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The Effect of Pulsator on Washing Performance in a Front-Loading Washer

Eung Ryeol Seo, Hee Tae Lim, Eunsuk Bang, Soon Cheol Kweon, Jeoung-Kyo Jeoung, Ji-Hoon Choi

Abstract**—**The object of this study is to investigate the effect of pulsator on washing performance quantitatively for front-loading washer. The front-loading washer with pulsator shows washing performance improvement of 18% and the particle-based body simulation technique has been applied to figure out the relation between washing performance and mechanical forces exerted on textile during washing process. As a result, the mechanical forces, such as collision force and strain force, acting on the textile have turned out to be about twice numerically. The washing performance improvement due to additional pulsate system has been utilized for customers to save 50% of washing time.

Keywords**—**Front-loading washer, mechanical force, fabric movement, pulsator, time saving.

I. Introduction

LAUNDERING is a process of eliminating the unwanted substance or soil from textile. The complex mass transfer process involves physiochemical reaction and mechanical forces. However, due to long duration for the mass transfer process, the detergent, warm water as well as mechanical forces are used to accelerate the washing performance for time saving [1]. The studies on the effects of physiochemical factor or ultrasonic wave as a mechanical force are introduced [1]-[3]; however, only few researches have been conducted to study the relation between mechanical force and washing performance.

For effective removing of soil from textile, the mechanical forces can be improved by increasing the friction or impact between cloth and cloth, cloth and water jet, or cloth and wall surfaces of washer. At the same time, the removed soils need to be washed away by the water flowing through cloth. Another factor for better washing performance is the bending and stretching of textile using water jet or external mechanical forces. Some literature reported the improvement of washing performance by 35% with more external force and detergent [4]. Eventually, the key factor can be how to make textile go through more complicated motion. In this sense, the study on the movement of textile during washing process is essential to find the key to improve the performance of domestic washer. Park et al. [5] evaluated the statistical correlation from fabric movement by tracking the textile during washing process. The general finding was that the drape coefficient, which represents stiffness of fabric, had a high correlation with the fabric movement. The fabric with high drape coefficient tents to rotate all-around the drum. Yun et al. [6] found the complex movement as well as number of folding showed higher detergency than single movement. Yun and Park [7], [8] extended the study to save energy and time by investigating the correlation between fabric movements and washing efficiency. However, previous studies have focused on fabric movement mainly exerted by centrifugal force due to rotating drum and lifters of front-loading washer. This fabric movement shows quite monotonic two-dimensional pattern with less movement in drum axis direction.

This paper is focused on the study of complex three dimensional movement pattern exerted by the pulsator installed at the rear side of drum which generates more mechanical force in rotating axis direction. In addition, numerical method with particle-based flexible body simulation has been adopted for numerical comparison between two cases.

Eung Ryeol Seo is with Samsung Electronics Inc., Suwon, Korea (corresponding author, phone: 82-10-7756-0856; fax: 82-31-8062-9327; e-mail: eungryeol.seo@samsung.com).

Hee Tae Lim, Eunsuk Bang, Jeoung-Kyo Jeoung, Soon Cheol Kweon, and Ji-Hoon Choi are with Samsung Electronics Inc., Suwon, Korea (e-mail: ht12.lim@samsung.com, es.bang@samsung.com, Jk.jeoung@samsung.com, infiniti@samsung.com, jh03.choi@samsung.com).

II. Experimental Details

A. Test Cases

Two types of front-loading washers from Samsung are tested for washing performance with and without pulsator to verify the effect of pulsator. Unlike the conventional washer, new washer, Qdrive, has counter-rotating pulsator at the rear side of drum as shown in Fig. 1. Hereafter, the washer with rear pulsator will be called as washer to differentiate from conventional washer.

B. Operation Condition

The pulsator in washer has separate rotating driver which gives more independency to increase the washing performance. The best washing performance occurred experimentally when drum and pulsator rotated in an opposite direction. The operating conditions for two washers are listed in Table I.

C. Performance Test Procedure

Five kinds of artificial soil strips including sebum, carbon/black oil, blood, cocoa and red wine were used as laundry dummies per EMPA 108 standard. Washing performance test has been conducted per IEC 60456:2010 5th edition as follows.

1) Install two washing machines (conventional and new).
2) Put 50% of laundry compared to rated loading quantity for each washing machine.
3) Operates the cotton course with temperature of 40 °C.
4) After completion of operating course, unload the base load and remove the soiled strip for color measurement.

5) Using the following Kubelka-Munk equations in (1), compare the difference between soiled strips from each washer to calculate the percentage soil removal [8];

Kubelka-Munk equations

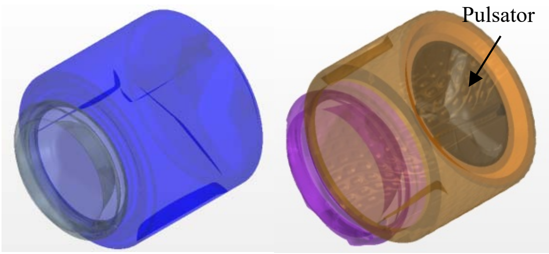
$$K/S = \frac{(1-R)^2}{2R} \tag{1}$$

where K = coefficient of reflectivity, S = coefficient of light scattering, R = observed reflectance.

Percentage soil removal

$$D\ (\%) = \frac{(K/S)_s - (K/S)_w}{(K/S)_s - (K/S)_u} \times 100 \tag{2}$$

where subscript s denotes the soiled cloth (unwashed); subscript w denotes the washed cloth; subscript u denotes the unsoiled cloth.



(a) Conventional (b) New

Fig. 1 Control volumes for numerical cases

TABLE I
COMPARISON OF OPERATION CONDITION FOR TWO SYSTEMS

	Rotating Cycle	Drum RPM	Pulsator RPM
Conventional	27s on /4s off	47	NA
New	27s on /4s off	50	140 in opposite direction

III. Experimental Results

The detergency comparison for two washers is listed in Table II. The percentage soil removal for conventional washer is 58.9%, while that of new washer is 69.6% which shows 18% improvement in detergency.

Among soil strips, the degree of improvement in carbon black/oil, which is influenced by mechanical power, was 81%. Because the conventional washing machine under mass production has been optimized for years in cleaning performance, an additional 18% improvement in performance is meaningful.

Performance improvements can also be used to reduce cleaning time.

In Fig. 2, the washing time is reduced by about 50% when the washing performance of new washer reaches the same level as that of the conventional washer.

TABLE II
COMPARISON OF PERCENTAGE SOIL REMOVAL BY TWO WASHERS

		Reflectance Y of EMPA 108 soil strip					
		Sebum	Carbon/ Black Oil	Blood	Cocoa	Red Wine	Total
D (%)	Conventional	55.6	22.6	94.5	55.5	66.2	58.9
	New	65.2	41.0	95.3	68.2	78.1	69.6
Performance Improvement		17%	81%	1%	23%	18%	18%

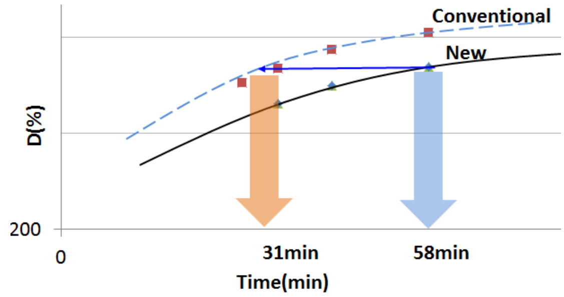


Fig. 2 Washing performance along time

IV. Numerical Details

In order to verify the effect of pulsator on washing performance numerically, SAMADII-Washing beta version using particle-based flexible behavior has been used for simulation. These simulation methods and tools are suitable for the large deformation problem of flexibile body which was difficult to solve in the existing solvers with finite element method. In order to improve the speed of analysis time, high speed parallel operation using GPU (Graphic Process Unit) was performed.

Particle-based mass-spring-damper techniques for modeling flexible bodies such as cloth are shown in Fig. 3. Mass of cloth is applied to the mass point, and the external forces exerted on the cloth are calculated by spring force in (3). Additional spring connecting two-point-distance mass is implied to calculate the bending and stretching of the cloth.

$$\vec{F}_{ij}(\vec{x}_i, \vec{x}_j) = \begin{cases} -k_c\left(\dfrac{l_0 - l}{l_0}\right)\dfrac{\vec{x}_j - \vec{x}_i}{|\vec{x}_j - \vec{x}_i|} & (0 < l_0 - l) \\ -k_e\left(\dfrac{l_0 - l}{l_0}\right)\dfrac{\vec{x}_j - \vec{x}_i}{|\vec{x}_j - \vec{x}_i|} & (l_0 - l < 0) \end{cases} \tag{3}$$

$$\text{where, } k_c < k_e$$

Numerical analysis studies were also conducted on two specified washers in the performance test. For actual behavior analysis, as shown in Fig. 4, the conventional washer consists of a fixed front door, a moving drum body, and three lifters attached to the drum. In addition to the conventional washer, the new washer has a counter-rotating pulsator at rear side. Numerically, all the surfaces mentioned above were treated as wall contacting with cloths. Thirty cloths with size of 410x820 mm are simulated inside of drum to meet 3 kg of loading quantity for performance test. Also, considering the installation condition of the washing machine, it is assumed that the drum tilting angle is 3 degrees.

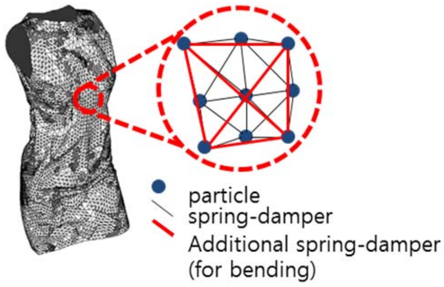
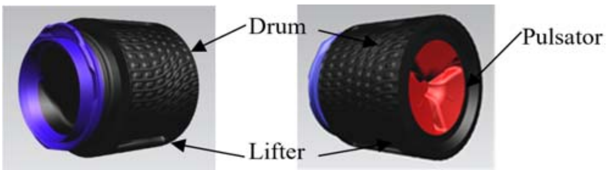


Fig. 3 Flexible body modelling with concept of spring-damper system



(a) Conventional drum (b) New drum with pulsator

Fig. 4 Control volumes for numerical cases

In order to find the effect of pulsator on washing performance, the definition of the mechanical forces applied to 30 cloths. The coordinate system for calculation of the movement and the force on the cloth is shown in Fig. 5.

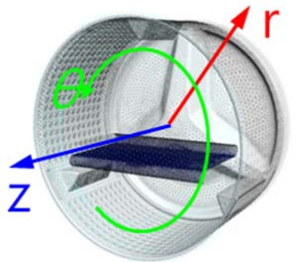
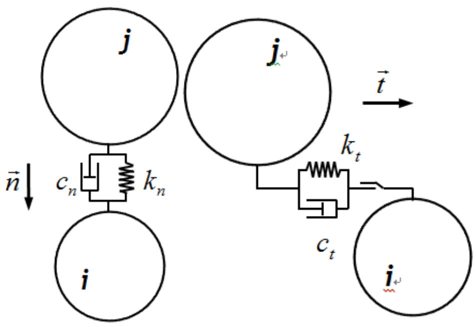


Fig. 5 Coordinate system in rotating drum



(a) Normal force (b) Tangential force

Fig. 6 Voigt model of DEM

Fc is collision energy between cloth and cloth which is the mechanical force due to collision and friction between mass point and mass point composing cloth. Fw is collision energy between cloth and wall which is the mechanical force due to collision and friction between mass point composing cloth and mass point composing wall such as drum, lifter and pulsator. Fs is strain energy of cloth which is the mechanical force due to bending and stretching of spring defined in Fig. 3.

For further detail, the diagram of mass-spring-damper system is depicted in Fig. 6 which is the basic concept of DEM (discrete element method). The governing equations are calculated using the physical modeling of mass, spring, and damper.

The contact model between two neighboring masses is defined using spring and dashpot following Voigt model. The contact force F_N in normal component and the contact force F_T in tangential component are calculated using (4) and (5).

$$\vec{F}_{n,i} = K_n \delta_n \delta_n^{1/2} \vec{n} + C_n \delta_n^{1/4} \vec{v}_{n,ij} \quad (4)$$

$$\vec{F}_{t,i} = \left|\vec{F}_{t,i}\right| \vec{t} \quad (5)$$

$$\left|\vec{F}_{t,i}\right| = \min\left\{\mu_d \left|\vec{F}_{n,i}\right|, \left|K_t \delta_t \delta_n^{1/2} \vec{t} + C_t \delta_n^{1/4} \vec{v}_{t,ij}\right|\right\} \quad (6)$$

where, δ, K and C mean overlap, spring coefficient and damping coefficient, respectively. The subscript n and t stand for normal and tangential, respectively, while μ is friction coefficient.

Equation (4) consists of spring force and damping forces together. Using the equations, the accumulated contact forces between cloth and wall are calculated in the washing process.

V. Numerical Results

In order to verify the effect of the pulsator on washing performance, the movement of the cloth and the mechanical forces defined in numerical details are compared.

A. Initial Condition for Cloths

Initial loading condition for the cloths is important factor which can affect the simulation results. In order to realize the initial random loading condition, the thirty cloths are dropped in the up-right cylinder one by one. The bottom of cylinder and the top of cylinder have been replaced with the pulsator and the glass door, respectively. Finally, the cylinder has been inclined to the position of front-loading washer as shown in Fig. 6.

B. Comparison on Mechanical Forces

The effect of pulsator on the mechanical forces defined in previous chapter has been compared for conventional and new washers in Fig. 7. The forces have been calculated for each cloth and accumulated over the calculation time.

It shows that the collision forces between cloth and cloth (Fc) exerted by new washer is 2.3 times bigger than that of conventional washer. The collision force between cloth and wall (Fw) and the strain force (Fs) are also increased by twice than those of conventional washer.

Increased force variation can affect the movement of the mass points of the cloth, therefore the magnitude of the average acceleration of each mass point has been compared for two washers in Fig. 9 which shows 18% increase in the acceleration due to forces from various direction. Finally, the increase of the defined forces and acceleration of the mass point have contributed the increase of washing performance.

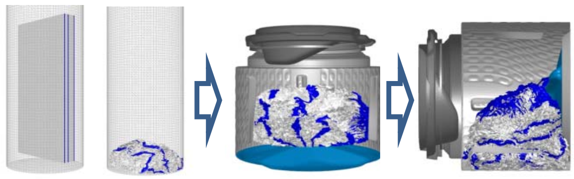
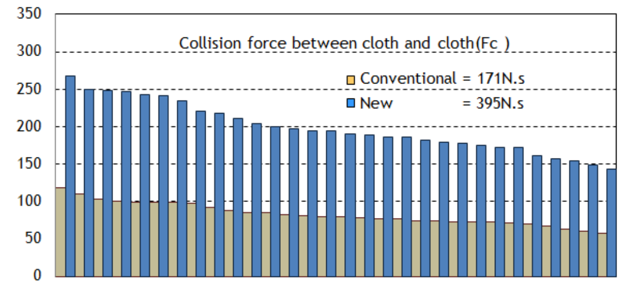
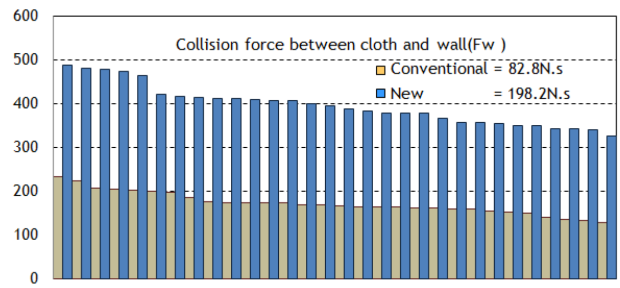


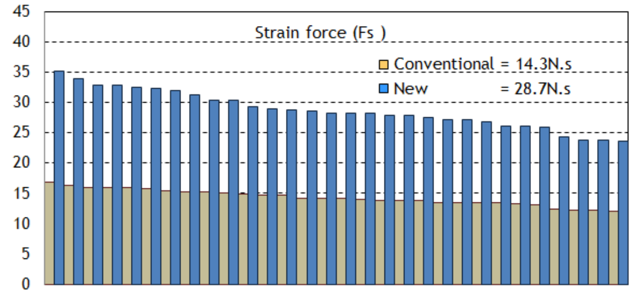
Fig. 7 Initial position setting for 30 cloths



(a) Comparison of Collision force between cloth and cloth

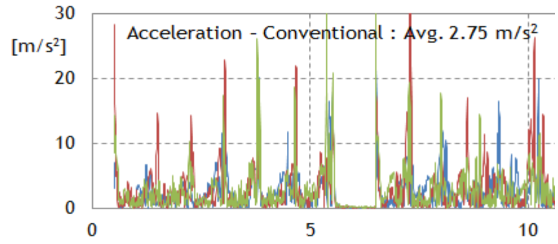


(b) Comparison of Collision force between cloth and wall

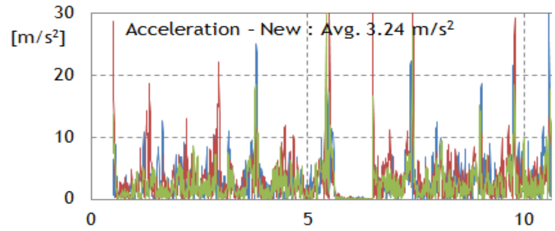


(c) Comparison of strain force of cloth

Fig. 8 Comparison of mechanical forces on 30 cloths by two washers



(a) Acceleration of cloths by conventional washer



(b) Acceleration of cloths by new washer

Fig. 9 Comparison on acceleration of center of cloths by two washers

VI. Conclusions

1) The new front-loading washer equipped with pulsator shows 18% increase in washing performance or could save washing time by 50% compared to the conventional front-loading washer.
2) In order to verify the effect of the pulsator on the washing performance, a quantitative study on the change of forces interacting among cloths and walls is conducted using mass-spring-damper concept.
3) Numerical result shows that the mechanical forces and acceleration have been increased more than twice and 18%, respectively affecting on washing performance.

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