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Dynamic response of a composite propeller blade subjected to shock and bubble pressure loading

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ABSTRACT

The interaction between an underwater explosion and a composite propeller involves several physical phenomena that an accurate numerical simulation needs to capture. These include proper description of the initial explosion shock wave, of its propagation in the water, and of its interaction with the propeller blades and any other neighboring boundaries. In this work, a numerical procedure which links a compressible flow solver with an incompressible flow solver is applied to capture both shock and bubble phases efficiently and accurately. Both flow codes solve the fluid dynamics while intimately coupling the solution with a finite element structure code thus enabling simulation of full fluid–structure interaction. This numerical approach is applied to the simulation of the interaction between an underwater explosion and a multi-layered propeller blade made of a set of composite materials. Fiber orientation in the various layers is studied to understand which combinations of materials and fiber orientations give the strongest resistance in terms of both bending and twisting of the blade.

1. Introduction

The interaction of an underwater explosion (Undex) with a neighboring structure has been an area of interest for the fluids and structures communities for a long time (Cole, 1948; Taylor, 1963; Chahine et al., 1996; Wardlaw and Luton, 2000; Geers and Hunter, 2002; Shin, 2004; Liang and Tai, 2006; Young et al., 2009; Zhang and Zong, 2011; Farhat et al., 2013; Wang et al., 2012). The complex dynamics is the result of an initial shock wave created by the detonation, followed by the growth and collapse of a bubble with very strong dynamics, and the interaction of the shock and the bubble with the structure. While the shock has a very short duration (microseconds), the dynamics of the bubble produces a long duration load with pulses, which could strongly excite the natural frequency of the structure. This could result in large motions and strains and the survival of the structure to the initial shock may not be a sufficient design constraint for a composite propeller.

While there are many studies on the dynamics response of ships (e.g. Liang and Tai, 2006; Sprague and Geers, 2006; Zong et al., 2008; Zhang and Zong, 2011), submarines (e.g. Kim and Shin, 2008), and propellers (Young et al., 2009) to the shock loading from underwater explosions (Undex), fewer studies in the open literature consider the effects of Undex bubbles on ships (Chahine et al., 1996; Wardlaw and Luton, 2000; Zong et al., 2008) and we are not aware of any studies that have addressed Undex bubbles interaction with propellers. Also, several studies have considered the response to Undex shock of composite structures such as composite cylinders (McCoy and Sun, 1997), laminated pipeline (Lam et al., 2003), and

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clamped composite plates (Fleck and Deshpande, 2004; Qiu et al., 2004; Rathbun et al., 2006). The focus of these studies has been on the response of the considered structure to the compression phase during shock wave impact and less attention was given to Undex bubble effects. Analytical modeling of a clamped sandwich panel response to the Undex shock decomposes the events into three stages (Fleck and Deshpande, 2004). The first is due to momentum transfer of the liquid to the beam, the second is due to the core compression, and the third is due to plate bending and stretching. Although such assumptions work well for plane waves, additional considerations are needed for the response of the structure to the Undex bubble which requires fully coupled FSI simulations (Chahine et al., 1996; Wardlaw and Luton, 2000).

Several researchers have conducted investigations evaluating the performance of composite propellers in other aspects than survivability to underwater explosions. Composite propellers have similar speed, fuel consumption, operating life, and horsepower requirements as their metal counterparts (Lin, 1991a) while having the advantage of lower weight to size ratio. Lin (1991b) calculated the stresses and deformations of a composite marine propeller and compared them to an isotropic NAB propeller. The NAB propeller was found to have 50% less elastic deformation compared to a composite propeller made of multiple layers of braided fiber. Lin and Lin (1996) coupled a 3-D Finite Element Method (FEM) with a vortex lattice method (VLM) and later they added an algorithm to their FEM coupled with VLM procedure to evaluate the optimum stacking sequence of the fiber composites (Lee and Lin, 2004). A more recent study (Young, 2008) used a combined Boundary Element Method (BEM) with FEM to study fluid–structure interaction of flexible composite propellers in sub-cavitating and cavitating flows. The study demonstrated that inclusion of FSI was crucial in determining the blade deformation and the fundamental frequencies of the propeller. Similar work for fiber-reinforced plastic composite propellers studied the bending–twisting coupling effects of anisotropic composites and load-dependent self-adaption behavior for performance improvement (Motley et al., 2009).

In the present study, the numerical procedure developed to study the interaction of an underwater explosion and a composite propeller blade during both the Undex shock and bubble phases is described in Section 2. The study of a propeller blade made of several layers of composite materials with different fiber orientations is then presented and its response to a close-by small explosion is investigated to understand which materials and fiber orientations improve performance. A conventional Undex configuration is then studied and the effect of fiber orientations to improve propeller resistance analyzed.

2. Numerical approach

In the present study, a time decomposition scheme is utilized to solve numerically the different stages of an Undex interaction with a composite propeller. This scheme combines the advantages of both a compressible code and an incompressible solver to capture the shock and bubble phases. As illustrated in Fig. 1, two time domains are considered both involving fluid–structure interaction computations. The initial shock phase dominated by compressibility is modeled using a multi-material compressible Euler equation solver, Gemini (Wardlaw et al., 2003). This is applied to properly capture the shock wave phase. After the shock moves out of the computational domain, the liquid becomes virtually incompressible and the flow filed is controlled by the bubble dynamics. This phase is then modeled with a BEM approach.

Although Gemini can accurately predict both Undex shock and bubble dynamics phases, it requires very fine gridding and significant computational resources to capture the full period of the bubble up to the point of touchdown, given the wide differences between the shock propagation time scale and the bubble dynamics time scale. To facilitate the simulations, a special link procedure is developed to transfer the solution of the compressible flow solver to become the initial conditions for the bubble flow modeling. The bubble dynamics phase involves mostly incompressible fluid dynamics and is modeled using a liquid boundary element method (BEM) potential flow solver, which has been shown to be very efficient in modeling underwater explosion and cavitation bubble dynamics problems (Chahine and Perdue, 1989; Zhang et al., 1993; Kalumuck et al., 1995; Chahine et al., 1996, 2003; Chahine and Kalumuck, 1998; Jayaprakash et al., 2012; Chahine, 2014). The following phases involving liquid compressibility, such as reentrant jet impact or rebound with a shock, can be solved again with the compressible solver.

Both the compressible and incompressible fluid codes are coupled with the structure dynamics code, Dyna3D (Whirley and Engelmann, 1993), which uses a finite element approach not BEM and provides a full fluid–structure interaction (FSI) solution for the full history of interest to the Undex dynamics. More details of the above is presented below.

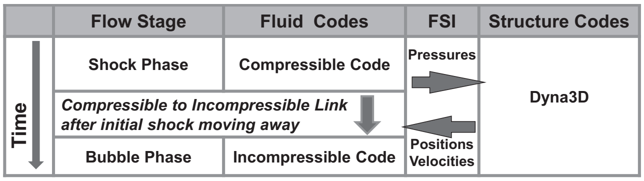

Fig. 1. Schematic diagram of the time domain decomposition hybrid scheme used in the present numerical approach to simulate the interaction between a deforming structure and both phases of an Undex event (shock and bubble).