Aerospace Science and Technology 30 (2013) 108–118

Contents lists available at SciVerse ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Research on application of single moving mass in the reentry warhead maneuver ☆

Changsheng Gao, Wuxing Jing, Pengxin Wei *

Department of Aerospace Engineering, Harbin Institute of Technology, Harbin, 150001, PR China

ARTICLE INFO

Article history:
Received 3 September 2012
Received in revised form 17 July 2013
Accepted 17 July 2013
Available online 25 July 2013

Keywords:
Single moving mass
Reentry warhead
Actuator layout
Control system design

ABSTRACT

Moving mass is one of the control actuators, whose configuration in the warhead is the basis of application in engineering for moving mass control technology. The servo forces, which drive the moving mass to move, affect the translational and rotational motion of the missile. It not only could increase the moving range of the center of system mass, but also reduce the requirement for the roll channel. Firstly, a single moving mass control mode, which consists of the rotation of rail around the longitudinal body-axis and the translation of the moving mass along the rail, is presented. Then, the 8-DOF dynamic model is established and the coupling characteristics between the attitude control and the servo-loop control are analyzed in this paper. Based on the above analysis, the attitude tracking control law is designed by using sliding mode theory. Finally, the problem about the terminal guidance of reentry vehicle is studied by numerical simulation: the state of moving mass is controlled by the servo force, and the missile attitude is controlled by adjusting the position of moving mass so that the excepted overload designed by using the proportion guidance could be tracked exactly. The simulation results verify the validity of the proposed method.

1. Introduction

Maneuver is one of the effective penetration measures for the reentry warhead. As the dynamics pressure is very high after the reentry warhead into the dense atmosphere, its maneuver could be achieved by using lift, whose control principle is adjusting the body attitude relative to the incoming flow. The aerodynamic rudder is a typical attitude control actuator, for example, the U.S. Pershing II reentry warhead is controlled by using the aerodynamic rudder. The warhead attitude could be controlled by adjusting the aerodynamic rudder deflection, which could change the control moment of the rudder surface relative to the center of mass. Moving mass is another attitude control actuator. The warhead could achieve the maneuver by moving the actuator mass in the body of warhead. Currently, the moving mass control has been researched in a voluminous literature, which mainly related to the spin satellite [7], exoatmospheric interceptors [10], submarines [3,19], and airships [2], etc.

In recent years, the research about the moving mass control applying in the field of reentry vehicle maneuvering has drawn wide attention. The characteristics of high Mach determine that such aircraft is suitable for the moving mass control technology. The moving mass could control not only the roll channel, known as Moving Mass Roll Control (MMRC), but also the pitch and yaw channel, known as Moving Mass Trim Control (MMTC). Petsopoulous et al. [12] and Thomas and Frank [18] studied the problems about the moving mass control in roll channel of the reentry warhead. Regen and Kavetsky [13] researched the problems about the moving mass control in pitch and yaw channels of the reentry warhead. Mukherjee and Balaram [11] investigated the moving mass control system in the entry descent landing phase of Mars lander. The MMRC requires the vehicle with a non-axisymmetric structure, which could provide greater lateral overload, while the structure of traditional reentry warheads is axisymmetric, so the MMTC problems of reentry warheads are more concerned.

The configuration of the moving mass in the axisymmetric reentry warheads is one of the key problems that the MMTC technology applies in the engineering. Whether the control actuator is within the warhead is the significant difference between the moving mass control and rudder control. Though the warhead could have a good aerodynamics shape by setting the actuator in the body, it makes more difficult to design the internal layout of the warhead. Taking into account the limit of the internal space and overall parameters such the mass of moving mass, it needs to be considered how many moving mass should be configured, how the moving mass rail should be placed and so on. Frost and Castello [4,5] investigated the ability of an internal rotating mass unbalance to actively control both fin- and spin-stabilized projectiles. But for a traditional STT (Skid To Turn) vehicle, the above configurations

☆ This work was supported by National Natural Science Foundation of China (NSFC) under Grant 10902026.

* Corresponding author.
E-mail address: weipengxin1988@gmail.com (P. Wei).

1270-9638/$ – see front matter
http://dx.doi.org/10.1016/j.ast.2013.07.009

could only supply one channel control ability, i.e. either longitudinal or lateral control ability. Rogers and Castello [15,16] considered a translating moving mass control mechanism applicable to both fin- and spin-stabilized configurations. But the c.m. (center of mass)'s change of the system is a circle around the body x-axis and not arbitrary, so the control authorities of above configurations are limited. Double moving mass is a commonly used configuration at the moment. The double moving mass control style could be divided into the orthogonal layout style and non-orthogonal layout style according to whether the rail rotates or not. The characteristics of orthogonal layout style are that the rail is fixed and the moving mass is moving. The expected move of the system's center of mass is achieved by controlling the position of two moving masses in two rails, which are fixed on the body orthogonally. On the contrary, the characteristics of non-orthogonal layout style are that the rail is rotary and the moving mass is fixed on the end of rail. The expected move of the system's center of mass is achieved by controlling the rotation angle of two rails around the longitudinal axis of the warhead. Taking axisymmetric reentry warhead as the research subject, a single moving mass control style is proposed in this paper. The control style combines the advantages of double orthogonal control style and non-orthogonal style, i.e., the MMTC could be achieved by the movement of the moving mass and the rotation of the rail.

By controlling the rotation angle of the rail and the position of moving mass in the rail, this single moving mass control style could not only increase the moving range of the center of system mass, but also reduce the requirement for the roll channel, combining the advantages of two double moving mass control styles.

Dynamic analysis and optimization of the overall parameters are another key problem for the MMTC technology applying in the engineering. Robinett et al. [14] studied the ability for inertial force, principal axis misalignment and other physical objects to impact the attitude of the warhead body. The analytical expressions of the required trim moment for ballistic missiles maneuvering are given in case of ignoring the dynamic characteristics of moving mass. The open literatures mainly focused on the problems about trajectory and attitude dynamics. At present, the dynamics problems of body-loop and servo-loop considering the dynamics characteristics of moving mass should be discussed further. Based on the above problems, this paper takes the single moving mass control style as the research subject, and develops the system coupling dynamics analysis. The servo force drives the moving mass to move in order to adjust the state of moving mass, but its impact on the body rotation and translation can't be ignored. Therefore it makes the dynamics analysis become more difficult for this missile.

The design of the attitude control system is a research focus of the moving mass control technology. PID control, feedback linearization, sliding mode control and other methods have been adopted. Because the servo force that drives the moving mass to move will have a greater impact on the rotation and translation of the warhead, the design of guidance and control loop considering the dynamic characteristics will be the focus of future research. This paper is aimed at three key problems of the moving mass configuration, dynamic analysis and the design of control loop. Combining with the internal relation between three key problems, the research is carried out deeply.

2. Configuration of attitude control actuator

As the attitude control actuator of the warhead, the configuration of moving mass is not only the focus of the overall design, but also affects the structure of missile dynamics modeling. The layout of equipments in the warhead and dynamic model of the warhead will have big differences if the configuration of moving

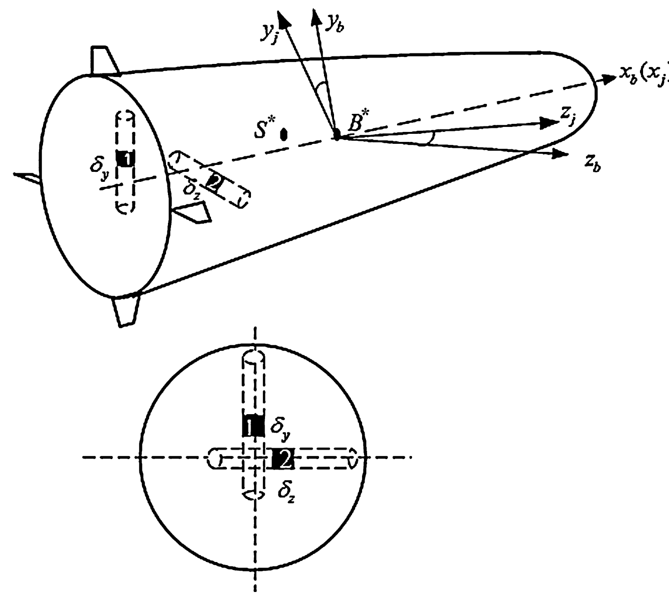

Fig. 1. Diagram of orthogonal layout style with double moving mass.

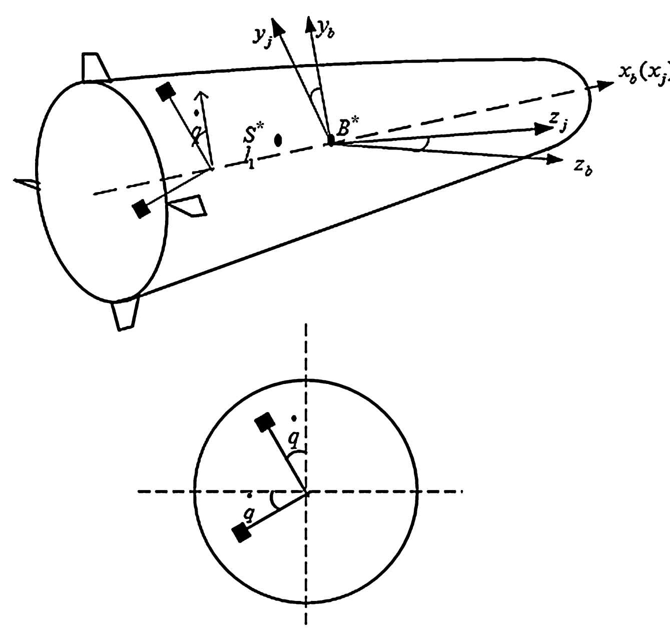

Fig. 2. Diagram of non-orthogonal layout style with double moving mass.

mass is different. For the axisymmetric and non-spinning reentry warhead, in order to track the command overload of the pitch and yaw channel, double moving mass control style was adopted usually. According to whether the rail rotates or not, the double moving mass control style could be divided into the orthogonal layout style and non-orthogonal layout style.

The characteristics of orthogonal layout style, which is shown in Fig. 1, are that the rail is fixed and the moving mass is moving. Two rails are orthogonal to each other and parallel to two axes of the body coordinate system. By controlling the state of moving mass in the rail, the attitude tracking control of pitch and yaw channel could be achieved exactly.

The characteristics of non-orthogonal layout style are that the rail is rotary and the moving mass is fixed on the end of rail, as shown in Fig. 2. The attitude control of the warhead is achieved by controlling the rotation angle of two rails around the longitudinal axis of the warhead.