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Measurement and modeling of supersonic hailstone impacts

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ABSTRACT

Hailstone impacts can be detrimental to the lightweight structures of aerofoils – from ground-based wind turbine blades to supersonic aircraft wings. Hailstone impacts have been studied and modeled in recent years but the work has not yet reached a higher-velocity regime that is relevant to many current applications. We have pushed higher into this regime with new approaches in both modeling and experimental measurement of hailstone impacts. The impulses of hailstone impacts on a flat plate were measured up through supersonic velocities and over a range of impact angles using the Sum of Weighted Accelerations Technique (SWAT) developed at Sandia National Laboratories. These results are compared with the impulses predicted by finite element simulations that improve upon existing material models from literature. The result of this work is a hailstone impact model, calibrated by experiments, that is capable of capturing the impulses imparted on structures by hailstones traveling up to supersonic velocities and impacting over a range of angles.

1. Introduction

Damage from supersonic hail impacts was first studied in the late 1960s through experiments where representative hailstones were fired into thin aluminum plates at high velocities [1]. The angle of impact and velocity of the hailstone were varied to determine the values where penetration of the plate would occur for different plate thicknesses. The hailstone impacts were not characterized beyond noting the amount of permanent deformation in the plates. Later, much work was done to characterize the fragmentation of the hailstones [2–6]. This work focused on the breakup of hailstones as a function of size, velocity, impact angle, and the impact surface. The main purpose of this work was to understand the amount and character of the ice entering a turbine engine in order to evaluate the potential effects on the combustion reaction; there was no measurement of the forces or momentum transfer from the impacts. More recently, Kim and Kedward [7,8] measured and modeled impulses imparted by hailstone impacts at speeds up to 200 m/s. Experimental measurements were made using a dynamic force transducer attached to the back of a target plate. The finite element model showed reasonable agreement with experiments provided that the material properties were adjusted for each velocity. A similar experimental approach was used by Pereira et al. [9] to measure the impact force of cylindrical ice projectiles up to a higher velocity (~220 m/s). Resonances in the load cell at these velocities were approaching the amplitude of the signal and may have prevented measurements at higher velocities. These data and supplementary measurements made at lower velocities using a drop tower [10] were used to calibrate a model utilizing an Eulerian approach that incorporated strain-rate effects and an equation of state for the ice [11]. Others have explored and compared additional numerical techniques for modeling the hail impacts on an aircraft fuselage [12]. Since this study, there has been work to better characterize and model the material behavior of ice [13–15]. Most recently, a finite element model with an improved material model incorporating viscoplasticity was presented and validated against experiments [16]. This improvement allowed the yield strength of the ice to vary spatially within the hailstone. The highest strengths occurred near the impact where strain rates were highest. A tensile failure criterion in the material model also allows the simulations to exhibit cracking similar to what was observed through high-speed photography of the experiments. The authors obtained good agreement with experimental measurements of the imparted hailstone impulse over their full range of experiments with a single material model for the ice.

In previous work there is some discussion of the behavior of hailstones at higher velocities, but there is not any direct measurement of the hailstone impulse at velocities exceeding 220 m/s. McNaughtan and Chisman easily exceed this velocity in their experiments but they did not measure the impulse exerted by the hailstone during impact. Others increase the kinetic energy of impacts by increasing the mass of the hailstone, but not the velocity. This approach does not probe the changes in material response and failure modes that may occur at higher velocities. Several authors have inferred or stated outright that at some velocity the material properties of the hailstone will become insignificant and the impulse will be determined solely by the mass/momentum of the hailstone.

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Combescure et al. [17] show that at relatively low velocities (120 m/s) the impacts of ice and an equivalent mass of water have very different results; plastic deformations in the target plates are larger and more localized in the case of the ice. Pereira et al. mention that the behavior becomes more fluid-like at higher velocities. Tippmann et al. show that at the beginning of the impact the impulse is determined by the elastic properties of the ice. Later on, at the time of the peak impulse, the hailstone has been completely traversed by cracks and its behavior has begun to be driven by a fluid-like response dominated by momentum. This transition in behavior is explored more thoroughly in the following paper as the velocity and angle of the impact are varied.

The work presented here builds upon the Tippmann et al. hailstone material model and expands the range of hailstone impact velocities and angles over which the imparted impulse has been measured. We have performed experiments with impacts over a range of angles from 10° to 90° (normal impact) and velocities spanning from a 150 m/s normal impact to an impact at 677 m/s with a 10° impact angle. Data from these experiments were used to calibrate a hailstone material model that adds the capability of converting highly deformed elements into mass particles. This approach was important in capturing the full impulse of the impact, beyond where elements become highly distorted. We also explore the effects of how elements are failed and show that full 3D simulations produce different results than quarter-symmetry models. This calibrated hailstone model is used to explore the velocities where the hailstone impulse transitions from being determined by the material properties of the hailstone to being fully determined by mass and the transfer of momentum. In the future, this model will be used to study hailstone impacts on aeronautical structures.

The remainder of this paper is organized as follows. The next section provides a description of the experimental work, including the process used for making the ice balls, the experimental setup, and the post-processing of the data done to extract the impulse imparted by the hailstone. The subsequent sections describe the finite element modeling approach used to simulate the experiments and make a comparison of the simulated and experimental results. This comparison shows good agreement between the filtered results and uses the calibrated model to extend predictions into the velocities where the measurement technique was unable to capture the entire impulse.

2. Materials and methods

Hailstone impact experiments were performed at Sandia National Laboratories' Terminal Ballistics Facility. Ice balls were fired from a powder gun using a pusher/sabot that was stripped away from the ice ball after exiting the barrel. The target was a suspended aluminum plate instrumented with an array of accelerometers on the back face. Video from three high-speed cameras was recorded to study the location and behavior of the ice ball at impact and to verify that the hailstone was intact and not exhibiting cracks before impact. The following section provides a more detailed description of the design of the experiment and the measurements taken.

2.1. Mock hailstones

Experiments were performed using molded balls of ice reinforced with cotton according to the ASTM standard F320-10. Approximately 0.67 g of cotton filler is used for each 20.57 mm diameter ice ball. Throughout this paper we will refer to these ice balls as hailstones. True hail-ice forms in layers and has a lower density than molded ice due to large amounts of porosity. The use of molded ice balls is considered conservative in that their higher density and strength would cause more damage to an impacted structure than a true hailstone. The hailstones were formed in a split mold using distilled water with dye added to improve the visibility of cracks in the ice during impact. The mold was created using a Projet 3510 printer with the VisiJet M3-X material. The hailstones were frozen and stored in a −18 °C freezer. Monitoring the temperature of the specimens showed that they froze and cooled 17 °C within 3 hours. The nominal diameter of the hailstones was 20.57 mm. Before firing, the weight of each hailstone was recorded. The average weight of the hailstones was 4.30 g; further details are presented later in Table 1.

2.2. Experimental setup

The smooth bore gun used to fire the hailstones had a 762 mm-long steel barrel with a 20.57 mm bore. A shortened, pre-primed eight-gauge shotgun shell filled with smokeless powder provides the explosive charge. The amount of powder for the shots ranged from 10 to 53 grains to reach velocities ranging from 150 to 680 m/s. The stack-up for each shot included the powder, a nitro card (cardboard disc), wadding, and a second nitro card. See Fig. 1. The assembly was neither pressed nor crimped. For each shot, the barrel was chilled and loaded with a shell, a chilled pusher, and a hailstone. A consistent procedure was followed to minimize warming of the hailstone and ensure each hailstone experienced the same conditions. Being able to prototype quickly with a 3D printer, we were able to explore several sabot and pusher designs. The pusher pictured in Fig. 2 was found to yield the most accurate shots and to provide good separation from the hailstone after exiting the barrel. The pusher was designed to split in half after leaving the barrel. A cardboard disc was used to separate the pusher from the hailstone and help the pusher to split open. After leaving the barrel and splitting apart, the pusher was stripped away from the hailstone by the stripper plate. Cameras were placed to capture high-speed (20,000–55,000 fps) movies of the stripper plate and to provide a top and oblique view of the impact of the hailstone on the instrumented target. The cameras and lighting were triggered as the hailstone passed the chronograph in order to capture the entire path of the hailstones through their fields of view. A schematic of the experimental setup is shown in Fig. 3.

The target used for the hailstone shots was a 7075 aluminum plate with dimensions 27.9 × 30.5 × 5.1 cm (11 × 12 × 2 inches) weighing 12 kg (26.5 lbs). The plate has four 1.27 cm (½-inch) through holes used to support the plate. Elastic cords were used to suspend the plate in a way that approximated 'floating' boundary conditions. On the back are twenty 0.635 cm (¼-inch), drilled and tapped, holes used for attaching accelerometers. Fig. 4 shows a schematic of the plate with the pertinent dimensions and the locations where the accelerometers are attached side-by-side with a photograph of the instrumented plate being held in position by the supporting elastic cords. The accelerometers used were Endevco 7270A-20K-M6 (20K g's) and were selected for their built-in mechanical filters that are designed for shock measurements. The accelerometers are designed with a dynamic range from DC to 10 kHz. These accelerometers were positioned to avoid stationary points of the mode shapes of the plate, as determined from finite element analysis (FEA).

2.3. SWAT analysis

The Sum of Weighted Accelerations Technique (SWAT) allows one to calculate the forces acting on a body by measuring acceleration at a finite number of locations on the body [18]. This approach has several benefits. If sufficiently instrumented, it can resolve the net force acting on the body in three orthogonal directions. Additionally, the measurement is much less sensitive to where the impact occurs – using this technique with a large plate provides an easy