Physics-Based Modeling of Hydrodynamic Ram Phenomena

What is Hydrodynamic Ram?

A fundamental aspect of reducing the vulnerability of aircraft to projectile impact involves the ability of designers and analysts to accurately model the complex fluid- and solid-mechanical behavior resulting from hydrodynamic ram (HR). Within the context of military aircraft applications, an HR event typically involves the impact and penetration of a fluid-filled structure (e.g., an aircraft wing or fuel tank) by an armor-piercing (AP) or high-explosive (HE) projectile. The term HR refers to the high fluid-pressures that arise in these situations. A typical HR event, however, will involve underlying physical phenomena that become exceedingly complex due to the transmission of the physical effects through the interaction of the projectile, the fluid, and the structure; as well as the abnormally excessive structural damage that results from this fluid-solid interaction (FSI).

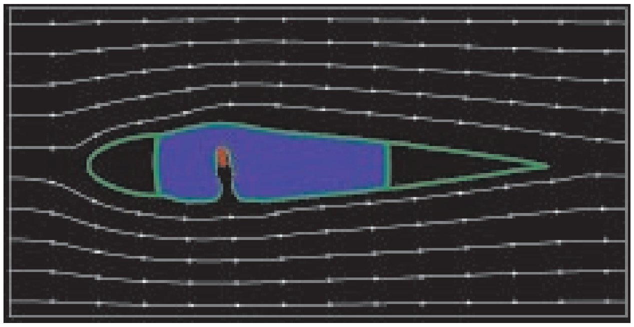

Figure 1: Two-dimensional simulation involving the impact and penetration of a 23-mm AP projectile (red) into the fuel tank of an aluminum aircraft wing (green). Note the presence of airflow (white streamlines) over the wing and the deformation of the wing structure due to the incompressibility of the water (blue).

The nonlinear coupling that develops between the fluid and solid materials dictates that a detailed mathematical description of the HR problem will be inherently complex. Effects related to the presence of airflow over the structure further complicate this description. Additional complexities arise when consideration is given to the solid-material behavior associated with the high degrees of deformation induced in the thin shells and composite materials used in aircraft structural component fabrication. A successful modeling effort must include the computational capability for treating not only the multiple fields and material phases that are present in these problems, but the complex interaction between these fields and phases as well. In addition, the solid-material behavior, the accumulation of material damage, and the various modes of structural failure—characteristic of large strain and high strain-rate structural response—must be modeled properly.

Computational Technique: A Unique Approach to FSI Modeling

At Los Alamos National Laboratory (LANL), a unique, physics-based approach to modeling the phenomena associated with HR has been developed. This new approach involves the use of a library of continuum mechanics codes known collectively as CFDLIB. Originally, the codes were intended for use in solving computational fluid dynamics (CFD) problems. The library has subsequently been modified, however, to provide solid-modeling capabilities as well. To solve the governing equations of motion for a given problem, a finite volume formulation has been combined with an arbitrary Lagrangian-Eulerian (ALE) split computational cycle. The library provides both two- and three-dimensional solutions to multifield/phase problems involving arbitrary numbers of material classes and arbitrary flow-speed regimes.

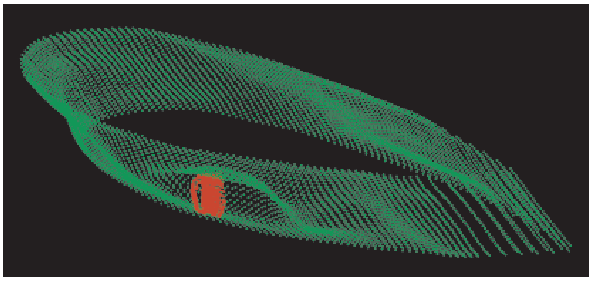

Figure 2: Three-dimensional simulation involving the impact and penetration of a 23-mm AP projectile (red) into the middle section of an aluminum aircraft wing (green) containing water (not shown). Here the ends of the wing section have been removed for clarity. Note the HR-induced deformation away from the impact zone.

To allow for solid-material modeling, the original ALE technique has been modified to include a particle-in-cell (PIC) methodology for the purposes of characterizing the material strengths and evolving the stress state in these materials through the use of appropriate constitutive models. The PIC technique is particularly suited to applications involving FSI, since the method provides a Lagrangian description of the material behavior. Furthermore, the technique provides solutions for high degrees of deformation in these materials, follows deformation through initial material failure, and models problems involving penetration without the usual numerical complexities associated with classical Lagrangian solutions. This technique, therefore, provides fully coupled solutions to problems involving multiple fields of interpenetrating continua and offers scientists at LANL a useful research tool for exploring highly specialized problems in continuum mechanics.

Constitutive Modeling: Describing the Behavior of Solid Materials

The computational technique previously described requires suitable constitutive descriptions for the solid materials involved in a given problem. Modeling the dynamic response of solids to the large strain and high strain-rate loadings characteristic of HR events requires a detailed mathematical description for the material behavior. Consequently, nonlinear, inelastic, anisotropic material response—including effects due to work hardening, thermal softening, strain-rate dependence, and material failure—must be considered and modeled correctly. Materials research is currently being conducted at LANL for the purposes of developing accurate and computationally efficient models for both homogeneous and heterogeneous materials, with the goal of implementing these material descriptions into relevant engineering analyses.

A research program based on experimental investigation, theoretical development, and numerical simulation is being pursued. The experimental component is required to identify material properties, to quantify the material response to deformation, and to provide insight into the fundamental deformation and failure mechanisms of various solids. The theoretical component is necessary to develop the mathematical models that will ultimately describe the material behavior. Naturally, issues concerning thermodynamic consistency, numerical stability, and computational efficiency are an essential aspect of the theoretical development. Finally, computational simulations are required to demonstrate the versatility of the new models and to establish the validity of the principles used in their construction.

In an effort to develop material models that are valid outside the range of direct experimental verification, physically based models (as opposed to empirically based or *ad hoc* models) are of interest. Plasticity models, which accurately account for the hardening phenomena due to strain and strain-rate effects, have been developed for describing the elasto-plastic behavior of metals. Constitutive models have also been constructed for characterizing the rate-dependent, visco-plastic deformation of polymers. Models for various modes of structural and material failure have been incorporated into the constitutive models. And finally, efforts are being made to mitigate the usual numerical complexities that develop with the incorporation of failure phenomena into continuum analyses. The ultimate goal is to provide a predictive capability for analyzing the effects of HR on engineering structures manufactured with a variety of materials—from homogeneous solids to advanced structural composites.

Composite Material Modeling

Composites represent an important class of materials that combine the advantageous mechanical and physical properties of two or more constituents in a manner that permits easy manipulation of the underlying microstructures during the manufacturing process. These materials, therefore, can be designed at the microstructural level for specific engineering purposes. The advantages associated with the use of composite materials, however, are often diminished by the complex nature of analyzing their behavior. In general, obtaining a fully resolved description of the micromechanical behavior of composite structures is not possible. Some information concerning the response of these structures at the micromechanical level, however, may be critical for certain engineering analyses. Descriptions of the macromechanical behavior and the corresponding HR-induced damage (e.g., debonding and delamination) in composite materials are obtained by employing a micromechanically based homogenization technique known as the Method of Cells. In this technique, details concerning the micromechanical behavior of the individual constituents and their interfaces are used to develop constitutive models for the composite materials under investigation.

Higher-Order Plate/Shell Theory

Thin, laminated, composite structures have many potential engineering applications—including use as aircraft wing and fuselage skins. Laminated structures, however, are susceptible to failure by delamination between layers, due to the low transverse strength at the interlaminar interfaces. Delamination results in significant degradation of the mechanical response characteristics of these structural components. Therefore, before all of the potential applications of laminated composites can be realized, analytical tools that can accurately predict the behavior of delaminated structures must be developed. A generalized, higher-order theory for modeling the delamination behavior of thin composite plates and shells has been developed at LANL. A higher-order theory is necessary for efficient modeling of HR phenomena, since these problems typically require the simulation of geometries that are large relative to the thickness of the aircraft

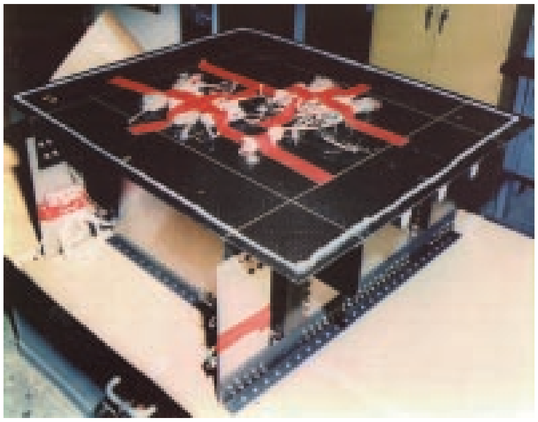

Figure 3: Air Force composite test specimen representing the lower half of an aircraft wing (upside down). With the tank full of water, the projectile impacts the geometric center of the specimen.

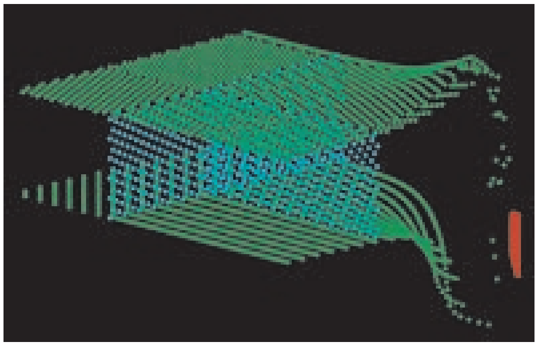

Figure 4: Simulation of the Air Force composite test specimen impact experiment (one-quarter symmetric model). The top plate (green) is a composite laminate, the bottom plate (green) and two vertical walls (cyan) are aluminum, and the projectile (red) is a 23-mm AP round.

wing skin. The theory is also required for accurately modeling the stress distributions through the thickness of the thin plates and shells—information that is ultimately required for accurate delamination prediction.

Fluids and High Explosives

Finally, a successful modeling effort must include constitutive descriptions for the pressure- and temperature-dependent dynamic behavior of the liquids and gases present in HR problems. Furthermore, the potential use of HE dictates that the complex behavior of this material must be considered as well. The computational technique previously described provides a number of equations of state (EOS) for describing the dynamic behavior of liquids and gases. In addition, turbulent fluid behavior can be modeled using a multifluid K-ε model. Lastly, a JWL EOS is currently being incorporated into the continuum mechanics codes for describing the solid-to-gas transition of HE material.

Collaborations

At LANL, scientists from the Theoretical Division's Fluid Dynamics Group (T-3) have collaborated with individuals from the Materials Science and Technology (MST) and Engineering Sciences and Applications (ESA) Divisions to interpret experimental data and to implement material models into engineering analyses. Currently, scientists from T-3 are working with experimentalists from MST to investigate the fracture properties of composite materials and to validate the corresponding material models that have been developed for use in the HR analyses. Investigations relevant to the design of weapons systems have been pursued with other Department of Energy laboratories and with branches of the Department of Defense. In particular, collaborations with the Air Force on composite-plate-impact problems and on problems related to HR have resulted in further validation of the computational techniques previously described. Industrial collaborations with General Electric have culminated in the development of mathematical models for composite materials. And finally, collaborations with researchers in academia have been productive in addressing fundamental material modeling issues. These collaborations allow scientists at LANL to benefit from the experience and expertise of researchers from a variety of organizations.

Applications

By combining a unique computational approach with accurate and efficient material models, scientists at LANL are developing new modeling techniques, which are suitable for application in a wide variety of technical fields. These techniques can be used to model the phenomena associated with HR, and will ultimately provide useful predictive tools for designing improved aircraft structural components. The new modeling capabilities offered by these techniques will assist aircraft design engineers in reducing uncertainties in aircraft tests and evaluations. As a result, costly modifications late in design programs will be avoided, and eventually, the survivability and safety of both military and commercial aircraft will be enhanced.

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