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Soft impacts on aerospace structures

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ABSTRACT

This article provides an overview of the literature dealing with three types of soft impacts of concern for the aerospace applications, namely impacts of rain drops, hailstones and birds against aircraft. It describes the physics of the problem as it has become better understood through experiments, analyses, and numerical simulations. Some emphasis has been placed on the material models and the numerical approaches used in modeling these three types of projectiles.

Contents

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1. Introduction

This article deals with the impact of rain drops, hailstones, and birds on aerospace structures. These three types of impacts are usually considered to be soft impacts even if it is difficult to define what constitutes a soft impact as opposed to a hard impact [1]. Soft impacts are sometimes defined as impacts in which the stresses generated far exceed the strength of the projectile but are far below the strength of the target [2,3]. Often publications dealing with hard impacts such as those occurring when a tool is dropped on a composite structure state that their analytical or numerical models are applicable to bird strikes and hail strikes. The following will show that this is not the case.

Current research emphasis is on the development of efficient approaches for numerical simulation that requires adequate models of the material behavior and efficient numerical methods for handling the large deformations and flow of soft projectiles. In many cases the projectile behaves as an inviscid fluid and sometimes artificial viscosity is introduced to avoid oscillations in the predicted response. Other material models are also used for the projectile while for the target elastic models, viscoelastic models and various plasticity models are used. Modeling a highly deformable projectile is challenging when using Lagrangian or Eulerian descriptions of the deformation. Approaches combining these two continuum descriptions are found to be more efficient and the Smooth Particle Hydrodynamics (SPH) method that considers the material as a series of particles appears as the favorite approach for modeling bird strikes in particular. The article focuses on soft impacts on aircrafts and in particular the impacts due to rain, birds and hailstones.

2. Liquid impact

Research on this topic started in 1928 with an investigation of the erosion caused by the collapse of cavities on the surface of steam turbine blades [4]. Since then, the scope broadened to include rain erosion on acrylic materials for aircraft transparencies [5] and forward facing airplane components [6], particularly those made out of composite materials. Currently, rain erosion is also a significant issue for the leading edges of wind turbine blades made out of composites with either glass or carbon fiber reinforcement [7] and require special coatings [8]. In addition, to these obvious reasons to study liquid impacts, we will see that at typical impact velocities birds behave like fluid during impact.

Cook [4] discusses the erosion caused by the collapse of cavities on the surface of steam turbine blades. Considering a column of water of impacting a rigid surface with a velocity V, the kinetic energy of a layer of thickness Δh prior to impact is $\frac{1}{2}\rho V^2 A\Delta h$ where A is the cross-sectional area of the column and ρ is the density of the fluid. After impact, the velocity of the fluid is zero and the kinetic energy has been converted into potential energy $\frac{1}{2}pe_{\mathrm{v}}A\Delta h$ where the volumetric strain $e_v = p\beta$. Equating these two energies gives the pressure $p = V\sqrt{\rho/\beta}$. The compressibility β is the inverse of the bulk modulus B and $\sqrt{B/\rho} = C$, the speed of sound in the fluid. This pressure is usually written as

$$p = \rho CV \tag{1}$$

and is commonly called the water hammer pressure. The bulk modulus of water is 2.2 GPa and its density is 1000 kg/m^3 so c=1483 m/s. Cook considered impact velocities in excess of 120 m/s. When V=120 m/s, Eq. (1) predicts a water hammer pressure of 178 MPa which is of the same order of magnitude than the yield strength of engineering materials. The wave velocity C is related to the acoustic wave velocity C_{a} and the particle velocity by C=C_a+kV where k is approximately equal to 2 when V< 1000 m/s as indicated in [9]. Therefore, at high impact velocities, the shock wave velocity is significantly higher than the acoustic wave velocity.

Another view of this problem is that the motion of the fluid is governed by the wave equation and that, after impact against the rigid surface, a compressive wave propagates into the fluid with a velocity C and the pressure behind the wave front is the water hammer pressure (Eq. (1)). When the water column impacts an elastic half-space, two waves propagate away from the interface: one into the fluid and the other into the solid. The water hammer pressure is

$$p = \frac{z_1 z_2}{z_1 + z_2}V = \frac{\rho_1 c_1 \cdot \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2}V \tag{2}$$

where $z_1 = \rho_1 c_1$ and $z_2 = \rho_2 c_2$ are the mechanical impedances of the liquid and the solid [10]. Eqs. (1) and (2) predict the pressures during the initial phase of the impact between a liquid and a solid. As soon as the impact initiates and the shock wave starts to propagate upwards, relief waves initiating at the periphery of a cylindrical liquid projectile start to propagate inwards (Fig. 1). For water jet of radius r impacting a solid surface, the impact phase ends when these release waves reach the central axis at time t=r/C. That marks the end of the high pressure phase. After that, the flow can be considered to be incompressible. For incompressible flows, on a stream line, Bernoulli's principle states that $\frac{V^2}{2} + gz + p/\rho = \text{constant}$. When applied to the stream line along the axis of the projectile we found that the stagnation pressure is

$$p_s = \rho V^2/2 \tag{3}$$

After that the pressure at the stagnation point falls to $p_s = \frac{1}{2}\rho V^2$. The ratio of the water hammer pressure (Eq. (1)) to the stagnation pressure $p/p_s = 2C/V$ is always large which indicates the importance of the initial stage of the liquid–solid impact.

For a spherical water drop impacting a rigid surface [11,12], the contact radius at the end of the high-pressure stage and the duration of that high-pressure stage are $r = RV/C$ and $\tau = 3RV/2C^2$. The pressure in the compressed region behind the shock wave is not uniform and is highest just behind the contact edge. The pressure at first contact (Eq. (1)) increases to approximately three times that value right before jetting [13]. The average pressure during the impact phase is given by $p = \frac{1}{2}\alpha\rho CV$ where the factor ½ is due to the spherical shape of the drop and the factor α tends to one for high impact velocities (Engel, 1955 [14]).