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Clothes washing simulations

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ABSTRACT

Better washing machine designs and operation could reduce energy and water usage and extend cloth life. Washing machine studies have been traditionally empirical, since laundering typically involves complex motion of many cloth pieces in an inhomogeneous (fluid, cloth, detergent, agitator) setting. This paper presents a physics-based model of fully-submerged clothes washing in two- and three-dimensions. Multiple cloth pieces are modeled as thin elastic plates with tensile, shear, bending, and torsional stiffness, while the wash fluid is modeled with the incompressible Navier–Stokes equations. The fluid–cloth interaction is modeled via an immersed boundary method, and complex two- and three-dimensional agitator geometries are simulated with a Cartesian domain-mapping technique. The simulations have relatively coarse resolution that does not resolve all length scales for typical washing machine operating conditions. Hence, the converged results shown here are for moderate Reynolds numbers (Re). The simulation results include cloth stresses, torque on the wash basket, and the motion and deformation of the submerged cloth pieces. Specifically, the 3-D results show that the cloth stresses increase and the torque exerted on the outer wash basket decreases with increasing Re. The simulations examine how cloth motions differ with Reynolds number and cloth loading. The results reveal that for an agitator-driven 3-D wash geometry at higher Re, cloth pieces near the agitator at the bottom of the wash basket are first pushed by centrifugal force towards the outer stationary walls of the wash basket, then rise towards the top surface where they return to the axis of rotation and then sink towards the agitator. The variation of the center of mass positions of the cloth pieces are shown to increase for higher Re operating conditions.
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1. Introduction

Clothes washing machines (washers) are ubiquitous in the modern world. However the clothes washing process has largely escaped a detailed computational analysis because a physically-meaningful numerical description of the relevant phenomena has not been formulated. Detailed physical descriptions of wash processes should account for the coupled, unsteady, complex, and three-dimensional motions of the fluid and cloth mixture when driven by the complex and moving geometries of the agitator and wash basket. Numerical solution strategies must simultaneously be appropriate for three-dimensional motion of a fluid and nearly arbitrary deformation of the cloth. This study describes a clothes washing simulation developed from first principles that attains these goals.

Most numerical models use computational grids with discrete points for solving the fluid and solid dynamic equations separately. However, if the grids are designed to conform to the domain boundaries, then the unsteady cloth motion and a moving agitator or wash basket would require redesigning the grid at every time-step, a task that could dominate the computational effort. Hence, most existing washing machine studies are limited to testing and empiricism. The studies given in [1–4] model washing machines by idealizing clothes as a single fabric ball and then analyzing its motion; [1] has also modeled each possible stage of the ball's motion in a horizontal-axis wash basket. Such reduced-order methods are suitable for real-time control designs.

However, higher-fidelity simulations are needed to improve designs to meet ever-increasing demands for better resource utilization. The empiricism in the existing models used for machine development – such as in [1] – are likely insufficient for preliminary design. Thus, models, such as that presented here that better capture the fundamental cloth–water–agitator interactions of washing machine processes are needed. Note that there is a rich literature on modeling and simulating cloth motion without coupling to a high-fidelity fluid model [5–11]; these models are mainly developed for the computer graphics industry.

The capabilities, characteristics, and limitations of the simulations reported here are as follows

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- The simulations allow nearly arbitrary deformation of submerged pieces of cloth in a container with a complicated time-dependent shape.
- The submerged cloth pieces are modeled as elastic impermeable thin plates that undergo large deformations [12]. In particular, cloth pieces have appropriately high extensional and in-plane-shear stiffnesses, and appropriately low bending and torsional stiffnesses.
- The fluid is considered to be incompressible and viscous. Thus, the Navier–Stokes equations are solved through the model given in [13]. The fluid has the density of water, but its viscosity is elevated to prevent numerical problems at the modest grid resolutions of the current simulations.
- The cloth and fluid dynamics are coupled using an Immersed Boundary (IB) method [14]. In particular, the local fluid and cloth velocities are equal based on the viscous no-slip condition combined with cloth impermeability. The IB method has been used for many problems involving single and multiple flexible solids in viscous fluid flow (e.g. [15–21]).
- The moving solid surfaces of the washing machine's basket and agitator are modeled through a Cartesian domain-mapping technique. This approach avoids generation of a new grid at each time-step.
- The air–water interface is approximated as a flat perfect-slip surface.
- The modest-grid-resolution results presented here do not simulate all the scales of unsteady and turbulent fluid motion at the Reynolds numbers of representative washing processes. Thus, the current results are for moderate Reynolds numbers. Since this simulation attempt is the first of its kind, the emphasis here is on model development rather than high-resolution results.

The fluid/flexible-structure interaction component of the simulation is validated in [15,22] for problems involving the flutter regimes of thin cantilever beams, the natural frequencies of elastic plates, and the motion of a flexible filament in a gravity-driven viscous flow. Additionally, the method for handling the irregular geometries on a Cartesian grid is validated in this text for the problems of circular-Couette flow and the flow over a circular cylinder.

The remainder of this paper is organized as follows. In Section 2, the coupled equations of motion for the cloth pieces and the wash fluid are given. Here, the mechanical coupling of cloth and fluid is simulated by adding local body forces and density to the Navier–Stokes (fluid) equations to represent the stresses and inertial loads the cloth applies to the fluid. Then, in Section 3, a domain-mapping technique is described for simulating complex unsteady washing machine geometries with a stationary Cartesian grid. Section 4 introduces the simulation output measures. This is followed by the presentation of the two- and then three-dimensional simulations in Sections 5 and 6, respectively, with an emphasis on cloth motions and the cloth stresses. Finally, Section 7 summarizes this effort and provides conclusions.

2. Physical and numerical models for the fluid–cloth mixture

The current simulations use an Immersed Boundary (IB) method [14,23], to couple the motions of the cloth and fluid. The fluid and cloth have the same local velocity $\mathbf{u}$ so there is no relative slip or penetration at the cloth/fluid interface, and the Navier–Stokes equations have external forcing $\mathbf{f}$ due to the cloth loading to describe the combined motion of the fluid/cloth mixture:

$$\rho(\mathbf{x},t)\left(\frac{\partial\mathbf{u}(\mathbf{x},t)}{\partial t}+\mathbf{u}(\mathbf{x},t)\cdot\nabla\mathbf{u}(\mathbf{x},t)\right)=-\nabla p(\mathbf{x},t)+\mu\nabla^2\mathbf{u}(\mathbf{x},t)+\mathbf{f}(\mathbf{x},t), \tag{1}$$

$$\nabla\cdot\mathbf{u}(\mathbf{x},t)=0, \tag{2}$$

$$\mathbf{f}(\mathbf{x},t)=\int\mathbf{F}(\boldsymbol{\eta},t)\delta^*(\mathbf{x}-\mathbf{X}(\boldsymbol{\eta},t))Kd\boldsymbol{\eta}, \tag{3}$$

$$\rho(\mathbf{x},t)=\rho_f+\int\frac{1}{K}\rho_s q\delta^*(\mathbf{x}-\mathbf{X}(\boldsymbol{\eta},t))Kd\boldsymbol{\eta}, \tag{4}$$

$$\mathbf{U}(\boldsymbol{\eta},t)=\int\mathbf{u}(\mathbf{x},t)\delta^*(\mathbf{x}-\mathbf{X}(\boldsymbol{\eta},t))d\mathbf{x}, \tag{5}$$

$$\frac{D\mathbf{X}(\boldsymbol{\eta},t)}{Dt}=\mathbf{U}(\boldsymbol{\eta},t). \tag{6}$$

Here, $\mathbf{x}$ is the vector of independent spatial variables that parameterize the fluid volume, t is time, p is pressure, μ is the dynamic fluid viscosity. The location of a point on the deformed cloth mid-plane is $\mathbf{X}(\boldsymbol{\eta}, t)$, as shown in Fig. 1, where $\boldsymbol{\eta} = (r, s)$ and $\boldsymbol{\eta} = (s)$ are two- and one-dimensional parameterizations on the cloth mid-plane, for the three- and two-dimensional simulations, respectively. The simulations use two different grids: a moving Lagrangian mesh for discretizing $\boldsymbol{\eta}$ on the cloth, and a stationary Cartesian grid for discretizing the fluid volume $\mathbf{x}$. K is the Jacobian of the deformed cloth mid-plane, ρ is the combined fluid/cloth mixture density, ρ_f is the uniform fluid density, ρ_s is the undeformed cloth density, while q is the cloth thickness ($\rho_s q$ is the mass per unit area of the cloth). $\mathbf{F}$ in Eq. (3) is the divergence of the cloth stress-resultants, derived briefly (with K) in the Appendix A and in more detail in [22], for a thin plate undergoing large elastic deformations. We will only mention here that $\mathbf{F}$ is related to: (1) the local extension/contraction, (2) the normal curvature, (3) the geodesic torsion, and 4) the surface shear at any point $\mathbf{X}(\boldsymbol{\eta}, t)$ for a given piece of cloth. Cloth thickness effects are included in $\mathbf{F}$ by the large-deformation plate theory; however the cloth thickness is not geometrically modeled as the clothes are assumed to be 2-D elements embedded in a 3-D fluid volume. The external forcing $\mathbf{f}$ in Eq. (1) is related to $\mathbf{F}$ through the relation given in Eq. (3). For a 2-D piece of cloth in a 3-D fluid volume, $\mathbf{F}$ is a 2-D quantity – it is defined throughout the deformed cloth mid-plane $\boldsymbol{\eta}$ – and hence $\mathbf{F} = \mathbf{F}(\boldsymbol{\eta}, t)$, but note that Eq. (1) and $\mathbf{f}$ are defined for the 3-D fluid volume. Eq. (3) constructs $\mathbf{f}$ by using $\mathbf{F}$ and regularized Dirac delta function δ^*. The same approach is used for expressing the 2-D cloth density $\rho_s q$ in 3-D via Eq. (4). The function δ^* in Eqs. (3)–(5) is a smooth approximation to a three-dimensional Dirac delta function and is described in Eqs. (7) and (8) below.

Eq. (5) determines the cloth velocity $\mathbf{U}$ from the fluid velocity field $\mathbf{u}$, while Eq. (6) defines the Lagrangian advection of the cloth pieces. On the undeformed cloth mid-plane, r and s are arclength parameters that are everywhere orthogonal. In Fig. 1, $\mathbf{e_s}$ and $\mathbf{e_r}$ are unit vectors tangent to constant r and s lines and $\mathbf{e_n} = \mathbf{e_s} \times \mathbf{e_r}/|\mathbf{e_s} \times \mathbf{e_r}|$ is the cloth-surface normal vector.

The cloth pieces are assumed to be thin, so cloth elastic and inertial forces are first multiplied with the uniform cloth thickness, and then these local forces are spread onto the fluid grid using a regularized Dirac delta function δ^*, as in Eqs. (3) and (4). As suggested in [23] for $\mathbf{x} \in \mathbf{R^3}$, δ^* is approximated with a Cartesian product of one-dimensional functions ϕ:

$$\delta^*(\mathbf{x})=\phi(x)\phi(y)\phi(z),\quad \text{where } \mathbf{x}=(x,y,z), \tag{7}$$

and

$$\phi(r)=\begin{cases}\frac{1}{2\varepsilon}\left(1+\cos\left(\frac{\pi r}{\varepsilon}\right)\right), & \text{if } |r|\leqslant\varepsilon\\ 0, & \text{otherwise}\end{cases}. \tag{8}$$

For $\mathbf{x} \in \mathbf{R}^2$ the approximation is similar, but in this case $\delta^*(\mathbf{x}) = \phi(x)\phi(y)$. The one-dimensional regularized Dirac delta function ϕ has a compact support width of 2ε. In the simulations

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