FINAL REPORT

Reduced Order Modeling of Dynamic Planing

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14. ABSTRACT
Waid and Kermeen completed static experiments using cylinders planing on free liquid surfaces. Their data represents the foundation for characterization of forces imparted on a planing cylinder. Several authors have derived simplified or analytic formulations of the impact forces on a cylindrical body interacting with a curved free surface. This article presents a Computational Fluid Dynamics (CFD) based approach to modeling such dynamic forces. A curved free surface is generated in a CFD water tunnel simulation by ventilating a gas filled wake aft of a curved deflector. The computational planing cylinder is then repeatedly plunged into the curved free surface. The CFD force record is used to reveal the dynamically added mass of the cylinder. Results indicate that the modeling approach taken accurately replicates the complex physics of the dynamic motion of the cylinder interacting with the surface. When added mass of the dynamic interaction is significant, a phase difference appears between the cylinder position and force time histories. Phase offsets between cylinder position and force have been observed across different plunging frequencies, suggesting a significant added mass effect. With the success of this approach (obtaining dynamic forces based on CFD), reduced-order models of the added mass can be created.

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1 Introduction

This report describes work supported by ONR grant N00014-16-1-2222 on basic research into the fundamental fluid dynamics of a solid circular cylinder planning on a rough curved fluid surface flow. The study resulted in development of a novel reduced order modeling method that produced a numerically efficient and accurate characterization for dynamic planning simulation. The work is presented in the following sections that include:

- Abstract
- Computational dynamic planing force model

2 Abstract

Waid and Kermeen completed static experiments using cylinders planing on free liquid surfaces. Their data represents the foundation for characterization of forces imparted on a planing cylinder. Several authors have derived simplified or analytic formulations of the impact forces on a cylindrical body interacting with a curved free surface. This article presents a Computational Fluid Dynamics (CFD) based approach to modeling such dynamic forces. A curved free surface is generated in a CFD water tunnel simulation by ventilating a gas filled wake aft of a curved deflector. The computational planing cylinder is then repeatedly plunged into the curved free surface. The CFD force record is used to reveal the dynamically added mass of the cylinder. Results indicate that the modeling approach taken accurately replicates the complex physics of the dynamic motion of the cylinder interacting with the surface. When added mass of the dynamic interaction is significant, a phase difference appears between the cylinder position and force time histories. Phase offsets between cylinder position and force have been observed across different plunging frequencies, suggesting a significant added mass effect. With the success of this approach (obtaining dynamic forces based on CFD), reduced-order models of the added mass can be created.

3 Computational Dynamic Planing Force Model

The contents of this section were presented at the 10th International Cavitation Symposium (CAV2018), May 2018, hosted by Johns Hopkins University at the Renaissance Baltimore Harborplace Hotel, MD, and for which a technical paper was published in the conference proceedings titled as "Computational Modeling of Dynamic Planing Forces".

3.1 Planing Dynamics Characterization

The dynamics of bodies interacting with free surfaces has been extensively studied in the past in the context of surface craft hulls planing on flat, or undulating surfaces[1-4] (and many others). These models are for prismatic hulls in flat water or oncoming perpendicular waves, not for hull impacts or for lateral curvature of the free surface. There exists comparatively little literature on the forces imparted to a body on a laterally curved free surface. The work of Waid and Kermeen[5] represents the most extensive experimental investigation into the steady forces on a cylindrical body planing on a curved free surface, but lacks data regarding dynamic effects. Yen et al.[6] conducted experiments that were in some ways similar to the Waid and Kermeen work. In addition they developed a quasi-steady model for the planing forces. Vasin and Pareyshev[7] presented a two dimensional potential flow model for the impact forces of a circular object inside a circular ventilated wake. It would be a relatively simple task to combine Vasin and Paryshev's potential flow model with strip theory to derive an impact load. While this approach could be insightful, it is still not a fully three dimensional approach. Kulkarni and Pratap[8] and Rand et al.[9] both use an added mass estimate combined with strip theory to predict the additional loading on the body impacting a laterally curved free surface. To the authors' knowledge there exists no computational or experimental attempts specifically oriented toward assessing the dynamic component of the impact loads on a cylindrical body on a laterally curved free surface.

This section reports on a high-fidelity Computational Fluid Dynamics (CFD) approach for assessing the forces during the impact of a cylindrical body on a curved free surface. The modeling approach is a fully three dimensional CFD simulation of the cylinder impact. This allows extraction of relevant information about the impact that is typically difficult to acquire from an experiment, such as wetted area of the cylinder. In order to better facilitate usage of the data collected from the computations, a reduced order modeling technique[10] is employed to isolate the dynamic component of impact loads. It is found that the dynamic component of the impact force can be approximated using a linear force coefficient model, but further investigation is required to understand the extent to which that model is valid.

3.2 Computational Approach

The computational fluid dynamics software, StarCCM+[11], was employed to compute the physical quantities of interest. Numerics are second order accurate in time and space, and care was taken to ensure asymptotically convergent results. Solutions were based on a finite volume discretization with an incompressible, locally-homogeneous multiphase approach and the volume of fluid, HRIC scheme[12]. The resulting mean equations of motion (continuity, water volume conservation, and momentum) are cast in a Reynolds averaged form and closed with a Spalart-Allmaras Improved Delayed Detached Eddy Simulation[13] turbulence model within StarCCM+. Local convective Courant numbers were verified to fall within the bounds prescribed for best use of the HRIC scheme. An overset mesh strategy (also second order accurate) was employed to facilitate motion of the CFD test article relative to the CFD tunnel test section.

The computational domain was setup to mimic an experimental setup in a 0.3048 meter water tunnel. The two half-cylinders under test were 0.0762 meters and 0.0889 meters in diameter. Each cylinder had a 2° angle of attack relative to the incoming free stream velocity, which was perpendicular to the domain gravity vector. Figure 3.1 shows the computational domain used in the CFD simulations. A round deflector centered at the top dead center of the tunnel approximately 0.3 m from the leading edge of the cylinder, was used to generate a gas filled wake, bounded by a curved free surface. The cylinder was plunged into the water to the same maximum immersion depth at various frequencies. A free stream velocity of 8.53 m/s entered the domain. The average radius of the curved free surface, defined from the top dead center of the computational domain was 0.115 m.

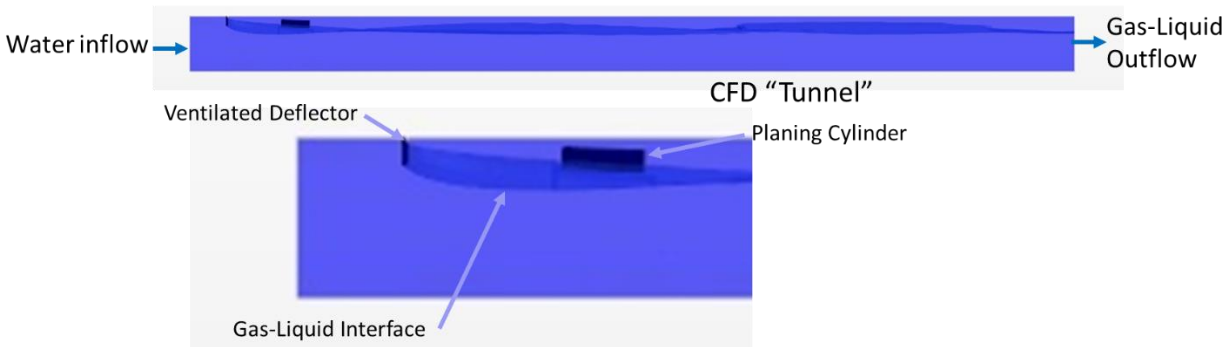

Figure 3.1 - Depiction of the computational domain.

3.3 Results

The data collected from each CFD simulation includes time histories of the cylinder drag, lift, cylinder vertical position, cylinder vertical velocity and the wetted area of the cylinder. Figure 3.2 shows the cylinder partially immersed in the curved free surface and highlights some of the terms used in the following discussions and analysis. The cylinder immersion, h, is defined as the vertical distance traveled by the cylinder after contact with the curved free surface. The immersion rate, $\dot{h}$, is time rate of change of the immersion. An approximation of the wetted length, L, of the cylinder is deduced from the wetted surface area of the cylinder using Equation 1[14], where S is the wetted area of the cylinder, R is the cylinder radius. Equation 1 was derived from a planar slice of a cylinder, which differs from the intersection of a cylinder with a curved surface, but the error incurred by using the approximation is expected to be small. The lift and drag directions are shown in Figure 3.2; the lift direction is parallel to the positive y-axis of the domain, while the drag direction is parallel to the positive x-axis of the domain. The cylinder coordinate system is also shown in Figure 2.2. The cylinder normal force, Z, and cylinder axial force, X, can be derived from the lift and drag time histories via Equation 2.

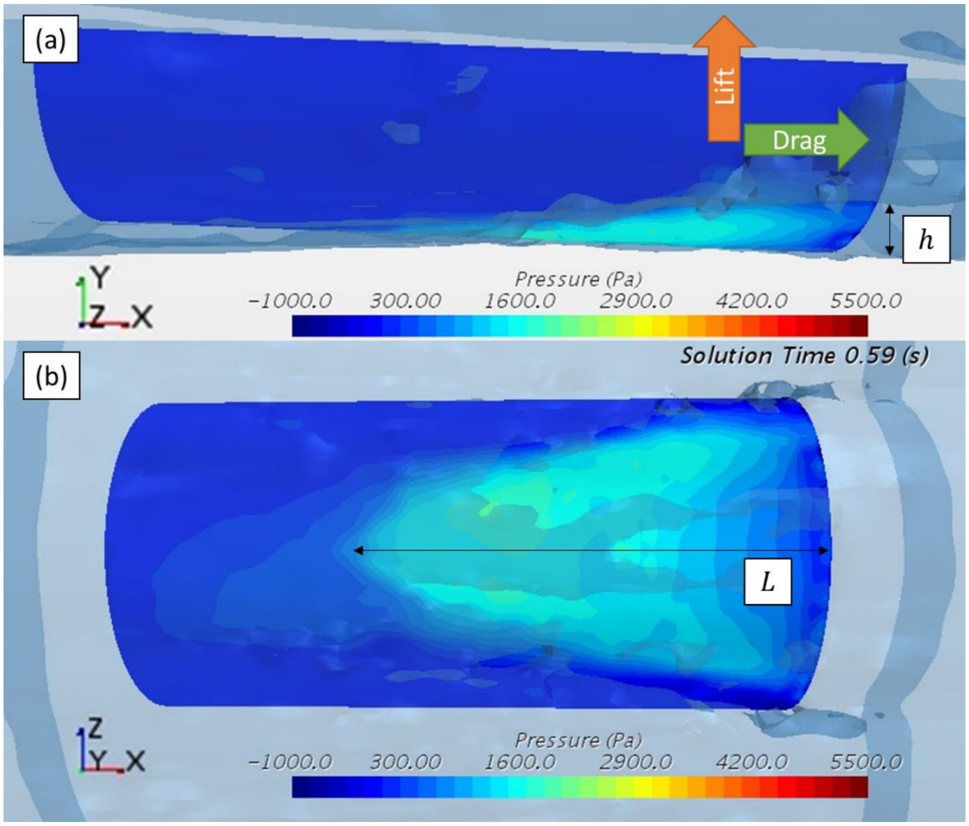

Figure 3.2: Example of dynamic cylinder immersion. (a) Side view (b) Bottom view

$$L = \frac{Sh}{2R\left[\sqrt{2hR - h^2} + (h - R)\left(\frac{1}{2}\pi \tan^{-1}\frac{h - R}{\sqrt{2hR - h^2}}\right)\right]} \tag{1}$$

$$\begin{aligned} X &= -D \cos 2° + L \sin 2° \\ Z &= -L \cos 2° - D \sin 2° \end{aligned} \tag{2}$$

$$\begin{aligned} X' &= \frac{X}{\frac{1}{2}\rho V_\infty^2 R^2} \\ Z' &= \frac{Z}{\frac{1}{2}\rho V_\infty^2 R^2} \end{aligned} \tag{3}$$

The vertical and axial forces on the cylinder are non-dimensionalized using Equation 3. The time histories of non-dimensional cylinder normal force and immersion for several vertical oscillation frequencies are shown in Figure 3.3 (a)-(d). In Figure 3.3 (a)-(d) a negative immersion means that the cylinder is above the water surface. The dynamic nature of the impact forces is apparent from the phase offset between the force time history and the immersion time history, highlighted in Figure 3.3 (d).

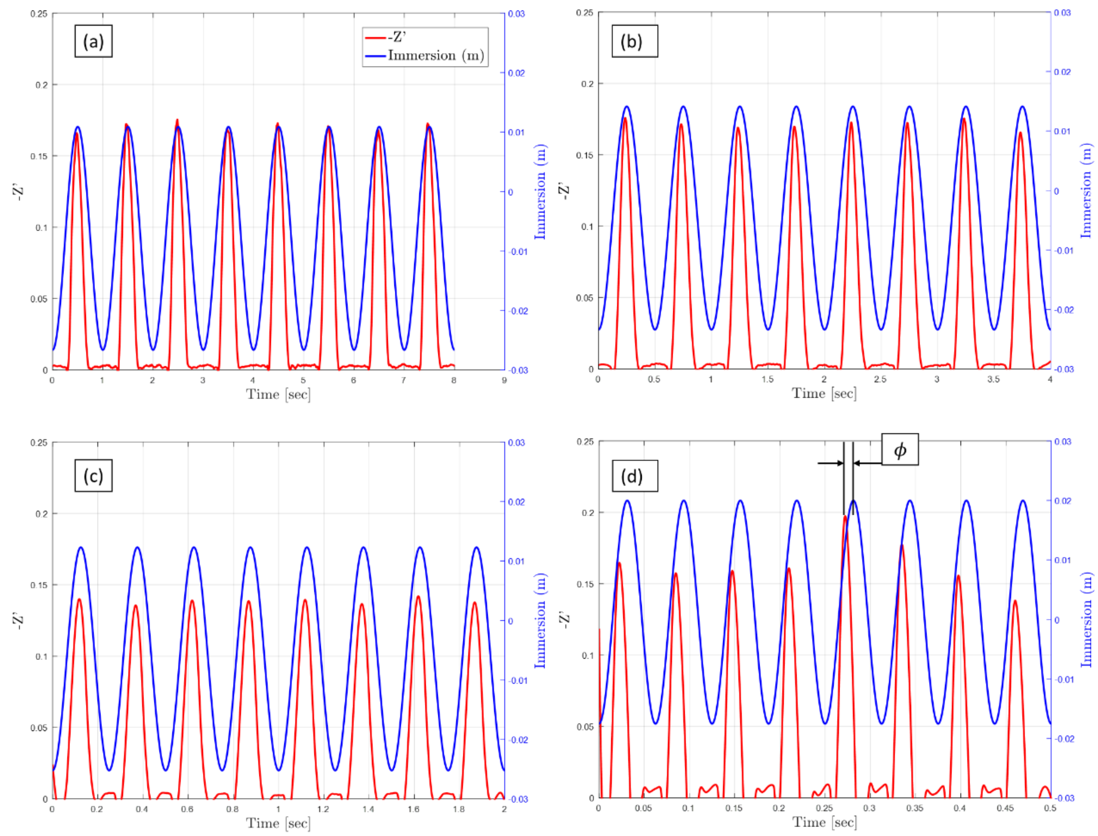

Figure 3.3: Time histories of the non-dimensional vertical force on the cylinder and the immersion. (a) 1 Hz (b) 2 Hz (c) 4 Hz (d) 16 Hz.

To further demonstrate the presence of a dynamic component of the planing forces during an impact, the methodology of Yen et al.[6] was employed and compared to the force time histories from the computations. Figure 3.4 shows that there is a distinct difference in the force magnitudes, along with a phase difference between the quasi-steady approach implied using Yen et al.'s model and the unsteady computations. In Figure 3.4 the computational lift data was non-dimensionalized according to Yen et al. so as to provide a direct comparison. Also, the large excursions of the lift coefficient calculated using the model of Yen et al. are due to vanishingly small wetted lengths on the cylinder as it is enters and emerges from the water. A favorable comparison of the dynamic computational data as the cylinder is exiting the free surface and the quasi-steady approach suggests that the computational model is correctly predicting the forces present on the cylinder during the course of the impact events.

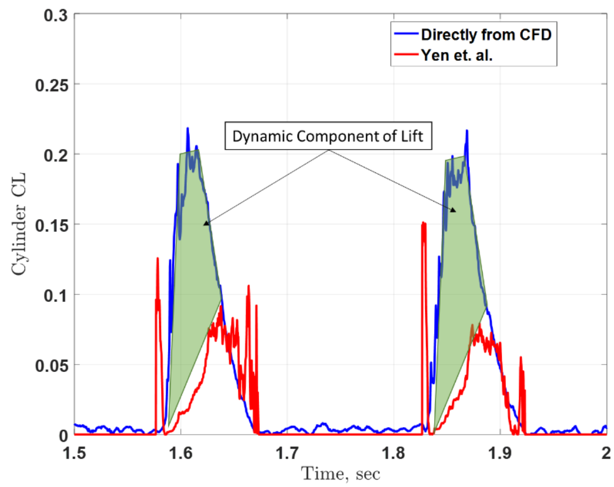

Figure 3.4: Comparison against a quasi-steady approach to the unsteady computational approach (computational data from the 4Hz oscillation frequency shown).

3.4 Analysis

A well-accepted method for modeling the apparent mass of an accelerating, fully submerged, body is provided by Goodman[10]. Following Goodman, the immersion and immersion rate time histories are given by Equations 4 and 5, in which h_o is the amplitude of the immersion half-sine wave and ω is the oscillation frequency in radians per second. The vertical time history of the force can be reduced to components that are in-phase and out-of-phase with the immersion time history, as shown in Equation 6, here we use the subscripts *"in"* and *"out"* to denote the in-phase and out-of-phase components, respectively. The in-phase and out-of-phase components of the force time history then can be derived from the force and immersion time histories calculated by the CFD via Equations 7 and 8, in which Z_o is the amplitude of the force half-sine wave and ϕ is the phase difference between the immersion and force time histories in radians. Thus, the part of the force time history that is out-of-phase with the immersion time history represents the dynamic portion of the cylinder loading, $Z_{\dot{h}}$. It is proposed to model this dynamic loading as a linear coefficient derived from the change in Z_{out} with respect to the reduced frequency of oscillation given by Equation 9, where $\dot{h_o'} = \frac{h_o}{\omega}\frac{\omega R}{V_\infty}$. Using this type of model the dynamic portion of the impact loading could be given by $Z_{dynamic} = Z'_{\dot{h}}\ \dot{h}\ \frac{1}{2}\rho V_\infty^2 R^2$.

$$h = h_o \sin \omega t \tag{4}$$

$$\dot{h} = h_o \omega \cos \omega t \tag{5}$$

$$Z = Z_{in} \sin \omega t + Z_{out} \cos \omega t \tag{6}$$

$$Z_{in} = Z_o \cos \phi \tag{7}$$

$$Z_{out} = -Z_o \sin \phi \tag{8}$$

$$-\frac{\partial Z_{out}}{\partial \dot{h_o'}} = Z_{\dot{h}} \tag{9}$$

Figure 3.5 shows the in-phase and out-of-phase components of the force time history as a function of the non-dimensional reduced frequency. A linear, zero-intercept, fit has been applied to the out-of-phase data for both cylinder diameters. The non-dimensional immersion rate coefficient for the 0.0762 meter diameter cylinder is $Z'_{\dot{h}} = -0.58989$ and for the 0.0899 meter diameter cylinder $Z'_{\dot{h}} = -0.2963$, as provided in the figure. The negative sign of the coefficient indicates that the force due to the impact opposes the motion, which is physically correct. The data suggests that a linear approximation would provide a reasonable prediction of the additional loading imparted to the cylinder from the impact with the water. The data also implies that the assumption of a zero-intercept for the linear coefficient is sensible. The results for the 0.0889 m diameter cylinder show that the dynamic impact planing forces are dependent upon the ratio of the body radius to the radius of the curved wake. However, additional simulations must be executed in order to provide additional data at lower reduced frequency, to explore more fully the linear assumption of the model, and more deeply explore the dependency of the immersion rate coefficient on other variables such as the cylinder-to-wake radius ratio, Froude number and cylinder angle of attack relative to the gas-filled wake centerline.

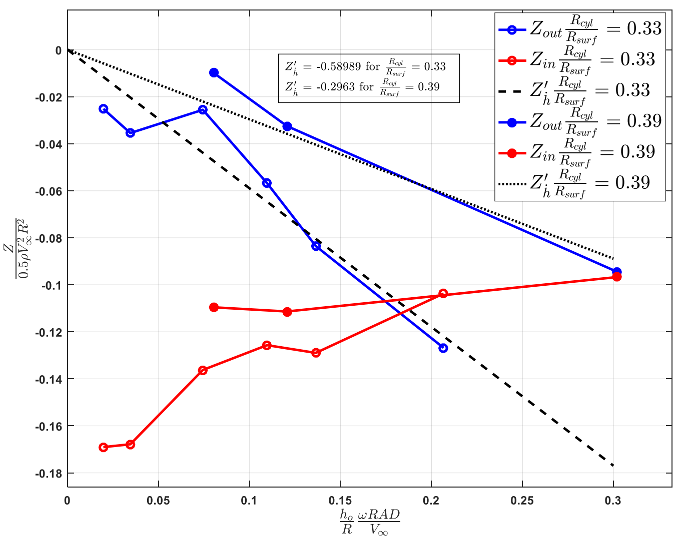

Figure 3.5: Analysis of the vertical force due to the immersion rate of the cylinder.

4 Conclusion

A full three dimensional CFD approach has been employed to assess the additional loading on a cylindrical body impacting a curved free surface due to the dynamic nature of the interaction. A reduced order model has been proposed. Future work includes performing additional CFD simulations to more comprehensively explore the validity of the proposed reduced order model, to explore other parameters which could affect the magnitude of the immersion rate coefficient, and collection of experimental data for validation purposes.

Additional details related to the present work can be found in the Distribution D report authored by Begg, Lindau, Smith and Martinelli, titled “Interacting Cavity Stability and Vehicle Control Forces Simulation Study“, archived 2021 with the US Defense Technical Information Center (DTIC).

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