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Experimental and numerical investigation of water impact on air-launched AUVs

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ABSTRACT

Air-launched autonomous underwater vehicles (AUVs) are subjected to huge impact loads in the early stage of water entry, which may cause structural damage or failure of electronic components, especially in the case of high speed water entry. Therefore, it is very imperative to carry out experimental and numerical research on the impact loads of air-launched AUVs. An experimental study of the water entry of air-launched AUVs with different launch velocities and angles was conducted using high-speed photography and sensing technology. The axial and radial accelerations of AUVs under different working conditions at the early stage of water entry were obtained. Furthermore, a coupled finite element technique and the smooth particle hydrodynamics method (FEM-SPH) is employed to model the water entry process of air-launched AUVs. Numerical simulation results such as the peak of impact acceleration were compared with the presented experiment results. The good agreement between the experimental results and the numerical simulation results revealed the capability and accuracy of the numerical algorithm in solving the problem of AUV water entry.

1. Introduction

Autonomous Underwater Vehicles (AUVs) have a wide range of applications in marine geoscience, and are increasingly being used in the scientific, military, commercial, and policy sectors (Wynn et al., 2014). Theire civil use mainly involves deepwater exploration, sunken salvage, underwater cable laying and maintenance, whereas they are mainly used in the military for underwater reconnaissance, underwater communications, information operations and anti-submarine operations, anti-mine operations and other fields. The rapid deployment of air-launched AUVs from helicopters or aviation antisubmarine planes is a capability that will reduce the transit times to the objective areas and increase the range of operations from the base unit. In addition, a single launch vehicle could simultaneously carry and release multiple AUVs, which would greatly reduce the search time for a wide range of objective areas.

Water entry is a type of impact event to which high-speed marine vessels are often subjected (Faltinsen, 2005; Abrate, 2011). An air-launched AUV will suffer a huge impact load at the beginning of a water entry, which may cause trajectory deflection and damage to its structure and inner components in severe cases. Therefore, calculating the trajectory and water impact forces, especially during the initial entry stages, where the maximum impact loads occur, is of great importance when designing air-launched AUVs. The high-speed water entry of an air-launched AUVs is a very complex process that involves the problem of unsteady motion and interaction of air, water, and the AUV body. Water entry problems have been studied theoretically and experimentally by many researchers and scientists for more than a century because of their extensive applications in numerous industries, especially ocean and coastal engineering.

The solution of the water entry problem is greatly dependent upon the change in the boundary shape of the water surface, which is highly non-linear, making the problem extremely complex and difficult to solve analytically. Von Kármán (Von Kármán, 1929) carried out the earliest theoretical study on the water entry of a structure. Based on the theory of potential flow, he gave a general description of the water inflow process and proposed an additional mass method to calculate the impact load. Subsequently, this method has been widely used. However, this method ignores the local uplift of the water surface and can not calculate the slamming pressure near the contact surface of the object and free surface. In addition, it can not explain some of the phenomena that occur during slamming. Wagner (1932) theorized the method of Von Kármán, taking into account the effects of the changes in boundary conditions, including calculations of the piled-up water surface and spray thickness.

In terms of experimental research on the water entry problem, since

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Worthington and Cole (1900) first used flash photography to observe the phenomenon of small balls entering water, many researchers have carried out a large number of experimental observations on the process of water entry using various methods. The objects of this experimental study are mainly small spheres and wedges (Gilbarg and Anderson, 1948; May 1951; Chuang, 1966; Truscott and Techet, 2009; Panciroli et al., 2015; Hurd et al., 2017). The effect of atmospheric density, surface condition and the rotation of spheres on the development of water cavitation were the main concern of these experiments. Roe (2005) carried out the initial water entry test on the remote environmental monitoring units (REMUS) AUV and obtained the maximum value of the impact acceleration at different pitch angles. However, the speed of entering water was greatly limited by the height of the launcher, because the height of the launcher was fixed, and the initial speed is obtained through the free fall of the REMUS AUV. Allen (2013) focused on obtaining high quality measurements of the loading and responses of flexible hull panels during slamming events. Additionally, a range of analytical theories for the prediction of the loads and pressures acting on a rigid wedge have been compared to the experimentally measured values. The experiment on shallow angle water entry of ballistic projectiles was performed by Truscott et al. (2009). The projectile dynamics, critical entry angle, and cavity formation were discussed for various bullet geometries, and the results showed that successful water entry was a function of the length-to-diameter and tip shape. Gu et al. (2012) researched the hydro-ballistic trajectory and cavity of a half sphere bullet and general pistol bullet by a high speed digital video recorder and drew the conclusion that the head shape of a bullet has an important influence on the hydro-ballistic stability of its motion. An experimental investigation of the water entry of a rectangular plate with a high horizontal velocity component was presented by Iafrati (2016). Russo et al. (2018) proposed an integrated experimental and theoretical framework to isolate the effects of an oblique and asymmetric impact on the water entry of a rigid wedge. Through particle image velocimetry and a complementary array of sensors, they systematically analysed the role of the heel and velocity angles on the pile-up evolution, hydrodynamic loading, and energy imparted to the fluid flow. The analysis of the data focused on the spray formation, spray root shape pressure distribution and scaling, pressure peak and propagation velocity, total loads acting on the plates, and position of the center of the loads. Jiang (Jiang et al., 2018) investigated the fundamental flow characteristics of a constraint posture projectile under different entry angles and ventilation rates. Jalalisendi and Porfiri (2017) studied the water impact of a slender beam both experimentally and theoretically. A mathematically tractable framework was proposed to predict the elastic deformation and rigid body motion of a beam impacting the water surface in free fall. Eventually, they came to the conclusion that the hydrodynamic loading could be determined by the level of submersion of the cross-section and its local velocity and acceleration at each location on the beam.

Along with the development of computer simulation technology, an increasing number of scholars have adopted various numerical simulation methods to study the impact of water entry on structures. Aliabadi et al. (Aliabadi and Tezduyar, 2000) applied the interface capturing method on the basis of the finite element method-volume of fluid (FEM-VOF) method. He et al. (HE et al., 2012) used the VOF and dynamic mesh method to simulate the multiphase flow and movement of a water entry body. Erfanian (Erfanian et al., 2015) explored the water entry problem of a spherical-nose projectile using a coupled eulerian-lagrangian (CEL) method. Meshless techniques are often employed to solve the difficulties of a finite element (FE) calculation, such as large mesh deformation and mesh distortion. Jackson and Fuchs (2008) conducted two vertical drop tests of a 5-ft-diameter composite fuselage section into water and conducted a simulation using both the arbitrary lagrangian-eulerian (ALE) and smoothed particle hydrodynamics (SPH) approaches. Some improved SPH methods, such as new kernel function, new boundary condition treatment, $\delta^{+}-$SPH are applied to numerical simulation of fluid structure interactions, see (Yang et al., 2014; Nair and Tomar, 2014; Gong et al., 2016; Sun et al., 2018).

The VOF method can effectively guarantee the conservation of a physical quantity, but it is difficult to accurately calculate the normal and curvature of the interface. Moreover, the method of interface reconstruction is complex, and it is more difficult to promote to higher dimensions. The ALE method is based on the arbitrary movement of the reference frame, which is continuously rezoned in order to allow a precise description of the moving interfaces and to maintain the element shape. However, when the grid is considerably distorted, it will still cause serious errors in the numerical results (Huerta and Liu, 1988). The finite element method (FEM) is an efficient method for dealing with impact and explosion mechanics problems. However, it will be frustrated by the challenges of grid distortion, and the calculation will have a decreased accuracy or be interrupted during the calculation of multi-medium or large deformation problems. As a mesh-free numerical method, SPH can handle large deformation problems well. The interfaces between different materials are formed naturally. In this way, the coupled FEM-SPH algorithm takes into account the advantages of using SPH to process mesh distortion and large deformation, as well as the high efficiency of the FEM. Zhang (Zhang et al., 2011)presented an alternative method for coupling the FEM and SPH in a lagrangian framework, and the perforation of a cylindrical steel projectile impacting a steel plate target was simulated to demonstrate the performance of the FEM-SPH coupling algorithm. Grimaldi et al. (2012)used the FEM-SPH method to simulate the water entry of a steel structure.

The experimental research on large-scale rotary bodies under different water entry conditions is relatively scarce. The aim of this study was to experimentally investigate the impact load of a full-scale AUV during water entry, and the coupled FEM-SPH method was used to numerically obtain the influences of velocity, angle, and angle of attack on the impact acceleration. The feasibility and accuracy of using this method in an AUV high-speed water entry impact test were verified.

2. Experimental setup and data processing

2.1. Apparatus

All the experiments were carried out in the integrated tank of the Key Laboratory of Unmanned Underwater Vehicle, Northwestern Polytechnical University. The tank is rectangular, with a working length of 70 m and width of 44 m. The depth of the water entry test was 7 m. The experimental model diagram is shown in Fig. 1, and the specific parameters of the AUV are listed in Table 1.

The complete experimental setup is shown in Fig. 2. The main components of the test system were the launch device, accelerometer, high-speed cameras, supplemental lamps, PC, data acquisition system, and analysis module. The launch device mainly included an air compressor, a launch support frame, and a launch tube. The maximum pressure produced by the air compressor was 0.8 MPa. The length of the launch tube was 2.5 m, and its inner diameter was 205 mm. The angle adjustment device of the launch support frame allowed a range of 0°–90° for the launch angle. By varying the pressure value of the air compressor, the AUV obtained a different ejection speed. The Model 4630A triaxial piezoresistive accelerometer, manufactured by Measurement-Specialties, USA, was used in the test. The Model 4630A triaxial accelerometer is available in ranges from ± 2 g to ± 500 g with 5000 g of shock protection and a sampling frequency of 60 kHz. The acceleration sensor and data acquisition module were enclosed in a housing, and the data output interface for connecting the PC was reserved (see Fig. 3). During the experiment, two normal high-speed cameras were arranged to capture the aerial posture and instantaneous speed as the AUV touched the water surface, while two other underwater high-speed cameras were placed to obtain the underwater

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