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Debris area distribution of spacecraft under hypervelocity impact ☆

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ABSTRACT

Cross-sectional area is an important parameter for spacecraft breakup debris as it is the directly measured data in space observation. It is significant for observing and analysing the spacecraft breakup event to accurately modelling the area distribution of the breakup debris. In this paper, experimental study has been performed on debris area distribution characteristics of spacecraft under hypervelocity impact. The tests are carried out at the ballistic ranges of CARDC. Aluminium projectiles are launched to normally impact the simulated spacecrafts at about 3.0 km/s. The simulated spacecrafts are made up of aluminium plates, filled with some simulated electronics boxes, each of which was installed with a circuit board. "Soft-catch" devices are used to recover the breakup fragments. The test results show that: 1) the relationship between the cross-sectional area and the characteristic length of debris, which can be obtained in the logarithmic coordinates by linear fitting, represents the debris shape characteristic in a certain extent; 2) the area-to-mass ratios of fragments show normal distributions in the logarithmic coordinates; 3) debris made of different materials can be distinguished by different peaks on the distribution curves; 4) the area-to-mass ratio distributions can be expressed by a linear superimposition of several normal functions which represent the main materials of the spacecraft.

1. Introduction

Spacecraft fragmentation due to collision or explosion is one of the main sources of space debris [1]. Breakup model that is used to describe the population of breakup debris is important for orbital debris environment evolution, impact risk assessment and debris mitigation. There are two main approaches to model the breakup debris. One is a theoretical method, such as suggested by Smirnov et al. [2,3], a continuum model for breakups of thin-walled containments was derived from fracture mechanics. They obtained a Weilbull distribution for debris mass and an equal radial velocity values for all the fragments. However, for a spacecraft of complicated structure and variety of materials, the responses under hypervelocity impact conditions are very complex. It is difficult to derive a physics-based model to describe the responses and consequent breakups. Therefore, most of the breakup models, such as FAST [4], IMPACT [5], EVOLVE [6], are empirical models based on breakup data obtained through laboratory impact tests and space observation.

Cross-sectional area and area-to-mass ratio are important parameters for spacecraft breakup debris as they are directly related to the space observation data. Thus debris area distribution is a main composition of the breakup model. Presently, a systematic description for area and area-to-mass characteristics of spacecraft breakup debris

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Nomenclature

x, y, z	three dimensions of fragment (m)
A_x	debris average cross-sectional area (m^2)
A_{x-y}	projected area in the x–y plane (m^2)
A_{y-z}	projected area in the y–z plane (m^2)
A_{z-x}	projected area in the z–x plane (m^2)
A/M	debris area-to-mass ratio (m^2/kg)
$D_{A/M}$	area-to-mass ratio distribution function
L_c	debris characteristic length (m)
N	normal distribution function
P	A/M probability density distribution
λ	logarithm value of characteristic length
χ	logarithm value of area-to-mass ratio
μ	mean value of normal function
σ	standard deviation of normal function

is from the NASA Standard Breakup Model [6]. The main data used in the development of above model is the SOCIT4 satellite impact test conducted by NASA in 1990s [7]. In this model, the average cross-sectional area A_x is modelled as having a one-to-one correspondence with debris characteristic length L_c as follows:

$$A_x = \begin{cases} 0.540424{L_c}^2, & L_c < 0.00167 \text{ m} \\ 0.556945L_c^{2.0047077}, & L_c \geq 0.00167 \text{ m} \end{cases} \tag{1}$$

For debris with L_c smaller than 8 cm, a single normal function is utilized to describe the area-to-mass ratio distribution:

$$D_{A/M}(\lambda, \chi) = N(\chi, \mu(\lambda), \sigma(\lambda)) \tag{2}$$

where $\lambda = \log_{10}L_c$, $\chi = \log_{10}(A/M)$, and $N(\chi, \mu, \sigma)$ is a normal distribution in χ about the mean value of

$$\mu(\lambda) = \begin{cases} -0.3 & \lambda \leq -1.75 \\ -0.3 - 1.4(\lambda + 1.75) & -1.75 \leq \lambda < -1.25 \\ -1.0 & \lambda \geq -1.25 \end{cases} \tag{3}$$

with a standard deviation of

$$\sigma(\lambda) = \begin{cases} 0.2 & \lambda \leq -3.5 \\ 0.2 + 0.1333(\lambda + 3.5) & \lambda > -3.5 \end{cases} \tag{4}$$

For debris with L_c larger than 11 cm, the area-to-mass ratio distribution is described as bi-normal function:

$$D_{A/M}(\lambda, \chi) = \alpha(\lambda)N(\chi, \mu_1(\lambda), \sigma_1(\lambda)) + (1 - \alpha(\lambda))N(\chi, \mu_2(\lambda), \sigma_2(\lambda)) \tag{5}$$

However, in recent breakup events such as Iridium 33-Cosmos 2251, the observed fragments area-to-mass ratio distribution is not agree well with the model prediction. Especially for fragments of Iridium 33, the distribution appears to be higher and more than two peaks on the distribution curve [8]. It implicates that the current model should be further refined. To better understand the physical properties of breakup fragments, Hanada et al. [9–11] have conducted a series of microsatellite impact tests in recent years. They find a difference in the area-to-mass ratio distribution between their tests and the prediction by the NASA standard breakup model. Then they suggest describing the area-to-mass ratio distribution by a bi-normal distribution, rather than by a single normal distribution as the NASA model does, to incorporate two peaks shown in their results. However, it is not enough for completely describe the cross-sectional area and A/M ratio properties of spacecraft fragments and more studies are still needed.

To get an overall knowledge of spacecraft fragmentation and its consequence, a series of simulated spacecraft impact tests have been performed at ballistic ranges of China Aerodynamics Research and Development Center (CARDC) in past 3 years [12,13]. In this paper, we present the outcome of three tests and discussed the cross-sectional area and area-to-mass distributions of the spacecraft fragments.

2. Spacecraft impact tests

2.1. Test facilities

Spacecraft impact tests are carried out at the ballistic range of CARDC. The launcher of the range is a 50 mm calibres two stage light gas gun (LGG) as shown in Fig. 1 [14]. It is driven by gunpowder. The combustion gas of the gunpowder pushes a piston to compress hydrogen gas in the first stage. Then the highly compressed hydrogen gas accelerates a projectile in the second stage right after the gas rapture a diaphragm between the stages. The projectile can be launched up to 6.5 km/s. The simulated spacecraft is suspended in the impact chamber, being surrounded by polystyrene foam plates. The density of the foam is about 0.2 g/cm^3. The thickness of single layer foam plate is about 10 cm. In front of impact surface of the spacecraft there is one layer foam plate with a hole so that the projectile can pass through. There are three layers of foam plates in the

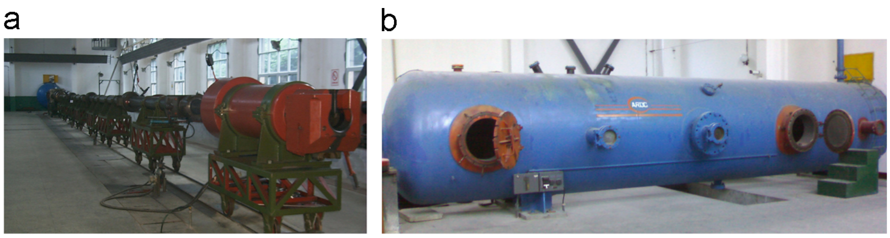

Fig. 1. Test facilities: (a) 50 mm calibres LGG, (b) Impact chamber.