## 1 Introduction and Motivation

**Intro to hypervelocity**

Recent developments in hypersonic capabilities by the United States’ foreign adversaries [1], along with the increasing amount of micro-meteoroid/orbital debris (MMOD) [2], are creating a demand in the scientific community for hypervelocity impact (HVI) investigations. Hypervelocity impact occurs when a projectile with a relative velocity greatly exceeding the standard temperature and pressure speed of sound (commonly defined as greater than Mach 5 or 2000 m/s) [3, 11], impacts a material or structure. Defending against these HVIs is crucial as even microscopic projectiles traveling at hypervelocity pose a serious threat [4, 5, 6, 2]. Due to these threats, developing structural materials to protect against HVIs is vital to the future of space travel.

**Intro to HVI Lab**

The Hypervelocity Impact Laboratory (HVIL) at Texas A&M University conducts research to enable unique high strain-rate materials characterization along with multiscale numerical model development and implementation. The HVIL features a robust testbed for the development and testing of materials to mitigate HVIs. Experiments are conducted using a state-of-the-art two-stage light gas gun (2SLGG) capable of launching 2-10 mm diameter projectiles at velocities in the range of 2-8 km/s. The laboratory is equipped with a high-speed camera capable of filming up to 10 million frames per second, as well as other diagnostic equipment such as a flash x-Ray system. This highly capable in-situ diagnostic setup allows for the comprehensive study of hypervelocity impact phenomena.

**Intro to 2SLGG**

Achieving hypervelocity with an increasing projectile mass is a considerable feat. The 2SLGG, shown in Figure 1, accelerates projectiles in two stages: first, a firing system ignites a primary charge in the firing breech, located at the most uprange point. This charge in turn lights the secondary charge, whose mass serves as the 2SLGG’s primary performance variable. The resulting expanding gas forces a polymer piston downrange through the pump tube. This piston compresses a light gas, typically hydrogen. The gas is compressed into the central breech, which hydraulically separates the high-pressure pump tube (first stage) from the evacuated launch tube, blast tank, and target tank (second stage) via a petal valve (*i.e.*, pressure disk). Upon reaching a critical pressure, the petal valve ruptures, freeing the high-pressure working gas into the launch tube and thus rapidly accelerating the projectile package, comprised of a projectile and a sabot, downrange towards the blast tank (Figure 1). Before each hypervelocity test, the blast tank is vacated of air with a vacuum pump. Then, 0.1–0.35 atm of nitrogen is introduced to form a low-density atmosphere for the projectile package to travel through. This introduced pressure via nitrogen gas is referred to as the backfill pressure. The 2SLGG features a smooth-bore launch tube that allows multiple size projectiles to be launched using a sabot.

**Intro to Sabot**

Sabots are fabricated devices that carry the projectile during launch and fit flush inside the launch tube. In addition to being used in 2SLGG’s, sabots are utilized in many ordnance and ballistics applications; they enable the launching of most regular and irregular subcaliber projectile geometries [12]. During launch, a sabot provides stability to the projectile as the projectile package undergoes extreme acceleration. A sabot with the equivalent caliber as the flight tube is crucial to achieving the desired hypervelocity by ensuring a tight seal between the inside of the bore and the package, which guarantees efficient transfer of energy from the expanding gas to the projectile package [7]. A tight seal also prevents assymmetric loading on the projectile package during launch, which can alter the projectile’s flight path once in free flight [12].

After the projectile package exits the muzzle, the sabot serves little purpose and must be discarded without disturbing the projectile’s flight [12]. Projectiles travelling at hypervelocity in atmosphere require a low-drag condition to preserve kinetic energy [8]. In experimentation, projectile mass is measured to understand the energy transfer to the target on impact [9]. For these reasons, the sabot must be discarded before the projectile impacts any target. Various methods are used in both hypervelocity testing and ballistics applications to achieve this sabot separation [8]. Spin separating sabots use angular velocities induced by a rifled bore to separate the sabot petals while allowing the projectile payload to continue traveling on its nominal launch trajectory. This method has limitations, as the bore of the launch tube must be manufactured with a low-pitch rifling to both rotate the projectile package and protect against stripping of the rifling from repeated firing [8].

**Sabot separation techniques**

A more common sabot separation configuration in hypervelocity testing is aerodynamic-induced separation [7, 8, 12]. The HVIL’s 2SLGG uses aerodynamic separation for hypervelocity testing. Aerodynamically separating sabots vary in shape and size based on the experimental or ballistic requirements imposed on them [12]. Sabots used to launch long-rod penetratorsIn hypervelocity testing utilizing spherical projectiles, a typical aerodynamically separating sabot is a nylon right circular cylinder separated into three or four azimuthal sections, or petals, that enclose the projectile at the downrange edge. For spherical shapes, the projectile fits in a machined spherical cup that is formed when the four sabot petals are assembled. On the inside surface of each petal, serrated edges fit together to enhance even force distribution through all four petals. The outer diameter of the sabot package is machined to sit flush inside the bore of the launch tube. Sabot packages are designed with a cup-like indention on the forward-facing edge to encourage aerodynamic separation. When the package exits the launch tube after accelerating, ram pressure from the sabot travelling through atmosphere produces a resultant aerodynamic force and moment on the sabot petals causing them to separate radially outward from the axis of penetration (Figure 2d-e), which is defined by the trajectory of the projectile. The amount of atmosphere that the sabot encounters, the mass/shape of the sabot, and the muzzle velocity determine the degree of separation [10, 12]. In the HVIL, the sabot package is separated by the nitrogen gas (N) due to its inert properties, low-cost, and availability. The nitrogen gas is introduced through the target tank, bringing the target tank, blast tank, and flight tube to the same backfill pressure. Figure 2a-c shows an a typical sabot design for a spherical projectile. The cavity and longitudinal dimensions change depending on the projectile shape and size. For more complicated materials and geometries, even more sabot modifications may be necessary. All the experiments considered in this work were conducted using either a 4 mm or 10 mm spherical projectile and its respective sabot.

**Sabot separation characterization**

Historically, sabot separation characterization has been conducted through trial-and-error processes for individual 2SLGGs and typically varies from facility to facility [10, 12]. Unique launching requirements and the nature of extreme launching performance prompt specialized, diagnostic, iterative design for each hypervelocity testing configuration. Attempts have been made to empirically model sabot flight and impact properties. Grosch et al. (1993) have observed an experimental relationship between sabot separation and flight chamber pressure ( Torr) for a constant velocity. These tests were conducted using two-piece 1.78 mm diameter nylon lexan sabots.

Swift et al. introduced a straightforward, analytical method to approximate sabot separation utilizing the sabot petal’s geometry and density, as well as properties of the atmospheric medium that induces separation [8]. This analysis produced a second order differential equation describing the angular acceleration of the sabot petals as a result of the aerodynamic moment. Integrating this equation yields the angle of rotation between the sabot petal and the nominal projectile flight path as the sabot petal pivots about its uprange corner. The angle of rotation is expressed as a function of the distance the package has travelled through atmosphere. Implementing this model gives a relatively effortless estimate of the angle of the sabot at a fixed distance in its flight trajectory (*i.e.* traveling through the blast tank and impacting the sabot stopping plate). This model, however, is not completely accurate in describing sabot separation phenomena in the HVIL’s 2SLGG. Experimental results show that as the sabot rotates about its uprange corner, it also experiences translational motion radially outward, resulting in the degree of separation [13-15]. The angular acceleration equation neglects the radially outward aerodynamic forces that cause translational movement of the sabot radially away from the nominal projectile flight path. Guillot et al. solved this problem through the development of the AVCO and modified AVCO sabot separation codes [13-15]. They validated their codes by testing long-rod penetrators with fin-stabilized sabots in the low hypervelocity regime. Schmidt (1979) also developed simple empirical models using similar sabot configurations in the ballistic regime. However, these models are typically limited to velocities of less than 3 km/s.

During the initial testing and calibration of the HVIL’s 2SLGG, sufficient sabot separation was achieved through an iterative trial-and-error process of tuning launch parameters (*e.g.* backfill pressure, muzzle velocity, *etc.*). The HVIL team formulated an elementary model to predict sabot separation given these parameters; however, inherent value exists in developing an empirical model to accurately predict sabot separation that encompases the majority of the hypervelocity testing regime. Efficient sabot separation reduces both testing turnaround time and consumable testing resource expenditure. In the development of new hypervelocity testing facilities, preexisting methods and models are invaluable in the preliminary optimization of any 2SLGG performance, despite the likelihood of varying launch requirements with facility. The present study develops a rigorous empirical model to investigate the effects of launch parameters on the degree of aerodynamic sabot separation for the Texas A&M University Hypervelocity Impact Laboratory’s two-stage light gas gun, with the goal of validating future analytical models utilizing aerodynamic laws, such as computational fluid dynamics (CFD) codes.

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