

Transmedia Vehicle Inbound Load Lowering: Research and Progress

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Abstract: Transmedia vehicle can travel freely between the two media of water and air, which is regarded as an important branch technology for the development of future vehicles. However, the transmedia vehicle water entry process is accompanied by large impact loads, and the sudden change of loads can easily cause damage to the head structure of the vehicle, which seriously affects the stability and safety of the vehicle and poses a great challenge to the safety of the on-board equipment. This paper summarizes the main research ideas at home and abroad and puts forward the future outlook around the method of vehicle water entry load reduction. At present, the relevant methods and technologies of transmedia vehicle water entry load shedding are still immature, and the research on the improvement of the head shape of the vehicle, the design and improvement of the skin material and structure are the focuses of the research, and numerical simulation and model test are the main research methods of vehicle water entry load shedding.

Keywords: transmedia vehicle, inlet load reduction, structural optimization, material design, inlet jet

1. Introduction

At present, with the vigorous development of marine science and the increasing diversification of human marine activities, the efficiency of traditional single-media vehicles can no longer meet the demand for the use of air and sea cross-domain missions, and researchers are focusing their attention on transmedia vehicles. Transmedia vehicles can freely transition between air and water, two media with different densities, and can survive in amphibious environments for a long period of time, so they have been widely used in both military and civilian fields.

The mission scenarios of transmedia vehicles include four scenarios of air navigation, underwater navigation, and in and out of water movement, among which the in-water stage is the most complicated one in terms of mechanical properties of transmedia vehicles. In the standard state, the density of water medium is 775 times that of air medium, causing a sudden change of load at the moment of water entry, resulting in a strong impact load on the vehicle, characterized by short duration and high pressure peak. This condition can lead to damage to the airframe structure, especially the head structure of the vehicle, and pose a great challenge to the safety of the equipment.

The mainstream solutions focus on four aspects: optimizing the shape design of the vehicle head to achieve load shedding, using special materials to make the vehicle head or masking on the vehicle head to absorb energy and load shedding, using gas for load shedding, and adding shock absorbers. This paper focuses on these four methods.

2. Head Shape Optimization

Existing studies have shown that the head shape of a vehicle affects the contour and area of the vehicle in contact with the water, which in turn affects the in-water impact load. The existing vehicle head design mainly comes from two ideas: one is from the existing research or improvement of the vehicle with flat head, conical head, ellipsoidal head and other head types, and the other is the bionic design.

2.1. Optimization of Existing Head Shape

Studies comparing trajectories, velocities, and forces of various head shapes during water entry reveal that impact loads on ellipsoidal heads depend on head geometry parameters, and that the maximum water entry impact load on the projectile decreases when the ratio of the short and long axes of the head shape increases, and that the conical head-shaped projectile suffers the smallest impact load when entering the water at low velocities. Wang [1] loads of a flat-head-shaped, cone-angled, spherical and ellipsoidal head vehicle during vertical water entry at different velocities, and found that the ellipsoidal head was subjected to the smallest loads. Ma et al. [2] the optimal solution of the head profile curve of transmedia vehicle by using the RBF agent-based model and multi-island genetic algorithm based on the existing transmedia vehicle water entry research: it is between ellipsoidal and pointed head profile, combining the characteristics of different regions of ellipsoidal and pointed head profiles, with ellipsoid-like front end, and the slope of change of the back end of the head is more gentle compared to that of the pointed head profile. The optimized head shape builds 60.16% of the maximum impact stress than the flat head shape.

2.2. Bionic Shape

Organisms have evolved a series of excellent morphological structures through long-term natural selection. Most of the existing studies on the bionic shape of transmedia vehicles are based on the head of waterbirds. Waterbirds such as boobies and kingfishers dive into the water from high altitude to catch fish in order to achieve fast water entry. Sharker et al. [3] fabricated a number of waterbird head shapes for water entry impact tests and analyzed the effects of the head shape and the water entry method on the safety of water entry impacts, and found that the head shapes of the dive-entry waterbirds could reduce the impact loads better than those of glide-entry waterbirds. Crandell et al. [4] analyzed the effect of head shapes on the safety of water entry impacts through the water entry impact tests. et al. [4] demonstrated that the beak and head shape of waterbirds are the key to load reduction through water entry tests and CFD numerical simulation methods. Wu [5] et al. utilized the kingfisher head model and designed the ovoid head spinning into a body as shown in Fig:

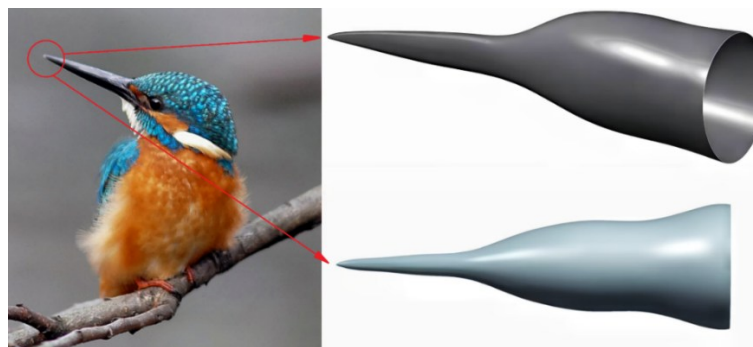


Figure 1: Kingfisher and kingfisher head model [5,6].

The equation of its head curve is:

$$y = \frac{D}{2} \sqrt{1 - \frac{x^2}{L^2}} \quad (1)$$

Where $D = 30\text{mm}$ is equal to the diameter of the kingfisher head-shaped elongate body, and $L = 30\text{mm}$ is the head length of the spinning body. He found that the Kingfisher head-shaped elongated body was effective in suppressing the peak axial impact acceleration and reducing the drag force of the elongated body during the early stage of water entry. Afterwards, Wu et al. used the kingfisher head size as a benchmark and the body of the dragon louse as a basis to construct the fuselage of the transmedia vehicle.



Figure 2: Model of dragon louse and dragon louse body [6].



Figure 3: Splice model of kingfisher head and dragon louse body [5].

This design reduces peak impact acceleration by 71% at an entry velocity of 3.96 m/s.

Luo et al. [7] designed several typical configurations based on Wu et al. using a bird's wing as a bionic object, with reference to the flight process of boobies, and compared with the traditional streamlined fuselage, it is found that this combined bionic fuselage makes the maximum value of the surface pressure of the vehicle in the process of water ingress reduced by 20.9%, and the maximum overload is reduced by 39.4%. It can be seen that the combined bionic fuselage has a great advantage in water entry performance, and the smaller impact load also improves its safety.

3. Special material load shedding

The skin of the head of the aircraft can be downgraded using special materials. Common materials are porous materials and multicellular materials.

3.1. Porous materials

A solid containing pores distributed in an arbitrary or regular manner within it can be called a porous medium, a common space occupied by a liquid or a gas or by a multiphase substance, with the solid phase as the solid skeleton, and the space without a solid skeleton is called a pore.

Wang [1] selected a flat-head type vehicle as the object of study, compared the use of different porosity of the metal medium, the use of different thickness of the porous medium of the front end of the vehicle, and found that the metal porous medium in the thicker can significantly reduce the peak value of the load suffered when entering the water, and the lower the porosity of the head of the vehicle suffered the smaller the load.

The porous materials commonly used in the market for aircraft skins are porous titanium alloys, porous stainless steel and porous nickel, and their main properties are as follows:

Table 1: Classification of commonly used metal porous materials.

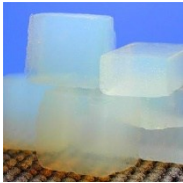
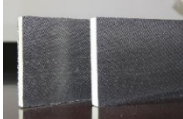
Commonly used metal porous material categories	Common Manufacturing Methods	Dominance	Flaws
Porous Titanium Alloy	Powder metallurgy method: technically relatively mature, but the distribution of porosity and the control of the structure are difficult. Selected laser melting method: technically difficult.	High specific strength, high structural strength while reducing weight, good corrosion resistance and stable high temperature performance.	Commonly used manufacturing methods are costly, difficult structural connections, and difficult to process.
Porous stainless steel	Powder metallurgy method, wire mesh sintering method: relatively mature technology. Chemical corrosion method: technically difficult.	Excellent corrosion resistance, controllable cost, good processability	High density, poor high temperature performance, poor electromagnetic shielding performance
Porous Nickel	Electrodeposition method: technically difficult. Powder metallurgy method: technically relatively mature.	Good electrical and thermal conductivity, good corrosion resistance	Commonly used manufacturing methods are high cost, relatively low structural strength, high temperature, high humidity environment performance is not stable

3.2. Multicellular materials

Multicellular materials refer to materials with a large number of internal pores and a certain cell structure, which have excellent structural properties such as low density, high specific strength, high specific stiffness, etc. Xu et al. [8] designed several biomimetic honeycomb structures with corrugated features with reference to the microstructure of pomelo peels; Yang et al. [9] designed a bi-directional sinusoidal dot-matrix sandwich structure with reference to the hard tail structure of mantis shrimps; Ha et al. [10] proposed a bionic wavy honeycomb sandwich structure based on the beak of a bionic

woodpecker, and the energy absorption efficiency of the wavy honeycomb structure was increased by 125% compared with that of the traditional honeycomb sandwich panel.

Table 2: Classification of multicellular materials.

Multicellular material categories	Representative material	Featured Image	Structural characteristics	Dominance	Flaws
Metal polytope	Aluminum foam, copper foam		The pores are of various shapes, usually irregular polyhedra, with a wide size distribution and interconnected or partially connected pores.	High specific strength and specific stiffness to reduce weight while maintaining good mechanical properties	Complex production process, high cost, poor corrosion resistance
polymer multicellular material	Foam, aerogel		Both open and closed pores, large and unevenly distributed pore size, high porosity	Low density, good thermal insulation, good processability	Low mechanical strength, not suitable for high temperature and humid environment
Composite-based multicellular materials	Carbon fiber reinforced foam, glass fiber reinforced porous ceramics		Pore structure varies according to the ratio and distribution of matrix and reinforcing phase, etc.	Combines the benefits of many materials and can be customized to meet your needs	Complex preparation process, high cost, low interfacial bonding stability

4. Gas buffer load shedding

There are three main research ideas for the gas load shedding method approach: aerodynamic speed reduction and load shedding using parachutes; the use of flexible airbag cushioning devices; and the creation of an air layer on the outside of the head of the vehicle when entering the water.

4.1. Pneumatic load shedding

This method is based on the aerodynamic deceleration principle of parachute, when the parachute is unfolded, the contact area between the parachute surface and the air will be significantly increased, and at the same time, the shape of the parachute surface will cause the direction of the airflow flow to be opposite to the descending direction of the vehicle, which further increases the aerodynamic

resistance of the parachute and realizes the deceleration function. This method has begun to be applied to UAV safe landing and recovery systems, but is limited on transmedia vehicles by issues such as weight, layout and shape, and whether it can be reused.

4.2. Flexible airbags

When a flexible airbag is subjected to impact load, the compression flow of the internal gas can significantly cushion the impact force, thus reducing the impact of the impact load on the vehicle. Chen et al. [11] analyzed the deceleration characteristics, attitude change and depth of water entry of airbags and vehicles under different water entry angles by the process of water entry of airbags with annular closed cartridges. For the practical application of transmedia vehicles, flexible airbags can simultaneously meet the two application requirements of water entry load shedding and adjusting underwater buoyancy, which has a strong development prospect.

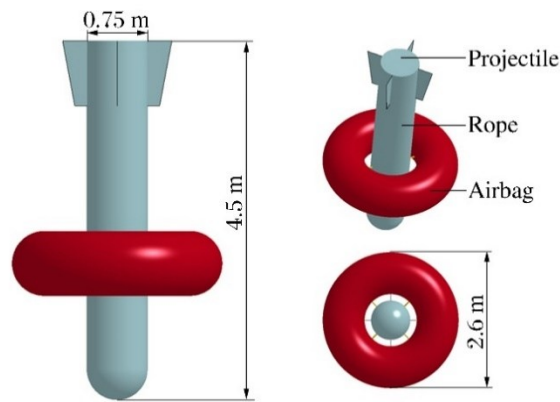


Figure 4: Schematic diagram of a flexible airbag with a ring [11].

4.3. Air layer

This method consists of two solutions, one is to inject gas into the water by making slits in the surface and setting up ventilation holes, which contributes to the formation of air bubbles in the water; the other is to launch a forward throw before the head of the vehicle touches the water, which will form air bubbles when it enters the water, and the vehicle will be the first one to enter the air bubbles when it enters the water.

Wei et al. [12] studied the effect of the head jet volume on the impact load through numerical simulation, and the results show that: the head jet can effectively reduce the impact load into the water, delaying the time of the peak load; its head and the side of the air bubble shell generated to reduce frictional resistance, with the increase in the volume of the jet, the more obvious the above effect.

Rabbi et al. [13] studied their water entry properties using tandem spheres. He defined the time dimensionless constant $Mt = \frac{|t_2 - t_1|}{t_p}$ to represent two possible cases of vacuoles, where t_1 and t_2 denote the time at which the front end of the two spheres enters the water surface, and t_p denotes the up-to-date time of the cavity created by the first sphere, respectively. When $Mt < 1$, the rear-firing sphere enters into the developing cavity; when $Mt > 1$ the rear-firing sphere interacts with the collapsing cavity. The load reduction ratio can be up to 78% in the former case and 90% in the case of tilted entry, but the latter is instead likely to impose a larger load on the vehicle. Yu Wang [1] investigated the development process of vacuoles for vehicles with different head shapes at different initial velocities of water entry, and showed that the radius of the vacuole formed by a flat-head vehicle is the fastest in decreasing, followed by vehicles with conical and spherical heads at different angles,

and the ellipsoidal head vehicle decreases the slowest. This method is novel, but there are fewer studies on this method, and there is a big limitation when it is really applied in practice, especially in the military field, the radar reflection when entering the water needs to be taken into account.

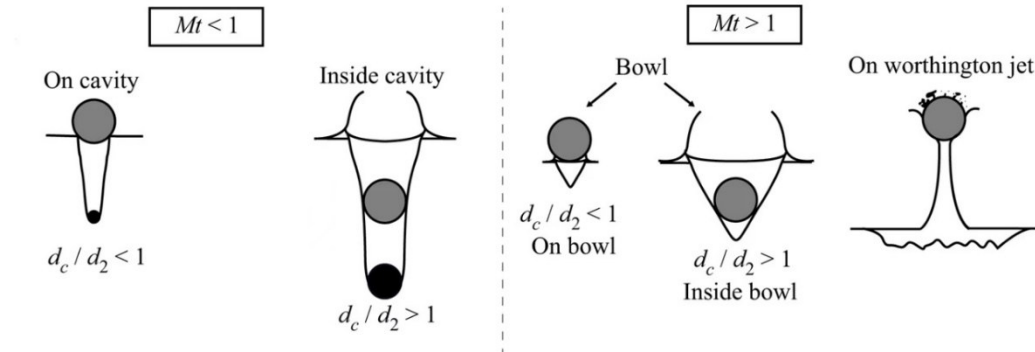


Figure 5: Schematic representation of a tandem sphere entering water [13].

5. Shock absorber load shedding

In addition to the previously described shock absorbers using flexible cushioning airbags, common methods include bionic structure-based shock absorbing designs, the use of shock absorbing hoods, and spring loaded shock absorbers.

5.1. Bionic design

Studies have shown that an elongated conical shape significantly reduces initial impact forces. The necks of seabirds such as brown boobies, northern pond geese, and gulls utilize this principle to allow them to enter the water at higher velocities without sustaining injuries. Brain et al. [14] quantitatively analyzed the effects of neck musculature and head geometry on the stability of the neck of the pond goose during entry into the water by simplifying the neck and head of the goose into an elongated elastic beam attached to a rigid tapered head, and the results showed that both the length and stiffness of the elastic beam and the taper of the conical head representing the head play important roles in reducing neck impact injuries. The results showed that both the length and stiffness of the elastic beam and the taper of the conical head representing the head play an important role in minimizing neck impact injuries. For comparison, experimental data from Sharker et al. [3] on real or 3D-printed almost models of birds make the study of the physical mechanisms of the load shedding process more reliable. Inspired by the neck contraction behavior of the kingfisher during water entry, Wu et al. [5] designed and fabricated a functional bionic spinner using a functional bionic approach by introducing a linear spring between the head and the body of the ovoid head spinner described in the previous section. The results showed that this design reduced the peak impact acceleration of the shell by 71% at a water entry velocity of 3.96 m/s. The results showed that the peak impact acceleration of the shell was reduced by 71% at a water entry velocity of 3.96 m/s.

5.2. Shock-absorbing headgear

The use of cushioning material in the direction of the vehicle's descent can protect the vehicle by absorbing energy in contact with the water surface when it enters the water. The shock-absorbing cowl has two major load reduction mechanisms: one is that the fragmentation of the protective cowl will produce violent disturbances on the liquid surface, and the subsequent head of the vehicle will contact the water surface as if it were a secondary water entry; and the other is that the foam aluminum plate inside the cowl can effectively attenuate the pressure peaks and further reduce the impact load.

Wang et al. [15] modified the equation of the intrinsic relationship of polyurethane foam under impact loading conditions to study the cushioning effect of the protective cowl. The analytical results show that the modified constitutive relation has the advantages of simplicity and versatility, and the effect of load shedding into water increases with the decrease of foam density and the shape parameter of the protective hood. Yao et al. [16] carried out the cushioning hood damage test into water, revealing the stages and processes of cushioning hood failure and damage and verified them through numerical simulation comparisons, and found that the failure criterion and the strain rate effect can lead to a large error in the results of numerical simulation. It is found that both the failure criterion and strain rate effect can lead to large errors in the numerical simulation results. The limitation of the cushioning cowl is that it may be damaged after entering water, and cannot realize the load reduction efficiency when re-entering water, so it is not applicable to transmedia vehicles that enter water repeatedly.

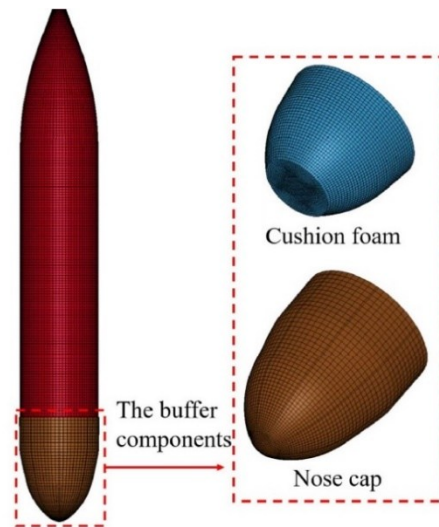


Figure 6: Schematic of the head cushioning cowl of the aircraft [16].

5.3. Spring dampers

A spring is introduced into the head of the vehicle to convert the kinetic energy of its collision with the free surface into the potential energy of the spring, a process that extends the time scale of the impact load and reduces the peak load. Wu et al. [17] designed a compressible nose-segmented projectile with a spring connection and qualitatively investigated the effect of the compression of the head on the initial impact acceleration, and the experimental results showed that the spring cushion can suppress the peak acceleration of the initial stage of the collision by means of the inlet process of the conversion of elastic energy to suppress the peak acceleration at the initial stage of collision.

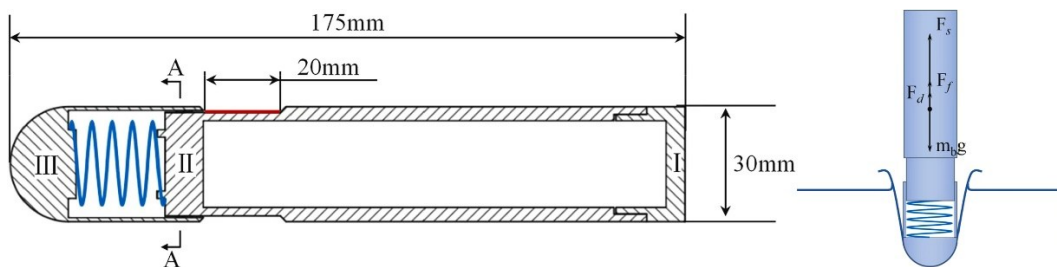


Figure 7: Schematic of spring damper structure and water entry in the head of the vehicle [17].

6. Integrated vehicle performance

For the consideration of the comprehensive performance of the vehicle, on the basis of the vehicle into the water to drop the load, the above mentioned drop methods also need to consider the impact on different vehicle sizes, and the stealth performance and sea surface communication.

Existing vehicle launching methods mainly include slide launching, splashdown launching and floating launching. Splashdown entry, also known as dive entry, is characterized by high speed and large impact load during the entry process; drift entry refers to the vehicle decelerating through the tension generated by its own rotor blades and then landing smoothly on the water surface. At present, small-sized vehicles often use splashdown and driftdown water entry, in which the driftdown water entry itself is subjected to the impact load of water entry is small, and due to the small-sized transmedia vehicle mass is small and the current experimental selection of materials used in most of the small-sized objects, splashdown water entry is subjected to the impact load is also relatively small, therefore, the current strategy is more effective for the small-sized cross-border in the vehicle load reduction. However, for the large-size transmedia vehicles, they mostly use splashdown water entry and have a large mass, so the effect of the current load-lowering methods will be relatively limited.

When using some of these methods, the addition of devices may affect the stealth performance of the vehicle, which should be avoided in consideration of military requirements. Rabbi's [13] loading strategy produces a forward throw of the head of the vehicle, and Zhao et al. [18] also investigated the effect of Orbital Angular Momentum (OAM) beams on the Radar Cross Section (RCS) effect by utilizing two metal spheres. Cross Section (RCS) effect, and found that different OAM modes have a significant effect on RCS. In addition, the complex water conditions that may be encountered by aircraft during surface activities, as well as the mutual interference of communication channels that may be generated by the communication between multiple aircrafts may affect the performance of their communication. Zhao et al. [19,20] have developed a RIS signal control board and an OAM antenna that can deal with the signals in complex environments, and Zhao et al. [21] also utilized the meta-surface to separate different communication channels, which can be used on the aircraft to effectively deal with the needs of real-time communication of multiple aircraft in complex environments.

7. Summary and outlook

Transmedia vehicles have the ability to enter and exit water repeatedly, and can efficiently accomplish water-air trans-area missions, which is one of the important directions for the development of future vehicles. Generally speaking, although great progress has been made in the method of transmedia vehicle's water loading and unloading, there is still a certain distance from its repeatable water loading and unloading to cope with complex mission scenarios. Considering the practical application requirements of transmedia vehicles, there are still a lot of issues worth studying.

(1) Research based on complex water entry task scenarios. Most of the existing research is based on vertical and head entry, and there is insufficient research on different angles, different attitudes and even more complex entry requirements. Common transmedia water entry methods include dive entry, slide entry, and drift entry. Among them, the tail of the vehicle touches the water first, so the optimization of the tail of the vehicle is still needed; the dive entry often involves different angles of water entry, so more research on water entry and load shedding based on different angles is needed.

(2) Research on Repeatable Use of Vehicles. Existing research still has a lot of designs that are not recyclable and cannot meet the demand for repetitive use of transmedia vehicles. When the mission requires frequent water entry and exit, the use of parachute and forward body entry cannot meet the demand, the use of cushioned cowl entry and lowering can only be used a small number of times due

to the rapid damage of the cowl, and other methods of water entry and lowering are still immature. Research on multi-part structure optimization and reusable methods is the key to solving this problem.

(3) Research on water entry in complex sea conditions. Most of the existing researches are based on the still water environment, but in the marine mission scenario, the vehicle water entry environment may also include waves, gusts of wind, surface currents, ice floes and other complex conditions, which will seriously affect the stability of the fuselage into the water, and the loads of the vehicle into the water will also have a huge difference with the still water state, so more researches on the load reduction of water entry in the complex water conditions are needed.

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