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Review

A survey on moving mass control technology

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ABSTRACT

Moving mass control is a control mechanism dedicated to regulating attitude of airborne vehicles by using motion of internal moving masses. This paper surveys the contemporary progress and problems of moving mass control technology in various capacities including spacecraft, spinning projectiles, underwater vehicles, unmanned aerial vehicles, and re-entry vehicles, special attention is paid to the moving mass configurations and its corresponding layout design methods. In addition, technological difficulties and developmental perspectives in dynamic analysis and attitude control problems of the underlying subject are also analyzed, and suggestions for future augmentation are proposed in the named field.

1. Introduction

Conventional attitude control problems of airborne vehicles can be categorized into three schemes, according to their respective actuators: aerodynamic control surface, jet thrust control, and moving mass control (i.e., MMC). More specifically, the first two schemes are commonly employed in airplanes, reentry vehicles, satellites, and underwater vehicles [1–6]. However, they both suffer inevitable physical limitations in specific situations, as is well known. For instance, performance of the control surfaces is closely related to aerial flow, as established in fluid dynamics, and the ablation resistance of rudders of hypersonic aircrafts is caused by hypersonic flow interaction, which could potentially damage rudder surfaces and even block steering gears [7]. Moreover, control efficiency of aerodynamic rudders decreases rapidly with increasing altitude [8], the same conclusion can be applied to underwater vehicles at a low speed since rudder joints are susceptible to corrosion. In addition, though jet thrust control is considered to be more efficient, it pales in comparison in term of payload-carrying capability due to the necessity of bringing sufficient fuels, and the jet flow disturbance caused by the thrust might be cubersome for attitude control system [9]. Compared with conventional aerodynamic control surfaces and jet thrust control, MMC, on the other hand, indulges attitude maneuver by regulating the internal moving masses. Therefore, advantage of using MMC technique over conventional actuators are twofold: I) The moving masses are contained entirely within thus produce no plumes; II) MMC takes full advantage of aerodynamic forces, thus saving energy and maximizing the payload-carrying ability.

This paper attempts to provide an overview of contemporary advances on MMC technology, including its applications in diverse fields and their respective outcomes. Detailed discussions of existing results are given in Sections 2–8, and Section 9 outlines the remaining challenges in the underlying field, conclusions are drawn in Section 10.

2. MMC in spacecraft

2.1. Attitude stabilization

As we know, spacecraft suffers from different kinds of torque disturbance, which greatly decreases the accuracy of attitude stabilization. MMC can counteract these disturbance torques to maintain stabilization by momentum exchange with internal moving masses. Therefore, researchers design different moving mass configurations to deal with different problems of attitude stabilization.

Childs [10] designed a moving mass control system to stabilize space stations. As shown in Fig. 1, a single moving mass is placed on the out of the spacecraft, which be served as a balance device to damp attitude oscillation and counteract torque disturbance. Compared with other control actuators (jet thruster or control moment gyroscope), this control mode has three desirable attributes: 1) light weight a total launch weight of 500 lb only need a control mass of 11 slugs, 2) simple structure the control logic is extremely simple and only angular velocity be measured, 3) power consumption, the moving mass control system requires a quite low level of power consumption.

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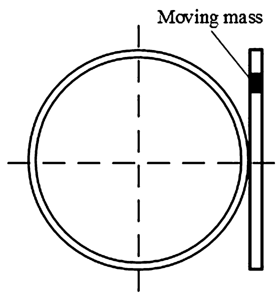


Fig. 1. Artificial space station and stabilizer configuration [10].

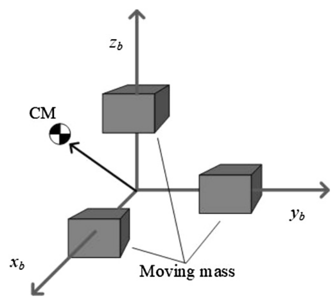


Fig. 2. CubeSat three-axis simulator [11].

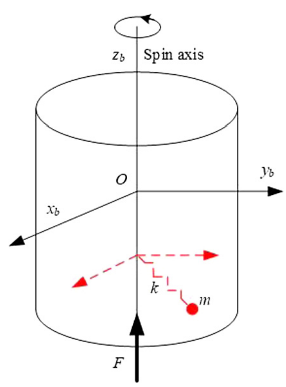


Fig. 3. Model configuration and mass properties [14].

Generally speaking, the gravitational disturbance torque for a spacecraft could be reduced by minimizing the distance between mass center and rotating center of spacecraft. To overcome the disturbance, control moment gyroscopes and reaction wheels are used for attitude control. However, these actuators are not realistic for small-size satellite due to their large volume and weight. Thus, Pellegrini and coworkers [11] presented an automatic satellite balancing system with three moving masses, as shown in Fig. 2. Three balancing masses were put along the three orthogonal directions of the body coordinate system. This balance system not only simplifies the satellite internal structure but also implement easily for small-size satellite.

Lorell and Lange [12] studied the feasibility of applying MMC to spinning satellites. For the spinning satellite, it was rather hard to achieve long-term pointing precision of the spin axis, because its attitude control systems were unable to counteract the effects of sensor-vehicle misalignments, the motion of the principle axes of inertia, and body-fixed disturbing torques. Therefore, they designed an automatic mass-trim system, which consists of two pairs of movable trim masses, to provide control torques thus eliminate errors resulting from these sources.

Janssens et al. [13,14] proposed a spring-mass system to avoid the phenomenon of nutation which often occurs in the spinning of upper stage with solid rocket engine. As shown in Fig. 3, the proposed system can remove the nutation angle in spinning motion as an absorber. Then, he studied the performance of this damping system for different types of satellites (prolate and oblate). For oblate satellites, this system would fail when axial thrust force reaches a certain value. For prolate ones, this system could keep the self-spinning motion stable under any amount of axial thrust force.

White and Robinett [15] studied deconing of spinning spacecraft as well. He designed two kinds of dual-mass controllers, as shown in Fig. 4. The first configuration has two masses which move axially but were displaced radially from the center. The second one has two axially displaced masses which operated along orthogonal radial axes. Dynamics modeling and analysis illustrated that although a single mass deconing system was capable in the axial mass case, the adoption of two-mass systems would give the spacecraft more capability in automatically balance-keeping. The orthogonal configuration could keep stable with third-order servo model, which could take both position and velocity as feedback information. However, the axial configuration could only adopt the second-order servo model for controller design, which only takes position as feedback information.

2.2. Attitude control

The uncontrolled rolling motion with large angular velocity could appear in the docking and reentry process of manned spacecraft and this phenomenon is extremely dangerous for astronauts. To deal with the problem, Edwards and Kaplan [16] studied uncontrolled tumbling of spacecrafts, and let the mass move parallel to the spinning axis, which changed the tumbling into a simple spin about the maximum inertia axis. Simulation results shows that, for a large scale space station, a moving mass with a mass ratio of 0.01 could finish the detumbling task in 2 hours.

El-Gohary [17–19] studied moving mass attitude control for three-axis stabilized satellites. He designed an active stabilizing system using three moving masses (see Fig. 5a), each of which moved parallel to one of the three principal axes of inertia. The proposed configuration guaranteed the asymptotic stability of the programmed motion, which was proved by Lyapunov method. El-Gohary and Hussein [20] also designed a stabilizer system that employs movable point masses within three circular channels in planes determined by three principal axes, as shown in Fig. 5. The

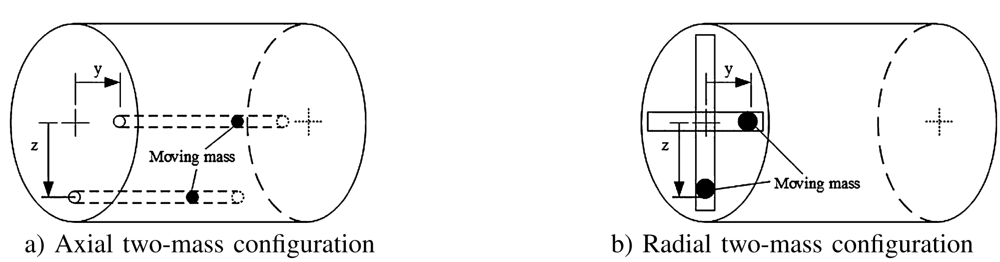


Fig. 4. Axial two-mass configuration and radial two-mass configuration [15].

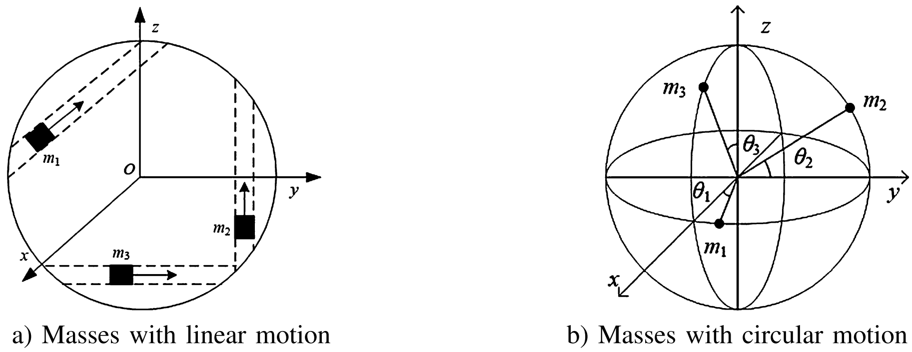


Fig. 5. Rigid body containing three moving masses [17] [20].

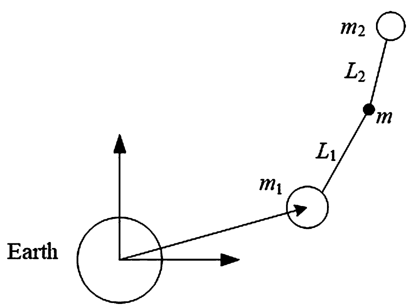


Fig. 6. Two-piece dumbbell model for a tethered satellite system with a moving mass [22].

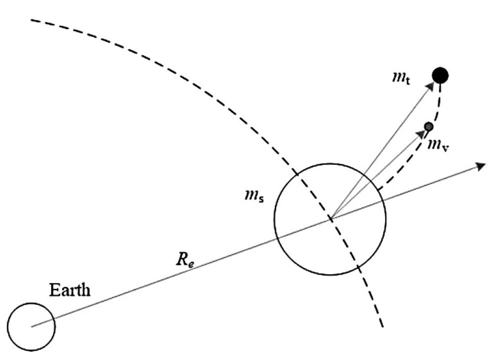


Fig. 7. Satellite appendage moving mass system [23].

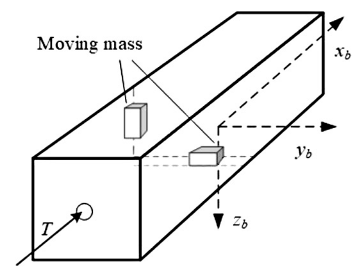


Fig. 8. Mass configuration for attitude control of CubeSat [24].

proposed rotating configuration can avoid perturbations problem during the straight moving mass unload process.

Fujii et al. [21] and Jung et al. [22] analyzed MMC in tethered satellite system, which generally consists of two main satellites connected by a tether and one movable mass moving along it, as shown in Fig. 6. The motion of the moving mass modified attitude and orbit of the satellite system. Analysis results showed that the quantity of the moving mass and its mass ratio influenced the oscillation amplitude of the orbital radius.

Oguamanam et al. [23] studied the control scheme for a combination of a beam and two moving masses, where the beam was cantilevered in the satellite, a point mass m_t is at the tip of the beam, and another moving mass m_v traverses the beam (see Fig. 7). The velocity and acceleration of the moving mass can modify the stiffness of the system. Considering the relative magnitudes of the system deformations, it was best to use a travel profile with the shortest constant velocity phase, or equivalently the smallest possible accelerations and decelerations.

Lu [24] studied the application of MMC in CubeSat. As shown in Fig. 8, four moving masses are placed around the satellite, of which the two along the z_b-axis could control the pitch angle, those along the y_b-axis could control the yaw angle. When the satellite maneuvering by using solid rockets, huge thrust force with alignment error and center-of-mass error would result in the maneuvering failure. Stabilization of satellites could be achieved by adjusting the deviation (center of mass to thrust axis) with moving masses.

Recently, a novel control mode based on momentum exchange is applied to satellite formation flying, which was first proposed by Ivanov et al. [25], as shown in Fig. 9. This concept is described as one satellite gains energy for orbit transferring by ejecting a single mass, and the other satellite grabs the ejected mass. Based on this idea, Shestakov et al. [26] studied how to minimize the flying time of the mass, and how to minimize the smallest ejecting velocity and how to guarantee the accuracy of orbit transfer.

3. MMC in spinning projectiles

For atmospheric vehicle, the aerodynamic force is an effective control force for attitude maneuvering as a non-conservative force. In particular, the position of the spacecraft's center of pressure with respect to the center of mass is modified by moving masses, which results in a change of the aerodynamic torque. The spinning projectiles, as a flight vehicle without propulsion, show weak maneuverability and stability. Thus, MMC can provide sufficient ability to correct typical trajectory errors and increase stability, which improve the maneuvering and attacking accuracy of weapons.

Murphy [27] studied stability and oscillating frequency properties of spinning projectiles with different configurations of moving masses. Fig. 10a shows a configuration of moving mass with linear motion. The axis of symmetry of the internal moving mass is assumed to cant at constant angle γ with respect to the body's axis of symmetry, and the plane of this cant angle is assumed to maintain a constant phase angle Φ_γ with the angle-of-attack plane. In this configuration, the forced gyroscopic motion can cause the fast-mode motion to grow to values in excess of 20 deg and thereby induce a rapid spindown. Fig. 10b shows the one with circular motion, in which ϵ denotes the amplitude and Φ_ϵ constant phase angle with respect to the angle-of-attack plane. This configuration

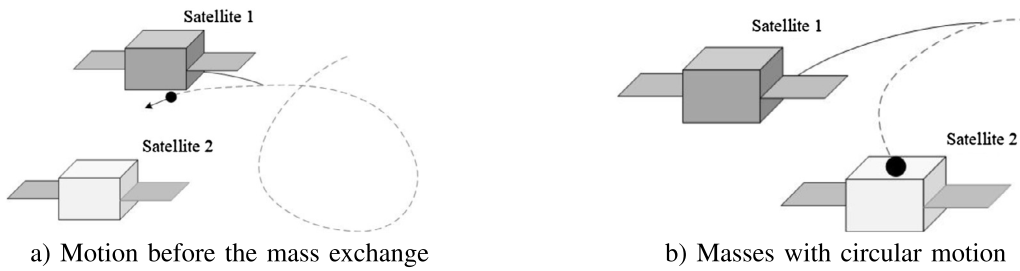


Fig. 9. Scheme of mass exchange control concept [26].

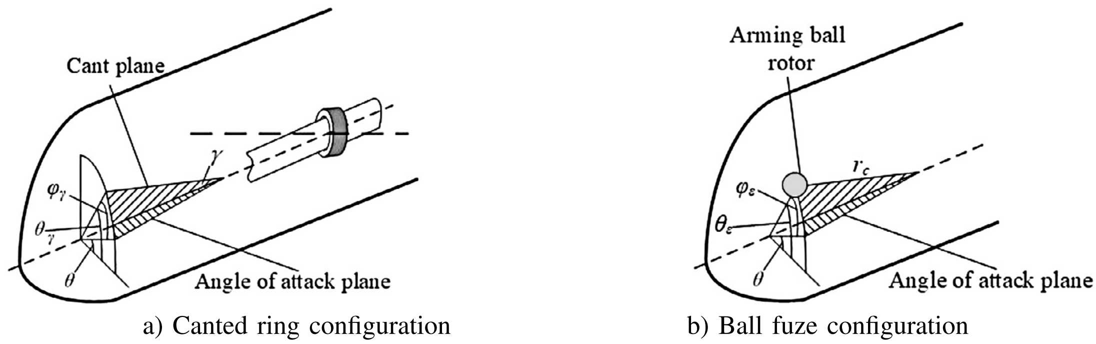


Fig. 10. Spinning projectiles with different configurations [27].

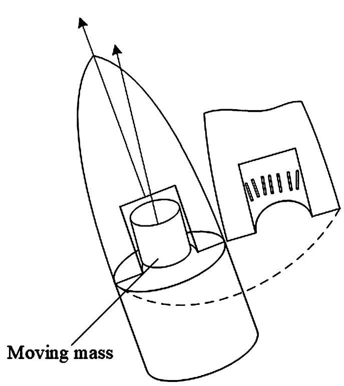


Fig. 11. Cutaway view of projectile with ballast and mechanical coupling [28].

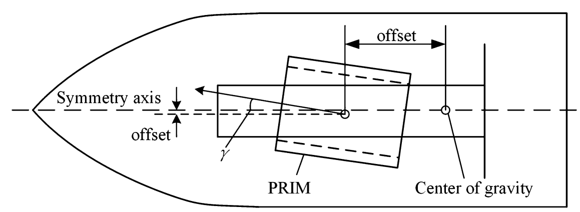


Fig. 12. Configuration of PRIM [29].

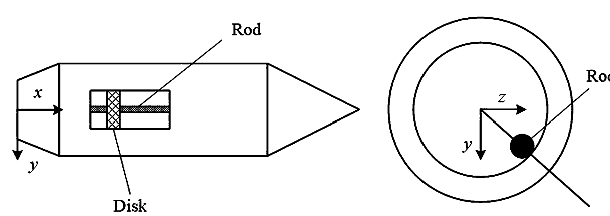


Fig. 13. Projectile mass configuration [30].

can decrease the damping rate of the fast-mode motion when the ball rotor rolls around the cavity.

Soper [28] studied the relationship between projectiles' stability and inner friction caused by moving mass. He designed a cylindrical cavity inside the spinning projectile, and put a cylindrical mass into it, as shown in Fig. 11. Analytical and experimental results showed that spin decay and cone angle growth were proportional to the friction coefficient between the mass and the cavity, and were proportional to the maximum cant angle between the mass and the projectile. Obviously, the offsetting angle between the middle axis of cylindrical moving mass and the body axis causes instability of the projectile. Nevertheless, the instability could be counteracted by spinning motion of the moving mass.

Hodapp [29] offered another method to improve stability. With the mass center of a partially restrained internal member (PRIM) deviating from the body axis, it provided a passive means for eliminating the PRIM-induced instabilities that sometimes cause range loss and deflection, as shown in Fig. 12. Analytical results illustrated that the increase of the offset could increase the stability of the projectile. However, this passive stabilizing method was restrained by the diameter of the projectile and the size of the moving mass.

Costello and Anderson [30] believed that future smart weapons need have the ability to correct typical trajectory errors. Therefore, he designed an internal unbalanced rotating part to modify trajectory and guarantee attacking accuracy. Fig. 13 shows the moving mass system with a steel rod, whose motion along the disk's inner surface moves the projectile center of gravity laterally away from the axis of symmetry. While the motion of the disk changes the longitudinal center of gravity of the projectile.

In addition, he proposed a control mechanism with an internal unbalanced rotating part [31], as shown in Fig. 14, where the internal disk is fixed on a rod, and the rod sticks to the disk with a deviation of ϵ. This configuration is much easier to implement than the previous one. By keeping the disk rotating in a desired way, the trajectory of the projectile could be modified. For instance, a 40 kg projectile with a diameter of 155 mm and a deviation of 3.8 cm from the center can ensure the falling adjustment region in 200 m $*$ 500 m.

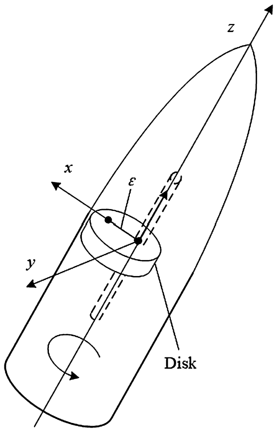


Fig. 14. Configuration with an internal unbalanced rotating part [31].

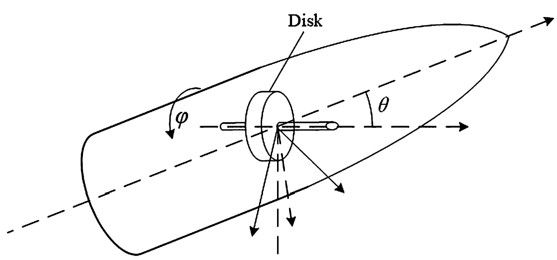


Fig. 15. Attitude coordinates schematic of a rotating internal part projectile [32].

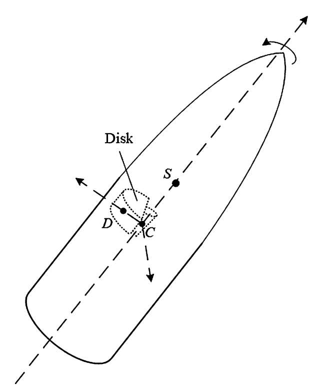


Fig. 16. Rotating mass unbalance control mechanism [33].

Frost and Costello [32] put the center of the internal rotating disk on the longitudinal axis, and kept a cant angle between the rotating axis and the longitudinal axis (see Fig. 15). This configuration can provide different dynamic effects by changing rotating rate, magnitude of cant angles, and different layout positions. Results showed that increasing the mass ratio of the disk would make the system unstable, however, when the cant angle is 90 deg, the mass ratio would not affect the stability.

Frost also proposed a rotating mass unbalance control mechanism [33], as shown in Fig. 16. The mass center of the disk was not on the body axis, because part of the disk was missing. Analytical results showed that the mass of the missing part and the deviation of the mass center affected the control ability of the moving mass.

Apart from rotating disk configuration, Costello also studied moving mass systems with linear motion [34,35]. As shown in Fig. 17, the first layout has an internal moving mass with lateral reciprocating motion. This layout is especially fit for spinning projectiles, because the trajectory is not modified by the deviation of center of mass, but by the dynamic coupling between the back-and-force movement and the spinning of the vehicle. The second layout has an internal moving mass with axial motion, which could improve the static stability of the projectile. Compared with projectiles with high stability, those with low stability are higher in maneuverability, but are easier to be disturbed during launch phase. Therefore, moving mass could be used to increase the stability during launch phase and to lower the stability after launch, which guarantees a stable launching process and high maneuverability thus improves control accuracy.

4. MMC in underwater vehicles

As flight vehicle control with aerodynamic forces, the control torque generated by fluid field would change with the mass center of underwater vehicles changes. Traditional underwater vehicles are controlled by rudders. However, joints of rudders erode easily in sea water for long-time detecting tasks, which causes structure damage. What's more, when underwater vehicles move with low speed, rudders exhibit low efficiency for attitude and trajectory control. Due to the unique control mode of MMC, it can solve the problems of attitude control of underwater vehicles.

Leonard and Graver [36] proposed a configuration of underwater vehicles which had two moving masses and a fixed wing. As shown in Fig. 18, one moving mass is fixed before the mass center, the other one is movable after the mass center. This configuration makes the vehicle have the ability of moving in navigating

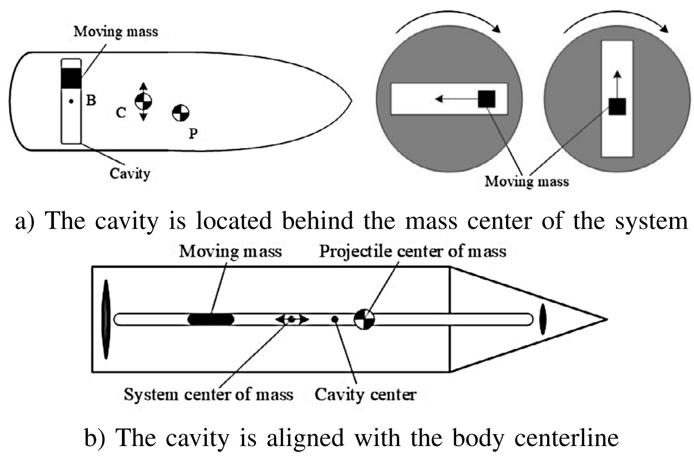
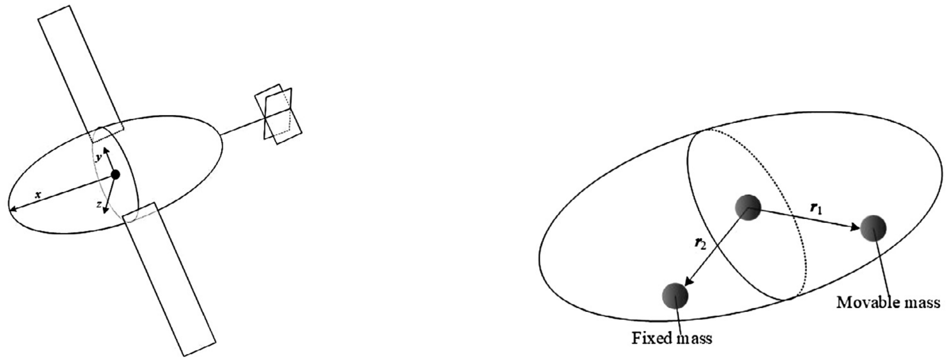


Fig. 17. Projectile with internal moving mass [35].



a) Underwater glider b) Moving mass configuration

Fig. 18. Configuration of underwater vehicle [36].

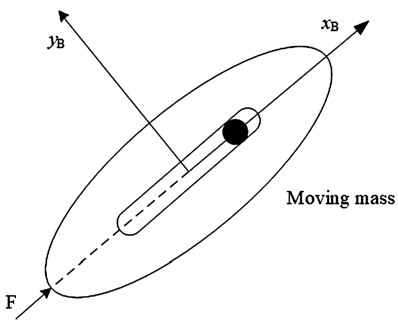


Fig. 19. The AUV and an internal moving mass [37].

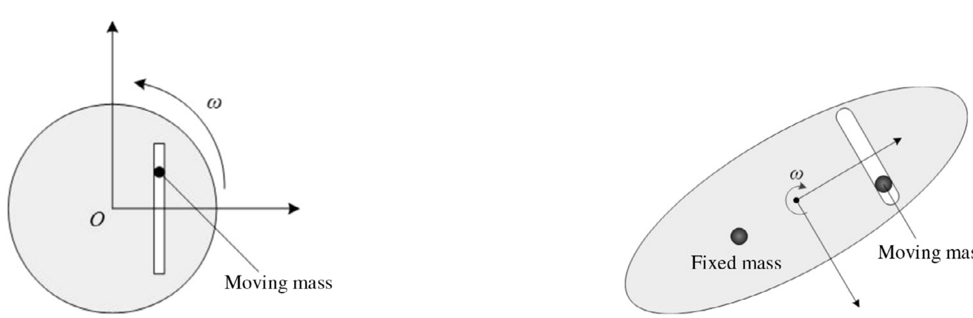
direction. Li et al. [37] investigated a control mode with a single moving mass in axial cavity and a rear thruster, as shown in Fig. 19. Since there are only two independent control inputs (point mass and thruster), the proposed control mode is underactuated.

Woolsey [38] [39] studied motion properties of moving mass along different axis, as shown in Fig. 20. Fig. 20a illustrates the moving mass moving in the spin plane of the body, while Fig. 20b shows the moving mass moving perpendicular to the body axis. He also proposed another control mode different from inner moving mass, which takes high-speed spinning disks as stabilizing actuators [40]. As shown in Fig. 21, three disks rotate about three principal axes of inertia. The rotation of disks generates momentum to control attitude. Obviously, this control mode does not rely on relative motion between the moving vehicle and fluid field, therefore, attitude adjustment could be made when the glider is static. This mechanism is similar to reaction wheel control of spacecraft, which used in flexible multibody systems with variable-speed control moment gyroscopes [41,42].

5. MMC in unmanned aerial vehicles

Recently, the development of unmanned aerial vehicles (UAV) progresses greatly and has been applied to military and commercial fields. As a flight vehicle controlled by aerodynamic forces, many investigators studied the feasibility of applying MMC to attitude control of UAV. Erturk and Dogan [43,44] applied MMC to attitude control of fixed-wing unmanned aerial vehicles. As shown in Fig. 22, they set a mass moving longitudinally within the fuselage and a laterally moving-mass within the wings. The one along the *x*-axis could generate pitching moment, the one along the *y*-axis could provide rolling moment. Since there is no actuator to provide yawing moment, the mass-actuated aircraft cannot make coordinated turns with zero side slip angle. Fixed-height stable turns could be made with the help of direction rudders. Compared with traditional aerodynamic rudder control only, this combination control method needs less thrust forces, because the reduction in control surfaces would result in small drag force and less lift loss [45].

Control ability analysis illustrates that, for a low-speed vehicle, moving masses generate larger control force than aerodynamic rudders. Thus, the flying efficiency could be improved by reducing the total mass of the vehicle. [46]. Investigations compared three different actuators of aircraft maneuvering: 1) only aero-actuation used, 2) only mass-actuation used, and 3) mass-actuation augmented with rudder. The comparison results show that the method of mass-actuation augmented with rudder effectively can reduce propeller torque and burden on the engine [47,48]. Their group also made a sample airplane to demonstrate the feasibility of applying linear moving masses to fixed-wing unmanned aircraft [49]. The internal mass actuation systems with linear electric actuator are inside both wings and a data acquisition system is used to record flight data. During test flights, the radio control transmitter is programmed to switch between aileron-actuation and mass-actuation.



a)A spinning disk with a point mass moving along a slot b)A planar underwater vehicle with two point masses

Fig. 20. Mass configurations of underwear vehicles [38].

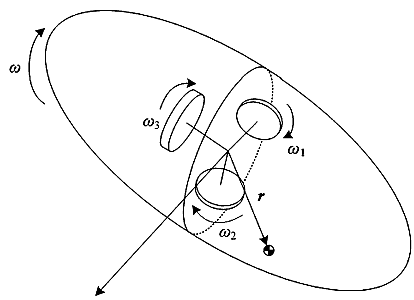


Fig. 21. A rigid body with rotors [40].

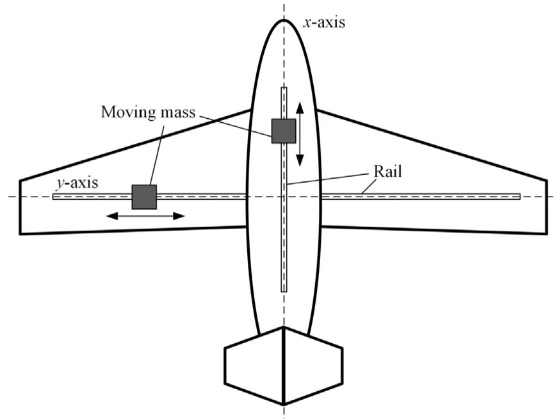


Fig. 22. Placement of the longitudinal and lateral moving-mass actuators [43].

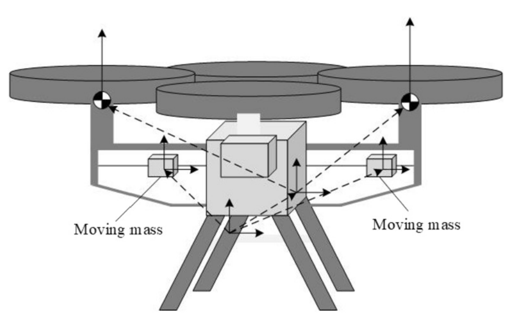


Fig. 23. Quadrotor coordinate frame [51].

Multirotor UAVs become increasingly popular in aerial photography, agriculture, and transportation. However, their development is limited by power source. Because performance of engines powered by battery is restricted by energy density, so that the long endurance tasks cannot be completed. Also, oil engines work longer, but lack in carrying capacity and stability [50]. Therefore, to improve UAV's efficiency, Haus proposed a control mode to change quadrotor's attitude by using moving mass to adjust the center of system mass [51]. As shown in Fig. 23, four moving masses are placed on four arms of the quadrotor. The moving mass motion could complete the rolling and pitching attitude control of the quadrotor, while altitude control and yawing control are still done by rotors.

Dynamic analysis of traditional rotor control and rotor-MMC shows that MMC exhibits faster response and needs less energy. However, the maximum moment generated by MMC relies on the weight of moving mass and deviating distance. Thus, the weight of moving mass and length of its arms need be optimized by optimization method. In addition, the response property of the system shows that the farer the moving mass plane deviates from the center of mass, the more stability of the closed-loop system. To demonstrate the feasibility of this control configuration, they proposed a classical PID controller and by the sample vehicle and built a laboratory testbed to emulate the dynamics of the system [52].

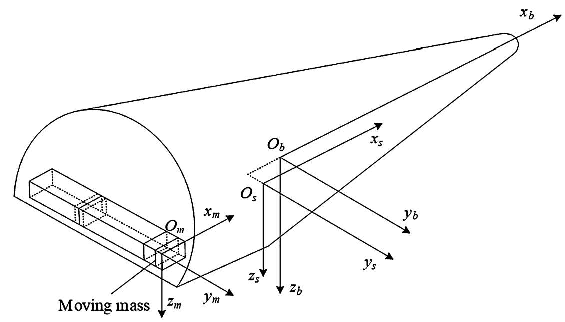


Fig. 24. The moving-mass element is located near the base [53].

6. MMC in reentry vehicles

Due to the actuator of MMC inside the vehicle body, it maintains aerodynamic shape and avoids ablation of aerodynamic rudders for hypersonic flight vehicles. MMC has been applied to attitude control of reentry vehicles since mid-1990s. There are mainly three control techniques: 1) moving mass roll control (MMRC); 2) moving mass trim control (MMTC); 3) improving attitude response by modifying static margin. In this section, a review of the moving mass control and its compound control mode with other actuators is presented.

6.1. Only moving mass configuration

Different configurations of internal moving masses determine different control mechanisms. A configuration with two or three moving masses offers the capacity of longitudinal and lateral maneuvering. Although the configuration with multiple moving masses shows outstanding and various maneuvers, it is difficult to implement for engineering because more actuators are contained within a limited space of the vehicle body to drive the moving masses. Thus, the single moving-mass control system, which is the simplest configuration, becomes focus configuration to provide roll control ability or generate a trim angle of attack (AOA) for maneuvering.

Regan discussed the application of the moving mass roll control of reentry vehicles [53]. As shown in Fig. 24, the moving mass controls rolling motion by left and right motion in the rail. Unlike flaps, MMRCs only need to counteract very small aerodynamic moments, which could be easily actuated by electric motors.

Robinett et al. [54] proposed two layouts for trim control of reentry vehicle, as shown in Fig. 25. Note that the second configuration needs only one moving mass and despin motor for actuation. For reentry vehicles with a high spinning rate, trim AOA is generated from principal axis misalignment, while for those with a low spinning rate, trim AOA results from a center of mass offset and aerodynamic drag. To ensure a reasonable size of moving mass, the static margin should be kept sufficiently small (less than 10%).

Jing and coworkers [55] designed a polar control method for single moving mass, combining advantages both in orthogonal and non-orthogonal configurations. As shown in Fig. 26, the characteristics of this control mode is that the rail is orthogonal to and rotates about the body axis, meanwhile the moving mass moves along the rail. Comparing with double moving mass control, this configuration could not only save inner space, but also reduce the pitch motion influence to the rolling channel.

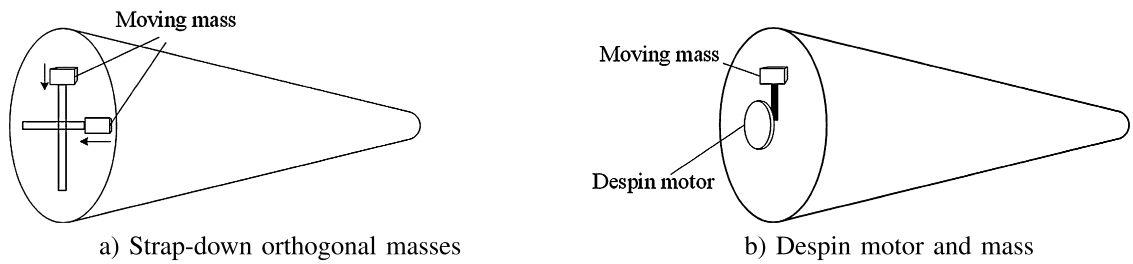


Fig. 25. Three moving mass layouts [54].

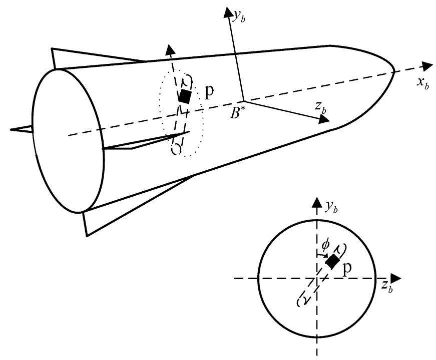


Fig. 26. Diagram of single moving mass layout style [55].

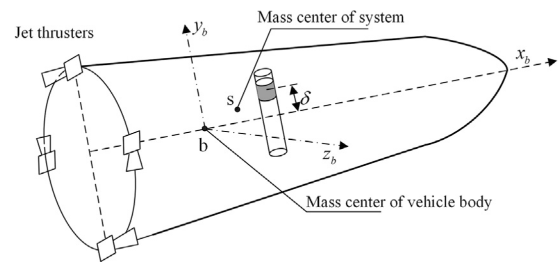


Fig. 28. Combination BTT control mode with single moving mass and jet [57].

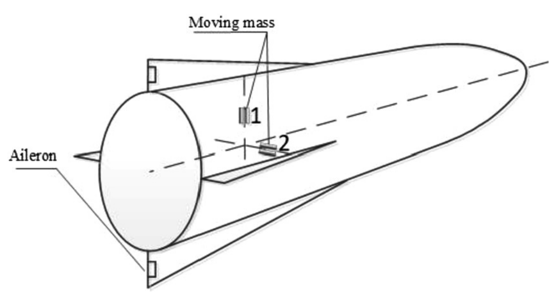


Fig. 27. Reentry vehicle with moving masses and ailerons [56].

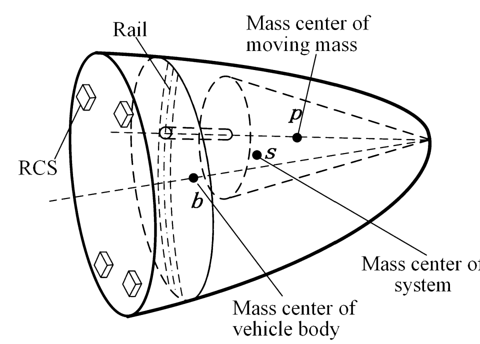


Fig. 29. Configuration of single moving mass reentry vehicle [59].

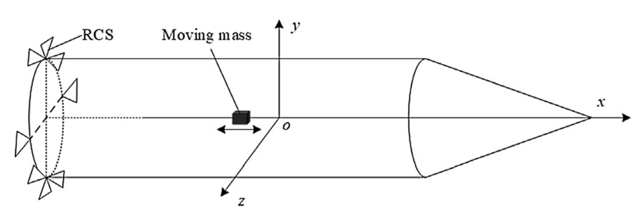


Fig. 30. Configuration of longitudinal moving mass [61].

6.2. Compound control with other actuators

Although the implementation of multi-masses configuration is difficult for inner structure design of reentry vehicles, single moving mass layout may not be enough for three-channel maneuvering. Therefore, to improve the maneuverability, many researchers combine MMC with other actuators.

Jing's research group proposed several compound configurations, one of which is MMC with differential ailerons [56]. As shown in Fig. 27, pitch and yaw channels are controlled by two orthogonal moving masses, while roll channel is controlled by ailerons. This compound control method combines advantages in both MMC and surface control.

They also proposed a bank-to-turn (BTT) control mode by combining MMC with jet thrust control [57]. As shown in Fig. 28, the moving mass placed on the longitudinal plane generates lift force, jet engines around the tail control the rolling motion. Then, they proposed a practical control scheme for engineering implement, dividing a control cycle into two steps: control rolling motion to the desired direction and then track guidance command with mass motion.

In addition, based on the BTT control above, they proposed a compound control mode with single moving mass and reaction control system (RCS) [58,59]. They extended the moving mass to a cone which took up a large portion of the total mass (see Fig. 29). The top of the moving mass was connected to the head by hinge, and the bottom moves along an arc rail under servo force. This configuration not only optimizes inner space of the vehicle, but also guarantees a high maneuverability due to the moving mass with a large mass ratio. Moreover, the equivalent experiment of the proposed configuration was developed to validate the feasibility of the proposed control mode [60].

Kong et al. [61] adopted RCS forces to generate AOA and sideslip angle directly, and placed moving masses in axial to modify static stability of the vehicle and to improve response speed, when the vehicle reaches the desired AOA or sideslip, jet thrust engines shut down and the control moment is adjusted only by moving masses for saving fuel (see Fig. 30). Moreover, when the vehicle suffers large disturbance, moving masses could be driving to keep the vehicle static stable, in which case attitude control accuracy is maintained by jet thrusters.

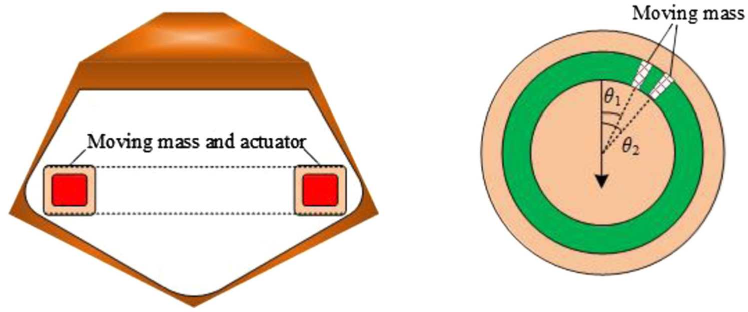


Fig. 31. Configuration of longitudinal moving mass [63].

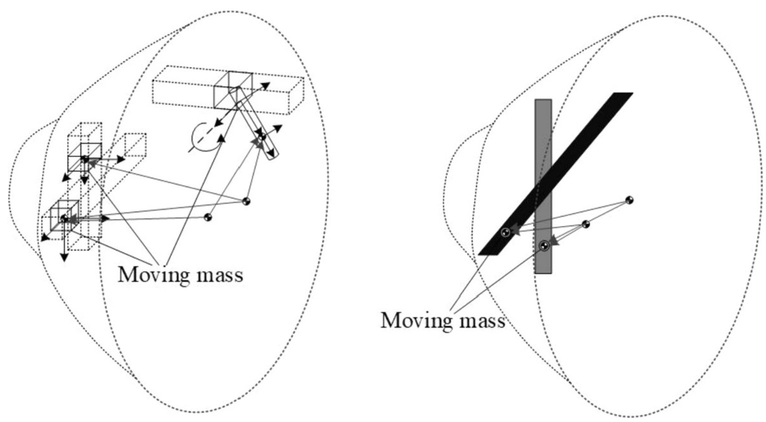


Fig. 32. Example entry vehicle with translation and rotation IMMA [65].

7. MMC in Mars reentry

For Mars landers, reentry process is of great importance. At present, over 40 Mars probes have been launched, however, only eight of them land and work successfully. Most landers adopted uncontrolled ballistic entry mode except for Mars Science Laboratory (MSL), which used bank angle guidance. Landing error circular radii of ballistic mode is normally over 80 km, thus it is difficult for precision landing. What's worse, the ballistic entry mode could not lift the orbit so that the lander cannot land on high altitude area [62]. Therefore, how to improve maneuverability, landing accuracy and landing adaptability, have been attracted much attention.

Balaram put a dual-masses mechanism into reentry spacecraft, as shown in Fig. 31. Two masses move along circular rail to shift mass center of the spacecraft and generates trim AOA. When $\theta_1 = \theta_2$, the lift force of the spacecraft reaches maximum value, when $\theta_1 = \theta_2 + \pi$, the lift force is zero. Using this configuration, reentry spacecraft possesses longitudinal and lateral maneuverability [63] [64]. He gave several observations regarding Mars reentry vehicle of MMC.

1) The whole reentry process lasts only several minutes. About 50 to 150 seconds after the start of reentry, the aim of aerodynamic forces is to slow down the vehicle and provide control ability of longitudinal range. MMC makes the most of aerodynamic forces within thin atmosphere.

2) Traditional blunt-head reentry vehicles achieve different Lift-to-Drag ratios (0.15–0.3) by changing its angle-of-attack, while MMC modifies trim angle-of-attack with its aerodynamic configuration maintained. For a reentry vehicle (300 kg) with a moving mass (10 kg), a Lift-to-Drag of 0.18, the maximum range control authority can reach 150 km. Therefore, this control mode not only counteracts initial error, but also reduces effects of aerodynamic disturbance.

3) Dual MMC system can maximize the lift force of the reentry vehicle with high dynamic pressure and decrease trim AOA for preparing to open parachute with a safe velocity.

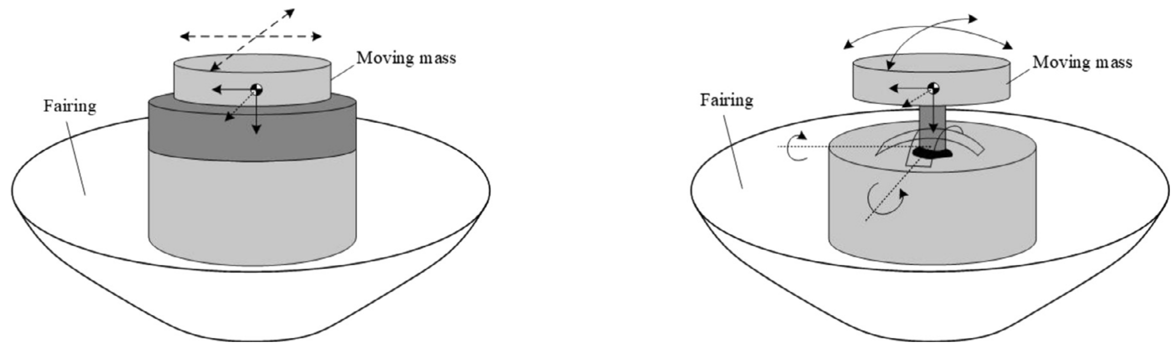
4) Compared with jet thrust control, in which lift direction control is realized by changing the sideslip angle, dual-moving-mass control system has higher reliability and lower risk.

Atkins [65] applied MMC to two kinds of mars explorers designed by NASA. One of them holds a diameter of 2.65 m, weight 602 kg; the other is Hypersonic Inflatable Aerodynamic Decelerators (HIADS) in High Energy Atmospheric Re-entry Vehicle Experiment (HEARVE), weighting 5.9 tons. The decelerator contains a fairing, which could spread and drag the vehicle when entering the atmosphere, slowing down by a large surface.

As shown in Fig. 32, for Mars Phoenix entry vehicle with blunt head, Atkins put two internal moving mass actuators which are orthogonal with each other. In this way, both pitch and yaw channels could be controlled. The third moving mass along the body axis could adjust the distance between the mass center and the center of pressure, thus changes the static stability. With the limitation of the vehicle's inner space and task requirements, dual moving mass configuration could basically meet the need of Mars landing. The internal moving mass actuating devices based on angle-of-attack and slide angle control could decouple the longitudinal channel and the lateral channel [66].

Because of unique combinational design of HIAD (gas drag mantle and cylinder payload), Atkins put the moving mass to its back, as shown in Fig. 33. The first one is with translational motion, the second one, rotational, both with two-degree-of freedom. The cylinder on the top is 1.5 m in height, 3.32 m width, 750 kg weight, 0.12 mass ratio.

Based on analysis of these two configurations in same simulation condition, Atkins concluded that rotational moving mass modify response ability and tracking accuracy of system more easily, which also has higher guidance accuracy and lower energy cost.



a) HIAD with top structure 2 DOF translation IMMA b)HIAD with top structure 2 DOF rotation IMMA

Fig. 33. Two configurations for HIAD [65].

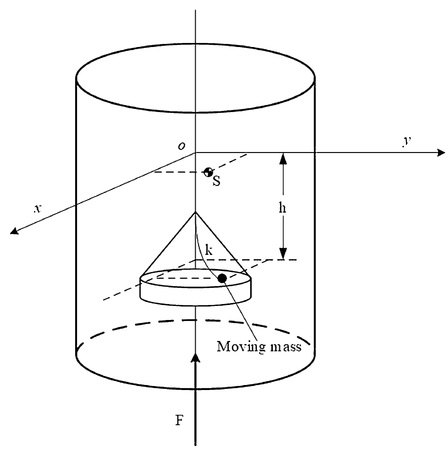


Fig. 34. Idealized Model and oscillators [67].

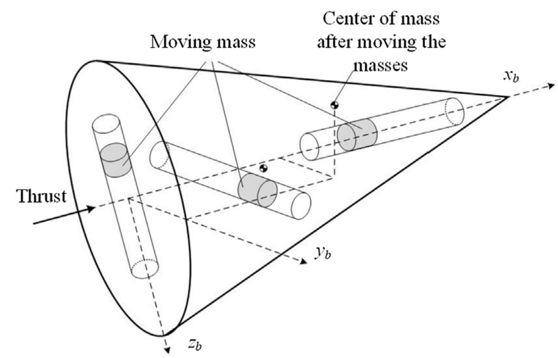


Fig. 35. Moving-mass actuated kinetic warhead concept [70].

8. MMC in other fields

To deal with instabilities of spinning rockets, Mingori and coworkers [67–69] designed a stabilizing system using spring-mass devices as shown in Fig. 34. Viscous force is generated by relative motion between the moving mass and the vehicle. Analytical results with the Lyapunov method show that three conditions must be satisfied for rotating with respect to the principle axis: 1) the thrust force is large enough; 2) the recover moment of moving mass is large enough; 3) moving mass moves after mass center of the vehicle.

Menon et al. [70] applied MMC to kinetic warhead, and designed a configuration with three moving masses. Three moving masses could provide pitch moment and yaw moment as shown in Fig. 35. In view of that the warhead needs high maneuverability, an integrated guidance and control model is built with 9 degrees of freedom. Then, response speed of this warhead could be improved with this integrated controller.

Stratospheric airships work at an altitude of 20 km and they are mainly applied in environmental monitoring, emergency rescue, and civil communication. Because of their huge size (with a length greater than 150 m, a maximum diameter greater than 40 m) and semi-flexible structures, how to efficiently control with proper actuators is worth studying. Chen [71] studied compound control mechanism that composed of aerodynamic control surfaces, vectored thrust, ballonet, and moving mass, as shown in Fig. 36. The longitudinal moving mass controls the airship's pitching angle, the transverse one controls rolling angle. Analysis and simulation of this control mode illustrate that there is no relationship between moving mass control ability and the airship's velocity, which means that moving mass control ability is more effective than that of aerodynamic surfaces in low velocity. Thus, MMC is especially suit for attitude control in high altitude.

9. Problems in MMC

9.1. Moving mass configuration

Actuators of MMC are equipped inside the vehicle, which not only destroys internal structure of the vehicle but also takes out internal available space. This situation gives rise to great difficulties for the layout of moving masses. Therefore, the optimal design for the moving mass configuration is an essential aspect for engineering implementation of MMC.

Based on the previous applications of MMC in different fields, we summarize several methods of the configuration of moving masses:

1) To avoid destroying inner structure of the vehicle, moving masses are generally put along trivial position of the vehicle. For example, the bottom of the vehicle, or outer side along the radius direction, or the tail of the vehicle.

2) Actually, besides the moving mass, there are other devices that take up inner space of the vehicle, such as servo system (electric motors, actuators) and batteries. Therefore, the decrease of the number of moving masses can minimize the occupation of inner space of the vehicle, and decrease the difficulty of the moving mass layout design. Consequently, to overcome the problem of maneuverability loss caused by decreasing the number of moving mass, some different movement types are adopted, such as the rotational rail and the arc rail.

3) MMC could be combined with rudder control or jet thrust control to solve different control problems by corresponding control mode. Compound control mode takes advantages of different

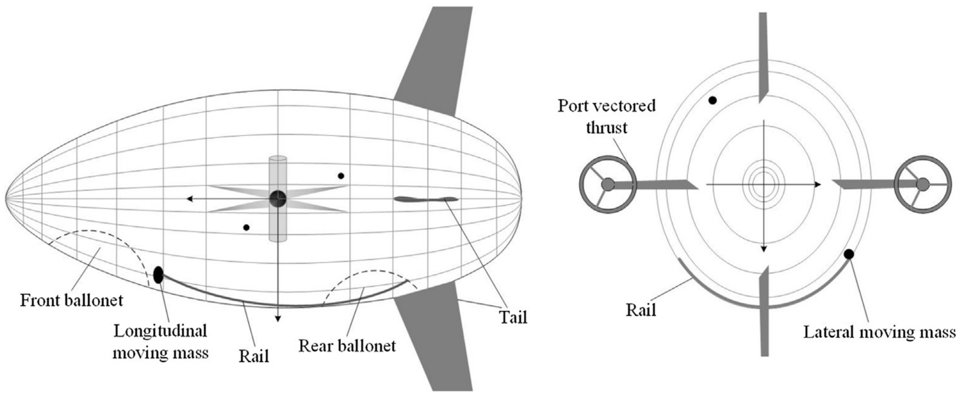


Fig. 36. The stratospheric airship with moving masses [71].

control modes, which could maximize vehicle's performance and decrease the difficulties in layout design.

4) Since moving mass takes up a large space inside the vehicle, a brand new view of moving mass layout could be that extending the internal moving mass to take up most of the internal space of vehicle body and the mass of moving mass account for most of the whole mass. In this way, we can put payloads of the vehicle into the moving mass. This layout not only increases the maneuver performance but also optimizes the internal space of the flight vehicle.

The control ability of single moving mass is limited. However, in consideration of mass, volume and actuation type of moving mass, the single moving mass configuration is applicable in practical engineering at present. In some application fields (like satellite stabilization, smart projectiles control), single moving mass configuration can accomplish control task perfectly. Furthermore, the compound control mode, in which MMC combines with other control actuators, can perform the better performance and maneuverability.

9.2. Nonlinear dynamics analysis

Dynamic analysis of traditional flying vehicles is based on small quantity hypothesis, and then analyzed with linear system theory [72,73]. In early times, the stability and control mechanism analysis of MMC are based on linear model [54,74]. However, the vehicle with moving mass is a variable structure, time varying, and multibody system. The relative motion and momentum exchange would result in coupling between the internal mass and the vehicle body. Thus, the moving mass vehicle is a complex dynamic system with strong nonlinearity and coupling. If we still neglect the nonlinear terms and apply traditional linear theory to dynamic analysis, it will result in unacceptable error and even essential mistakes. Therefore, it is necessary to investigate the nonlinear characteristics of the moving mass system by nonlinear dynamic theory. Such as nonlinear oscillation property, bifurcation characteristics, chaos phenomenon and so on.

At present, there are few nonlinear dynamics analysis about MMC. Li et al. [75] used Multiple-scale method to investigate the resonance nature of the moving mass flight vehicle which is described in Fig. 31. Numerical results show that the proposed system is of hardening spring characteristic when excitation frequency is near to different natural frequencies. The mass ratio and the relative position also lead to the occurrence of a jump phenomenon and multi-valued regions. Moreover, the mass ratio mainly affects the control authority of moving mass and the relative position mainly affects the stability. The reasonable design for parameters of the moving mass system can ensure stability and high performance of flight vehicle.

Wang et al. [76] studied bifurcation characteristics of single moving mass rolling control for reentry vehicle. Taking offset of the moving mass as a variable, he studied attitude convergence results of the vehicle with different initial conditions. According to bifurcation graphs, he summarized that the aerodynamic layout, the size of the moving mass, and the layout position have significant effects on the stable offset of the moving mass. Furthermore, the attraction domain of expected equilibrium point should be extended when the reentry vehicle is spinning with a large nutation angle. Doroshin [77] analyzed chaos mode for satellite with MMC, and found out that MMC would generate Shilnikov attractor that could be used to design effective attitude controller, and to suppress chaotic motion. Besides, based on the activation of the homo/heteroclinic chaos and strange chaotic attractor, chaotic analysis and simulations were conducted [78].

For vehicles with moving mass control, the mass ratio and relative position of mass center are important parameters for dynamic behavior and stability. Thus, it is necessary to analyze the influence of the two parameters by nonlinear dynamic analysis. The analysis results could not only provide theoretical support for structure design, but also design nonlinear controller based on nonlinear properties to improve controller performance. Therefore, more profound analysis should be done to reveal control potential of MMC.

9.3. Control problem

Because of the unique configuration and control mechanism, MMC generates deviation of principle axis of inertia. This result not only causes coupling between attitude channels, but also causes gyroscopic effect which generates the additional moment of inertia. Therefore, the dynamic system consisting of the vehicle and moving masses is a strong coupling and high nonlinear control system.

Classical control theory and modern control theory have applied in the design of MMC systems, including PID control [79], linear quadratic regulator [80], sliding-mode control [81], feedback linearization control [58], and back-stepping control [55]. For additional disturbance and uncertainties caused by the moving mass motion, the estimator can be used to estimate and compensate disturbances for the adaption of controller [59,82]. Recently, with the development of intelligent control, fuzzy logic and neural network are used to estimate and compensate uncertainties and modeling errors in MMC [83].

In traditional attitude control design, the servo loop of rudders is neglected or regarded as first order system to simplify the control system design [84,85]. However, in MMC system design, the dynamic behavior of the moving mass must be considered in design of the moving mass control system. Therefore, the attitude

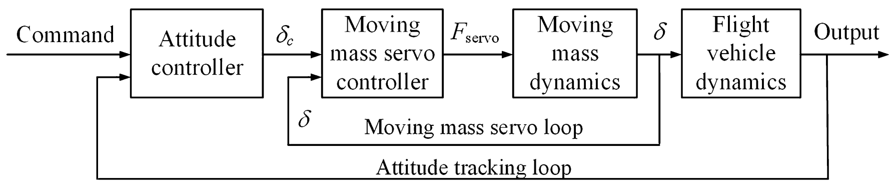


Fig. 37. Block diagram of dual loop control system.

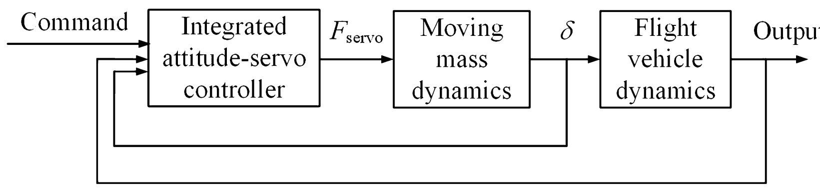


Fig. 38. Block diagram of integrated control of attitude-servo system.

control system includes the attitude tracking control loop and the moving mass control loop (servo control loop) [86]. As shown in Fig. 37, attitude control loop generates desired position of the moving mass according to the guidance command, while the moving mass control loop calculate the control servo force (moment) according to the desired position of the moving mass from attitude control loop.

The separate design process, which designs the attitude and the servo loop controller respectively, does not consider the inertia coupling caused by motion of moving masses and view the coupling term as disturbance to compensate. This design strategy is often effective, but when attitude command changes quickly, the control system response exhibits hysteresis and even become unstable.

Integrated attitude-servo design process integrates the attitude loop and the moving mass loop together, which generates the servo force (moment) directly according to the command, as shown in Fig. 38. In this strategy, the stability and performance of the control system are improved because the inertia coupling is full considered as information. The integrated design strategy is especially suited for the hypersonic flight vehicle which is a fast time-varying and strong coupling control system. Therefore, the integrated control of attitude-servo system, which can improve dynamic performance of the attitude controller by considering the coupling between attitude and servo, is worth to further study.

10. Conclusion

Moving mass control technology shows great advantages in improving dynamic properties, attitude control, and counteract disturbance. According to the review of current research, MMC has already obtained plenteous result in different fields with several decades' development. However, most works still stay at theoretic design and simulation, and is rather far away from engineering application. The main reason is that the configuration of the moving mass brings about the difficulty in applying it to practical use. Nevertheless, with the development of sensor technology and drive devices, we believe that the problem of moving mass configuration would be implemented in engineering practice. We hope this paper will encourage discussion and engineering practice regarding the future direction of aerospace applications of moving mass control.

Conflict of interest statement

There is no conflict of interest in this article.

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References

[1] A. Sofyalı, E.M. Jafarov, R. Wisniewski, Robust and global attitude stabilization of magnetically actuated spacecraft through sliding mode, Aerosp. Sci. Technol. 76 (2018) 91–104.
[2] Q. Mao, L. Dou, Q. Zong, Z. Ding, Attitude controller design for reusable launch vehicles during reentry phase via compound adaptive fuzzy H-infinity control, Aerosp. Sci. Technol. 72 (2017) 36–48.
[3] J. Ren, Q. Quan, L.B. Zhao, X. Dai, K.Y. Cai, Two-degree-of-freedom attitude tracking control for bank-to-turn aerial vehicles: an additive-state-decomposition-based method, Aerosp. Sci. Technol. 77 (2018) 409–418.
[4] C.-Y. Li, W.-X. Jing, C.-S. Gao, Adaptive backstepping-based flight control system using integral filters, Aerosp. Sci. Technol. 13 (2–3) (2009) 105–113.
[5] J. Peng, C. Li, X. Ye, Cooperative control of high-order nonlinear systems with unknown control directions, Syst. Control Lett. 113 (2018) 101–108.
[6] J. Petrich, D.J. Stilwell, Robust control for an autonomous underwater vehicle that suppresses pitch and yaw coupling, Ocean Eng. 38 (1) (2011) 197–204.
[7] C. Shao, L. Nie, W. Chen, Analysis of weakly ionized ablation plasma flows for a hypersonic vehicle, Aerosp. Sci. Technol. 51 (2016) 151–161.
[8] J.H. Wang, L.H. Liu, P. Wang, G.J. Tang, Guidance and control system design for hypersonic vehicles in dive phase, Aerosp. Sci. Technol. 53 (2016) 47–60.
[9] R. Chai, A. Savvaris, A. Tsourdos, S. Chai, Y. Xia, Optimal fuel consumption finite-thrust orbital hopping of aeroassisted spacecraft, Aerosp. Sci. Technol. 75 (2018) 172–182.
[10] D.W. Childs, A movable-mass attitude-stabilization system for artificial-g space stations, J. Spacecr. Rockets 8 (8) (1971) 829–834.
[11] S. Chesi, Q. Gong, V. Pellegrini, R. Cristi, M. Romano, Automatic mass balancing of a spacecraft three-axis simulator: analysis and experimentation, J. Guid. Control Dyn. 37 (1) (2013) 197–206.
[12] K.R. Lorell, B. Lange, An automatic mass-trim system for spinning spacecraft, AIAA J. 10 (8) (1972) 1012–1015.
[13] F.L. Janssens, J.C. Van Der Ha, Stability of spinning satellite under axial thrust and internal mass motion, Acta Astronaut. 94 (1) (2014) 502–514.
[14] F.L. Janssens, J.C. van der Ha, Stability of spinning satellite under axial thrust, internal mass motion, and damping, J. Guid. Control Dyn. 38 (4) (2014) 761–771.
[15] J.E. White, R.D. Robinett III, Principal axis misalignment control for deconing of spinning spacecraft, J. Guid. Control Dyn. 17 (4) (1994) 823–830.
[16] T.L. Edwards, M.H. Kaplan, Automatic spacecraft detumbling by internal mass motion, AIAA J. 12 (4) (1974) 496–502.
[17] A. El-Gohary, On the control of programmed motion of a rigid body containing moving masses, Int. J. Non-Linear Mech. 35 (1) (2000) 27–35.
[18] A. El-Gohary, Global stability of the rotational motion of a rigid body containing moving masses, Int. J. Non-Linear Mech. 36 (4) (2001) 663–669.
[19] A. El-Gohary, T. Tawfik, Optimal control of the rotational motion of a rigid body using moving masses, Appl. Math. Comput. 153 (2) (2004) 453–465.
[20] A. El-Gohary, A.M. Hussein, On the control of a rigid body using internal point masses I. Stabilization of an equilibrium position, Int. J. Non-Linear Mech. 36 (7) (2001) 1069–1074.
[21] H.A. Fujii, T. Watanabe, T. Kusagaya, D. Sato, M. Ohta, Dynamics of a flexible space tether equipped with a crawler mass, J. Guid. Control Dyn. 31 (2) (2008) 436–440.

[22] W. Jung, A.P. Mazzoleni, J. Chung, Dynamic analysis of a tethered satellite system with a moving mass, Nonlinear Dyn. 75 (1–2) (2014) 267–281.
[23] D. Oguamanam, J. Hansen, G. Heppler, Dynamics of an orbiting flexible beam with a moving mass, AIAA J. 39 (11) (2001) 2225–2227.
[24] Z. Lu, X. Zhang, Y. Yu, Q. Mo, W. Liao, Mass moment control modeling and layout optimization for CubeSat, Syst. Eng. Electron. 3 (39) (2017) 599–605.
[25] D. Ivanov, M. Ovchinnikov, S. Shestakov, Satellite formation flying control by mass exchange, Acta Astronaut. 102 (2014) 392–401.
[26] S. Shestakov, D. Ivanov, M. Ovchinnikov, Formation-flying momentum exchange control by separate mass, J. Guid. Control Dyn. 38 (8) (2015) 1534–1543.
[27] C.H. Murphy, Influence of moving internal parts on angular motion of spinning projectiles, J. Guid. Control Dyn. 1 (2) (1978) 117–122.
[28] W.G. Soper, Projectile instability produced by internal friction, AIAA J. 16 (1) (1978) 8–11.
[29] A.E. Hodapp, Passive means for stabilizing projectiles with partially restrained internal members, J. Guid. Control Dyn. 12 (2) (1989) 135–139.
[30] M. Costello, D. Anderson, Effect of internal mass unbalance on the terminal accuracy and stability of a field artillery projectile, in: 21st AIAA Atmospheric Flight Mechanics Conference, 1996.
[31] G. Frost, M. Costello, Stability and control of a projectile with an internal rotating disk, in: AIAA Atmospheric Flight Mechanics Conference and Exhibit, 2003.
[32] G. Frost, M. Costello, Linear theory of a rotating internal part projectile configuration in atmospheric flight, J. Guid. Control Dyn. 27 (5) (2004) 898–906.
[33] G. Frost, M. Costello, Control authority of a projectile equipped with an internal unbalanced part, J. Dyn. Syst. Meas. Control 128 (4) (2006) 1005–1012.
[34] J. Rogers, M. Costello, A variable stability projectile using an internal moving mass, Proc. Inst. Mech. Eng., G J. Aerosp. Eng. 223 (7) (2009) 927–938.
[35] J. Rogers, M. Costello, Control authority of a projectile equipped with a controllable internal translating mass, J. Guid. Control Dyn. 31 (5) (2008) 1323–1333.
[36] N.E. Leonard, J.G. Graver, Model-based feedback control of autonomous underwater gliders, IEEE J. Ocean. Eng. 26 (4) (2001) 633–645.
[37] J. Li, B. Song, C. Shao, Tracking control of autonomous underwater vehicles with internal moving mass, Acta Autom. Sin. 34 (10) (2008) 1319–1323.
[38] C.A. Woolsey, Reduced Hamiltonian dynamics for a rigid body mass particle system, J. Guid. Control Dyn. 28 (1) (2005) 131–138.
[39] C.K. Reddy, C.A. Woolsey, Energy shaping for vehicles with point mass actuators, in: American Control Conference, 2006, pp. 6–11.
[40] C.A. Woolsey, N.E. Leonard, Stabilizing underwater vehicle motion using internal rotors, Automatica 38 (12) (2002) 2053–2062.
[41] Z. Wang, Y. Jia, S. Xu, L. Tang, Active vibration suppression in flexible spacecraft with optical measurement, Aerosp. Sci. Technol. 55 (2016) 49–56.
[42] J. Liu, K. Pan, Rigid-flexible-thermal coupling dynamic formulation for satellite and plate multibody system, Aerosp. Sci. Technol. 52 (2016) 102–114.
[43] S.A. Erturk, A. Dogan, Trim analysis of a moving-mass actuated airplane in steady turn, in: 51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 2013.
[44] A. Dogan, S.A. Erturk, Trimming mass-actuated airplane in turns with zero side slip angle, in: AIAA Atmospheric Flight Mechanics Conference, 2014.
[45] S.A. Erturk, O. Daskiran, A. Dogan, Trim analysis of a moving-mass actuated airplane, in: AIAA Atmospheric Flight Mechanics Conference, 2012.
[46] S.A. Erturk, A. Dogan, Controllability analysis of a mass-actuated airplane, in: AIAA Atmospheric Flight Mechanics Conference, 2015.
[47] S.A. Erturk, A. Dogan, Propeller torque effect on cruise trim of standard and mass-actuated airplane, in: AIAA Atmospheric Flight Mechanics Conference, 2015.
[48] S.A. Erturk, A. Dogan, Propeller torque effect on steady-state turn trim of standard and mass-actuated airplane, in: AIAA Atmospheric Flight Mechanics Conference, 2016.
[49] S.R. Vengate, S.A. Erturk, A. Dogan, Development and flight test of moving-mass actuated unmanned aerial vehicle, in: AIAA Atmospheric Flight Mechanics Conference, 2016.
[50] A. Villegas, V. Mishkevich, Y. Gulak, F.J. Diez, Analysis of key elements to evaluate the performance of a multirotor unmanned aerial–aquatic vehicle, Aerosp. Sci. Technol. 70 (2017) 412–418.
[51] T. Haus, M. Orsag, S. Bogdan, Design considerations for a large quadrotor with moving mass control, in: 2016 International Conference on Unmanned Aircraft Systems (ICUAS), 2016, pp. 1327–1334.
[52] T. Haus, N. Prkut, K. Borovina, B. Marić, M. Orsag, S. Bogdan, A novel concept of attitude control for large multirotor-UAVs based on moving mass control, in: 2016 24th Mediterranean Conference on Control and Automation (MED), 2016, pp. 832–839.
[53] T. Petsopoulos, F.J. Regan, J. Barlow, Moving-mass roll control system for fixed-trim re-entry vehicle, J. Spacecr. Rockets 33 (1) (1996) 54–60.
[54] R.D. Robinett III, B.R. Sturgis, S.A. Kerr, Moving mass trim control for aerospace vehicles, J. Guid. Control Dyn. 19 (5) (1996) 1064–1070.
[55] C. Gao, W. Jing, P. Wei, Research on application of single moving mass in the reentry warhead maneuver, Aerosp. Sci. Technol. 30 (1) (2013) 108–118.
[56] R. Li, W. Jing, C. Gao, H. Du, Control system design for reentry warhead with mass moment compound actuate, Aerosp. Control 27 (4) (2009) 43–48.
[57] P. Wei, C. Gao, W. Jing, Roll control problem for the long-range maneuverable warhead, Aircr. Eng. Aerosp. Technol.: Int. J. 86 (5) (2014) 440–446.
[58] J. Li, C. Gao, W. Jing, P. Wei, Dynamic analysis and control of novel moving mass flight vehicle, Acta Astronaut. 131 (2017) 36–44.
[59] J. Li, C. Gao, W. Jing, H. Du, Attitude control of reentry vehicle with a pitch-control single moving mass, Sci. Sin. Technol. 46 (10) (2016) 1048–1056.
[60] J. Li, C. Gao, T. Feng, W. Jing, Novel moving mass flight vehicle and its equivalent experiment, J. Dyn. Syst. Meas. Control 140 (11) (2018).
[61] X. Kong, M. Yang, S.Y. Wang, Attitude control of mass moment and lateral thrust combined control flight vehicle, Comput. Simul. 26 (5) (2009) 52–56.
[62] A.I. Kozynchenko, Development of optimal and robust predictive guidance technique for Mars aerocapture, Dialog. Cardiovasc. Med. 30 (1) (2013) 150–162.
[63] J. Balaram, Sherpa moving mass entry descent landing system, in: ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, 2005, pp. 63–79.
[64] R. Mukherjee, J. Balaram, Attitude dynamics and control of moving mass multibody aeromaneuver vehicle, in: AIAA Atmospheric Flight Mechanics Conference and Exhibit, 2008.
[65] B.M. Atkins, Mars Precision Entry Vehicle Guidance Using Internal Moving Mass Actuators, Ph.D. dissertation, Virginia Tech, 2014.
[66] B.M. Atkins, E.M. Queen, Internal moving mass actuator control for mars entry guidance, J. Spacecr. Rockets 52 (5) (2015) 1294–1310.
[67] D. Halsmer, D. Mingori, The passive coning attenuator (PCA) – internal mass motion and axialthrust combine to produce asymptotic nutational stability, in: Astrodynamics Conference, 1992.
[68] D. Halsmer, D. Mingori, Nutational stability and passive control of spinning rockets with internal mass motion, J. Guid. Control Dyn. 18 (5) (1995) 1197–1203.
[69] Y. Yam, D. Mingori, D. Halsmer, Stability of a spinning axisymmetric rocket with dissipative internal mass motion, J. Guid. Control Dyn. 20 (2) (1997) 306–312.
[70] P.K. Menon, G.D. Sweriduk, E.J. Ohlmeyer, D.S. Malyevac, Integrated guidance and control of moving-mass actuated kinetic warheads, J. Guid. Control Dyn. 27 (1) (2004) 118–126.
[71] L. Chen, G. Zhou, X.J. Yan, D.P. Duan, Composite control of stratospheric airships with moving masses, J. Aircr. 49 (3) (2012) 794–801.
[72] H. Shen, Y. Liu, B. Chen, Y. Lu, Control-relevant modeling and performance limitation analysis for flexible air-breathing hypersonic vehicles, Aerosp. Sci. Technol. 76 (2018) 340–349.
[73] D. Zhang, S. Tang, Q.J. Zhu, R.G. Wang, Analysis of dynamic characteristics of the rigid body/elastic body coupling of air-breathing hypersonic vehicles, Aerosp. Sci. Technol. 48 (2016) 328–341.
[74] R.K. Li, C.S. Gao, W.X. Jing, Y.J. Qian, Moving mass control and performance analysis for aerospace vehicle, J. Astronaut. (2010) 1–7.
[75] J. Li, C. Gao, W. Jing, Y. Fan, Nonlinear vibration analysis of a novel moving mass flight vehicle, Nonlinear Dyn. 90 (1) (2017) 733–748.
[76] Y.F. Wang, Y.U. Jian-Qiao, L.L. Wang, S.U. Xiao-Long, Bifurcation characteristics of reentry vehicle with one moving point mass, J. Syst. Eng. Electron. 37 (6) (2015) 1338–1346.
[77] A.V. Doroshin, Initiations of chaotic motions as a method of spacecraft attitude control and reorientations, in: International Multiconference of Engineers and Computer Scientists, 2016, pp. 15–28.
[78] A.V. Doroshin, Attitude dynamics of gyrostat-satellites under control by magnetic actuators at small perturbations, Commun. Nonlinear Sci. Numer. Simul. 49 (2017) 159–175.
[79] L. Yang, D.Y. Guo, The application of fuzzy PID control by GA to attitude control system of mass moment missile, Mod. Def. Technol. 35 (2) (2007) 47–51.
[80] K. Kumar, Attitude control of miniature satellites using movable masses, in: SpaceOps 2010 Conference Delivering on the Dream Hosted by NASA Marshall Space Flight Center and Organized by AIAA, 2013.
[81] P. Lin, J. Zhou, Researching variable structure control of moving mass reentry-vehicles, in: IEEE International Conference on Computer Science and Information Technology, 2010, pp. 126–129.
[82] Z. Li, Moving centroid reentry vehicle modeling and active disturbance rejection roll control, Acta Aeronaut. Astronaut. Sin. 33 (11) (2012) 2121–2129.
[83] G.B. Liao, Neural networks and adaptive nonlinear control of mass moment missiles, J. Astronaut. 25 (5) (2004) 520–525.
[84] J. Mullen, S.C. Bailey, J.B. Hoagg, Filtered dynamic inversion for altitude control of fixed-wing unmanned air vehicles, Aerosp. Sci. Technol. 54 (2016) 241–252.
[85] Y. Chang, T. Jiang, Z. Pu, Adaptive control of hypersonic vehicles based on characteristic models with fuzzy neural network estimators, Aerosp. Sci. Technol. 68 (2017) 475–485.
[86] C. Gao, J. Li, Y. Fan, W. Jing, Immersion and invariance-based control of novel moving-mass flight vehicles, Aerosp. Sci. Technol.AESCTE4772 74 (2018) 63–71.