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Experimental and numerical study of water impact investigations for aircraft crashworthiness application analysis

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1. Abstract
It is important for crashworthiness of an aircraft fuselage and its structural components to evaluate the aircraft airworthiness in crash-landing scenarios on different terrains (i.e. rigid, soil, and water). In this study, a new experimental method by Doppler shift is performed to measure the velocity and thus the water impact loads of a rigid sphere bottom structure dropping onto a water surface. Doppler Effect measurements are conducted to precisely obtain the water impact responses acting on the structure. And experimental results are validated and evaluated with the classical experimental data, as well as numerical simulation performed on the explicit FEM code LS-DYNA. A penalty coupling algorithm within the frame of multi-material Arbitrary Lagrangian Eulerian (ALE) model is utilized to numerically simulate the experimental cases. It concludes that the Doppler measurement is a reliable and effective method to not just obtain the water-impact responses and its great potential to be applied to aircraft crashworthiness analysis.
2. Keywords: Crashworthiness, Water impact; Drop tests; Doppler measurement; Finite element analysis

3. Introduction
There have been various research programs are conducted by NASA, IDRF and FAA to investigate fixed-wing aircraft and rotorcraft crashworthiness in order to improve survivability in the event of a crash [1]. During a crash onto ground, soil or water, the structures must be able to absorb the kinetic energy and limit the impact forces and deceleration that are transmitted to the occupants to tolerable levels. While considerable research has been performed on testing of aircraft impacting hard surfaces and soft soil, few studies have been focused on impacting onto water surface. There are some differences between impacting onto water and rigid surfaces. Water impact loads depend on the fluid-structure interaction and contrarily rigid surface impact loads depend only on structural characteristics. Due to the complex crash event, the wetted surfaces will strongly influence the loads path changes and the floating time for the damaged structure because of the water pressure. It is necessary to develop a reliable experimental method to measure the water impact responses and become a part of methodologies used to water crashworthiness analysis.

Recently some analytical, experimental, and finite element methods have been available to water impact domain, such as ship slamming, aircraft ditching, space capsule water landing, and torpedo water entry and so on[2, 3]. Th. von Karman and H. Wagner were the pioneers to theoretically study water impact problem for the purpose of estimating the impact forces and pressures based on the conservation of momentum [4, 5]. The history of crashworthiness studies can be traced back to the 1910s. Miloh [6] solved the displacement, velocity, and acceleration histories of a rigid sphere analytically, by employing the matched asymptotic method. Generalized Wagner Model (GWM) was created using the linearization analysis on the exact boundary condition around the intersection between the body and the free surface [7, 8] and can thus obtain satisfactory results.

4. Experiment methodology and verification
R. Araki, A. Takita, et al [9, 10] used the Doppler shift and the modifying Levitation Mass Method (LMM) [11] to conduct a water impact experiment analysis of a rigid sphere impact on water at School of Science and Technology, Gunma University, Japan. In the paper the experimental drop test is simply introduced and test data are certificated with some classical water impact data and a close correlation is observed through the numerical simulation.

4.1 Experimental setup
The impact of a stainless sphere on the clam water surface with initial downward velocity with variable water-entry height and then plunging into the water is tested in this study by the Doppler measurement. The experimental setup (Figure 1) divides into four systems, including water pool, the laser Doppler measurement module, quick-releasing facility, and high-speed camera.

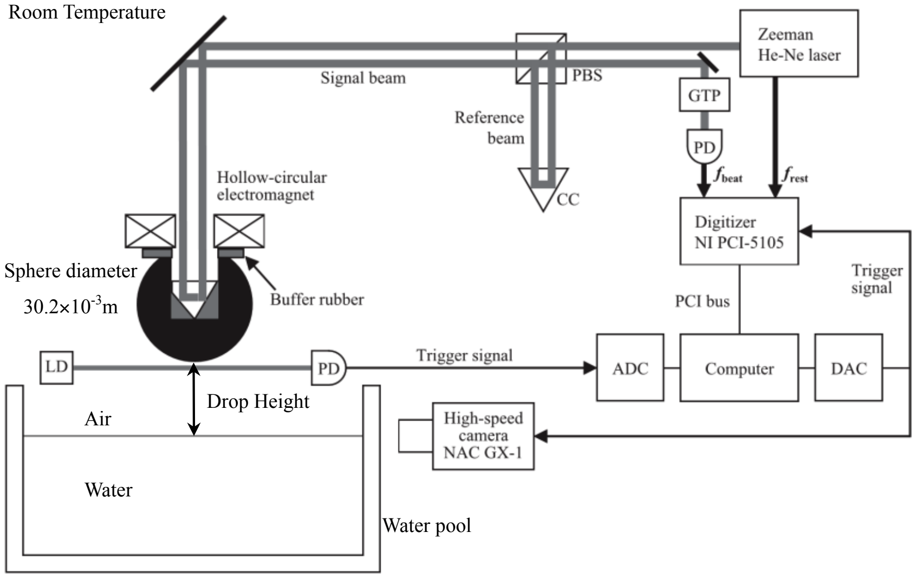

Figure 1 Experimental setup arrangement.

Code: CC=cube-corner prism, PBS=polarizing beam splitter, NPBS=non-polarizing beam splitter, GTP=Glan-Thompson prism, PD=photodiode, LD=laser diode, ADC=analogue-to-digital converter, DAC=digital-to-analogue converter.

Water pool is made of transparent acryl resin. During the test, it allows to adjust the variable dropping height which is between the bottom of the test article and water surface. The quick-releasing facility is equipped with a hollow-circular electromagnet to guarantee the test articles quick-release manually without any vibration. In this experiment, the test article is a tempered stainless sphere, which is punched a hole on the top and inlaid a cube corner prism. The total mass of the entire body is approximately 93.88 g. A high-speed camera (NAC Memrecam GX-1, NAC Image Technology, USA) is used to capture the images around the impact region with a resolution of 135 424 pixels and a frame rate of 15 000 fps. The digitizer and the high-speed camera are initiated by a sharp trigger signal generated using a digital-to-analogue converter (DAC). This signal is activated by means of a light switch, which is a combination of a laser diode and a photodiode.

The laser Doppler measurement module utilizes the laser Doppler interferometer to measure the velocity. A digitizer (NI PCI-5105, National Instruments Corp., USA) records the output signals of PD1 and PD2 with a sample number of 5M for each channel, a sampling rate of 30M samples per second, and a resolution of 8 bit. A Zeeman-type two-wavelength He-Ne laser in is used as the light source. Each beam has different frequency and orthogonal polarization. Differentiating the body's velocity which is calculated from the measured value of the Doppler shift frequency of the signal beam of the interferometer, the acceleration is calculated.

4.2 Experiment results and verification

Here only a test-run is conducted by the predetermined dropping position about 136mm from the water surface. In an effort to guarantee the reliability of measures and accuracy of test data, 7 drop measurements are taken in each set of measurements. The Levitation Mass Method (LMM) is developed to precisely measure the motion-induced time-varying beat frequency. Other water impact parameters, such as displacement, velocity and acceleration and impact force, are numerically calculated from the beat frequency. The results of the 7 drop measurements coincide well, indicating a high reproducibility of the measures [10]. In order to verify the experimental results, especially water impact force, the acquired water impacting acceleration is made to nondimensional impact drag coefficient as shown in Figure 2 in order to compare with some classical experimental data.

Comparing the new measures to the other classical experimental data, the repeatability and the reliability of the tests of impact accelerations are showed the effectiveness of the crashworthiness design for the sphere-bottom structures.

5. Numerical modelling and analysis

The main interest of the numerical simulations has been compared with the Doppler measure to estimate the efficiency of the nonlinear explicit codes to predict dynamic response of the structure. The fluid are defined as the ALE Multi Materials which is most versatile and widely using 1 point ALE multi-material element, the structure is modelled with the classical Lagrangian approach by the default Belytschko-Tsay element formulation.

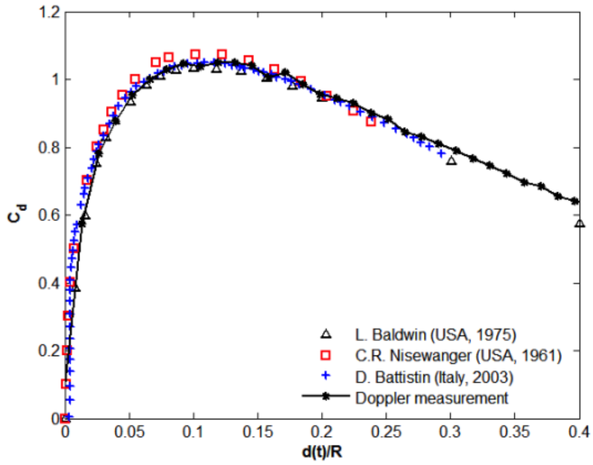

Figure 2 Comparison of Doppler measurement results with the experimental ones.

In order to reduce the computer time-consumption, only a quarter of the model is established with symmetric boundaries on XOY and YOZ planes, as shown in Figure 3. A cylindrical hole is embedded into the body in order to insert a cube corner prism. Meanwhile it demands the optical center coincide with the center of gravity of the sphere. For all the analysis cases the properties of the spherical body are taken as below. The mass of the impactor is 93.88 g. the density of the stainless steel body is 7650 kg/m^3; Young's modulus is 2.0×10^{11} N/m^2; and Poisson's ratio is 0.3. The Poisson's ratio and Young's modulus of the material do not change the behavior of the sphere part because of its rigidity.

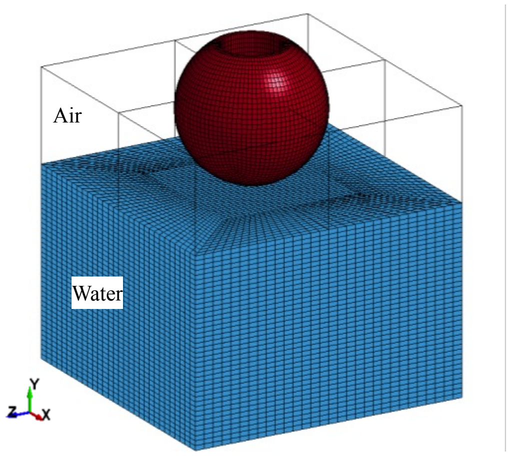

Figure 3 Three view of water impact model including air and water domain

The constitutive model and equation of state (EOS) model are simultaneously utilized to describe the nonlinear properties of a fluid or fluid-like deformation material in explicit dynamic codes LS-DYNA [12]. Material model *MAT_NULL and EOS model *EOS_LINEAR_POLYNOMIAL were contemporary used to model air. And then, the water was modeled using the Mie-Gruneisen EOS based on a cubic shock velocity-particle velocity. The penalty based coupling treats the FSI problem between a Lagrangian formulation modeling the structure and an ALE formulation modeling the fluid. The coupling mechanism between the MMALE and the structure is controlled by the keyword *CONSTRAINED_LAGRANGE_IN_SOLID (*CLIS). To get the proper numerical model and reach more correct solutions, convergence studies should be performed based on the convergence theorem, with respect to some parameters study. The selection of the contact stiffness based on the penalty coupling algorithm is required here. The coupling stiffness via the parameter PFAC, the penalty factor, in *CLIS should be analyzed in detail.

Numerical models of the experiment scenario are created and employed. Figure 4 show the comparison of the experimental, theoretical and numerical drag coefficient. The most concerned result is the maximum impact forces in the early-water entry. In the view of the acceleration peak and the overall shape of the curve, the prediction of nonlinear LS-DYNA codes coincides very well with one derived from the analytical MLM and shows a quite satisfactory agreement.

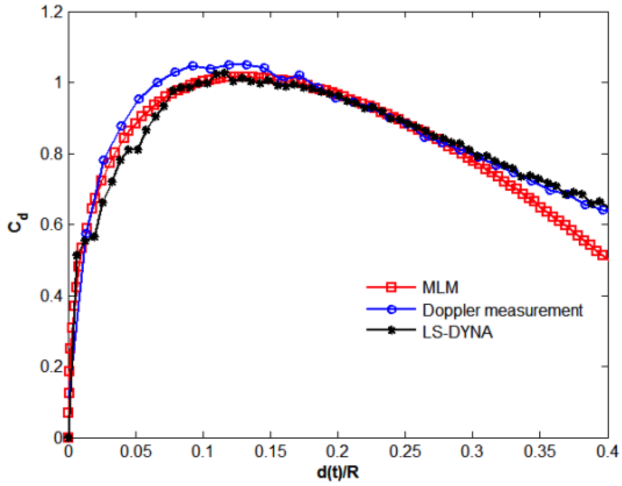

Figure 4 Numerical-analytical-experimental correlation for the impact drag coefficient

6. Conclusions

The present work is mainly to develop and verify a new suitable measurement of dynamic responses in water impact domain and its application is to be faced with aircraft crashworthiness analysis. The drop tests utilized by Doppler measurement are performed to precisely obtain acceleration, displacement and inertial impact force acting on the sphere bottom structure. The impact drag coefficient time histories are compared with other classical experimental results, together with the analytical method and numerical results. The results have been shown that Doppler measurement demonstrates the accuracy for predicting dynamic responses in water impact on a sphere. And it is feasible for other structures and it deserves further development for other crash-landing scenarios. The numerical simulation tests are efficiently carried out using a MMALE formulation and a penalty coupling algorithm to duplicate the experimental cases. And the verified numerical model can estimate the efficiency of the nonlinear explicit codes to predict the dynamic responses. They provide the opportunity to develop water impact analysis criteria for aircraft crashworthiness analysis.

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