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INVESTIGATION OF SEPARATION IN A STRAP-ON SPACE SHUTTLE SYSTEM

by

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INVESTIGATION OF SEPARATION IN A STRAP-ON SPACE SHUTTLE SYSTEM

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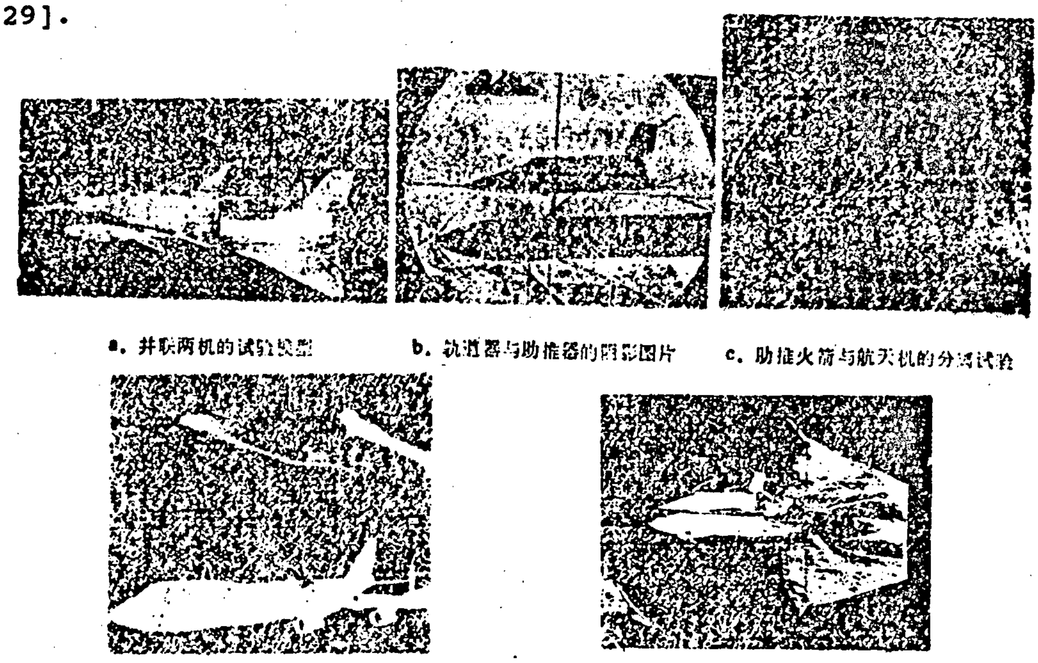
Abstract The separation research of the Orbiter/External Tank or Orbiter/Carrier in the United States is described in this paper. The analytical model of separation is presented for the parallel Space Shuttle system with the perpendicular launch. Meanwhile, the important problems of the safe separation are presented. The separation of the parallel Space shuttle system is a key technique in the future space technical fields. Our capability of resolving separation is described and the method of resolving separation is provided in this paper.

Key words space shuttle, carrier separation, separation dynamics.

I. General Status of Research on the Problem of Separation of the United States Space Shuttle

In the first stage of research and development on the U.S. space shuttle, a major aspect of research was the problem of space shuttle separation in addition to detailed research on aerodynamic forces and heat. Generally, the research activity can be divided into the following: the problem of the orbiter and the external tank (ET) separating in thin atmosphere [1, 2], and the problem of the orbiter and the carrier (booster) separating in dense atmosphere [3-14]. Based on numerous wind tunnel experiments (Fig. 1), large amounts of aerodynamic data on the mutual interference caused by these two bodies were obtained.

The M number in the experiments was in the ranges from sub-, tran- and supersonic velocities to approximately M=10. In these experiments, force measurements in the static and dynamic states [15] were conducted. In theoretical research [16], the separation locus of two bodies was simulated by using equations with six degrees of freedom. In the scheme of separating structures [17], the question was raised of whether tc use the separation propulsion apparatus [18] or whether not to adopt the apparatus [19] without any additional dynamic force. Due consideration was given to the fact that since the booster may malfunction before normal separation of the two bodies, a study was made on separation while a malfunctioning is occurring [20-29].



a. 并联两机的试验模型 b. 轨道器与助推器的阴影图片 c. 助推火箭与航天机的分离试验

d. 双支撑载机与轨道器的分离试验模拟 e. 尾部羽流干扰试验

Fig. 1.
Legend: a. Experimental model of two bodies in the strap-o space shuttle system; b. Diagram showing shadows of orbite and booster; c. Separation experiment of booster and spac shuttle; d. Simulation of separation experiment of double spar carrier and orbiter; e. Interference experiment on wake of empennage.

Generally, much research was conducted on separation problem of the two shuttle bodies in the United States. Based on several successful test flights, it was shown a breakthrough of the key separation technique was realized. However, further study on the problem of separation while a malfunction is occurring is still needed.

II. Analysis of Separation Problem for Two-Stage Space Shuttle

With repeated vertical takeoffs, two-stage orbital entry and horizontal landing, the space shuttle exhibits the typical problem of two bodies in a strap-on shuttle system separating. Similarly, for horizontal takeoffs, two-stage orbital entry and horizontal landing, this class of shuttle also has the two-body separation problem. So the study of the problem of two bodies separating in a strap-on shuttle system is also a research subject that must be explored in the future development of astronautic technology.

How to solve the two-body separation problem in a strap-on shuttle system? From preliminary research and analysis, the following research is needed to satisfactorily solve the two-body separation problem in a strap-on shuttle system.

1. Rigorously determine conditions for the safe separation of the two shuttle bodies

In the entire process from start of separation to the safe separation of two bodies in the shuttle, there should be adequate axial and normal distances between the centers of gravity of the two bodies. During the separation period, because of perturbations experienced by the two bodies due to various factors, no collision is allowed even though oscillations are produced in the two bodies. After separation, both shuttle bodies can fly normally. Thus, the following requirements should be satisfied:

The relative normal-direction acceleration between two shuttle bodies should be greater than a certain critical value

$$a_{N1} - a_{N2} \geq a_N$$

a_{N1} and a_{N2} are the normal-direction accelerations of the two shuttle bodies, respectively, at the separation point; a_N is a certain positive value, which is the safe critical value of the normal acceleration.

The absolute value of the relative axial-direction acceleration between the two shuttle bodies should be greater than a certain safe critical value.

$$|a_{A1} - a_{A2}| \geq a_A$$

a_{A1} and a_{A2} are the axial-direction accelerations of both bodies, respectively, at the separation point; a_N is a certain positive value, which is the safe critical value of the axial-direction acceleration.

The angular accelerations ε_1 and ε_2 (of the two shuttle bodies) while rotating around their respective gravity centers approach zero at the separation point.

In satisfying this condition, there is no compression due to the two shuttle bodies pressing on each other at the nose compartments of two bodies; thus, a difference in angles of attack readily occurs, for easier separation.

The maximum amplitude of oscillation for both shuttle bodies while rotating around their respective centers of gravity is not large enough to cause contact of both bodies in any position.

2. Study the role in separation played by the parameters of both shuttle bodies at the separation point, thus easily determining the optimal separation zone

First, a model of separation for both shuttle bodies is to be established.

For safe separation of both bodies, first one must determine the optimal separation safe zone. Thus, it is required to present a separation model for analysis and selection.

The mass distribution of both shuttle bodies can be indicated as follows: $G_1 > G_2$, $G_1 = G_2$, $G_1 < G_2$

G_1 is the orbiter mass; G_2 is the booster mass.

It can be divided into two cases according to the relative position of the two bodies; the orbiter is above the booster; and the booster is above the orbiter.

Based on the derivation of a model for the separation of two shuttle bodies, the role in separation that is played by parameters at the separation points is studied and analyzed.

Based on the analytical model thus derived, first the fundamental analysis model is adopted that the model of G_1 is greater than G_2 with the orbiter above the booster (see Fig. 2).

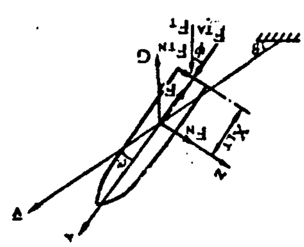


Fig. 2. Analysis of Forces Acting on a Space Shuttle

First, it is assumed that no lateral motion occurs during separation; we only discuss the motion within the plane of dipping and elevating motion. We can neglect the role in normal-direction acceleration played by the centrifugal force caused by bending. Within the time span of Δt during separation, there is very little variation of the dip and elevating angle around the respective centers of gravity of the two shuttle bodies; the effect on rotation of these two bodies is not considered.

As shown in Fig. 2, the normal-direction force, the axial-direction force and the moment of the force around the center of gravity point o in fuselage axis oxyz are as follows:

$$F_N = F_{TN} + F_N - G\cos(\theta + \alpha)$$
$$F_A = F_{TA} - F_A - G\sin(\theta + \alpha)$$
$$M_o = m_o - F_{TN} \cdot X_{LT}$$

Thus, we can derive that the normal- and axial-direction accelerations are a_N and a_A while the angular acceleration is ε.

$$a_N = F_N/M, \quad a_A = F_A/M, \quad \varepsilon = M_o/J,$$

In the equations, F_N and F_A are the normal- and axial-direction aerodynamic forces; m_o is the moment of dip and elevating aerodynamic force around the center of gravity; G is the gravitational force acting on the space shuttle; F_{TN} is the normal-direction component of the engine propulsive force (F_{TN} = T sin ψ); F_{TA} is the axial-direction component of the engine propulsion force (F_{TA} = T con ψ); and X_{LT} is the axial-direction distance from engine jet nozzle to the center of gravity of the shuttle.

Since the conditions of axial-direction acceleration can be satisfied very easily, we only discuss the role in normal-direction acceleration for the fundamental model as played by the following parameters:

(1) With increasing altitude, the value of $a_{N1}-a_{N2}$ is reduced, thus facilitating separation (Fig. 3).

(2) With increasing M number during flight, the value of $a_{N1}-a_{N2}$ is reduced, thus not facilitating separation (Fig. 4).

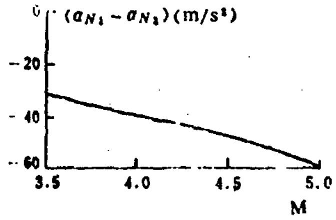


Fig. 3. Variation of (a_{N1}-a_{N2}) With Flight Altitude

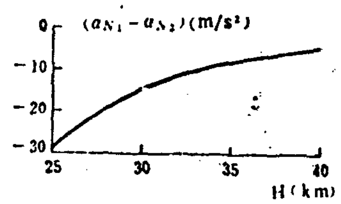


Fig. 4. Variation of (a_{N1}-a_{N2}) With Flight M Number

(3) With increasing angle of attack during flight, the value of a_{N1}-a_{N2} is decreased, thus not facilitating separation (Fig. 5).

(4) With variation in the dip angle of the flight trajectory, the effect on a_{N1}-a_{N2} is only very slightly affected (Fig. 6).

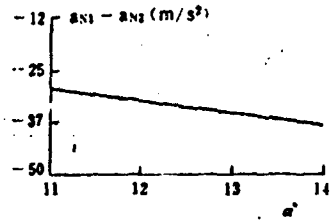


Fig. 5. Variation of (a_{N1}-a_{N2}) With Angle of Attack

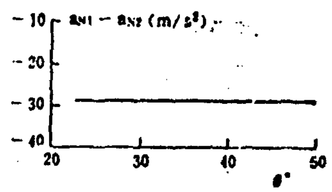


Fig. 6. Variation of (a_{N1}-a_{N2}) With Angle

(5) Variations of working conditions of booster rocket do have an effect on separation.

In the above-mentioned computations, the booster is in the shutdown stage. In the case of a booster that is functioning with the direction of the propulsive force deviating downward, this case is very advantageous to the separation of the two bodies. In this state, the force moments for the booster at the separation point should be in equilibrium.

As indicated by analyzing the fundamental model, the various parameters are related to the following: effect on normal-direction acceleration, as well as the ratio between the forces acting on the orbiter and booster, and their mass. The mass distributions of the two bodies are very important. If the mass distribution of the two shuttle bodies at the separation point is changed so that G_o is less than G_b [o indicates orbiter, and b indicates booster], then the effect of these parameters (other than θ) is just the reverse to what was found for the fundamental model. If $G_o=G_b$, the effect of parameter variation is very little.

3. Study of dynamic features of separation of the two shuttle bodies

In the above-mentioned study, our discussion proceeds by considering the orbiter and booster as two mass points; this is a necessary but not sufficient condition because the centers of gravity for these two bodies (or machines) are apart to a certain distance. It does not mean that these two bodies have separated safely. Hence, the study should advance to a further step of considering these two bodies as mass points. When these two bodies are disturbed, whether the perturbation rapidly converges and whether these bodies can avoid a collision, the simulation of six degrees of freedom, or the free-flight simulation should be conducted to perform strict examination in order to determine the reliable, optimal safe zone of separation..

4. Study of aerodynamic perturbation on two bodies during separation

In a two-body strap-on shuttle system, aerodynamic perturbations between these two bodies are unavoidable, thus affecting the effective forces and motions of the two bodies. Experiments on aerodynamic perturbations of the two bodies in the strap-on shuttle system were conducted in tran- and supersonic wind tunnels at the Aerodynamic Center; the different positions of these two bodies were examined. As revealed by results, the static perturbation between two bodies is quite serious (see Fig. 6). As pointed out in reference [15], there are synchronous oscillations of the two bodies, thus also having serious effects on the static and dynamic derivatives (see Figs. 7, 8 and 9). At a certain orientation angle, the static derivative (C_{ma}) becomes unstable; however, the dynamic derivative ($C_{ma}+C_{ma}$) becomes a positive value, causing divergence of the space shuttle. Therefore, such a study is quite necessary.

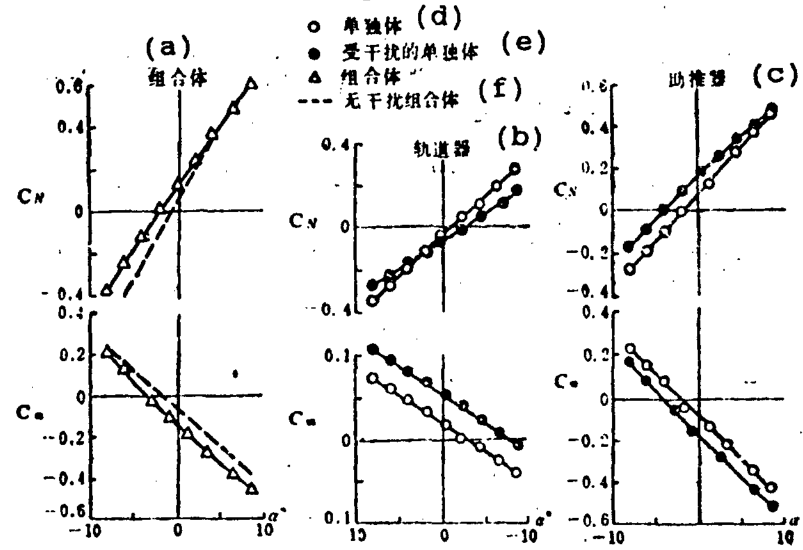


Fig. 7. Longitudinal Direction Static Perturbation Features of a Two Body Strap-on Space Shuttle System at M=1.6.
KEY; (a) Assembly (b) Orbiter (c) Booster
(d) A single body (e) A single body with perturbation
(f) Assembly --- assembly without perturbation.

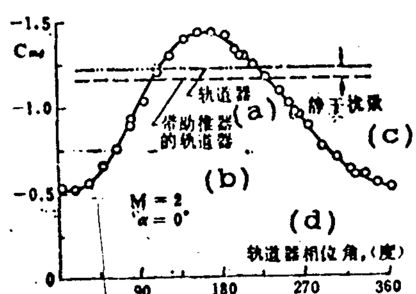


Fig. 8. Effect on Derivative of Moment of Dip and Elevating Force by Dynamic Perturbation of Two Shuttle Bodies

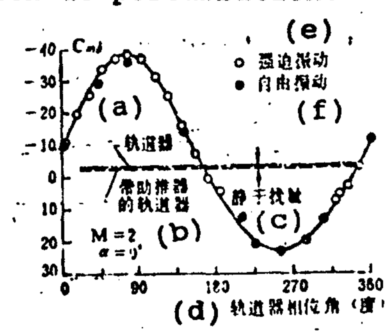


Fig. 9. Effect on Derivative of Dip and Elevating Attenuation by Dynamic Perturbation

KEY (for Figs. 8 and 9): (a) Orbiter (b) Orbiter with booster (c) Quantity of static perturbation (d) Phase angle (degree) of orbiter (e) Forced oscillation (f) Free oscillation

5. Study of separation of two bodies while malfunctioning

Malfunction separation refers to the case of malfunction suddenly developing after takeoff of the space shuttle (with orbiter and booster) but short of the separation point, thus requiring emergency separation. Hence, it is necessary to stu the separation problem under conditions of sub- and transonic velocities in order to ensure safety of the astronauts and the orbiter. In addition to the subjects of the above-mentioned study for normal separation, further study on the following subjects is required: effect on separation scheme, process and mechanism for conditions of abnormal separation, and special requirements due to the overall arrangement of the space shut as well as its dynamic installation system and control system

6. Study on separation mechanism of the two bodies

With the above-mentioned study, the safe separation zone determined. For a further step, research and development of reliable separation mechanism are required in order to execute safe separation. Schemes thus presented are as follows:

(1) Use a propulsion apparatus to execute separation by installing small rocket engines and high pressure cold gas bottles onto the booster. During separation, the required normal- and axial-direction accelerations are provided. This method is reliable but some appreciable weight additions are involved.

(2) Use the aerodynamic forces to execute separation by adopting the hinged connection approach at the strap-on locat of the two shuttle bodies. During separation, the two bodies have a relative motion; the orbiter maintains its original an of attack while the booster changes its angle of attack, thus

generating a sufficient relative normal-direction acceleration. This type of separation mechanism is light in weight; however, the separation mechanism at the orbiter strap-on location site is relatively complex.

III. Technical Scheme to Solve the Separation Problem of Two Bodies in a Strap-on Space Shuttle System

Based on the above-mentioned analysis on separation problem of the two bodies in a strap-on space shuttle system, it can be realized that the following are key techniques in executing safe separation of the two bodies: determination of conditions for safe separation of the two bodies, determination of the optimal, safe zone for separation, study of dynamic features and aerodynamic perturbations for separation of the two bodies, study of malfunctioning separation of the two bodies, and study of the separation mechanism for the two bodies. How to solve these problems? Through analysis, it was recognized that a method for combination of three major research means (theoretical computation, ground experimentation and flight testing) should be used in order to effectively solve the separation problem.

1. Study of ground experiments on problems of separating the two bodies

Existing experimental equipment for wind tunnel experiments in China can be used for the following research and experiments. In a transonic and supersonic wind tunnel, experiments on force analyses while ejecting bombs from a mother ship can be simulated and examined by using a system with a controllable orbit; and in a hypersonic wind tunnel, research and experiments on separation for the two shuttle bodies can be performed. In a supersonic wind tunnel, aerodynamic perturbation experiments of the two shuttle bodies can be performed; in addition, dynamic derivative balances for force oscillations for the entire model are equipped to measure the derivative for dip and elevating attenuation, and also for synchronous-oscillation experiments on the two shuttle bodies. As mentioned above, currently we have the capability oi ground experiments and research with preliminary simulation of separation for the two bodies in a strap-on space shuttle syster With efforts, the requirements on various experiments on force and pressure measurements are available to satisfy the separati of two shuttle bodies.

2. Develop theoretical research on the two-body separation problem

Under conditions of supersonic flights, mutual perturbatio from aerodynamic forces exist for a strap-on space shuttle system. How to compute the aerodynamic forces for this type of complex assembly is an aerodynamic computational problem that i relatively complex.

The numerical solution procedure of the Euler equation can be used to calculate the aerodynamic forces of an assembly of t strap-on nonspherical conical bodies. The Euler equation can also be used to calculate the complex exterior of a simplified space shuttle. On this basis, the aerodynamic forces for compl assembly can be developed.

3. Develop the simulation study of the six-degrees-of-freedom equation in simulating the separation problem of two shuttle bodies

To study the problem of two shuttle bodies separating safely, in addition to analyzing the mass-particle motion of tw bodies, it is more important to investigate the rigid-body movement of these two bodies. We must utilize the six-degrees-of-freedom equation to study the movement locus and other movement parameters during separation of these two bodies.

4. Develop the experimental study of simulating free flight and ordinary flight during separation of two shuttle bodies

To execute the separation of two shuttle bodies, free flight experiments are quite important, in addition to fostering experimental study and theoretical study. By utilizing free flight to simulate the separation of the two bodies, and to examine the rationality of the separation mechanism of these two bodies, we can examine and inspect whether or not the control system can execute safe separation. Hence, free flight and flight tests should be developed to perform separation experiment and study.

IV. Conclusions

The investigation of the separation of the two bodies in a strap-on space shuttle system is very necessary to space shuttles with two-stage orbital entry and full re-use. Related research has been done abroad. Three major means of theoretical analysis, wind tunnel experiments and study, as well as flight tests available in China can be used to pursue preliminary research on development of solving the separation problems of two shuttle bodies.

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