DYNAMIC MODEL OF A WASHING MACHINE BALANCING SYSTEM

(Fisher & Paykel Ltd)

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The client manufactures washing machines which have a cylindrical drum (with a nominally vertical axis) suspended within a cuboid outer box (called the envelope). The drum has a non-rotating outer part and a rotating inner bowl where the clothes (load) are placed. The centre of mass of the load will usually not lie on the axis of symmetry of the inner drum and thus there will be an out of balance load (OOBL) when the drum rotates. This causes the drum to rotate about an axis other than its axis of symmetry and causes the motion to be eccentric.

The client seeks to maximise the size of the inner drum (to maximise capacity) whilst minimising the size of the envelope (space required in laundry) and thus the clearance between the bowl and the envelope needs to be minimised (it is typically 25mm). This constrains the amount of eccentricity that can be tolerated before the drum collides with the envelope. Eccentricity is reduced by the use of balancing rings on the inner drum and by the design of the suspension system of the drum.

The client seeks a more comprehensive understanding of the dynamics of the system and in particular what causes the motion to be eccentric. They have always been able to successfully design balance rings and suspension rods which keep the eccentricity to acceptable levels for all reasonable OOBLs but the design approach has been somewhat 'trial and error'.

Observations and the client's experience suggest that eccentricity is relatively small during the low speeds of the wash cycle (say below 30rpm) and during the high speeds reached towards the end of the spin cycle (above 300 rpm and up to ~ 1,000 rpm) but that there are two speed ranges (traversed during the spin cycle) where the eccentricity can become large. The first occurs typically between 30 and 60 rpm and across a narrow speed range (for any given configuration and load). At such low speeds the drive motor has abundant torque and the undesirable eccentric motion can be avoided by rapidly accelerating through the speed range where it would occur. The second speed range occurs typically between 150 and 300 rpm and (for any given configuration and load) prevails over a wider speed range. This wide speed range combined with reduced motor drive torque available at these higher speeds mean that it is not possible to simply rapidly accelerate through the speed range and careful attention needs to be paid to the design of the suspension and the balance rings to achieve acceptable behaviour.

The team analysed the role of the suspension system and balance rings in minimising the eccentricity of the motion and scoped the requirements for a comprehensive dynamical model of the system.

The low speed mode corresponds to the natural frequency of the 'swing mode' of the drum hanging on the suspension rods (with or without drum rotation, the drum can simply swing from the suspension rods). This natural frequency was measured to be slightly below 1 Hz and the motion was excited at a rotational speed of ~ 50rpm at which the out of balance centrifugal force would excite the mode. The amplitude (and natural frequency) of the motion would change with suspension characteristics (stiffness and damping). However, the design of the suspension system is a compromise between minimising the amplitude of the motion of the drum relative to the envelope and minimising the transmission of high frequency vibrations (hence noise) from the drum to the envelope. Thus, though it would be possible to reduce the amplitude of the swing by stiffening the suspension or increasing the damping, both would tend to increase the transmission of high frequency vibrations to the envelope.

It should be noted that, at the speeds where the low-speed mode is observed, the centrifugal acceleration in the balance rings is ~ g/2 and the balance rings do not play a significant role in reducing eccentricity at these speeds. The simple model in the 'Simple Theory' section of Vankirk and Burmeister (1976), though for a system with a massive base plate on the drum and with horizontal suspension connections to the envelope, illustrates this mode. A model to describe this behaviour for the modern designs (no massive base plate) could be developed relatively easily. Overall, the team suggest that the current suspension system design achieves a reasonable compromise between suppressing eccentric motion in this mode and minimising vibrations and noise at higher frequencies and that the solution of rapidly accelerating through the critical speed is a sensible one.

Once higher speeds are reached, centrifugal forces dominate the system (note that centrifugal forces in the balance ring are ~ 5g at 135 rpm and increase as the square of rotational speed so this could be considered an effective threshold) and the inner drum will tend to rotate about its principal axis of inertia (axis about which the moment of inertia is minimal). Due to the OOBL, the principal axis is dissimilar to the axis of symmetry and hence the motion is eccentric. The balance rings are able to partially counterbalance the OOBL and bring the principal axis closer to the axis of symmetry (thus reducing eccentricity) but it can be shown that they are not able to completely remove the eccentricity. The model in MISG 2000 (Whiten and Broadbridge, 2000) provides a good description of the operation of the balance rings and the resulting, reduced eccentricity. A key assumption of this 2-D model is that the axis of rotation will be vertical and stationary, thus the motion of the drum is a simple 1-dof rotation (albeit about an axis inclined to the axis of symmetry). Key characteristics of such a motion are that the gap (vertical and horizontal) between a fixed point on the envelope and the upper rim of the drum is sinusoidal through time with fixed amplitude and frequency equal to the rotational frequency of the inner drum and the length of the suspension rods is also sinusoidal through time with fixed amplitude and similar frequency. Further, for this motion, the water in the balance rings will be stationary with respect to the ring and its position and profile will not be speed dependant.

Observations of the motion suggest that these displacements are sinusoidal and that the balancing water is stationary with respect to the balance rings and that the motion is the simple 1-dof motion predicted for high speeds (say above 300rpm) and for speeds below a critical threshold (~ 180 rpm for the configuration of the experimental rig available during the workshop). However, at the speeds where the eccentricity is high (approximately 180 rpm to 250rpm), the motion is not the simple 1-dof rotation described by the MISG 2000 model. This is evident as the gap between the drum and envelope does not vary sinusoidally and the water moves within the balance rings.

Thus, it appears that the assumption made in the MISG 2000 model about the axis of rotation being vertical and stationary is not valid at the speeds where the problem occurs and a richer model is required to describe the motion and understand the cause of the eccentricity. The two degrees of rotational freedom ‘suppressed’ in the MISG 2000 model can be described as precession and nutation, in these degrees of freedom the axis of rotation of the spin will itself pitch and roll. When precession and nutation occur, the eccentricity (of the drum’s rotation viewed in a horizontal plane) is likely to increase. There is no fundamental reason why precession and nutation will not occur. A brief analysis of a simple model developed to describe the dynamics and permitting precession and nutation suggest that there are spin-speed dependant terms which significantly affect the precession and nutation behaviour at higher speeds. However, much further modelling and analysis is required to provide a complete explanation.

The suspension system will play a vital role isolating and damping the resulting motion and it is possible that baffles which damp the motion of the water within the balance rings will also affect the motion. This is consistent with the client’s experience of significant design parameters which influence the eccentricity.

Further phenomena which were observed during the non-simple rotational motion were that there appeared to be standing waves between the baffles within the balance rings and that it appeared that the spin speed of the drum was not constant.

The spin speed is regulated by feedback control which manipulates the torque applied by the motor to drive the spin. Ideally, the spin speed will be ‘tightly’ controlled so that variations in spin speed to not create undesirable motions and potential disturbances to spin speed caused by undesirable motions are rejected by the control system.

It is not certain whether the standing waves in the balance ring sectors are an effect or a cause of the non-simple rotational motion. However, since the water is stationary within the balance rings when the rotational motion is simple (outside the 180 – 250 rpm range), there would have to be some self-generating effect for the waves to be the cause of the non-simple motion as the spin speed entered the 180-250 rpm range.

In summary, at high speed (say > 250 rpm) and below a threshold (typically 180 rpm), the motion is predominantly a simple 1dof rotation with the axis of rotation slightly tilted with respect to the axis of symmetry and slight (but acceptable) eccentricity. The balance rings operate well with the water stationary within them and the MISG 2000 model adequately describes the behaviour of the system. At intermediate speeds (say 180 – 250 rpm) the motion is non-simple with excessive (potentially unacceptable) eccentricity. Three candidate causes have been identified:

1. The motion is naturally non simple and precession and nutation naturally occur at these speeds.
2. Waves occur in the balance ring sectors and these force the rotational motion to be non-simple
3. The spin speed control is ineffective and spin speed fluctuations are the cause.

The 3rd potential cause is essentially a stand-alone issue and can be analysed and resolved independently. It is more likely that the 1 is the cause and the waves are an effect (though potentially aggravating the eccentricity). A richer model could be developed which describes the non-simple motion and how it is influenced by suspension system and balance ring design. This would be potentially useful to the client as a design aid.

References

Vankirk J and Burmeister L (1976) "An Automatic Balancer Design for a Vertical-Axis Clothes Washing Machine", Proceedings of ASME Design Engineering Conference & Show, Chicago, Ill., April 5-8, 1976.

Whiten WJ and Broadbridge P (2000) "A washing Machine Balancing problem", Proceedings of MISG 2000, Adelaide.

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