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Vibration Analysis of a Horizontal Washing Machine, Part III: Optimal Parameters

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Abstract:

The objective of this research work is to assign optimal parameters for the passive suspension of a horizontal washing machine and to assign proper value for the drum mass in order to increase the efficiency of the isolators and reduce the vibration velocity of the drum. The MATLAB optimization toolbox is used to maximize the isolation efficiency subjected to parameters constraints and a functional constraint which is the vibration velocity of the drum. The spinning speed is used as input variable to help the washing machine designer to assign a proper value for the spinning speed of his machine. The presented approach is capable of increasing the isolation efficiency to more than 97 % and reduce the drum vibration velocity to less than 14.8 mm/s RMS.

Keywords — **Horizontal washing machine, drum vibration, passive drum suspension, optimal drum mass and suspension parameters.**

I. INTRODUCTION

A washing machine is one of rotating machines class having severe rotating unbalance which excites excessive forced vibration which is harmful to the machine itself and to the surroundings through exciting structural born vibrations and noise. Therefore, the objective of this series of research papers is to help the washing machine designer to have a good idea about the vibration of the machine drum during the spinning cycle.

Turkaya, Kirayb, Tugcub and Sumerb (1995) discussed various formulations for suspension design optimization and implementation using grid and sequential quadratic programming optimization methods. The actual design of the test washing machine was verified for its optimality [1]. Turkaya, Sumer, Tugca and Kiray (1998) derived a nonlinear time variant rigid body dynamic model of the suspension system of a horizontal-axis washing machine. Their model and simulation were validated experimentally for suspension design optimization of horizontal washing machines [2].

Hyun, Chang, Jeon and Yoo (2004) presented the multi-body dynamic model of a drum-type washing machine. The transient and steady-state amplitudes of the simulation model had a good agreement with the prototype suspension model [3]. Lucas, Milasi and Araabi (2006) used a neuro-fuzzy locally linear model tree system for data driven modelling of the washing machine. They used also a neural computing technique based on a mathematical model for control of the washing machine [4]. Boyraz and Gunduz (2013) deried a 2D dynamic model of a horizontal wshing machine to examine the vibration characteristics of the spin cycle and improve its design proposing an optimal scheme based on genetic algorithms. They used acceleration data to yield the vibration displacement in 2D and the vibration frequency [5].

Kolhar and Patel (2013) proposed an idea for the optimization of a washing machine in terms of reduction of drum vibration, power consumption and water consumption. They used the solid Works program to model the washing machine. They could reduce the drum vibration, water consumption and power consumption of the washing machine [6]. Nguyen and Choi (2014) studied the optimum design of a flow-mode MR damper for washing machines. Their objective was to minimize the damping coefficient of the MR damper. They validated their results by experimental work [7]. Argentini, Belloli and Borghesani (2015) studied a vibrating system excited by a rotating unbalance and coupled to a tuned mass damper. They showed that proper tuning of the mass damper reduced the steady-state vibration by about 20 % with respect to a classically tuned damper [8]. Hassaan (2015) investigated the effect of drum mass and suspension parameters on the steady-state vibration displacement and velocity of the drum of a horizontal washing machine for spinning speed up to 1200 rev/min [9]. He also studied the effect of the drum mass and suspension parameters on the isolation efficiency of the suspension elements to decrease the dynamic force transmitted to the cabinet of the machine and causing vibration and noise [10].

II. PHYSICAL MODEL OF THE WASHING MACHINE

The drum of a horizontal washing machine is isolated from the cabinet by a suspension system comprising a number of springs and dampers to control its vibrations. Fig.1 shows a physical model for this dynamic system showing the location of the laundry unbalance during the spinning cycle [9], [11].

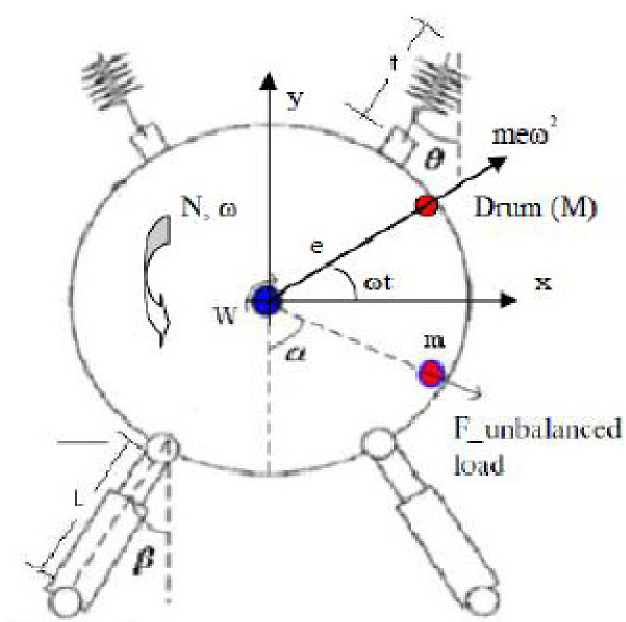

Fig.1 Physical model of the washing machine [9], [11].

The suspension elements are inclined with the vertical direction by angle Θ for the springs and β for the dampers. The laundry unbalance has a mass m and an eccentricity e. The drum spinning speed and mass are N and M respectively. Each spring has a stiffness k and each damper has a damping coefficient c. The drum motion is in the plane xy.

III. VIBRATION MATHEMATIC MODEL

It is possible to derive a mathematical model for the vibrating drum in the xy plane, i.e. of 2DOF characteristics. However, it is more easier to consider only the vibration motion in one direction (say the x-direction) [6]. Following this assumption, the vibration mathematical models were derived before in part I and II of this series as follows [9], [10]:

- Natural frequency, ω_n :

$$\omega_n = \sqrt{(k_e / M)} \quad \text{rad/s}$$

or $$f_n = \omega_n / (2\pi) \quad \text{Hz}$$

where: $k_e = 2k(\sin\Theta)^2$

- Damping ratio, ζ:

$$\zeta = c_e / (2M\,\omega_n)$$

where: $c_e = 2c(\sin\beta)^2$

- Exciting force, F_x:

$$F_x = me\omega^2 \cos \omega t$$

where: $\omega = 2\pi N/60$ rad/s

- Drum vibration amplitude, X:

$$X = (me/M)r^2 / \sqrt{\{(1 - r^2)^2 + (2\zeta r)^2\}} \qquad (1)$$

Where: $r = \omega/ \omega_n$

- Drum vibration velocity, V in mm/s RMS:

$$V = \omega X / \sqrt{2} \qquad (2)$$

- Transmissibility, TR:

$$TR = \sqrt{[1+(2\zeta r)^2]}/\sqrt{\{(1-r^2)^2 + (2\zeta r)^2\}} \qquad (3)$$

- Isolation efficiency η:

$$\eta = 100(1 - TR) \qquad (4)$$

IV. OPTIMAL DRUM MASS AND SUSPENSION PARAMETERS

The three parameters: drum mass, suspension damping coefficient and stiffness affect the vibration dynamics of the machine as clear from Eqs.1 through 4. The optimal values of the three parameters are evaluated as follows:

1. Optimization technique: The MATLAB optimization toolbox is used to solve the present optimization problem which is a constrained one through its command '*fmincon*' [12].
2. Objective function: The objective function in this work is the isolation efficiency given by Eq.4.
3. Parameters constraints: set as follows:

   $10 \le M \le 50$ kg

   $5 \le k \le 50$ kN/m

   $130 \le c \le 500$ Ns/m
4. Functional constraint: There only one functional constraint which is the drum vibration velocity given by Eq.2.
5. The upper bound of this functional constraint was a problem for the researcher. The washing machine during spinning transforms the whole laundry to a rotating unbalance which is a case I could not find its vibration severity according to any standard. I was in contact with a member of the vibration committee of the ISO standard for this matter. But I did not get any answer. Therefore, a maximum limit is set arbitrarily to 50 mm/s RMS.
6. Spinning speed: The spinning speed is a key variable in the vibration associated with the washing machine during the spinning cycle. Commercially, there is a wide range of this variable. Therefore its effect on the optimal parameters of the washing machine is investigated in the range: $300 \le N \le 1100$ rev/min.
7. The optimal washing machine parameters and the corresponding vibration functions against the spinning speed are given in Table 1.

TABLE I
OPTIMAL WASHING MACHINE PARAMETERS AND FUNCTIONS

N (rev/min)	M (kg)	k (N/m)	c (Ns/m)	X (mm)	V (mm/s RMS)	η (%)
300	50	5000	130	0.665	14.766	85.504
400	50	5000	130	0.637	18.802	91.083
500	50	5999.6	130	0.626	23.194	93.087
600	50	5999.7	130	0.618	27.463	94.709
700	50	5999.8	130	0.613	31.784	95.716
800	50	5999.8	130	0.610	36.137	96.397
900	50	6000	130	0.608	40.510	96.887
1000	50	6000	130	0.606	44.900	97.258
1100	50	5999.9	130	0.605	49.297	97.547

8. Vibration amplitude of the washing machine drum: The optimal peak vibration amplitude of the drum is shown in Fig.2.

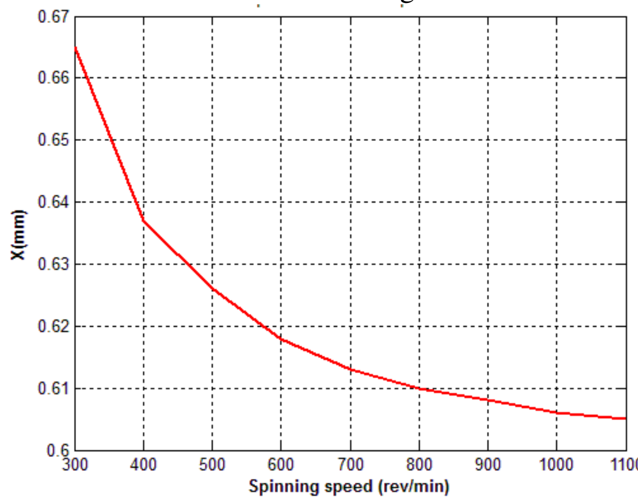

Fig.2 Optimal drum vibration amplitude.

9. Vibration velocity and isolation efficiency: The optimal vibration velocity of the drum as a measurement for the drum vibration severity and the isolation efficiency as an indication of the suspension efficiency are shown in Fig.3.

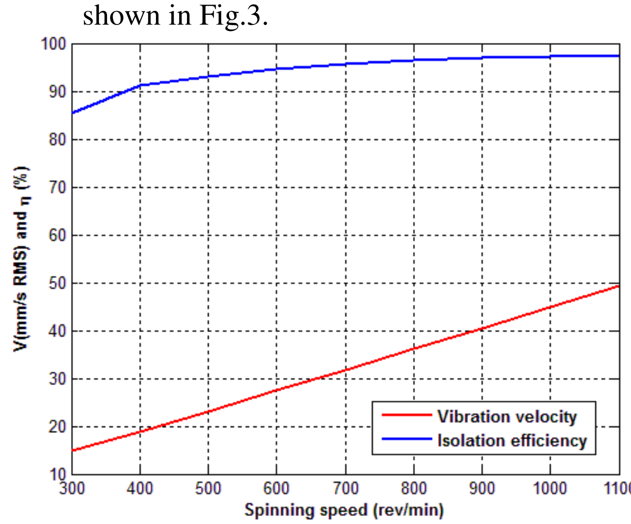

Fig.3 Optimal drum vibration velocity and isolation efficiency.

V. VIBRATION SEVERITY OF THE WASHING MACHINE

For rough estimation of the vibration severity of the horizontal washing machine vibration during the spinning cycle after the optimization process, the following procedure is followed:

1. According to B. Cease, the value of the vibration velocity of machines with spring mounts has to be multiplied by 0.6 before applying the guidelines the Bernhard general standard [13].
2. D. Bernhard set general standard for machinery vibration severity as follows [14]:

- Rough vibration: 5.1 – 7.6 mm/s.
- Very rough: 7.6 – 12.7 mm/s.
- Extremely rough: 12.7 – 15.2 mm/s.

3. The 0.6 the vibration velocity is plotted with the limits for the machine condition as assigned by Bernhard are plotted and shown in Fig.4.

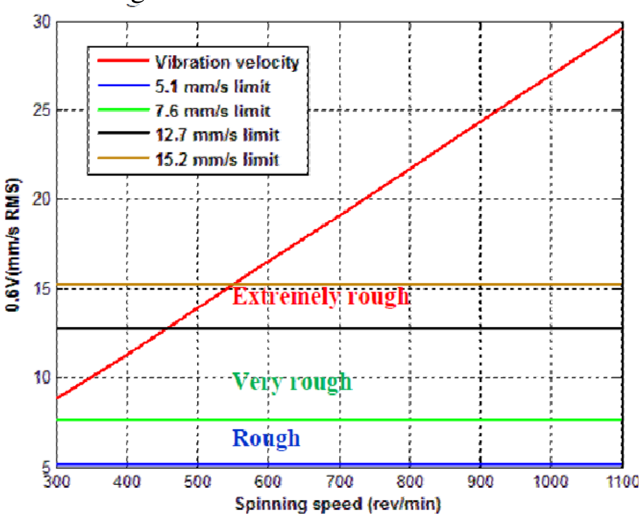

Fig.4 Vibration severity of the washing machine and Bernhard limits.

VI. CONCLUSIONS

- This research paper presented the third part of the research work regarding the vibration of horizontal washing machines.
- The optimal drum mass and suspension parameters was the objective of the work against spinning speed from 300 to 1100 rev/min.
- MATLAM optimization toolbox was used to achieve the target of this research work.
- The optimal drum mass settled at its maximum limit set in the optimization algorithm (50 kg).
- The suspension stiffness settled at a value of either 5 or 6 kN/m depending on the spinning speed.
- The damping coefficient settled at the minimum limit set in the optimization algorithm (130 Ns/m).
- The optimal vibration amplitude of the drum decreased from 0.665 mm at 300 rev/min spinning speed to 0.605 mm at 1100 rev/min.
- The optimal vibration velocity of the drum increased from 14.766 mm/s RMS at 300 rev/min spinning speed to 49.297 mm/s RMS at 1100 rev/min.
- The optimal isolation efficiency of the suspension increased from 85.50 % at 300 rev/min spinning speed to 97.55 % at 1100 rev/min.
- There was a contradiction between vibration severity and isolation efficiency. From point of view of vibration isolation, the spinning speed has to be increased, while it has to be decreased in behalf of vibration severity through decreasing the vibration velocity.
- The vibration severity of the washing machine was checked out against its spinning speed using Bernhard general standard.
- The machine vibration at spinning speeds in the range from 300 to 460 rev/min is very rough.
- Certain means of balancing the machine rotor during spinning are required to reduce the vibration velocity and generate good vibration severity.

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