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A FEM fluid–structure interaction algorithm for analysis of the seal dynamics of a Surface-Effect Ship

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Highlights

- Time-domain FEM model for evaluation of the seal dynamics of a surface effect ship.
- Focus on the free surface-structure algorithm to simulate complex and highly dynamic behaviour of seals.
- Innovative wetting and drying scheme able to predict the water action on the seals.
- Validations against experimental results.

Abstract

This paper shows the recent work of the authors in the development of a time-domain FEM model for evaluation of the seal dynamics of a surface effect ship. The fluid solver developed for this purpose, uses a potential flow approach along with a streamline integration of the free surface. The paper focuses on the free surface-structure algorithm that has been developed to allow the simulation of the complex and highly dynamic behaviour of the seals in the interface between the air cushion, and the water.

The developed fluid–structure interaction solver is based, on one side, on an implicit iteration algorithm, communicating pressure forces and displacements of the seals at memory level and, on the other side, on an innovative wetting and drying scheme able to predict the water action on the seals. The stability of the iterative scheme is improved by means of relaxation, and the convergence is accelerated using Aitken's method.

Several validations against experimental results have been carried out to demonstrate the developed algorithm.

Keywords: Surface effect ship; Seal dynamics; Finite element method; Fluid–structure interaction

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1. Introduction

The Transformable Craft (T-Craft) is a novel ship concept of the US Office of Naval Research, operative in multiple modes. T-Craft can deploy in an unloaded condition from the intermediate support base to the seabase, and then be used as a high speed connector to the shore, transporting wheeled and tracked vehicles through the surf zone and onto the beach.

T-Craft has been conceived as a Surface-Effect Ship (SES). A SES is a non-amphibious vehicle supported by an air cushion, with flexible seals at the bow and stern, and twin hulls, like a catamaran, at the sides. Due to the lack of air leakage at the craft sides, lift power can be reduced significantly compared with other type of Air-Cushion Vehicles (ACV). Also, it is possible to install conventional water propellers or waterjet propulsion, with rather smaller machinery space requirements compared to that for air propellers or fans used on ACVs. Furthermore, the SES can operate in modes of full displacement, partial air-cushion support, and full aircushion support.

Predicting the overall performance of a SES is of paramount importance to support the design phase, as the motion of the ship can be affected by the interaction between the air, the cushion, the ship structure, the seals, the sea waves and the sea bottom in the shallow water region. Different approaches with different types of complexity and accuracy have been taken to cope with this type of analyses.

In the last decade, there have been extensive applications of Navier–Stokes models to naval hydrodynamics problems. For example, Oñate and García-Espinosa [1] presented a stabilized FEM for fluid–structure interaction with free surface. In [2] Löhner et al. developed a FEM capable of tracking violent free surface flows interacting with objects. Also García-Espinosa et al. [3] developed a new technique to track complex free surface shapes. More recently, in [4], an application for the calculation of the flow about a SES in still water, using a commercial Volume of Fluid model, has been presented. While, in [5], Mousaviraad et al. uses an URANS solver for evaluating the manoeuvring performance of a SES. While the outcome of the analyses is outstanding, the CPU-time reported in this paper, makes this model quite unaffordable for being used during design stages.

Actually, it is a common consensus that solvers based on the Navier–Stokes equations are too expensive computationally speaking when it comes to simulate unsteady naval hydrodynamics problems. These sorts of problems can be more efficiently calculated using potential flow theory. This approach, jointly with the Stokes perturbation approximation, is widely used for analysis of seakeeping problems [6]. In [7], Connell et al., uses a boundary-element time-domain potential flow solver to calculate the multi-body seakeeping behaviour of a T-Craft SES and a LMSR in different scenarios. While, in [8], the same computational solver is adapted to calculate the manoeuvre of a SES.

Despite the complexity of the above referred SES computational models, none of them takes into account the seal dynamics, or the effect of free surface-seal interaction. However, it is well known the relevance of this interaction in the unsteady dynamics of a SES [9,10]. The complexity of this phenomenon makes impossible to develop a theoretical background, and prompts many design parameters to be traditionally decided by empirical formulas [9]. Actually, only limited theoretical and computational models have been developed to analyse seal dynamics [11–13].

This paper shows an extension of the work presented by Serván-Camas and García-Espinosa [6] in the development of an efficient seakeeping solver. In particular, it is focused in the recent work of the authors in the development of a computational model for the analysis of the complex and highly dynamic behaviour of the seals in the interface between the air cushion, and the water of a T-Craft [14]. The fluid solver developed for this purpose, uses a potential flow approach along with a stream-line integration of the free surface. While this approximation is much simpler than using RANS computations, significant outcomes can be obtained as well, allowing to significantly reducing computational time by 2 or 3 orders of magnitude even when computing on a regular desktop or laptop.

The developed fluid–structure interaction solver is based, on one side, on an implicit iteration algorithm, using a TCP/IP sockets link, able to communicate pressure forces and displacements of the seals at memory level and, on the other side, on an innovative wetting and drying scheme able to predict the water action on the seals.

The outline of this paper is as follows. In Section 2, we summarize the mathematical modelling and the details of the integration of the fluid equations. Section 3 describes the structural solver. Section 4 introduces the wetting and drying scheme and the fluid–structure interaction solver. In Section 5 different validation cases are presented. Finally, we arrive at some conclusions in Section 6.