M_0$$

and

$$M_0 = I\alpha\omega^2, \quad F_0 = M_0/i$$

where $I = \rho\pi r_2^2 b i^2$, $i = \sqrt{r_2^2/4 + b^2/12}$, ρ is fluid density, r_2 outer radius of the impeller, b the exit width of the impeller (including shrouds), α inclination of the shaft and ω pump rotational speed.

Figure 7 and 8 show how each component of the normalized fluid moment and force due to precession motion varies with precession/rotational speed ratio Ω/ω at four normalized flow rates (0, 0.5, 1 and 1.5 \times design flow rate). The influence of flow rate is relatively small and this suggests that the precession-oriented fluid force and moment are caused predominantly by pressure reaction applied to the surfaces of the tilting shrouds. Tangential moment m_t is caused primarily by the gyro reaction of fluid contained in the impeller and shows consequently a parabolic variation with respect to precession speed.

Radial moment m_r becomes positive between $\Omega/\omega = 0 \sim 0.5$ as seen from Figure 7. This positive radial moment feeds kinetic energy to the vibrating shaft and thus excitatory. This leads to the consequence that moment-induced excitation is applied to the impellers in precession at rotational speed higher than twice the critical speed of the shaft. This moment-induced fluid excitation could be a serious concern especially to an overhung impeller on a flexible shaft.

As to the influence of fluid force on the stability, tangential component f_t is responsible to the transfer of kinetic energy to the vibrating shaft. Positive tangential force in positive precession and negative one in negative precession exerts destabilizing effect on the vibration. f_t shown in Figure 8 indicates that precession-oriented fluid force applies destabilizing effect in positive precession with larger speed ratio ($\Omega/\omega > 0.6$) and in entire negative precession.

In consideration of the influence of fluid force on the stability of an overhang impeller, it should be noticed that a precession motion is always accompanied by a corresponding whirling motion. Consequently, the influence of precession-oriented and whirling-oriented fluid forces must be taken into account simultaneously. The result obtained by whirling experiments [1-4] shows such tendency that the whirling-oriented fluid force is stabilizing when precession-oriented one is destabilizing, and vice versa. Because of this mutual cancellation of two fluid forces, precession-oriented moment plays most important role for the stability of an overhung impeller.

Force and moment during precession motion are affected sensitively by the installation of impeller in the casing, especially by the gap between shrouds and surrounding casing walls. Further tests are being conducted to investigate such geometrical influences on the fluid force and moment.

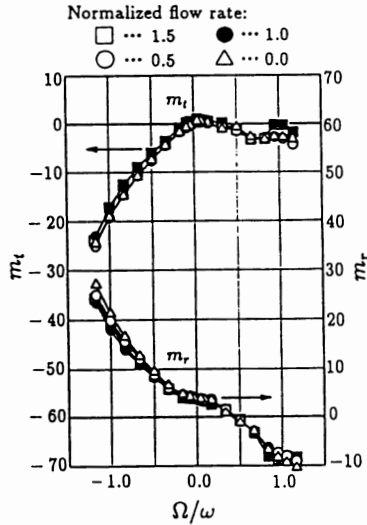


Figure 7 Normalized radial and tangential moment induced by precession

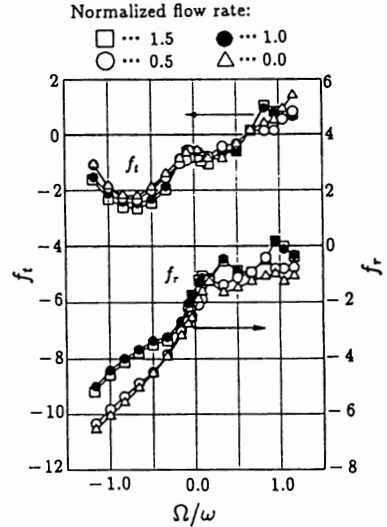


Figure 8 Normalized radial and tangential force induced by precession

Conclusion

Fluid force and moment acting on a centrifugal impeller in precession motion are measured at various precession/rotational speed ratio and discharge conditions. Force and moment are divided into radial and tangential components relative to the precession motion. Normalized force and moment components are plotted against speed ratio for various discharge conditions.

The result indicates that radial moment exerts destabilizing effect on positive precession at small speed ratio, $0 < \Omega/\omega < 0.5$, that is, at rotational speed higher than twice the critical speed. On the other hand, tangential force induces destabilizing effect on positive precession at higher speed ratio, $\Omega/\omega > 0.6$ and on entire negative precession. In the case of an overhung impeller, the influence of the above precession-oriented tangential force on the stability is diminished by the associated whirl-oriented one, since they work in the opposite direction, thus canceling each other.

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