Containing the cup in the Floating Cup axial piston machine

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ABSTRACT

In a floating cup axial piston machine, each piston has its own cuplike cylinder, floating on a barrel plate. A hold down spring prevents these cups from tilting off the barrel plate but allows them to slide over it, along a very small track. This paper will focus on the design of a hold down spring. Friction between the cup and its adjoining parts is studied and found to influence the optimal design of the hold down spring. However, on the machine efficiency the effect of this friction is negligible.

Keywords: axial piston machine, floating cup principle, construction, hold down spring, friction.

Nomenclature

D	cup bottom diameter [m]	p,q	moment arms [m]
F_c	centrifugal force on cup [N]	s	stroke of piston [m]
F_{spring}	contact force of spring on cup [N]	r	radial cup position [m]
M_{tilt}	tilting moment on cup [Nm]	s	stroke of piston [m]
R	piston pitch circle radius [m]	u	displacement of barrel cup contact force [m]
R_{spring}	effective spring contact radius [m]		
a	cup center of gravity position [m]	ρ	ρ-circle radius [m]
m	cup mass [kg]	ω	angular velocity [N]

1 Introduction

In 2002 Innas presented a new displacement principle for hydraulic pumps, motors and transformers [1]. Compared to conventional bent axis and slipper type machines the most striking changes were the balanced and symmetrical construction, the fixed pistons and, probably the biggest change, the absence of a barrel. In the new design the conventional barrel, with its limited 7 or 9 bores, is replaced by a more than double number of cuplike cylinders, floating hydrostatically balanced on a barrel plate (figure 1). A more recent improvement is the ringless piston sealing [2]. Since 2002 tests at Innas and in the industry have confirmed a very high hydro-mechanical and volumetric efficiency and a very small torque variation and loss [3,4,5,6]. It is expected that the increased number of cylinders will decrease flow pulsation and noise levels without increasing the production costs.

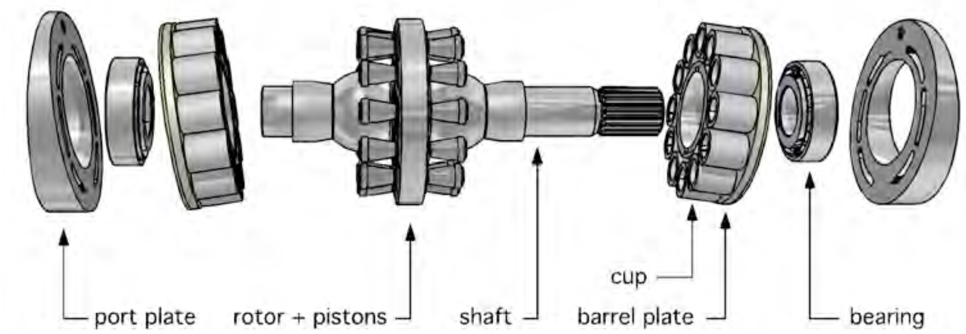

Figure 1: exploded view of the floating cup machine

already widespread in automotive production, can replace the usual milling and grinding of the conventional barrel. For other parts, like the port plates and the pistons, non-machining technologies are applicable too and they allow for a very competitive total cost price.

However, the separation of the cups from the barrel compels for some sort of containment of the cups. In the rotating machine, centrifugal forces act on the cup and without extra measures they will tilt off the barrel plate. In the first prototypes of the floating cup machine the cup was held down to the barrel with a holding plug and a positive hydrostatic balance force (figure 2). In this form-closed construction a minimal gap had to be allowed because of production tolerances. The seal land of the cup was balanced in such a way that, when pressurized, the cup was hydrostatically pressed to the barrel. When the cup was connected to the low-pressure kidney however, it tilted off the barrel at high speeds until it was caught by the plug. Connected to the high-pressure kidney again, the cup was pushed towards the barrel plate. But until it landed, there was extra leakage.

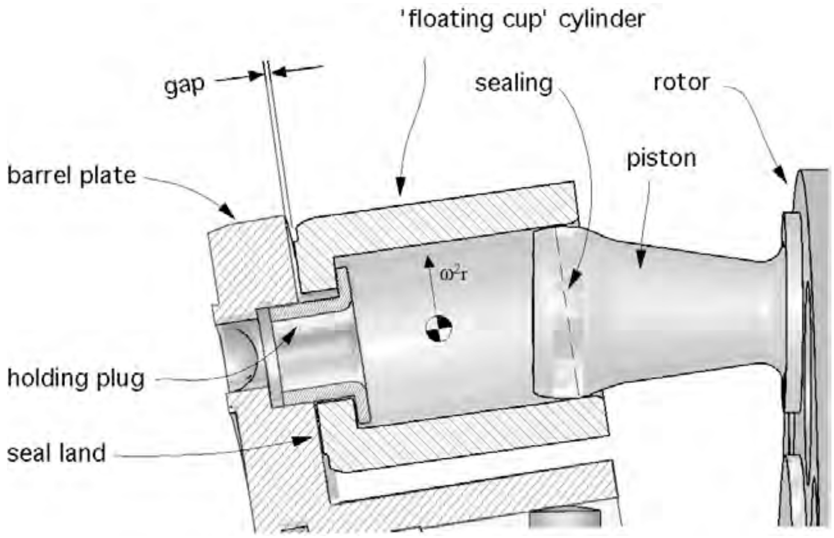

Figure 2: hold down by means of a plug, non-pressurized cup tilts from barrel plate

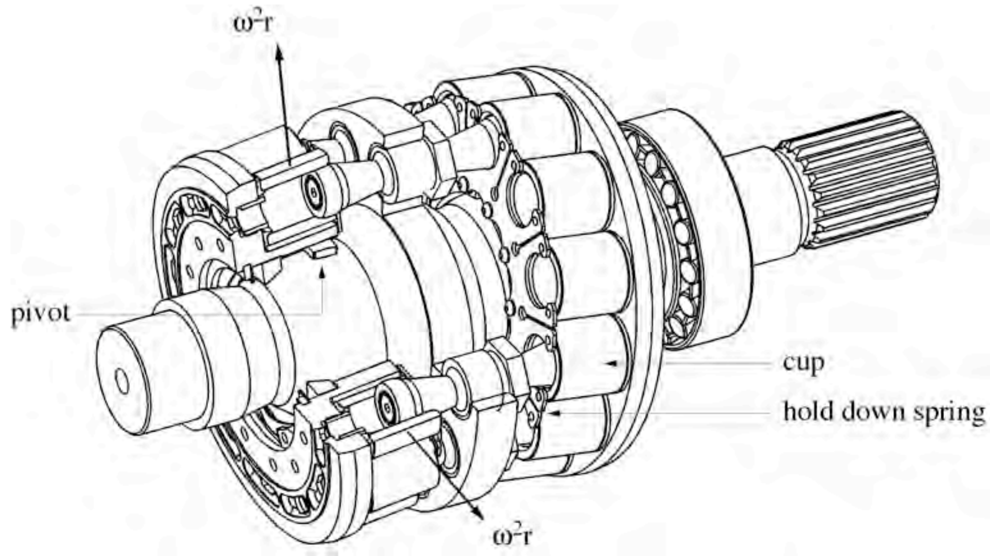

Figure 3: hold down by means of a hold down spring

It is known that optimizing the port plate grooves geometry can reduce noise and pulsation. This can only be done when the flow to and from the cylinders can be controlled by the grooves only and there is no uncontrolled secondary flow via a gap between the cup and the barrel plate.

In this paper an alternative construction is proposed: the hold down spring (figure 3). The spring presses the cup on the barrel plate whether it is pressurized or not and there is no need for a hydrostatic force anymore. This force-closed construction is less sensitive to production tolerances than the form-closed plug alternative and will therefore result in a cost reduction. The questions now arising are what minimal spring force is needed to prevent the cup from tilting and where on the top of the cup should this force be positioned?

When the situation is simplified by neglecting friction in the interfaces of the cup and its adjoining parts, the minimal spring force and optimal position of the spring force can be derived by analyzing the critical situation in which the centrifugal force exerts the largest tilting moment on the cup. This done in section 2.

However, friction in the aforesaid interfaces will increase the critical tilting moment. When friction is introduced in the calculation, the kinematics of the cups have to be taken into account as well and this makes the analysis rather complicated. Therefore the friction effects are not calculated analytically but numerically using a multi body model of the hold down construction. In paragraph 3 the kinematics are treated, to be followed by a study of the effect of friction forces in paragraph 4. The paper is concluded with a design of a hold down spring that will keep the cups on the barrel plate at a minimal hold down force.

2 Forces

Because of the spherical shape of the piston, the sealing line is always in a plane perpendicular to the axis of symmetry of the cup (figure 2). The seal land at the bottom of the cup is dimensioned in such a way that, when pressurized, the cup is hydrostatically in balance and no significant resulting hydrostatic forces on the cup remain. In figure 4 the centrifugal force on the cup and the reaction forces from the barrel, piston and hold down spring on cup are shown, assuming there is no friction. As the machine rotates, the piston head moves up and down in the cup. When the center of gravity of the cup coincides with the piston position (figure 4 left), the centrifugal force on the cup is conducted directly to the piston and no other reaction forces exist. When the piston moves away from this position an extra torque is created that tilts the cup from the barrel. This is prevented by pressing the cup to the barrel with a spring that acts on the top of the cup, which causes a contact force between barrel and cup (figure 4 right). The displacement *u* of the contact force to the spring force creates a moment that counteracts the tilting torque.

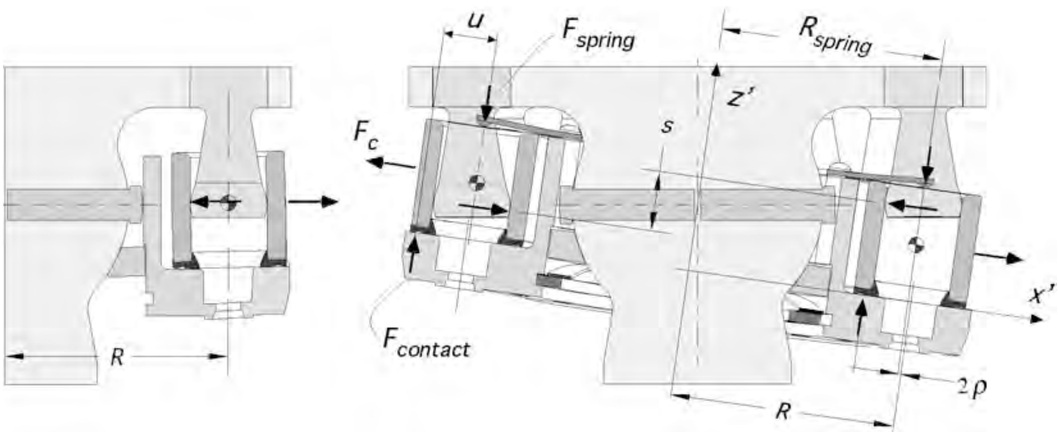

Figure 4: Forces on the cup, piston in middle position, TDC and BDC

Assuming the center of gravity of the cup coincides with the mean piston position and the spring force acts centrally on the top of the cup. In that case the maximum tilting torques are reached in TDC en BDC, because at that point the moment arm of the centrifugal force is maximal:

$$|M_{tilt}| = F_c \frac{s}{2} = \omega^2 m\, r \frac{s}{2}$$

The equilibrium of the cup demands a displacement of the barrel-cup contact:

$$u = \frac{\Delta M_{tilt}}{F_{spring}}$$

The cup will not tilt as long as the position of the contact force lies within the outer circle of the cup bottom. To limit the displacement u to the cup bottom radius a minimal spring force is needed:

$$F_{spring} = \frac{M_{tilt}}{u} = \frac{\omega^2 m\ r\ s}{2\ u} = \frac{\omega^2 m\ r\ s}{4\ D},\ (u \le \frac{D}{2})$$

For a 2x12 piston 28cc floating cup machine this means a spring force of 55 N is needed for speeds up to 3500 rpm. The spring–cup contact is placed centrally on the top of the cups in TDC and BDC. However, when the cups are in TDC or BDC they are moved 2 ρ radially inwards relative to the barrel (figure 4 right). The effective spring radius becomes:

$$R_{spring} = R - 2\ \rho$$

In reality the center of gravity of the cup is not placed at the mean piston position but a little towards the cup bottom (figure 5).

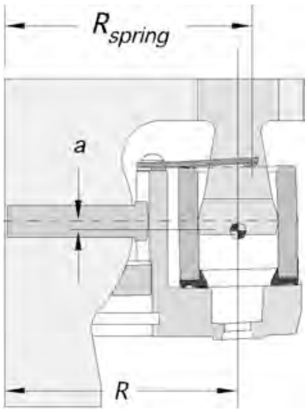

Figure 5: geometry

This increases the tilting moment at BDC and decreases the tilting moment at TDC:

$$\Delta M_{tilt} = \omega^2 m\ r\ a$$

Moving the spring–cup contact radially outwards can compensate this asymmetry:

$$F_{spring}\ \Delta R_{spring} = \Delta M_{tilt} = \omega^2 m\ r\ a$$

$$\Delta R_{spring} = \frac{\omega^2 m\ r\ a}{F_{spring}}$$

Now the effective spring radius becomes:

$$R_{spring} = R - 2\ \rho + \frac{\omega^2 m\ r\ a}{F_{spring}}$$

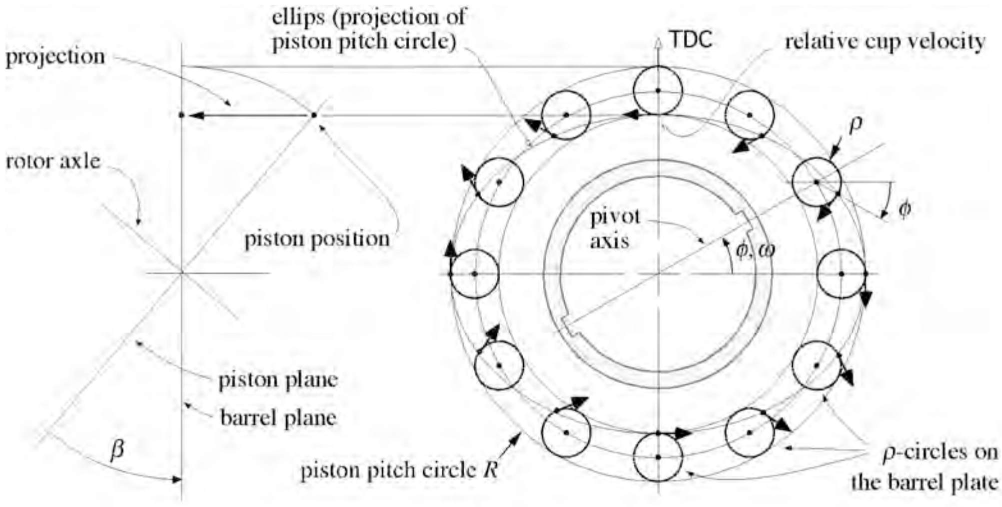

Figure 6: Relative movement of the cups on the barrel plate in case the barrel is driven by a constant velocity joint. In this example the number of pistons is 12 and the inclination between the rotor and the barrel is set at a value of β =40°.

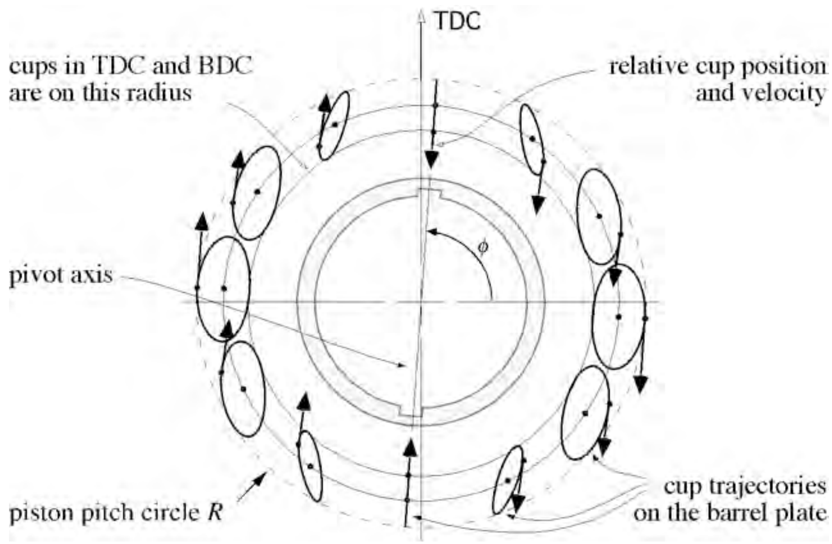

Figure 7: Relative movement of the cups on the barrel plate in case the barrel is driven by a pivot joint or some other kind of Cardan joint. In this example the number of pistons is 12 and the inclination between the rotor and the barrel is set at a value of β =40°.

3 Kinematics

In the floating cup machine the pistons are fixed onto the rotor (figure 1, 3). The barrel-cup assembly runs on the inclined face of the port plate. This inclination β ensures that the pistons move relative to the cups and pump oil. The inclination of the barrel-cup assembly is only possible when the cups are free to slide over the barrel plate. In the rotating machine the pistons move up and down in the cups moving from bottom dead center (BDC) to top dead center (TDC) and vice versa. The cups slide over the barrel plate along a very small track. Friction forces are directed to the opposite of the velocities of these motions.

The relative motion of the cup to the barrel plate is not as obvious as the piston-cup motion and needs extra attention. Achten [7] has already described this relative motion extensively. His conclusions are presented here.

As the pistons rotate, the cups move along an ellipse, which is the projection of the piston pitch circle on the inclined barrel plane (figure 4). In case of a constant velocity joint between axle and barrel the cups move along a small circle on the barrel ('ρ-circle', Walzer [8]). In the floating cup machine, the barrel is coupled via two simple pivots, mounted in the axle, that slide in slots in the barrel (figure 3). Since this is not a constant velocity joint, there is a relative rotation between axle and barrel that deforms the circles to ovals (figure 5). This deformation is dependent on the angular position of the cup to the pivot axis. The latter is the axis through the pivots. The circles of the cups on the angular position of the pivot even degenerate to a line. The relative velocities of these cups are radial only, just as the friction forces between the barrel and these cups are. The relative velocity of the other cups becomes pure radial too, but not when the cup is at TDC or BDC. This difference becomes of significance in paragraph 4 when the friction forces are studied in detail.

In a floating cup machine the strength of the piston neck restricts the inclination β to approximately 11º. At that inclination the ρ-circles and ovals are so small that they can hardly be plotted. In the figures 3 and 4 the inclination is therefore increased to 40º.

4 Friction

So far the minimal spring force and the optimal effective spring radius have been determined for a frictionless hold down construction. When friction is introduced, the kinematics of the cups have to be taken in account which makes the analysis rather complicated. This is why the hold down construction has been modeled with a multi body package. In the multi body model the cup body is connected with joints to the barrel, the hold down spring and the piston.

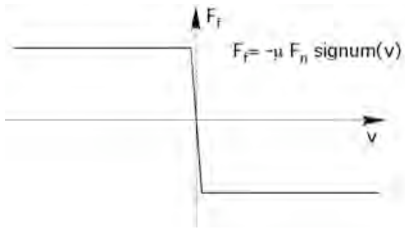

Figure 8: uniform friction model

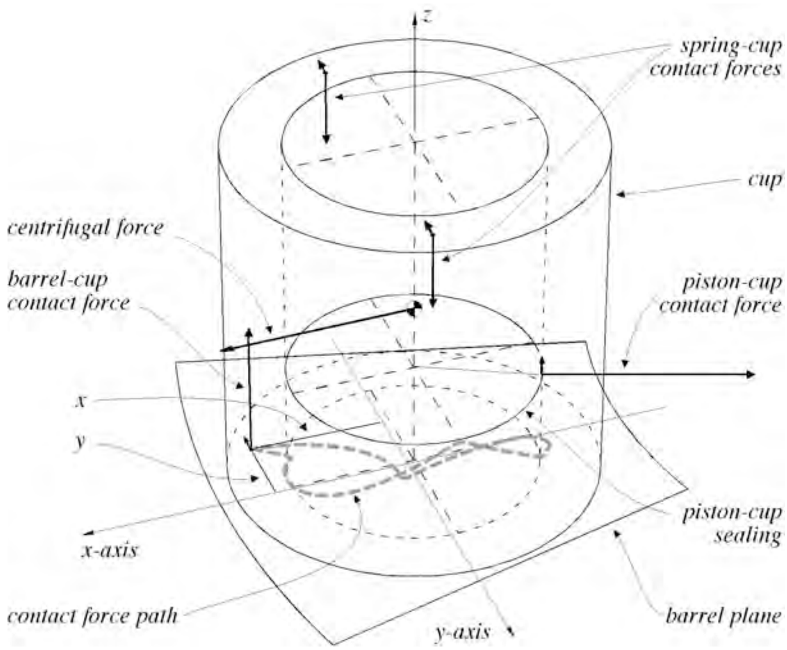

Figure 9: path of contact force, with friction

Although in reality the cup is free to tilt and even leave the barrel, in the model the joint between barrel and cup was modeled as a planar joint, only able to slide in the x- and y-direction over the barrel plane (figure 9). The translation in the z-direction and the rotations around the x- and y-axes were suppressed and reaction force F_z and moments M_x, M_y calculated. From these reactions the location of the contact force can be obtained:

$$x = \frac{-M_y}{F_z},\ y = \frac{M_x}{F_z}$$

When the machine rotates, the contact force moves along a path that is shown in figure 9. The cup will not tilt as long as the position of this contact force lies within the outer circle of the cup bottom.

Unpredictability is the nature of friction forces. The strategy chosen is to study friction in each of the interfaces of cup, piston, barrel and hold down spring separately and determine worst cases of combined friction effects. This is what you will find in the next paragraphs. Although in reality the sliding velocities are not constant, a simple uniform friction model was used, justified by the fact that worst cases are looked for only (figure 8).

In figure 14 contact force paths are shown for a construction with, and without friction. It is the critical situation for a 28 cc floating cup machine at 3500 rpm. Without friction the contact force stays exactly within the outer circle of the cup bottom ensuring the cup will not tilt. In the following paragraphs in each of the relevant interfaces friction is introduced separately at the same conditions to demonstrate its effect.

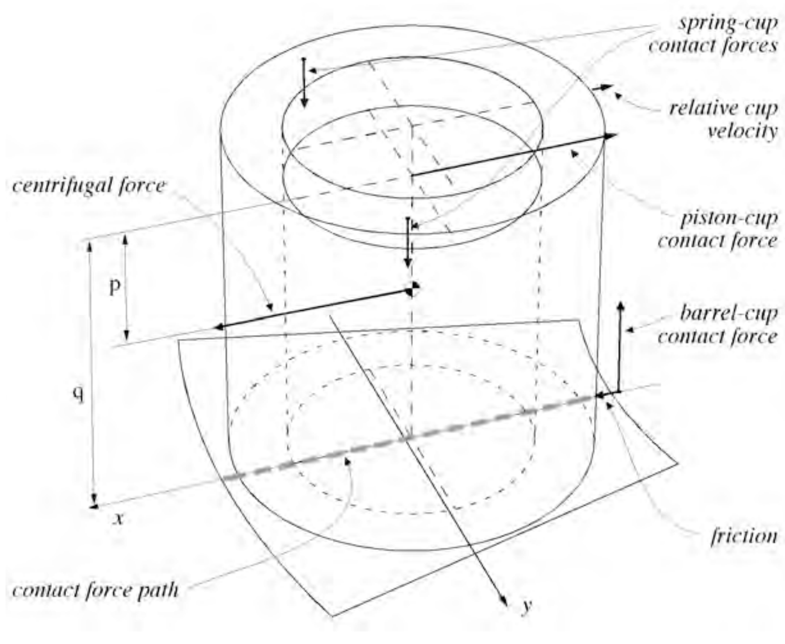

Figure 10: A cup at the angular position of the pivot. The friction forces between the barrel plate and the cup and the centrifugal force tilt the cup in the same direction. The piston is at BDC and than the moment arms of both forces are maximal.

4.1 Friction between cup and barrel

The friction force on the cup is directed opposite to the relative velocity of the cup to the barrel. The contact force and the friction coefficient in the cup-barrel interface determine its magnitude.

The largest total tilting moments on the cup are created when the centrifugal force and the friction forces tilt the cup in the same direction and the moment arms of both forces are maximal (figure 10). The moment arms become (sub-) maximal in BDC and TDC. Most cups move in tangential direction in BDC and TDC. Only the cups at the angular position of the pivots move in the radial direction (figure 5) and tilt the cup in the same direction as the centrifugal force. The largest tilting moment therefore works on these cups. Friction moves the contact force further outwards when the piston is in TDC, and inwards when the piston is in BDC. The moment arm of the friction force is longer in BDC because the cup center of gravity is placed somewhat below the mean piston position. In BDC the tilting moment becomes maximal. Compared to the frictionless situation, the diameter of the contact path is increased and its center is moved radially inwards. This is also true for the

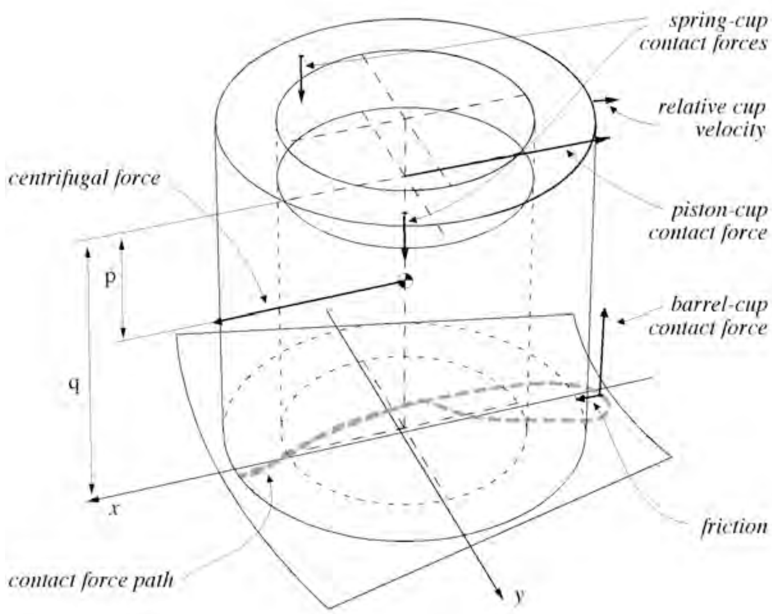

Figure 11: A cup at -30º to the pivot. The friction force between the barrel plate and the cup and the centrifugal force tilt the cup in the same direction. The piston is not yet in BDC and therefore the moment arms of both forces are not maximal yet.

cups that are not at the pivots angular position. However, for these cups the tilting moment is less critical because the maximal tilting moment of the friction force is not in the direction of the centrifugal moment. These cups do not move along a line but a small oval (figure 5) and their velocity at BDC is in the tangential direction. When they move in the radial direction the piston is not at its extreme position (figure 11).

To prevent the cup from tipping over, the spring force can be increased and the spring contact can be moved radially outwards. The contact paths of the cups at the angular position of the pivot are straight radial lines, the paths of the other cups show a tangential dimension which is caused by the friction in this direction.

4.2 Friction between cup and hold down spring

Friction at the top is very similar to the situation with friction at the bottom of the cup. The maximum moment arm of the friction force is now reached at TDC instead of BDC (figure 12). The center of the contact path is now no longer moved radially inwards but outwards.

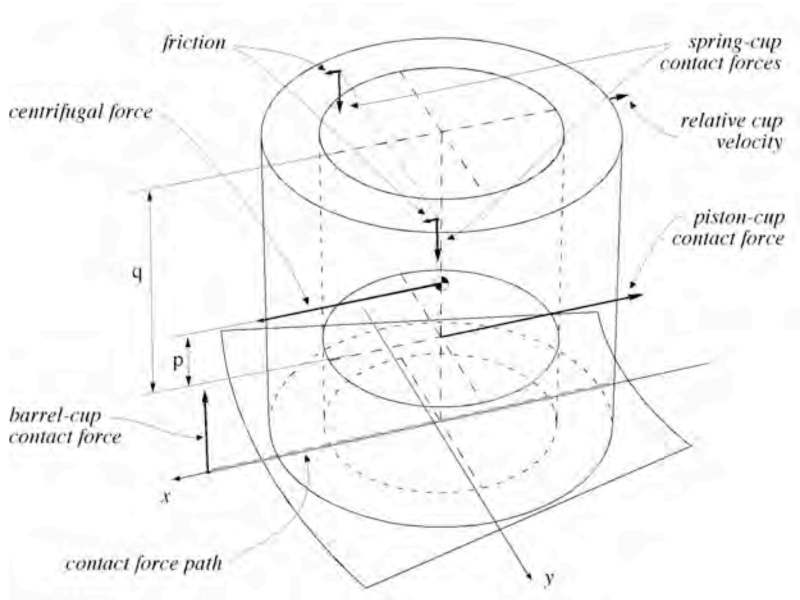

Figure 12: The cup at the angular position of pivot at TDC. The friction with the hold down spring and the centrifugal force tilt the cup in the same direction. The moment arms of both forces are maximal.

4.3 Friction between cup and piston

The centrifugal force presses the cup to the piston. When the piston moves up or down in the cup a friction force is created. This friction force is placed at the sealing circumference between both parts at an angle that is determined by the direction of the contact forces between both parts (figure 13). The critical situation is in TDC, when both the centrifugal force and the friction force are tilting the cup in the same direction and the piston moves up. At that moment the contact force between cup and barrel is minimal. Friction between cup and piston increases the diameter of the contact path and its center is moved radially outwards.

Because of the small clearance between cup and piston a clamping force can exist between both parts, which can make friction. This friction is assumed to be distributed evenly along the sealing circumference of the piston and cup. When the piston moves up the contact force between barrel and cup is decreased enlarging the diameter of the contact path. The center of this path remains the same when this load is applied. The effect of friction with the piston is indifferent to the angular position relative to the pivot. It applies to all cups equally.

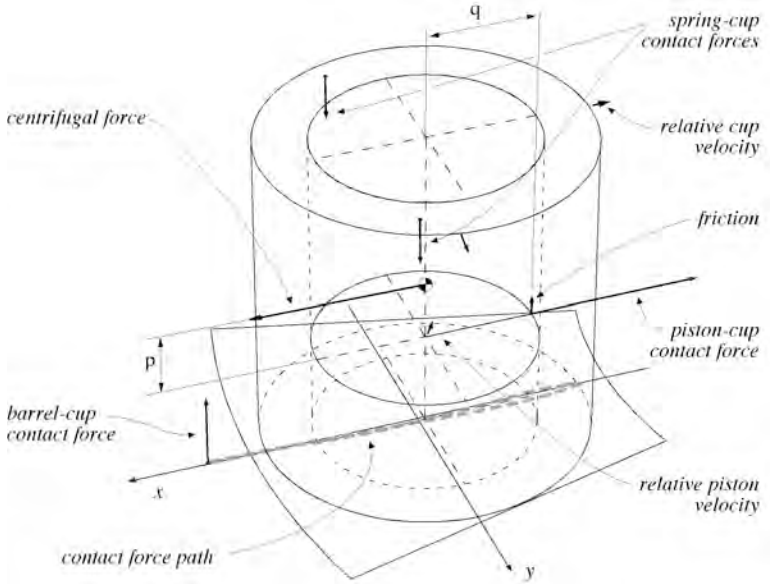

Figure 13: friction with piston, cup at 90º of pivot at TDC position

4.4 Combined friction

In the previous paragraphs the effect of friction in each of the relevant interfaces has been determined. It was shown that friction in each of the relevant interfaces enlarges the diameter of the contact force path and moves its center to a specific direction. Friction in the cup-barrel interface moves the path inwards while friction in the interface with the spring and the piston moves the path outwards (figure 14). This applies to all cups, not only to the cups at the pivots. It is now possible to define two worst-case situations in which the force path is moved outwards and inwards to the extreme (table 1). These worst cases are called 'outwards' and 'inwards'. A hold down spring design is now evaluated for both worst cases. The optimal design is defined as the spring force and the effective spring radius at which the contact force path becomes critical at both cases. In combined friction it is necessary to evaluate for cups at all angular positions relative to the pivot.

To determine the friction coefficients, dynamic friction forces were measured in a simple experiment outside the machine. In these measurements the dynamic friction coefficient never exeeded 0.15. Naturally friction is dependant on a lot of conditions and it is not easy to determine the exact governing friction coefficients. To get an indication of the sensibility to friction two sets of friction coefficients are defined, 'friction A' and 'B' in table 1. Figure 15 shows the worst-case situations 'inwards' (top) and 'outwards' (bottom) for the design for friction set A. For each set and the situation without friction an optimal design is calculated (table 2). Table 2 shows that the cup can be held down to the barrel with a limited hold down spring force and that friction causes a significant but limited increase of this force. It does influence the optimal geometry too.

Due to the limited normal forces and the small displacements, especially in the cup-barrel and cup-spring interfaces, the torque loss caused by friction is very small (table 3). Relative to the nominal torque of the machine these losses are negligible.

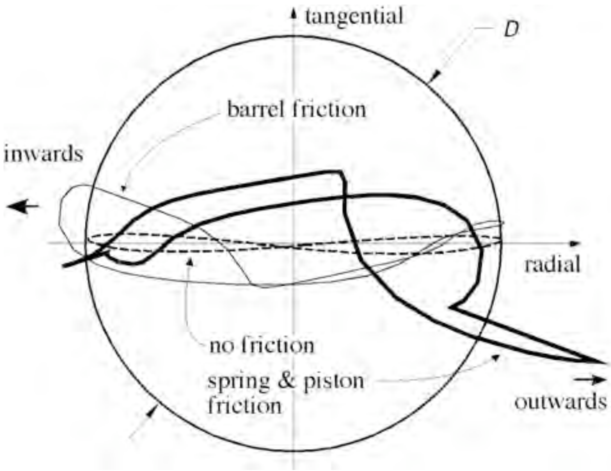

Figure 14: contact force paths with and without friction at the same spring force, effective radius and machine speed (3500 rpm) for a 28 cc floating cup machine

Table 1: worst-case friction coefficients and clamping force

	friction A		friction B	
	outwards	inwards	outwards	inwards
cup-barrel friction	0	0.1	0	0.15
cup-spring friction	0.2	0	0.3	0
piston-cup friction	0.05	0	0.075	0
clamping force [N]	20	0	30	0

Table 2: optimal hold down spring force and effective radius for a 28 cc floating cup machine with a maximal speed of 3500 rpm

	no friction	friction A	friction B
F_{spring} [N]	54	70	80
R_{spring} [mm]	38.99	37.9	37.5

Table 3: torque loss due to friction for a 28 cc floating cup machine at a speed of 3500 rpm.

	friction coefficient [-]	torque loss [Nm]
cup-barrel friction	0.1	0.07
cup-spring friction	0.2	0.14
piston-cup friction (clamping force 20 N)	0.05	0.45

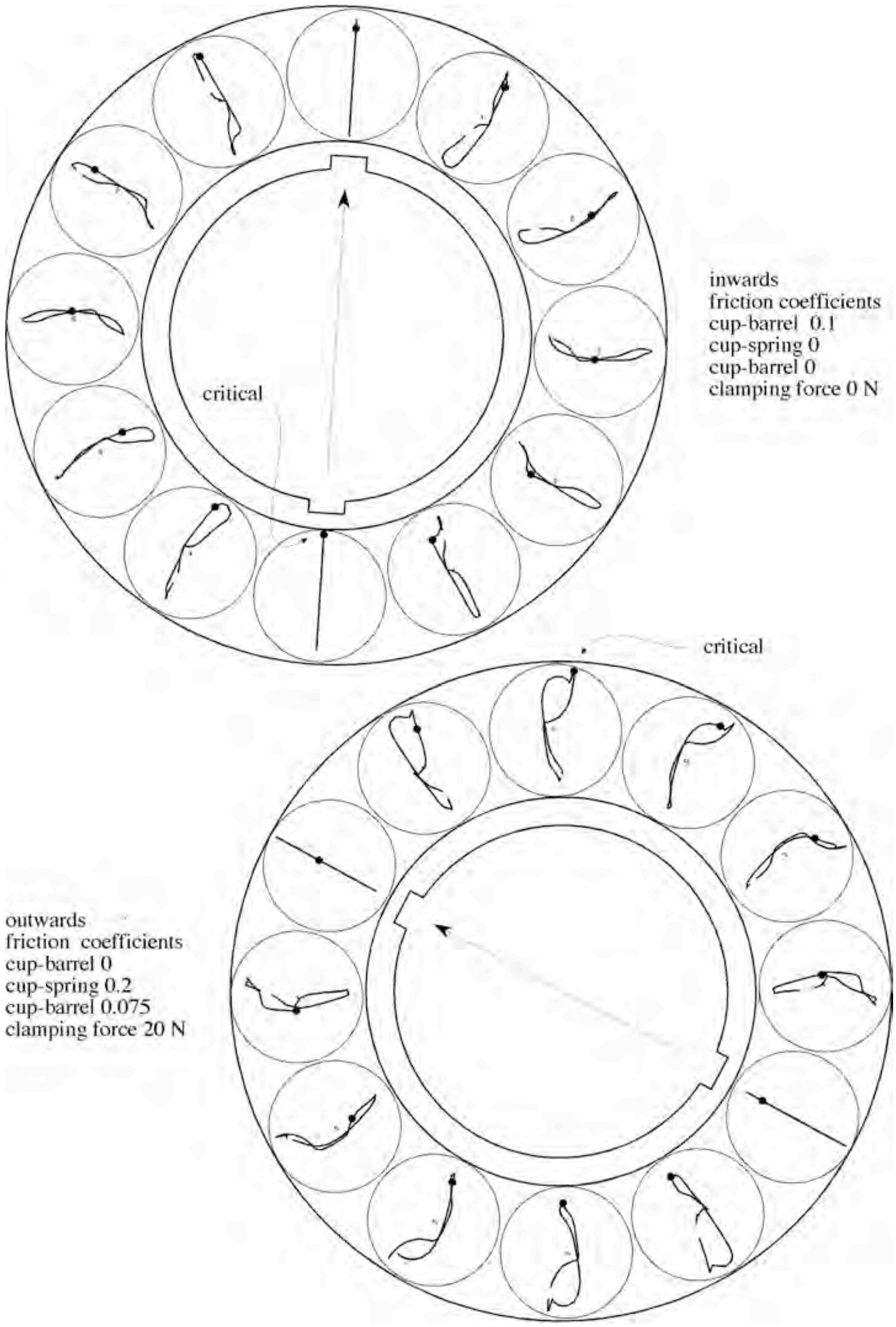

Figure 15: contact force paths for 28 cc floating cup machine at 3500 rpm with friction set A, the black dots show the actual position of the contact force between cup and barrel

5 Conclusion

The hold down spring is a viable alternative to hold down the cups to the barrel of the floating cup machine. It ensures that the cup is always pressed to the barrel plate. The gap between both parts remains closed and oil leakage is prevented. This facilitates the noise reduction by optimizing the port plate grooves. The new force-closed construction is less sensitive to production tolerances than the form-closed alternative with a hold down plug and therefore may result in a cost reduction.

The cup can be held down to the barrel with a limited hold down spring force. Friction in the interfaces of the cup with barrel, spring and piston causes a significant but limited increase of this force and does influence the optimal geometry. The effect of friction between piston and cup on machine efficiency however is very small. Due to the very small relative movement of the cup to the barrel and the hold down spring, the effect of friction between these parts on machine efficiency is negligible. Because friction may vary due to many conditions it is useful to optimize the design for a range of friction coefficients.

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