International Journal of Impact Engineering 62 (2013) 13–26

Contents lists available at SciVerse ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

In situ diagnostics for a small-bore hypervelocity impact facility

J.M. Mihaly*, J.D. Tandy, M.A. Adams, A.J. Rosakis

California Institute of Technology, MC 205-45, 1200 E. California Blvd, MC 105-50, Pasadena, CA 91101, United States

A R T I C L E I N F O

Article history:
Received 30 January 2013
Received in revised form
23 April 2013
Accepted 21 May 2013
Available online 31 May 2013

Keywords:
Hypervelocity impact
High-speed imaging
Debris capture
IR emission
Spectroscopy

A B S T R A C T

New *in situ* diagnostic capabilities and improvements made to the previously reported 1.8 mm bore, two-stage light-gas gun facility located at the California Institute of Technology are described. The Small Particle Hypervelocity Impact Range (SPHIR) facility is capable of routinely producing launch speeds of 5–7 km/s for launch package masses < 6 mg, with maximum speeds exceeding 10 km/s. The facility features a comprehensive ensemble of *in situ* diagnostics that are available for simultaneous implementation in every impact experiment. A fast (150,000 fps) camera is used routinely to provide impactor velocimetry. A gated, intensified ultra-high-speed camera is used in conjunction with an optical technique to create shadowgraph images of hypervelocity impact phenomena with very short exposure times (25 ns) and inter-frame times (<1 μs). This technique uses a constant 532 nm wavelength laser to deliver a collimated, coherent illumination beam orthogonal to the projectile flight direction that provides a 100 mm diameter maximum field of view. The ultra-high-speed camera produces 8 images with exposure and inter-frame times sufficiently short to enable sharp visualization of impact features with little motion blur at the test speeds of 5–7 km/s. Additionally, a debris capture system is located behind the target configuration during every experiment. This system is composed of layers of closed-cell foam and plastic film and provides depth of penetration and trajectory measurement for debris particles thrown behind the target. Lastly, the SPHIR facility utilizes two additional high-speed cameras coupled with two spectrographs to characterize the light emitted by the impact event. One spectrograph and its high-speed camera records UV–visible emission spectra in the wavelength range between 300 nm and 850 nm. The other spectrograph uses a high-speed, infrared camera to capture a single full-field image of the near-IR emission in the wavelength range of 0.9 μm–1.7 μm. These two spectrograph camera systems provide both visual and spectral data of the hypervelocity impact emission; yielding information regarding the molecular composition of both the impact ejecta and debris. The extensive diagnostic capabilities and techniques described can be used with a wide variety of impactors, target materials and target configurations to address a wide variety of engineering and scientific problems.

1. Introduction

Hypervelocity impact of meteoroids and orbital debris (MOD) on spacecraft poses a serious threat to spacecraft survival. Any spacecraft, particularly those intended for long duration spaceflight or entry, descent, and landing (EDL) must be designed with the capability to withstand extended exposure to the MOD environment. The Columbia accident serves as a tragic reminder of the critical nature of an entry vehicle's heat shield health and the potentially catastrophic consequences [1] of significant impact damage. Furthermore, the severity of the orbital debris environment continues to grow at an increasing rate as international involvement in space increases. Therefore, the importance of MOD shielding on spacecraft, and the continued improvement of shielding systems, is of paramount importance as the aerospace industry develops its next generation of space exploration vehicles.

Hypervelocity impacts induce a complex dynamic material response, which includes numerous interacting phenomena such as mixed phase flow, fragmentation, spallation, melting, vaporization, and ionization [2]. Due to such complexity, modeling success has been limited and remains inadequate. The current understanding of hypervelocity impact damage is obtained largely through experimental evaluation [3,4] of MOD shielding systems. The empirical models used to describe this data are specific to the materials/component configurations used in the tests and the test conditions. Such models cannot be safely extrapolated to other materials or conditions. Furthermore, given the high operating cost

* Corresponding author. Tel.: +1 6263954514.
E-mail address: jmmihaly@caltech.edu (J.M. Mihaly).

0734-743X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2013.05.004

Abbreviations

AGS	Average Grayscale
LSL	Laser Side-Lighting
MOD	meteoroids and orbital debris
SPHIR	Small Particle Hypervelocity Impact Range

of many impact facilities, the extensive shield testing required to adequately characterize the variability and hence, the uncertainty in shield performance can be prohibitively expensive. Often inadequate data exists to describe the stochastic damage mechanics that govern shield system performance. Therefore, the aerospace industry would greatly benefit from the development and implementation of low-cost methods to help characterize hypervelocity impact phenomena.

2. Facility overview

The Graduate Aeronautical Laboratories at the California Institute of Technology (GALCIT) has established the Small Particle Hypervelocity Impact Range (SPHIR), shown in Fig. 1, an experimental facility designed to study MOD impacts [5]. The facility's two-stage light-gas gun [6] uses compressed hydrogen or helium gas to launch small particles with diameters of 1.8 mm, to velocities up to 10 km/s. These launch packages are accelerated downrange into a large (1 m × 1 m × 2 m) target chamber with atmospheric levels maintained at pressures ranging between 1 and 50 mmHg (0.13–6.67 kPa). Launch packages are accelerated in a disposable, smooth bore (non-rifled) launch tube, which helps reduce the operational cost of the facility but makes the use of sabots more difficult.

The masses launched and the velocities attained in this facility are a good analog for MOD studies, but are not particularly unique. However, the SPHIR facility is unique given the array of simultaneous high-speed optical diagnostics operating routinely on each experiment. The facility therefore combines a low-cost of operation with high-volume of data output from each experiment. The large target chamber features multiple view-ports enabling the simultaneous observation of the experiment with a suite of high-speed diagnostics (described herein). The target chamber is shown in Fig. 2.

2.1. Impactor velocimetry

A common method to measure the impactor speed in light-gas gun experiments is to use a series of laser barriers which are interrupted by the impactor during its flight to the target. However, several factors complicate the application of such a method in the SPHIR facility. First, a luminous cloud of high temperature hydrogen gas precedes the exit of the impactor from the launch tube and follows the impactor in its flight to the target. Additionally, the small bore (1.8 mm) of the SPHIR facility requires the use of impactors that are smaller than those utilized in many other light-gas gun facilities. As a consequence, the detector signal interruption produced by the passing of such a small impactor at hypervelocities is brief and obscured by a low signal-to-noise ratio. These factors would therefore require the implementation of a specialized optical system [7] to utilize the laser barrier technique.

A simpler, less complex, solution is to use the Photron SA1 Fastcam to measure the impactor speed. When the impactor is traveling at greater than 4 km/s, the low-pressure atmosphere (0.13–6.67 kPa) in the evacuated target chamber is ionized directly in front of the impactor and forms a luminescent sheath surrounding and trailing the location of the impactor. This hot plasma sheath radiates sufficient light to enable high-speed imaging by self-illumination.

As shown in Fig. 1, the Photron camera is mounted above the target chamber looking down upon the flight path of the impactor. The distance from the camera to the impactor velocity vector is approximately fixed at 1.2 m with respect to the camera. A 25 mm, f/0.95 lens is configured with the Photron camera and provides a field of view of approximately 160 mm × 94 mm. The lowest available relative aperture is used to collect the maximum amount of light radiated by the impactor. At the nominal operating framing rate of 150,000 fps, this field of view is observed with 192 × 112 pixel resolution. A mirror, angled toward the target, is also located at the bottom of the target tank within the Photron camera's field of view. An illustration of this setup is provided by Fig. 3. This configuration allows visualization of both the impactor in flight to the target and the subsequent target impact flash. An

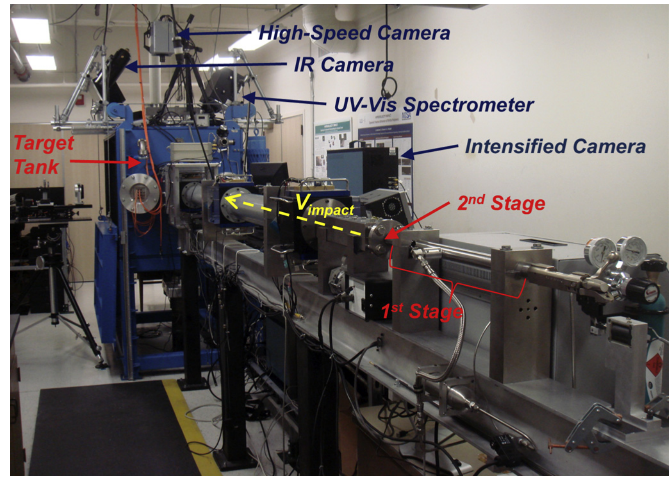

Fig. 1. The Small Particle Hypervelocity Impact Range (SPHIR) facility at Caltech. Diagnostics have been developed and implemented to complement this two-stage light-gas gun facility.

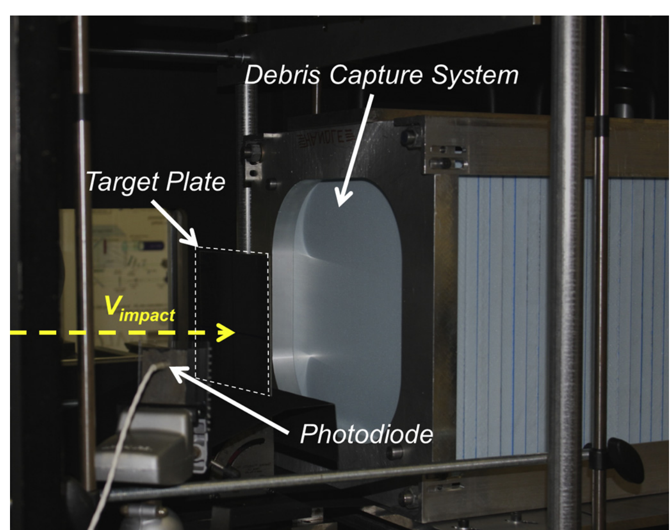

Fig. 2. Target chamber of the SPHIR facility, with target plate and nominal impactor velocity vector identified. The photodiode used to trigger diagnostics and the debris capture system is also shown.