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Modeling of surface cleaning by cavitation bubble dynamics and collapse

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ABSTRACT

Surface cleaning using cavitation bubble dynamics is investigated numerically through modeling of bubble dynamics, dirt particle motion, and fluid material interaction. Three fluid dynamics models; a potential flow model, a viscous model, and a compressible model, are used to describe the flow field generated by the bubble all showing the strong effects bubble explosive growth and collapse have on a dirt particle and on a layer of material to remove. Bubble deformation and reentrant jet formation are seen to be responsible for generating concentrated pressures, shear, and lift forces on the dirt particle and high impulsive loads on a layer of material to remove. Bubble explosive growth is also an important mechanism for removal of dirt particles, since strong suction forces in addition to shear are generated around the explosively growing bubble and can exert strong forces lifting the particles from the surface to clean and sucking them toward the bubble. To model material failure and removal, a finite element structure code is used and enables simulation of full fluid–structure interaction and investigation of the effects of various parameters. High impulsive pressures are generated during bubble collapse due to the impact of the bubble reentrant jet on the material surface and the subsequent collapse of the resulting toroidal bubble. Pits and material removal develop on the material surface when the impulsive pressure is large enough to result in high equivalent stresses exceeding the material yield stress or its ultimate strain. Cleaning depends on parameters such as the relative size between the bubble at its maximum volume and the particle size, the bubble standoff distance from the particle and from the material wall, and the excitation pressure field driving the bubble dynamics. These effects are discussed in this contribution.

1. Introduction

Non-chemical submerged surface cleaning is accomplished through application of shear forces at the surface to be cleaned large enough to lift adhered particles [1–4]. This can be achieved by using liquid jets or high frequency acoustic waves (ultrasonic, megasonic). Acoustic fields generate highly unsteady pressures and liquid motions, which exert high drag forces on solid contaminants and dislodge them from the surfaces being cleaned. Cleaning can also be achieved through generation of cavitation driven by intense pressure amplitude cycling between high negative and high positive pressures. Industrial scale implementation of ultrasonic cleaning covers many applications including cleaning of machine parts, jewelry, surgical instruments, laboratory equipment, textile, oil pipes, filter membranes, and semiconductor substrates [5–10]. Submerged liquid cavitating jets are also widely used for cleaning, cutting, drilling [11–13], and for controlled evaluation of materials' resistance to cavitation erosion [14–16]. Cavitation intensity produced by submerged jets can be varied in a very wide range through adjustment of the jet velocity, diameter, angle and standoff distance relative to the exposed surface, and the ambient pressure in which they are discharged [15].

Even though application of the above techniques is very widespread, the understanding of the physical phenomena involved is still limited due to the complexity and the multiple widely different scales of the mechanisms involved. The cleaning process involves activation and dynamics of sub-micron bubbles, which grow and collapse emitting shock waves and forming fast micro-jets in the micro- and milli-second time scales. In addition, the small spatial and fast temporal scales hinder clear visualization of the physical processes. Hoverer, various theoretical, experimental, and computational contributions have been made toward understanding cleaning processes involving cavitation. For example, the problem of surface contamination of silicon wafers in the microelectronic industry was studied in [17], which showed how removal efficiency varied with sonication time, temperature and particle size. High speed photography was used to understand

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the complex mechanisms (e.g. [5,18–22]). Collective bubble dynamics effects were considered in general in [23–28] and particularly for the mechanism of cleaning particles adhered to a solid substrate in [29]. The shock waves generated at bubble collapse also play an important role in the cleaning process. For instance, the pressures generated on the wall due to collapse of a bubble in a megasonic field were computed in [30,31] and other under various conditions in (e.g. [32,33]). One has to be careful, however, with this effect to not actually result in damaging the material surface being cleaned [15,32,39]. Another important mechanism for cleaning is to trigger oscillations of stable bubbles close to surface, which results in bubble translation near the surface and cleaning [34–38].

Cavitation is due to the local pressure in the liquid dropping below a critical pressure (often quoted to be the liquid vapor pressure for studies ignoring bubble surface tension), which drives omnipresent nano- and micro-bubble nuclei in the liquid to grow explosively [15,42,43]. When the pressure returns to a high value, bubble implosion occurs and generates high pressure pulses and shock waves. Many pioneering studies [44–47] have shown, experimentally as well as analytically, that the collapse of these cavitation bubbles near a rigid boundary results in high-speed reentrant liquid jets, which penetrate the bubbles and strike the nearby boundary generating water hammer like impact pressures. The high speed flow field, the large pressure variations, and the shock waves produce high local stresses on the adjacent material surface and are responsible for material micro-deformation, damage and failure, and high forces dislodging nearby particles or material layers to remove.

Simulation of the collapse of bubbles near boundaries has been an active research area since the pioneering work of [45]. The resulting reentrant jet has been found to play an important role in hydrodynamics and ultrasonic cavitation, as well as in large-scale underwater explosion problems [20,48–53] and in small-scale medical applications [54]. Modeling approaches started with incompressible potential flow methods using the observation that the dynamics of the concerned bubble is highly inertial where liquid viscosity influence is very low, while liquid velocities remain smaller than the sound speed enabling the assumption of incompressibility. Boundary element method approaches provided pioneering results [49,55,56]. However, in applications such as surface cleaning involving fluid domains very close to the wall boundary, i.e. totally immersed in the boundary/shear layer, viscous effects need to be accounted for. Also, for material removal studies, where the impact of the reentering jet at the boundary and the collapse of the remaining bubble ring emit shock waves, compressibility of the liquid needs to be accounted for in the simulations in order to capture these effects.

In this study, we consider these various approaches including some coupling between them, through space and/or time domain decomposition, and we simulate the response of dirt particles laying at the boundary or the deformation of a layer of material to remove from a rigid substrate. This paper aims at illustrating the various mechanisms and at highlighting the influence of the various physical parameters such as the pressure driving the bubble collapse, the bubble/particle relative size, the bubble distance from the particle/layer, and the properties of the material to remove.

2. Modeling approaches

The modeling of bubble dynamics near boundaries uses our general bubble dynamics and free surface modeling code, 3DYNAFS©. Four modules are used in the study presented here and described below.

(a) A potential flow module, 3DYNAFS-BEM© [49–54], which enables detailed modeling of the bubble reentrant jet with high accuracy because the interface is directly tracked and high grid refinement is feasible at a low cost since only surface (as opposed to volume) gridding is needed. This BEM code can account for the presence of a background flow around the bubble such as shear near a wall through use of the Helmholtz decomposition [57–59].

(b) Viscous effects and bubble dynamics can also be addressed by the viscous module 3DYNAFS-Vis© [60–62]. This solves the incompressible Navier–Stokes equations with the bubble interface captured either by a level set approach or through direct tracking of the interface with the help on an overset grid.

(c) The continuum model in the viscous code can be used to solve two-phase bubbly flows. The void fraction can be deduced from tracking bubbles in a Lagrangian fashion through coupling with 3DYNAFS-Dsm, which treats the bubbles as singularities accounting for their volume change and slip velocity relative to the liquid [60–62].

(d) Finally, compressible effects are handled by 3DYNAFS-Comp, which utilizes a mixed cell approach to consider a multi-material fluid domain with interface and shock wave capturing [63–65].

2.1. Boundary element model

The potential flow model used in this study is based on a Boundary Element Method (BEM) [49–54]. The Laplace equation, $\nabla^2\phi = 0$, is solved for the velocity potential, ϕ, defined through $\mathbf{u} = \nabla\phi$, where $\mathbf{u}$ is the velocity vector. A boundary integral method based on Green's theorem:

$$\int_\Omega (\phi\nabla^2 G - G\nabla^2\phi)\, d\Omega = \int_S \mathrm{n}\cdot[\phi\nabla G - G\nabla\phi] dS, \quad (1)$$

is used to solve the Laplace equation. In this expression Ω is the domain of integration having elementary volume $d\Omega$ and S includes all boundary surfaces of Ω such as the surface of the modeled bubble, the nearby surface to be cleaned, and the dirt particles. $\mathbf{n}$ is the local normal unit vector. $G = -1/|\mathbf{x}-\mathbf{y}|$ is Green's function, where $\mathbf{x}$ corresponds to a fixed point in Ω and $\mathbf{y}$ is a field point on the boundary surface S. Eq. (1) reduces to Green's formula

$$a\pi\phi(\mathbf{x}) = \int_S \left[\phi(\mathbf{y})\frac{\partial G}{\partial n}(\mathbf{x},\mathbf{y}) - G(\mathbf{x},\mathbf{y})\frac{\partial \phi}{\partial n}(\mathbf{y})\right] dS, \quad (2)$$

where $a\pi$ is the solid angle under which $\mathbf{x}$ sees the domain, Ω. Eq. (2) provides a relationship between ϕ and $\partial\phi/\partial n$ at the boundary surface S. Thus, if either of these two variables (*e.g.* ϕ) is known everywhere on the surface, the other variable (*e.g.* $\partial\phi/\partial n$) can be obtained.

To solve (2) numerically, the surfaces of all objects in the computational domain are discretized into triangular panels. To advance the solution in time, the coordinates of all surface nodes, $\mathbf{y}$, are advanced according to $d\mathbf{y}/dt = \nabla\phi$. The velocity potential on the bubble surface nodes is obtained through the time integration of the material derivative of ϕ, i.e. $d\phi/dt$, which can be written as

$$\frac{d\phi}{dt} = \frac{\partial\phi}{\partial t} + \nabla\phi.\nabla\phi, \quad (3)$$

where $\partial\phi/\partial t$ can be determined from the Bernoulli equation:

$$\rho\left(\frac{\partial\phi}{\partial t} + \frac{1}{2}\nabla\phi.\nabla\phi + gz\right) + p_l = p_\infty. \quad (4)$$