

Study on the Method of Calculation of the Additional Mass of Parachute

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Abstract

As is well known, the air drag experienced by a parachute when it is open is one of the important parameters that must be taken into account in studying the parachute opening process. If this term is not calculated correctly, it can have a negative effect on the parachute canopy, and may lead to errors in the number of parachute strings, the nominal diameter of the parachute, and the material selection, and eventually to parachute failure. Generally, there are several hydrodynamic methods in this calculation, including modeling the recovery system dynamic equations based on the drag characteristics in the calculation of canopy forces and calculating the load change during parachute opening. Thus, it can be seen that the accurate determination of the added mass is crucial for the calculation of the forces that the canopy experiences during parachute opening. In the past, the added mass was based on the assumption of an ideally expanded canopy shape using the added mass coefficient method, but no research on the added mass coefficient method has been developed so far. To this end, this paper formulates the concept of the additional mass of the parachute and develops the UAV-parachute system equations of motion. Also, through numerical calculations, two engineering calculations of the added mass are presented : the internal mass method and the expansion radius method. Considering both methods, it was concluded that the dilatation radius method is better for calculating the radial and axial additional mass of the parachute.

Keywords: Aerodynamic decelerator, open process, arbitrary lagrangian euler method (ALEM), infinite mass, parachute rope

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INTRODUCTION

Parachutes are used not only as a means of saving pilots' lives from aircraft air accidents, but also as a means of transporting and delivering people and materiel into the air.

Parachutes are also used for sports games as the technology of parachute making and descent is developed.

Recently, there has been a radical improvement in the structure and performance of parachutes, and their applications are growing.

In particular, the parachute is strong vertically and can fly in a horizontal direction and its control is flexible so that it can fly in a proper way at the destination of parachute. Therefore, it is widely used in various sports games and military field.

Therefore, the DPRK is faced with the task to expand the variety of parachute and further perfect it and at the same time expand the field of its use.

The introduction of computer simulation in the research and development of new parachutes of our own style with superior structure and performance will save much development cost and effort.

Although the working principle of a parachute is simple, the analysis of the related work is by no means easy.

For example, air filling of a parachute is a complex physical process occurring in a short time, and rapid changes in the appearance, air power, mass characteristics, and weight of the parachute result in a combination of turbulence and the fluid structure that the parachute fabric operates.

Due to the complexity of the parachute working process, it is difficult to accurately model and analyze the implementation theory, and the parachute design often requires large-scale wind tunnel tests and aerial drop tests to confirm and verify the final state of the art.

To obtain satisfactory analytical results for the parachute dynamics problem, it is very important to determine the exact weight of the parachute added.

The U.S. is developing a specialized study of parachute-added quality during the parachute research and manufacturing of Orion, and is trying to combine theoretical modeling and testing to increase the calculation accuracy for parachute-added quality, thus ensuring the reliability of the key performance parameter simulation analysis during the entire parachute system operation [1].

Although our country has been working on the problem of added mass of parachute for many years, no study has been carried out on how to determine the added mass coefficient in the dynamics analysis of parachute.

To this end, we have investigated the method of calculating the added mass of a parachute by the expansion method.

CONCEPT OF THE ATTACHED MASS OF A PARACHUTE

The body is subjected to inertial resistance when moving in a variable speed ideal fluid under the action of an external force, and the inertial resistance is expressed in the form of momentum, as if the mass of the fluid in which the body interferes is increased, and the mass of this part is called the additional mass [2].

Additional mass is a generalized concept and includes not only translational mass terms but also rotational inertia terms and the combination of translational and rotational motion.

The additional mass and the additional mass moment of inertia are vector quantities, and in the six-degree-of-freedom equations of motion, both the additional mass and the additional mass moment of inertia have 36 fractions, which are shown in the added mass matrix.1.1. SPH governing equations in the fluid flow field

The conservation equations for a continuous fluid are written as follows:

$$M_f = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} & \lambda_{16} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} & \lambda_{24} & \lambda_{25} & \lambda_{26} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} & \lambda_{34} & \lambda_{35} & \lambda_{36} \\ \lambda_{41} & \lambda_{42} & \lambda_{43} & \lambda_{44} & \lambda_{45} & \lambda_{46} \\ \lambda_{51} & \lambda_{52} & \lambda_{53} & \lambda_{54} & \lambda_{55} & \lambda_{56} \\ \lambda_{61} & \lambda_{62} & \lambda_{63} & \lambda_{64} & \lambda_{65} & \lambda_{66} \end{bmatrix} \quad (1)$$

In the equation, M_f is the additive mass matrix, λ_{ij} is the additive mass component, ($i, j = 1 \sim 6$).

As for axisymmetric parachute, the additional mass terms are the mass terms $\lambda_{11}, \lambda_{22}, \lambda_{33}, \lambda_{55}, \lambda_{66}$ and the three preceding terms are related to the coordinate direction.

The latter two terms are the moment of inertia terms, which affect the angular velocity and are related to the coordinate direction and the position of the origin.

Also, among the mass terms λ_{22} and λ_{33} are the same, while in the moment of inertia λ_{55} and λ_{66} are the same [3].

Regarding parachute, especially during parachute air filling, the acceleration and magnitude are relatively large, and the influence of the additional mass must be taken into account in the calculation of the parachute load.

In general, the drag force acting on the parachute during the fall can be expressed as

$$F_s = \frac{1}{2} \rho V^2 \cdot (C_x A) + (M_A + M_V + M_P) \cdot \frac{dV}{dt} + V \cdot \frac{dM_A}{dt} + W_V \cdot \sin \theta \quad (2)$$

In the equation, F_s is the drag of the parachute, ρ -air density, V -velocity, C_x is the parachute drag coefficient, A is the reference area, M_V, M_P, M_A are the aircraft mass, parachute mass, weighted weight, W_V is the aircraft gravity, t is the time, and θ -ballistic tilt angle, respectively [4].

From the above equation, it can be seen that the additional mass has a significant effect on the drag of the parachute.

Therefore, clarifying the method of determination of the added mass is of great importance for parachute design and application.

NUMERICAL CALCULATION METHOD OF THE ADDED MASS OF PARACHUTE

Based on the derivation of the fluid motion law, each additional mass term can be determined by Eq. (3).

$$\lambda_{ij} = \iint_S \rho \phi_j \frac{\partial \phi_i}{\partial n} dS \quad (i, j = 1 \sim 6) \quad (3)$$

In the equation, ϕ_j is the velocity potential function of the flow field, n is the unit external normal vector of the surface area, and S is the surface area of the body [5].

It follows that the main thing in calculating the added mass is to calculate the potential function.

To this end, numerical methods based on BEM are used.

To determine the distribution strength, an algebraic equation can be obtained by choosing the appropriate “control point” for the parachute so that the potential function satisfies the conditions of the winding flow at the control point [6].

Assuming that the ambient air is an incompressible gas when the parachute is working and that the velocity potential satisfies the Laplace equation in the flow field, it has the following governing equation:

$$\nabla^2 \phi = 0 \quad (4)$$

When calculating the parachute-coated surface by dividing it into N elements, placing the same intensity source on each element and setting the control point, the velocity potential of each control point can be expressed as

$$\phi(X_0) = \sum_{k=1}^N q_k \int_{S_k} G(X_0, X) dS \quad (5)$$

In the expression q_k is the source strength, $G(X_0, X)$ is the Green's function, k is the element sequence number ($k=1, 2, \dots, N$), N is the element quantity.

That is, the velocity potential and velocity at each control point can be obtained through superposition of all source effects, and the combination of the governing equations and boundary conditions can be used to obtain a linear algebraic system of equations for the strength of each elementary source [7].

After solving this system of equations, we can obtain further velocity potential and velocity of any point in the flow field and finally obtain the additional mass of the parachute using Eq. (6).

$$\lambda_{ij} = \iint_S \rho \phi_j \frac{\partial \phi_i}{\partial n} dS = \sum_{k=1}^N \rho(\phi_j)_k \left(\frac{\partial \phi_i}{\partial n} \right)_k S_k \quad (6)$$

The CFD program is used to calculate the additional mass of the body, first modeling the flow field around the body, partitioning the grid and providing boundary conditions.

And when it is calculated, the body undergoes unsteady motion according to the laws of motion established in the flow field, calculates the force and moment exerted by the fluid on the body, and calculates the additional mass of the body through the analysis of the force exerted by the body.

To simulate the motion of the parachute, dynamic mesh can be used to solve the motion of the domain for inertial coordinate systems or to add a source term to the momentum equation to ensure the accuracy of the flow field pressure distribution [8].

In [9], the calculation of the additional mass was carried out using CFD software during air filling of a planar circular parachute.

Overall, it is concluded that the instantaneous shape of the parachute must be clarified, whether the modeling solution is obtained using BEM or the additional mass of the parachute is calculated using CFD software.

Since the change of the continuity rate after the parachute is in steady state of operation is slow, the effect of the additional mass on the system's motion and load is considered to be very small.

During the parachute air-filling deployment, the shape of the parachute is very complex, highly

variable, and affected by various factors such as wind field, load-motion variation, etc.

To calculate the added mass accurately, the correct parachute air-filling process must be obtained according to the numerical method described above.

To obtain the variation of the parachute ventilation profile, the parameter identification should be performed on the basis of images taken during the combined CFD and flow solids simulation analysis, wind tunnel tests, and air-drop tests.

METHOD OF PROCESS CALCULATION

The numerical calculation of the added mass of the parachute is very complicated and is generally done using the process calculation method.

The domestic and foreign scholars have proposed a variety of methods to relate the characteristics of the air-filling process of the parachute, including the calculation of the resistive area, the calculation of the internal mass and the calculation of the air-filling radius.

Resistance Area Calculation Method

The method of calculating the area of resistance is a method that assumes that at any time the additional mass of the parachute is determined by the area of resistance [10].

$$M_A = k_A' \rho (C_x A)^{3/2} \quad (7)$$

In the equation, k_A is the additional mass reference coefficient based on the resistive area and is generally confirmed by experiments.

In Ref. [1], the U.S. identified the additional mass of the parachute according to this method when studying and manufacturing the parafoil of the Apollo, but the detailed coefficient values were not disclosed.

Internal Mass Calculation Method

This calculation focuses on the mass of air contained inside the parachute and the external mass that it is released.

The additional mass of the parachute is expressed as the sum of two parts, the internal mass and the external mass.

The internal mass refers to the air mass contained in the parachute at any time, while the external mass refers to the additional mass calculated according to the potential flow theory [11].

The calculation method of the additional mass of the parachute is as follows.

$$M_A = M_{in} + M_{ap} \quad (8)$$

In the expression, M_{in} indicates the internal mass of the parachute and M_{ap} indicates the external mass.

In this method, the internal mass is determined from the air density and the shape of the parachute at that time.

Based on the potential flow theory, the external mass also depends on the parachute external shape.

For axisymmetric parachutes, we can assume the shape of the parachute during air filling is hemispherical and add again a segment of the ideal shape of the conical shape, based on [2], the equation for calculating the internal mass and external mass during air filling is as follows:

$$M_{in} = \frac{2\rho D_0^3}{3\pi^2} \left[1.058 - \frac{(T^* - 1.31)^2}{1.62} \right]$$

$$M_{ap} = \frac{\rho}{4} \frac{D_0^3}{\pi^2} T^{*5/2} \quad (9)$$

In the equation, D_0 indicates the nominal diameter of the parachute, T^* is the normalization time, and t_m is the parachute's filling time.

Gas Filling Radius Calculation Method

Similar to mass calculation, air-filling radius calculation also needs to determine the air mass contained inside the parachute, i.e., the internal mass.

However, different from the internal mass calculation method, this method can be determined by multiplying some coefficient whose additional mass depends on the internal mass of the parachute without considering the external mass.

A simple model can be developed for axisymmetric parachute air filling processes, characterized by variations in air filling radius R_c for radial motion changes except for axial motion [12, 13].

Then the corresponding parachute weighted mass is divided by the radial weighted mass M_{Ar} and the axial weighted mass M_{Ax} , which are determined by Eqs. (12) and (13), respectively.

$$M_{Ar} = \rho k_r' V_{in}' \quad (10)$$

$$M_{Ax} = \rho k_x' V_{in}' \quad (11)$$

In the equation k_r is the radial weighted mass coefficient, k_x is the axial weighted mass coefficient, and V_{in} is the packing gas of the parachute.

The k_x and the dimensionless air-supply radius (i.e., the ratio of the air-supply radius of the parachute at any time and the full-filled air-supply radius) are directly proportional, which can be determined by Eq. (14).

$$k_x' = k_{xf0}' \cdot R_c^* = k_{xf0}' \cdot \frac{R_{c(t)}}{R_{cp}} \quad (12)$$

In the equation, k_{xf0}' indicates the initial air filling factor, R_c^* the secondary air filling radius, $R_{c(t)}$ the air filling radius at any time, and R_{cp} the air filling radius at the full filling of the parachute.

In the previous work, we can take k_r' based on wind tunnel and flight test data for parafoils with different shapes and areas, where the initial air-filling coefficient can be expressed as a square function of the gas-filling initial velocity and the system-stabilized falling-rate ratio, and the magnitude of k_x' can be selected and calculated based on the interpolation curve shown in Figure 1 [14].

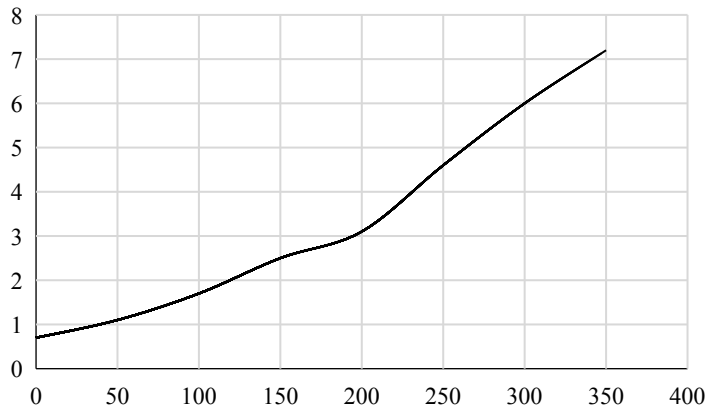


Figure 1. Original term interpolation curve of axial added mass coefficient.

In Equation 13, N_h is the square of the ratio of the initial air filling velocity V_i of the parachute and the steady-state falling velocity V_s of the system.

$$N_h = \left(\frac{V_i}{V_s} \right)^2 \quad (13)$$

The internal mass of the parachute is determined by the shape and size of the parachute at any time.

Based on Refs. [15-17], assuming the shape of the parachute is a typical hemisphere, the internal mass of the parachute can be further simplified.

$$M_{in} = \rho \cdot \frac{2\pi R_{c(t)}^3}{3} \quad (14)$$

A more accurate method is to perform an analytical calculation of the gas charge by referring to the actual image of the gas filling process [15].

For example, reference to [16] shows that using the aerial drop test video, a parachute approaches an ellipsoid during gas filling and calculating the gas filling area using an ellipsoid is more accurate than the shape of the hemisphere and cone assemblage.

COMPARATIVE ANALYSIS OF DIFFERENT PROCESS CALCULATION METHODS

Calculation of the Resistance Force Area

Features

At any time, the additional mass of the parachute is determined by the resistive area, and the accuracy of the calculation of this method is determined by the accuracy of the resistive area and the reference coefficient, and is therefore corrected using experimental data.

Applications

In the case of parafoil, it is advisable not to use it as much as possible.

Method of calculation of internal mass

Features

This method depends on the air quality contained inside the parachute, and the additional mass is the sum of the internal mass and the external mass.

Applications

In this method, external mass must be calculated based on the potential flow theory and the results

of the present calculations of isovolumic ellipsoids are assumed, which can lead to relatively large errors.

The present experiment is difficult to obtain the external mass of the parachute, and it is difficult to modify the calculation results [17].

However, this method can be used for new parachute models where experimental data are lacking.

Calculation of air filling radius

Features

The additional mass is calculated by multiplying the internal mass of the parachute by a certain coefficient that is correlated.

The radial weighted mass coefficient is considered constant.

The axial additional mass coefficient is also calculated by considering the relative change of gas filling radius.

Applications

The calculation error of this method is mainly determined by the calculation error of the filling volume of the parachute and the selection error of the reference coefficient.

Currently, the most used method is the one.

APPLICATION OF PARACHUTE ADDITIVE MASS CALCULATION

Regarding parachute process applications, the calculation of the additional mass is mainly considered in two aspects.

First, additional mass should be considered in the dynamic simulation analysis of the parachute system.

The results of the present study showed that the effect of the added mass can be almost neglected when the density of the body is much larger than that of the surrounding fluid.

When the difference between the density of the body and the surrounding fluid density is not large, the influence of the additional mass must be taken into account in the dynamic modeling.

Since the parachute is made of a flexible superradiant material, its average density is comparable to the air density.

Therefore, additional mass must be considered when establishing a dynamic simulation analysis model of a parachute.

Second, additional mass must be considered to determine the drag of the parachute.

The maximum load on the parachute is when the parachute has its full shape, i.e. when it is fully filled.

For parachute diversion in an infinite mass situation, the dynamic load factor method is often used to calculate the maximum divergence load of a parachute, and for parachute diversion in a finite mass situation, another method is used.

For different parachute types, the dynamic load factor and dynamic load reduction factor all use the data obtained based on the test data.

According to the gas-filling radius calculation method described in this paper, the mass term in the additional mass matrix can be determined.

However, for the moment of inertia term in the additional mass matrix, we do not take the reference coefficient value corresponding to the current air-filling radius calculation, and we have to calculate the additional moment of inertia according to the air corresponding to the air-filling type of the parachute.

For example, assuming that the gas-filled volume of the parachute is a hemispherical volume determined by the gas-filled radius, the additional moment of inertia can be calculated according to Eq. (15).

$$\lambda_{55} = \lambda_{66} = \rho \cdot \frac{2\pi R_{c(t)}^3}{3} \cdot \frac{R_{c(t)}^2}{4} = \rho \cdot \frac{\pi R_{c(t)}^5}{6} \quad (15)$$

For the application of parachute peak parachute load calculation, we take as an example some parachute moderator.

The moderator is a conical belt parachute with a mass of 0.17 kg, nominal area of 0.35 m² and resistance area of 0.122.5 m², and a recovery weight of 14 kg.

The recovery is ejected at 1,800 m above sea level, 400 m/s flight speed and 81 tilt of the trajectory, opening the parachute.

According to the gas filling radius calculation method described so far, the additional mass of this parachute can be calculated, and the radial and axial loading masses of the gas filling can be calculated as 0.0247 kg and 0.0314 kg respectively, and 14.5% and 18.5% of the mass of the parachute itself.

Based on Eq. (2), the calculations can be carried out to obtain that the axial force of the parachute (i.e., the maximum overload) is 10.56 kN when the air charge is filled.

For the conical band umbrella, this is an infinite mass state, and one can take a dynamic loading factor of 1.05, and the maximum umbrella load result obtained by calculating is 10.57 kN, so both are basically identical.

It can be concluded that it is perfectly possible and has a wider application value to calculate the additional mass of the parachute and the open load of the parachute using the air-filling radius calculation method described in this paper.

CONCLUSION

Based on the concept of additional mass and the characteristics of the parachute, the influence of the additional mass should be taken into account in the dynamic analysis of the parachute.

Although numerical calculations can be carried out for the added mass of the parachute using potential flow theory, boundary element method or CFD-specific application, the air-filling stage of the parachute has the deformation characteristics of a large flexible body, so that the calculation is carried out through fluid-structure coupling method or comparative analysis through test images to identify the air-filling type at each time.

After obtaining the additional mass of the parachute, the drag of the parachute can be calculated more accurately, which will be important in the design of the parachute.

Finding the maximum parachute load based on the added mass is a way to approach reality in real design and application.

However, the present experimental data are lacking in coefficient values and no studies have been conducted on the moment of inertia terms, so further studies are needed in this paper.

REFERENCES

1. Yu Li, Shi Xianlin, Ming Xiao. Numerical simulation of parachute during opening process [J]. *Acta Aeronautica et Astronautica Sinica*, 2007, 28(1): 52–57.
2. Purvis J W. Theoretical analysis of parachute inflation including fluid kinetics [R]. AIAA 81–1925, 1981.
3. Stein K R, Benney R J, Steeves E C. A computational model that couples aerodynamic structural dynamic behavior of parachutes during the opening process[R]. NASA-ADA 264115, 1993.
4. Stein K R, Benney R J. Parachute inflation: a problem in aeroelasticity [R]. NASA-ADA284375, 1994.
5. Tutt B A, Taylor A P. The use of LS-DYNA to simulate the inflation of a parachute canopy [R]. AIAA 2005–1608, 2005.
6. Tutt B A, Taylor A P, Jean C B, et al. The use of LS-DYNA to assess the performance of airborne system North America candidate ATPS main parachutes [R]. AIAA 2005–1609, 2005.
7. Peskin C S. 3-D parachute simulation by the immersed boundary method[J]. *Computers and Fluids*, 2009, 38: 1080–1090.
8. Takizawa K, Tezduyar T E. Computational methods for parachute fluid structure interactions [J]. *Arch Comput Methods Eng*, 2012, 19: 125–169.
9. Takizawa K. Fluid structure interaction modeling of spacecraft parachutes for simulation based design [J]. *Journal of Applied Mechanics*, 2012, 79: 1–9.
10. Jia He, Rong Wei, Cheng Guoliang. The simulation of parachute inflation process based on LS-DYNA software [J]. *Spacecraft Environment Engineering*, 2010, 27(3): 367–373. 293
11. Numerical Study of Parachute Dropping Based on Moving Meshes Method, The society of Fiber Science and Technology, 2016
12. Automated Image Measurement of Parachute Projection Area under Inflation Process, International workshop on Information and electronics Engineering, 2012
13. The Study of Parachute Inflation Course based on Fluid- Structure Interaction Method, Chinese Journal of Aeronautics, 2014
14. H. Cheng, Y, N, Zhan, X, Yang, L, Yu, and X, Chen, *Ind, Textila*, 65, 324, 2014
15. Cheng H, Yu L, Yin ZW. A new method of complicated folded fabric modeling. *J Harbin Inst Technol* 2012;19(2):43–7
16. Karagiozis K, Kamakoti R, Cirak F, Pantano C. A computational study of supersonic disk-gap-band parachutes using Large-Eddy simulation coupled to a structural membrane. *J Fluids Struct* 2011;27(2):175–92.
17. Kenji T. Fluid structure interaction modeling of spacecraft parachutes for 19 simulation-based design. *J Appl Mech* 2012;79(1):1–9.