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主論文の要旨

論文題目 NUMERICAL SIMULATION ON AERODYNAMICS OF A SUPERSONIC FLEXIBLE PARACHUTE SYSTEM USING A FLOW AND STRUCTURE COUPLING METHOD （流体構造連成解析法に基づく超音速パラシュートの空力特性に関する数値解析）

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論文内容の要旨

The present doctoral thesis basically treats the supersonic flow over a parachute system, where the compressible Navier-Stokes equations are numerically solved. The parachute system employed here consists of a capsule and a canopy. In some cases with a relatively small trailing distance between the capsule and the canopy, the flow field around a parachute model shows complex flow patterns including wake/shock and/or shock/shock interactions. Therefore, the objective of the present thesis is to investigate the effects of such wake/shock and shock/shock interactions on the flow fields, and the aerodynamics and shape of the canopy associated with the performances of the parachute systems, where rigid or flexible canopies are employed.

Chapter 1 introduces the background and overview of the relative work on supersonic parachute, and describes the objective of this study.

Chapter 2 presents the numerical methods used for the flow and structure calculations in this study, including the fluid-structure coupling method.

In the flow calculation, the three-dimensional compressible Navier-Stokes equations were solved to simulate the supersonic flow over the two-dimensional, three-dimensional parachute systems, the calculations were performed using a parallel in-house structured single-block code. To evaluate the inviscid fluxes, the Simple High-resolution Upwind scheme (SHUS) was adopted; the accuracy of this scheme is improved by using the 3rd MUSCL scheme with the Van Albada flux limiter, while the viscous terms were calculated by the usual 2nd order central differencing scheme. The coefficient of viscosity was computed according to Sutherland ’s law. The numerical code is featured by the 3rd total variation diminishing Runge-Kutta scheme to obtain time accurate results in unsteady calculations.

On the other hand, in the axisymmetric flexible case, the axisymmetric compressible Navier-Stokes equations were solved to simulate a flexible parachute by using the in-house CFD code. For spatial discretization, primitive variables at each cell interface were interpolated by using the 2nd-order MUSCL scheme with the Van Albada flux limiter, inviscid numerical fluxes at the cell interface were calculated by using Simple Low-dissipation AUSM scheme (SLAU). The viscous terms were evaluated by the 2nd-order central differencing scheme. Regarding time integration, the 2nd-order Runge-Kutta scheme is used to obtain time accurate results in unsteady calculations. The coefficient of viscosity was computed according to Sutherland's law.

No turbulence models are used in the present study, because till now most of the algebraic turbulence models were quite unreliable for separation flows. In addition, in the flexible cases, the immersed boundary method was employed to deal with the moving boundary of a flexible canopy.

In the structure calculation for the flexible cases, the mass-spring-damper (MSD) model was applied to solve the structural dynamics of the parachute. The explicit 2nd-order Runge-Kutta scheme was used to obtain time-variations in the canopy model calculation.

In order to solve the coupling problem, it is first separated into the fluid and structure parts. The pressure distribution on the canopy surface as the fluid force is obtained from the result of flow simulation, which is used to calculate the displacement and velocity of each canopy node. Then, those data are provided to calculation by the immersed boundary method. The method to solve the fluid and structure equations can be classified into weak and strong coupling schemes; in the former the governing equations are solved separately in a time domain, while in the latter they are solved concurrently. It is known that the strong coupling method is more stable and robust, while the weak coupling method is more flexible. In this study the method of strong coupling is employed for the two-dimensional case, while the method of weak coupling is employed to solve the axisymmetric case and three-dimensional case.

In Chapter 3, numerical simulation was carried out for three-dimensional rigid models at a freestream Mach number of 2.0, where the complicated aerodynamic interferences and the unsteady flow field with pulsation phenomenon are shown and discussed in detail.

Two models were considered: Model A and Model B. The former is the same model as used in the experiment, where the canopy is connected with the capsule by a rod, and the whole system is supported by a thicker rod to the wind tunnel model support system, while the latter is basically close to the model A except for rods, where the model B has no rods. The objective of this case is to examine the flow field produced by these models, and analyze the effects of aerodynamic interference such as shock/shock and wake/shock interactions on it. The numerical results show good agreement with the experimental data in the case of the model A. In addition, it was found that the effects of the connecting rod on the flow field and pressure distribution on the body surfaces are rather small; the pulsation mechanism for the Model B is identical to that for the Model A.

In addition, the unsteady flow pulsation phenomenon observed in this study can be divided into three processes.1) At process 1, the bow shock ahead of the capsule is nearly stable. 2) At process 2, the capsule wake interacts with the canopy shock, and the movement of the wake-rear shock interaction is predominant. 3) At process 3, intersections of the fore and the rear shocks move more outward in the radial direction.

In the unsteady flow mode, the bow shock formed ahead of the capsule inflates periodically and moves outward in the radial direction, which is caused by upstream propagation and lateral expansion of the complicated wake/rear shock and fore shock/rear shock interaction systems.

Moreover, there are two key factors for the present pulsation phenomenon; one is the pressure difference between the capsule and the canopy, and the other the shear layer and vortex region produced by the wake/rear shock and the foreshock/rear shock intersections.

Chapters 4, 5, and 6 present a way to apply the immersed boundary method to a fluid-structure interaction problem involving supersonic flexible parachute models, including two-dimensional, axisymmetric, three-dimensional model, respectively. In the three cases, time variations of change in canopy shape and complicated unsteady flow field with aerodynamic interference for supersonic flexible parachute models were successfully simulated at supersonic speeds ranging from M=1.6 to M=2.1. The objective of these cases is to analyze the effects of aerodynamic interference such as wake/shock interaction on the canopy dynamics and to examine the effects of parameters such as Mach number, the ratio of the diameter of the capsule to that of the canopy, and the trailing distance between the capsule and canopy. As a result, it was found that the immersed boundary method works well to solve supersonic flexible parachute problems.

In the two-dimensional parachute case, only the steady foreshock and the wake/rear shock interaction were observed, which was produced by the weak interference and large deformation of the canopy. In addition, in the axisymmetric parachute case, the complicated wake/rear shock and foreshock/rear shock interactions were observed.

On the other hand, in the three-dimensional flexible parachute case, it is found that there are two key factors for the parachute dynamics; one is the unsteady change in the canopy shape and the other the aerodynamic interference between the capsule wake and the canopy shock. As the trailing distance relatively increases, the phenomenon of “ canopy area oscillation ” was generated; however, reducing the canopy size in the case of relatively small trailing distance, the canopy was less deformed.

In addition, reduction in Mach number has a large effect on the performance of the flexible parachute system. In the 2D parachute case, at Mach 1.6, the shock wave formed in front of the capsule is not conical in shape, and moves upstream with a cyclic change of pressure inside the canopy. When the canopy takes a rather small shape, the foreshock moves downstream. In addition, as Mach number decreases, the pressure coefficient on the canopy surface becomes larger. In the axisymmetric flexible case, the pressure coefficient itself oscillates with time and its amplitude changes from small to large at Mach 1.6, which illustrates that the weak aerodynamic interaction turns stronger with the pressure coefficient maintained at a higher value than in other Mach number cases. As a result, the canopy shape changes more slowly. On the other hand, in the 3D flexible parachute case, the canopy has a smaller deformation than in higher Mach number cases, due to weaker interactions between the capsule wake and the canopy shock. Therefore, in this case the value of drag coefficient becomes higher.

Finally, Some general conclusions as well as the difference between rigid and flexible cases are summarized in Chapter 7.

Regarding aerodynamic interactions, there are some differences between the rigid (3D) case and the flexible case (axisymmetric and 3D). In the rigid case, the rear shock periodically moves upstream and first interacts with the wake and then with the foreshock, where the unsteady flow mode is a pulsation mode. On the other hand, in the axisymmetric flexible case, due to a shrinkage deformation of the edge part of the canopy, the rear shock always stays near the edge part of the canopy, periodically interacting first with the wake and then with the foreshock. In addition, in the 3D flexible case, the capsule wake plays a more significant role in interference as well as a great contraction of the canopy shape, so that the canopy shock interacts concurrently with the wake and the foreshock near the edge part of the canopy during a time period, where the unsteady flow mode is not a pulsation.

The mechanism for the unsteady flow mode was found to be consistent at supersonic speeds ranging from Mach 1.6 to 2.2 in the 3D rigid case or to 2.1 in the axisymmetric flexible case. In the 3D rigid case, as the freestream Mach number increase, the bow shock ahead of the capsule moves closer toward the capsule, and the capsule wake interacts with canopy bow shock stronger, and the aerodynamic interaction region comes closer to the center of parachute system, which lead to the pressure on the parachute surfaces become larger. In the axisymmetric flexible case, as Mach number increases, the shock wave ahead of the capsule is more conical, which leads to stronger aerodynamic interactions, and the interaction locations are closer to the canopy. This causes more severe shrinkage deformation of the canopy shape.

The performance of the flexible parachute system depends on several factors: i.e., the trailing distance, Mach number, and the ratio of the capsule diameter to the canopy diameter. From the comparison of all the cases treated in the 3D flexible calculation, it was found that two parameters: i.e., the capsule size and the trailing distance, have the largest impact on the drag coefficient of the parachute system. That is, the smaller the capsule size becomes, or the longer the trailing distance becomes, the larger the drag coefficient becomes. In addition, the canopy size has a large effect on the drag coefficient; that is, with a relatively small trailing distance, smaller canopy size can produce larger drag coefficient. On the other hand, in the longest trailing distance cases examined in this study, smaller Mach number can produce larger drag coefficient.