An evaluation of computational methods to specify the effects of liquid balancers

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ABSTRACT

The presented study deals with the automatic balancing by use of fluid balancers. Influences on the fluid forces by radial or tangential partitioning of the fluid cavity and its radial eccentricity, which may result from manufacturing, are examined experimentally. In comparison, analytical solutions of the fluid mechanical equations relying on the shallow water theory published in the literature are checked against these results. Additionally, computational fluid dynamics (CFD) simulations based on the volume-of-fluid (VOF) approach are examined to identify effects not described by the analytical solutions. With a view to estimate the necessary balancer dimensions in an early development stage and to pursue multi-body simulations of centrifuges the evaluation of available modelling approaches with experimental data leads to more insight in all development stages.

1 INTRODUCTION

In order to reduce the cycle time of centrifuges by means of shorter run-up and run-down phases, one may develop lightweight rotors. Moreover this has positive effects on the handling at rotor switchovers and, in the case of averages, the decreased kinetic energy leads to less impact. One major trade-off to this are increased vibrations due to the higher unbalance to rotor mass ratio. Automatic balancing devices are capable of positioning a balancing mass, fluid or solid, in order to counterbalance the rotor imbalance. This is especially useful for rotors with varying unbalances during the rotors service life such as laundry in washing machines and samples in laboratory centrifuges.

As known for dynamic systems there is a phase shift between the excitation and the deflection of a system while passing a resonance frequency. In contrast, the unconstrained masses in rotating balancing devices, driven by the centripetal force, tend to move to the location with the highest distance to the axis of rotation. Given an excitation by unbalance the balancing mass will align with the unbalance at subcritical angular velocities, thus resulting in increased rotor deflections and will oppose the unbalance at supercritical velocities, ideally compensating the unbalance completely.

The models for ball balancers are obtaining satisfying results, e.g. (1), and incorporate the most influential parameters on the counterbalancing capability such as rolling resistance, the runway eccentricity with respect to the rotational axis and the viscosity of the enclosing fluid. Though the counterbalance mass in fluid balancers is lower than the solid bodies in ball-balancers, the influence of wall roughness is negligible (2) and the reduced noise can be favourable. In order to define the design parameters for liquid balancers, i.e. the cavity dimensions, the fluid viscosity or manufacturing tolerances, a good understanding of the dynamics is required, especially the fluid dynamics.

With the scope on vibration reduction in automatic washing machines with vertical axes of rotation there has been increased research on fluid balancers in the past years. Bae et al. (3) present a lumped mass model (figure 1) for the stationary state with constant angular velocity Ω and rotor deflection e perpendicular to the rotational axis. The velocity is assumed to be high enough so that the centripetal acceleration is exceeding the gravitational acceleration g leading to the assumption of a vertical phase boundary between the fluid and the air. This leads to a resulting force of the fluid mass of

$$F = m \cdot \Omega^2 \cdot (e + c) \qquad (1)$$

under the condition of moderate deflection and an always fully wetted outer wall along the circumference. With m, Ω, e, c, q, R_i, R_o, h being the fluid mass, the angular velocity, the balancer deflection, the centre of fluid mass, the cavity filling ratio, the inner and outer radius of the cavity and the cavity height respectively. Equation (1) can be transferred to

$$F = m \cdot \Omega^2 \cdot \frac{e}{q} \cdot \left(1 - \left(\frac{R_i}{R_o}\right)^2\right)^{-1}, \qquad (2)$$

leading to an enhanced force by decreasing the filling ratio q and maximizing the radial extend of the cavity. The limits of this model get clear when considering a fully filled cavity, which has no balancing effect at all (2). Moreover Jung et al. (3) identified

$$q = \frac{V_{fluid}}{V_{fluid} + V_{air}} = 0.5 \qquad (3)$$

as the optimal filling ratio experimentally. Another characteristic not represented by the lumped mass model is the occurrence of an additional critical frequency at which the dynamical behaviour of the fluid leads to excitation of the rotor. The study on the whirling behaviour of fluid in rotating cylinders by Berman et al. (5) shows the analogy of the centrifuged fluid to a shallow water film under the influence of gravitation so that the shallow water theory applies (6).

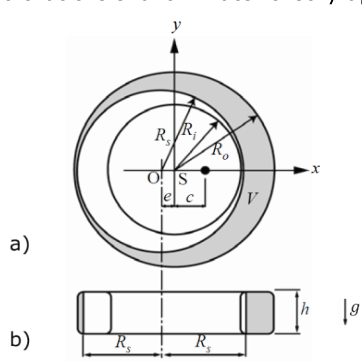

Figure 1: The centre of fluid mass in a deflected and rotating liquid balancer (4). a) Top view b) view perpendicular to the axis of rotation (—·—)

In particular, an additional resonance arises under the condition

$$\Omega = \Omega_0 \cdot \frac{1}{1-\left(\frac{R_i + R_o}{2 \cdot R_o}\right)^{0.5}} > \Omega_0 \tag{4}$$

for the specific case of q=0.5, exciting surface waves on the liquid layer. Taking the rotor dynamic and the fluid dynamic equations into account Yoshizumi (7) upon others examined this behaviour numerically. An approximate analytical solution for the balancing effect of fluid balancers is provided by Langthjem and Nakamura (2) concluding that the fluid does not antagonize the rotor imbalance like a lumped mass and is not able to compensate it completely. Though bringing more insight into the fluid dynamics, the agreement with experimental results diversifies at different operating speeds and an optimal filling ratio could not be derived.

CFD simulations were carried out by (3) amongst others, optimizing the geometry of the cavity. The integration of baffles influences the fluid dynamics in order to suppress the adverse excitation at subcritical velocities, in which washing machines are operating a significant amount of time during the washing process before starting the spin cycle at supercritical velocities, at which the balancer shows its desired behaviour. As presented, there are modelling approaches with different complexities to estimate the balancing capabilities of fluid balancers ranging from lumped mass models to CFD simulations. The letter however leads to computationally intensive co-simulations, if transient solutions are the objective.

In the present study, the characteristics of the fluid motion in fluid balancers were examined experimentally while altering the cavity geometry. Also, in contrast to the mentioned studies on washing machines, the scope of the experimental setup was to evaluate fluid balancers for smaller scales, such as laboratory centrifuges. These results are presented in the subsequent section. The third section is discussing the applicability of different modelling approaches in multi-body simulations and compares the experimental data with the results gained from these models.

2 EXPERIMENTAL STUDIES

In order to characterise the automatic balancing effect of liquid balancers in a scale similar to laboratory centrifuges, a discoidal rotor with small height is fixated on a vertically mounted shaft as shown in figure 2(a). The shaft is driven by an asynchronous motor, which is suspended by three rubber bushings providing stiffness and damping to the system. In the speed range up to 20 Hz a resonance frequency near 8 Hz with translational deflection perpendicular to the rotational axis and shear loading of the bushings was identified. The deflection of the rotor is sensed by laser triangulation and the rotor provides several threaded holes distributed on the circumference to hold variable unbalances. In the depicted experiments a mass of 2.4 grams is used leading to an unbalance of 220 gmm. A cavity to hold the fluid is covered by acrylic glass to allow optical examination. Extruded rings were produced to change the geometry of the cavity, figure 2(b).

Firstly, the asynchronous excitation as referenced in (5) was examined with the presented centrifuge. The hydraulic jump in the fluid layer is visible (figure 3) during operation under the resonance condition described by equation (4) and results in increased excitation (figure 4), when running at Ω for more than a few seconds. This resonance excitation is slightly above the critical speed of 8 Hz and has to be considered in the process of defining the operating speed, keeping in mind that the self-balancing effect is only beneficial at supercritical speeds.

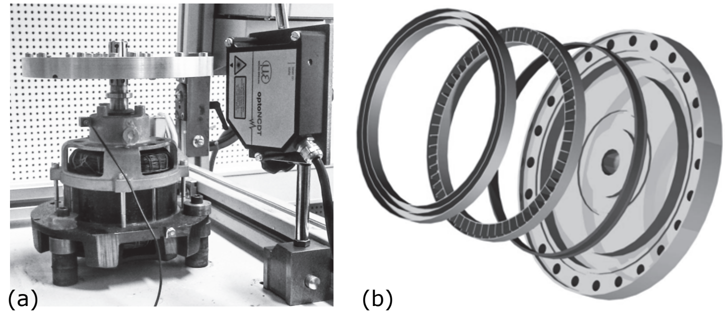

Figure 2: Experimental setup with a discoidal rotor. a) Measurement setup b) cavity rings to influence the fluid behaviour. From left to right: Radial partitioning, tangential partitioning, imposed runway eccentricity

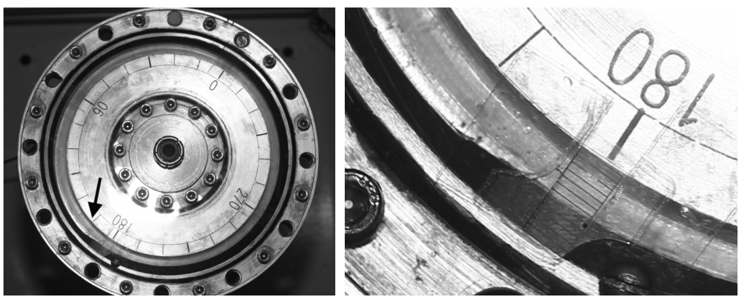

Figure 3: Hydraulic jump on the liquid layer in a cylindrical cavity with the rotational velocity satisfying the resonance condition Ω = 1.25 Ω_0 = 10 Hz

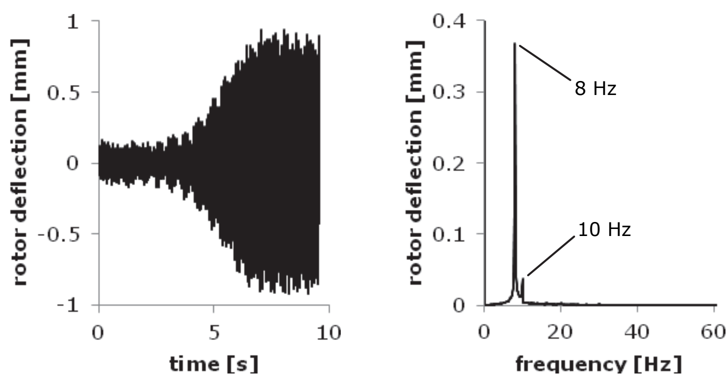

Figure 4: Deflection of the rotor in the time domain and frequency domain due to asynchronous whirl when reaching the resonance condition at 10 Hz

Secondly, in order to probe advantageous structural modifications, the rotor was equipped with rings to divide the cavity radially or tangentially (figure 2(b)). As stated in (8), a radial midway partitioning has the best effect on the self-balancing effect. A tangential partitioning was tested to restrain the fluid dynamics and therefore hydraulic jumps. With the help of small communication bores in the baffles near the outer wall the pressure induced fluid distribution is assured, so that the fluid can accumulate opposite to the rotor imbalance at supercritical speeds.

Figure (5) shows the measured excitation at different discrete velocities during a quasi-static run-up with and without a partial filling of the cavity with fluid. The unbalance to rotor mass ratio yields 0.2%.

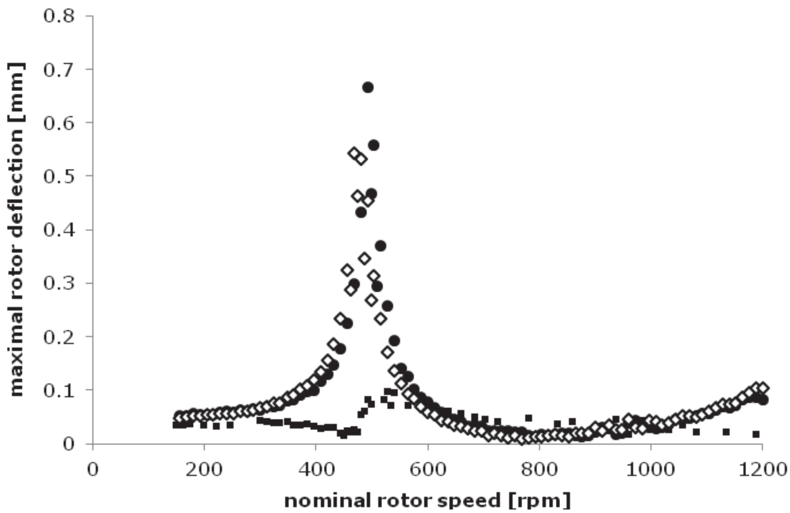

Figure 5: Unbalance excitation of the rotor. ▪ Initial unbalance excitation • dry rotor (q=0) with an additional unbalance of 220 gmm ◇ 220 gmm additional unbalance with fluid (q=0.5) in the cavity

The balancing effect in the investigated configurations is not as distinct as expected and neither the baffles nor the radial partitioning show significant improvement in comparison to the configuration without any structural modifications. The lack of influence of the baffles stands in line with (2), who identify the asynchronous whirl as the driving counterbalancing phenomenon.

In order to determine the influence of production accuracy and the resulting eccentricity of the fluid cavity with respect to the rotational axis, another ring was used which creates said eccentricity by e = 1 mm (equation (1)) without bringing additional unbalance to the system by itself. The direction of eccentricity leads to two extremes. One worst case by shifting the fluid centre of mass towards the rotor imbalance location and one best case by shifting it in the other direction opposing the imbalance. The conducted experiments show a distinct influence of radial runway eccentricity (figure 6).

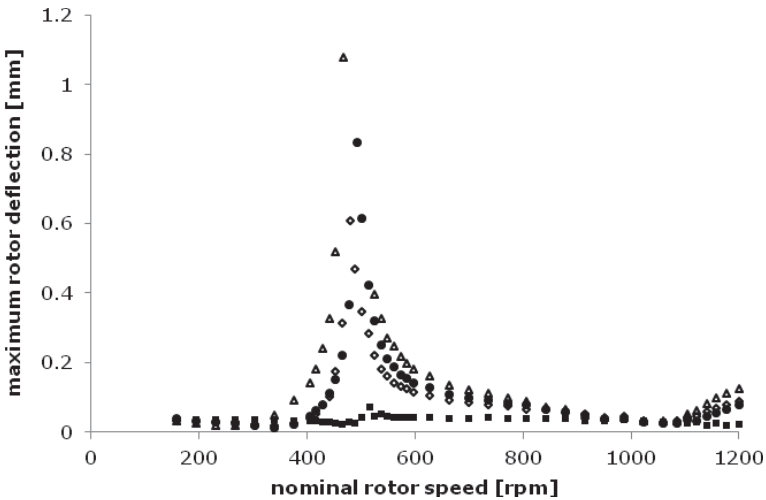

Figure 6: Liquid balancer deflection under the influence of runway eccentricity induced by the rapid prototyped ring. ▪ Initial unbalance excitation • dry rotor (q=0) with an additional unbalance of 220 gmm △ 220 gmm additional unbalance and a runway eccentricity of 1 mm in the same direction ◇ 220 gmm additional unbalance and a runway eccentricity of 1 mm to the opposite side

Concerning the dimensions of the rotor and the fluid runway used in the setup, the effects of production tolerances are in the same scale as the potential to balance the rotor. In order to identify required fluid chamber dimensions and tolerances on the runway eccentricity in the scope of a given unbalance to rotor mass ratio, computational models should be used to reduce the quantity of experiments. The rotor setup is simulated with an extract of models in the following section.

3 COMPUTATIONAL METHODS

The stationary solution for a lumped mass model presented by (4) is not feasible for the design of liquid balancers. It neglects the fluid dynamics superimposed to the rigid body motions. In addition to that, the eccentricity e is defined as a constant input parameter to determine the fluid forces F on the wall (equation (2)). But due to the balancing effect of the fluid, the eccentricity becomes transient, leading to an interdependency between F and e. The tridimensional CFD simulation on the other hand can solve the dynamical behaviour through discretisation. In order to simulate the two phase problem the Volume-Of-Fluid approach delivers a viable model. The phase boundary can be determined and the resolution is dependent on the discretisation of the domain. The rotor movement is introduced through suitable boundary conditions for the domain delimiting walls, which can be altered between time steps to simulate transient operation. Furthermore, the discretisation in a CFD simulation is capable of modelling freeform contours in the fluid chamber, which are not suited to be modelled analytically.

The comparison of the fluid forces on the runway for the special case of a stationary operation with constant eccentricity e has shown that the lumped mass model and the CFD simulation lead to the same results described by equation (2). An implemented co-simulation between the CFD model and a multi body system for the centrifuge needs optimizations with respect to performance. Even though the

CFD is carried out in a rotating reference frame to avoid the modelling of moving walls the transient change of the centre of rotation leads to increased computational cost for each time-step. This leaves the transient solution open for future research.

4 CONCLUSIONS

The conducted experiments show that the performance of fluid balancers is sensible to the eccentricity of the fluid runway similar to ball-balancers and therefore care has to be taken when defining the runway tolerances. Furthermore, the effect of the considered fluid balancer is not sufficient for the unbalances in the scope of the research of laboratory centrifuges. With increased runway diameter of fluid balancers, as implemented in automatic washing machines, the balancing effect reaches a profitable extent. A sophisticated modelling of the fluid dynamics is needed in order to identify the cavity dimensions at which the application of fluid balancers start to be profitable. Current advances in analytical solutions still lack to model certain effects of fluid balancers leaving the CFD simulation to model fluid balancers for the design of small scaled centrifuges.

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