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A simplified metric for formulating and assessing elastic launch dynamics

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ABSTRACT

Elastic launch devices are widely used in aviation and aerospace, whereas the accurate assessment and practical control of their dynamic performance are often complicated. We propose and validate a metric approach to simplify the launch dynamics, regardless of unstable elastic parameters and various device distributions. The nonlinear relationship between main separation parameters and elastic potential energy is derived and quantified by the defined metric, which achieves the effective assessment and control of launch process in a simple way. The metric theory is proved by the actual ground tests of a typical launch using the pre-compressed spring devices. In addition, the approach has been successfully applied to evaluate and optimize TianTuo-1 satellite launch, reflecting small errors and easy operation in practical use.

1. Introduction

Launch dynamics directly influences the launching reliability and onboard instruments of flight vehicles [1]. Elastic launch dynamics, depending on stored elastic potential energy transformed into kinetic energy, occurs in most launch processes, like satellite separation, rocket stage separation, planetary probe separation, special payload release [1–4], etc. These launches or separations represent crucial and major events that must be successfully executed to fulfill mission requirements. What one envisages in a launch is a clean separation, which means avoidance of lateral angular velocity and elimination of collision between the separating bodies. A higher angular velocity may cause tumbling and reduction in the life of a launched satellite, and how to fulfill the clean separation of small satellites is now one of the most important issues to be solved [6].

Clean separation is difficult to achieve due to tip-off rates [3,4], mainly caused by elastic parameter deviations, asymmetric device distributions, center of mass, frictions [5], etc. Strict parametric control is a regular method adopted to obtain the high reliability and accurate separation performance. However, due to diverse uncertainties of production, machining, and assembly, this method costs more and does not work well in reality, especially when the high-precision separation is required. The assessment of elastic launch dynamics has received the attention of several investigators. Jeyakumar [7] established a statistical assessment method based on the system modeling of satellite separation; and Tayefi [8] solves the issue by formulating the elastic spring launch and using a response surface method. These investigations can give a correct analysis, but need complex modeling and expensive calculation.

With the demand of fast evaluation and reliable application in engineering, elastic launch dynamics calls for a metric approach. In this paper, a metric of elastic potential

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energy is presented and employed for the quantitative characterization of launch dynamics, which makes the accurate prediction and convenient control possible. Simplified metrics have been applied in many fields like seat comfort prediction [9], thermal stress assessment [10], redundant system reliability [11], etc. The first attempt is made here to design a simplified metric for formulating and assessing different influence degrees of elastic launch devices. Based on the metric, we establish a set of assessment and control approach for elastic launch, which is demonstrated and applied in ground tests and on-orbit flight of TianTuo-1 satellite.

2. Simplified metric definition

Present studies often employ elastic parameters, like spring stiffness and stroke length [12], to formulate the launch dynamics and numerical computation to solve the equations. As these elastic parameters may change randomly during the separation and the governing equations are nonlinear, it is tough to obtain the exact effects of elastic devices. In order to constitute a simplified metric, it is a novel idea to tackle the issue by using elastic potential energy, which is a scalar depending on the deformation of elastic devices.

Specifically, the initial energy of elastic devices is assumed as E_{i0}, and the remaining is as E_{it}. When mechanical friction and air resistance are ignored, the potential energy acting on separated bodies is $E_i = E_{i0} - E_{it}$ $(i=1, 2, \ldots, n)$. The simplified metric of elastic potential energy is

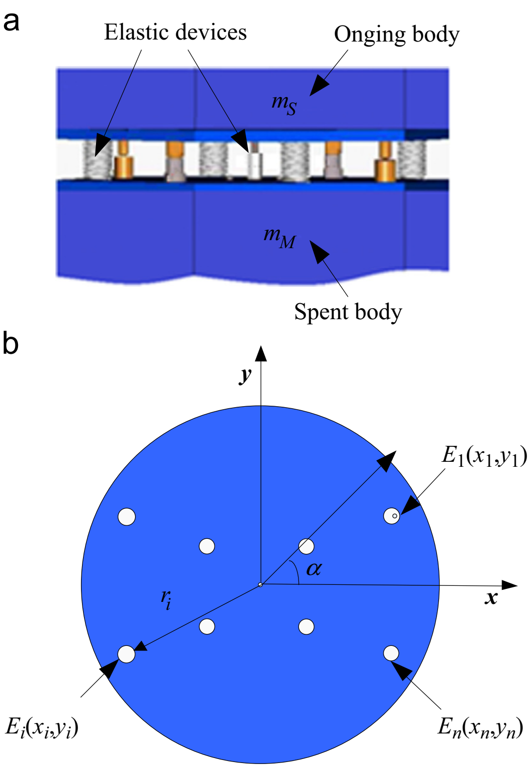

Fig. 1. (a) Schematic diagram of a typical launch using elastic devices and (b) distribution of elastic potential energies in the separation plane.

defined as

$$e_i = \sqrt{\frac{m^*}{n} E_i}, \tag{1}$$

where n is the number of elastic devices, and $m^* = m_S m_M / m_S + m_M$ is the reduced mass. m_S is the mass of the ongoing body and m_M is the mass of the spent body. Eq. (1) physically means that every simplified metric is determined by the acting energy and the reduced mass. Fig. 1 describes a typical launch system using elastic devices and a potential energy distribution in the separation plane, where $r_i = x_i \vec{i} + y_i \vec{j} + z_i \vec{k}$ is the position vector of the ith spring location. As $F_i = -k\xi_i \cos(f_s t)$ (k is the spring stiffness, f_s is the frequency, and ξ_i is the stroke length), $E_i = \frac{1}{2} k {\xi_i}^2 (1-\cos^2(f_s t))$ is obtained.

3. Launch dynamics assessment

In order to describe elastic launch dynamics by the defined metric, the equations of motion

$$\begin{cases} \frac{1}{2} m_S v^2 + \frac{1}{2} m_M V^2 = \sum_{i=1}^{n} E_i \\ m_S v = m_M V \end{cases}, \tag{2}$$

$$\begin{cases} I_x \dot{\omega}_x + (I_z - I_y)\omega_y \omega_z = M_x \\ I_y \dot{\omega}_y + (I_x - I_z)\omega_x \omega_z = M_y \\ I_z \dot{\omega}_z + (I_y - I_x)\omega_x \omega_y = M_z \end{cases}, \tag{3}$$

are introduced. Here v represents the separation speed of ongoing body, $[\omega_x, \omega_y, \omega_z]$ are the angular velocities in three directions, $[I_x, I_y, I_z]$ is the principal moment of inertia, and $[M_x, M_y, M_z]$ is the total external moment. As the ongoing body is usually symmetrical (viz., $I_x \approx I_y$) and the lateral disturbing force is extremely small, $I_x \dot{\omega}_x = M_x$ and $I_y \dot{\omega}_y = M_y$ are obtained in this case. Hence,

$$\frac{m_S v^2}{2 m_M}(m_S + m_M) = \sum_{i=1}^{n} E_i, \tag{4}$$

$$I_x \omega_x = \int_0^t M_x dt = \int_0^t \sum_{i=1}^{n} F_i y_i dt = \sum_{i=1}^{n} k\xi_i \sin(f_s t) y_i / f_s, \tag{5}$$

$$I_y \omega_y = \int_0^t M_y dt = -\int_0^t \sum_{i=1}^{n} F_i x_i dt = -\sum_{i=1}^{n} k\xi_i \sin(f_s t) x_i / f_s. \tag{6}$$

As the spring frequency is $f_s = \sqrt{nk/m^*}/2\pi$, separation speed and angular velocity are derived as

$$m_S v = \sqrt{2m^* \sum_{i=1}^{n} E_i} = \sqrt{2n \sum_{i=1}^{n} e_i^2}, \tag{7}$$

$$I_x \omega_x = \sum_{i=1}^{n} y_i \sqrt{2kE_i}/f_s = 2\sqrt{2}\pi \sum_{i=1}^{n} e_i y_i, \tag{8}$$

$$I_y \omega_y = -\sum_{i=1}^{n} x_i \sqrt{2kE_i}/f_s = -2\sqrt{2}\pi \sum_{i=1}^{n} e_i x_i. \tag{9}$$

Consequently, $v = \sqrt{2n\sum_{i=1}^{n} e_i^2}/m_S$, $\omega_x = 2\sqrt{2}\pi \sum_{i=1}^{n} e_i y_i / I_x$, and $\omega_y = -2\sqrt{2}\pi \sum_{i=1}^{n} e_i x_i / I_y$ are all derived. Main