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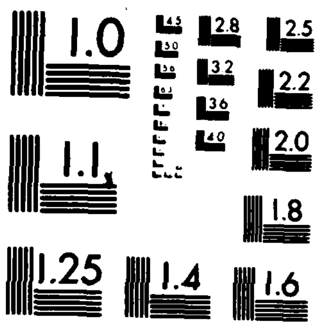

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

SEPARATION BETWEEN STAGES OF MULTISTAGE CARRIER ROCKET

by

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FOREIGN TECHNOLOGY DIVISION

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SEPARATION BETWEEN STAGES OF MULTISTAGE CARRIER ROCKET

Xue Yu

Separation between stages in a multistage carrier rocket is an important problem to solve for a successful launch of a ballistic missile, artificial satellite or spacecraft. This article presents a brief introduction to the principle, mechanism and method of separation between stages.

The long range ballistic missile (with its warhead), artificial satellite, and spacecraft use a multistage rocket as their carrier. Due to the fact that separation between stages during flight of a multistage rocket can cast off, in sequence, the stage in which the propellants have been exhausted, the weight of the final stage at ignition cutoff is considerably reduced. Thus, the guided missile and spacecraft can attain a relatively high and necessary velocity. Therefore, separation between stages is one of the important problems in development of large carrier rockets.

We can see from development of the rocket and guided missile that separation between stages has developed on the technical foundation of warhead separation. In an earlier period, the warhead separation used a separation system of spring or pneumatic apparatus--detonating bolts. These springs are in the compressed state at ready positions, and during separation the detonating bolts connecting the warhead and missile body are ignited to extend the springs in producing a separation force to separate the warhead from the missile body. Later, small reverse thrust solid fuel rockets were used in place of springs for installation beside the missile body. As the missile body receives the reverse thrust of the solid fuel rockets, the missile flies on with a reduced velocity, gaining a relative distance between the warhead and missile body resulting in a separation.

Basically, the principle of separation between stages of a multistage carrier rocket is the same as warhead separation applying a separation force to the body to be separated. However, technically the separation between stages is considerably complicated. The upper stage(s), including the other stages and payload besides the castoff stage, weighs some tens to hundreds of tons. On the other hand, separation between stages not only casts off the lower empty stage, but also ensures that the engine of the upper stage ignites during the separation procedure and the carrier rocket requires proper control along with many more problems in coordination of various systems. Nevertheless, through the development process, researchers are constantly making conclusions about their experience. After many experiments, the objective rules of separation between stages have been mastered; new separation mechanisms and separation methods are proposed.

Connecting Mechanism for Separation Between Stages

At present, almost all multistage rockets are of the series type as shown in Figure 1. Generally detonating bolts connect the various stages; the detonating bolts have been the connecting mechanism used for conventional separation up to the present. The requirements of detonating bolts are reliable connection, so as to have sufficient rigidity of the carrier rocket, and reliable and quick ignition during separation, to release the two adjoining stages. In earlier times, reliability of detonating bolts was low, and thus fragments following detonation caused damage to instruments and equipment. Therefore, redundant components and parallel circuits were used to improve reliability, with the installation of fragment shielding plates. Later, detonating bolts that did not produce fragments and detonating rope were developed. The detonating rope winds around the inner surface (in a fixed position) of the thin cover of the interstage sector. During separation, electricity is switched on to ignite the detonating rope; the (dynamite powder) gas abruptly expands toward the direction of the thin cover and cuts the thin cover like a knife (see Figure 2 showing the principle of cutting the thin cover by a detonating rope). Recently, a new type of detonating rope was developed; the dynamite is packed in thick plastic tubes. As the dynamite detonates, the plastic tube expands to cut the thin cover; the tube itself does not break. Therefore, no fragments or impurities cause damage to instruments and equipment. As the combustion speed of dynamite is very fast, about 7000 meters per second, the synchronization of this setup is better than that of the detonating bolts. In the development of space technology and increasing carrier capacity, the loading on multistage rockets is increased. Thus, a new design problem emerges as more detonating bolts (for connection) are required, with a larger diameter of each bolt. At present, more and more detonating ropes are used in guided missiles and spacecraft in a trend of replacing the detonating bolts.

Separation Methods Between Stages

Generally, there are two types of separation between stages of a carrier rocket: hot separation and cold separation (separation with additional force). The so-called hot separation means to separate two adjacent stages by the action of a gas jet from the engine of the upper stage; refer to Figure 3. The engine of the upper stage begins ignition when the two stages are still connected to each other. Generally, the separation procedure is as follows: the lower stage sends forth a command for cutoff of engine ignition to reduce the thrust. When the thrust of the lower stage is reduced to a certain value, the engine of the upper stage ignites. At the same time, exhaust ports of the interstage sector are opened to expel the hot gas stream; in some cases, exhaust ejection comes from a truss type interstage sector. When the force of the jet stream (of the engine of the upper stage) acting on the lower stage attains a certain value, the detonating bolts or rope ignites to release the lock and separate the two stages. Then, the attitude control system of the upper stage is activated in the predetermined procedure. Hot separation has the advantages of high separation force, short time of losing control and high reliability. However, disturbances also correspondingly increase; quite a few exhaust ports

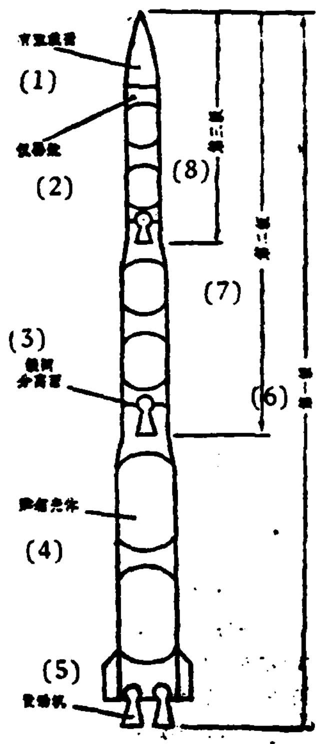

Fig. 1. Structuural diagram of series type multistage carrier rocket.
Key: (1) Payload; (2) Instrument cabin; (3) Separation surface between stages; (4) Shell of storage tank; (5) Engine; (6) First stage; (7) Second stage; (8) Third stage.

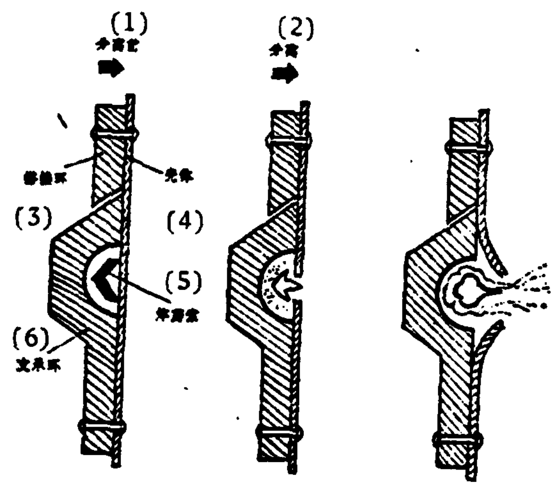

Fig. 2. Diagram showing the principle of cutting the thin cover by a detonating rope.
Key: (1) Before separation; (2) During separation; (3) Connecting ring; (4) Shell; (5) Detonating rope; (6) Support ring.

(or truss type structures) should be opened at the interstage sector, and a heat insulation layer should be added on top of the lower stage tank, with sturdy installation to prevent damage by too high pressure and the hot stream of the engine exhaust from the upper stage. Sufficient distance should be maintained between the jet nozzle opening of the upper stage engine and the tank top of the lower stage; thus, the positive shock wave produced by the jet stream of the upper stage engine does not penetrate deeply into the jet nozzle in order to avoid affecting normal operation of the upper stage engine. This layout increases the length and weight of the rocket structure.

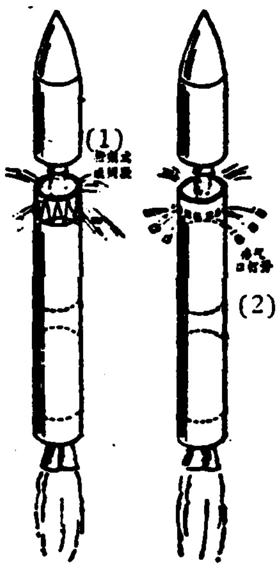

Fig. 3. Schematic diagram showing hot separation.
Key: (1) Truss type interstage sector; (2) Opening of exhaust ports.

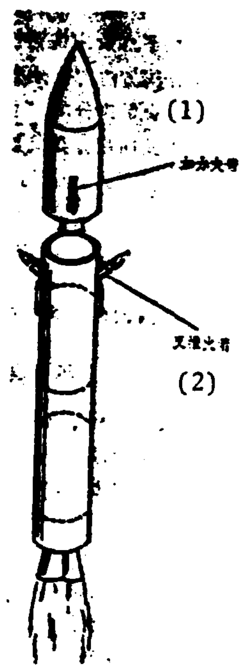

Fig. 4. Schematic diagram of cold separation.
Key: (1) Auxiliary force rocket; (2) Reverse thrust rocket.

Cold separation is different from hot separation since the separation relies on the addition of an auxiliary force and reverse thrust solid fuel rockets. The upper stage engine ignites only after two stages have separated; therefore, this is called cold separation or separation with auxiliary force; refer to Figure 4. During separation, the reverse thrust rockets push the lower stage away and the auxiliary force rockets accelerate the upper stage. The upper stage engine ignites only after these two stages are separated by a certain distance. Advantages of this type of separation are separation with a relaitively small active force, relatively steady operation process, smaller disturbances, no exhuast ports required at the interstage sector, and no heat insulation required. Of course, the solid fuel rockets should have very high reliability.

Attitude Control During Separation Process

When a carrier rocket ascends through the atmosphere, interstage separation proceeds in the predetermined sequence. Due to high altitude wind and the [imperfect] manufacture of the carrier rocket itself, as well as installation errors in the engine, there are certain attitude angles and angular velocity when the rocket begins to separate. In addition, disturbances (such as non-synchronization between ignition cutoff and starting of engines, asymmetry of thrust decrease and ignition of detonating bolts) cause constant variation of attitude in the upper stage. Thus, the attitude control system of the upper stage has a relatively high initial attitude angle and angular velocity during control initiation. The magnitudes of the initial attitude angle and angular velocity are related to the attitude angle and angular velocity when the rocket begins to separate between stages. In addition, in the upper stage the characteristics of control initiation of the attitude control system are related to the flight altitude of the carrier rocket during separation.

At a relatively low altitude, such as 30 to 40 kilometers, the effect of aerodynamic force is relatively high, and consideration should be given that the carrier rocket may have relatively great drift. Once the two stages are separated, the attitude control should be resumed as fast as possible. Otherwise, the allowable initial conditions of the upper stage will be exceeded. For separation at a relatively high altitude (higher than 30 to

40 kilometers) or in space outside the atmosphere, the effect of the aerodynamic force is very small. Therefore, the time lag for control initiation of the upper stage can be slightly prolonged. During the period of decreasing thrust after engine (of the lower stage) ignition cutoff, it is still difficult to control the not yet separated carrier rocket; thus the interference effect during ignition cutoff can be decreased.

For precise guidance, the upper stage needs to have sufficient control force to correct deviations caused by asymmetry of thrust, shifting of the center of gravity of the rocket, and wind disturbance. At present, most carrier rockets have swinging engines and floating engines (a type of small engine capable of swinging). Obviously, during the separation process the carrier rocket is in the state of low thrust or without any thrust, and the attitude control system will not maintain a steady attitude for the carrier rocket; therefore, it is required that the interstage separation should be accomplished within a very short span of time.

Collision Problem During Separation

We know that generally there is a connecting sector between stages of carrier rocket; refer to Fig. 1 for the sector immediately below the separation surface. A portion or the entire engine of the upper stage is fitted in the connecting sector. When the detonating bolts begin ignition and two stages separate with lock release, the upper stage engine pulls out from the connecting sector. At the same time, the interference moment around the center of gravity of various stages produces an angular acceleration to the stages, and thus relative rotation occurs in the two stages. In this situation of relative motion, if improper design considerations are given, the two stages (for separation) will collide. In order to avoid collision after lock release, the important problem is to know whether or not any portion of the upper stage collides with the connecting sector underneath after lock release between the two stages. This requires calculation of relative motion between the two separated stages to determine a "collision space," which is one portion of the connecting sector of the lower stage. No portion of the upper or lower stage is allowed to enter this "collision space"; in other words, no component is installed so as to maintain a certain collision space. Thus, during separation of two stages with lock release, the relative motion in the connecting sector will not lead to collision.

During calculation, besides the normal separation situation, consideration should be given to possible malfunctions (in the case of failure of one or two reverse thrust rockets during ignition). The separation should be ensured even when the most unfavorable situation occurs.

In another collision case, when two stages are separated, the thrust decrease is not sufficient after ignition of the upper stage engine, and the separation distance of the two stages is relatively short; the lower castoff stage catches up to the upper stage under the action of aftereffect thrust following engine ignition cutoff and causes a collision. Therefore, during cold separation the reverse thrust and auxiliary force rockets should have sufficient thrust and operation time. In the case of hot separation, the detonating bolts can only ignite after a greater force (of the engine gas stream following ignition of the upper stage engine) acting on the lower stage than the aftereffect thrust of the lower stage; thus, the two stages separate from each other. Therefore, in design of the separation sequence between stages, consideration should be given that not too great an attitude drift (of the rocket) is produced by delay of control initiation of the attitude control system of the carrier rocket, and the upper stage should have as fast as possible control initiation. Further consideration should be given that the relative distance for two stage separation should not be too short and a sufficient time interval should be reserved to enable the engine thrust to increase to a certain value. This requires us to analyze and treat the problem dialectically.

Ignition of Upper Stage Engine

Perhaps the key portion of the entire separation process is the ignition of the upper stage liquid fuel engine under conditions free of thrust. This is because during the instant of flight of the carrier rocket without thrust, the propellants will move forward from the bottom of the fuel tank; in the case of a pump type conveyance system for low temperature propellants, such as liquid oxygen and hydrogen, gas bubbles will be produced at the turbine pump opening with a phenomenon of "gas corrosion." Thus, the propellants cannot flow normally to the combustion chamber, causing unsteady combustion, even leading to a dangerous explosion. Why does the explosion occur?

The reason lies in the resistance produced by high altitude air (though it is thin) to the carrier rocket under high speed flight. When there is a thrust, the air resistance is overcompensated, and sufficient thrust remains to accelerate the carrier rocket. When the thrust becomes zero, the carrier rocket is hindered by aerodynamic drag, and the accelerating flight (of the rocket) becomes decelerating flight. However, aerodynamic drag only applies to the shell of the carrier rocket, not to propellants inside the fuel tank. Then, the velocity of forward motion of the missile body is slowed down by aerodynamic drag while the propellants under the motion of inertia move forward from the bottom of the fuel tank in a relative motion.

Then, why are gas bubbles produced by the low temperature propellant at the pump opening? We know that when the pressure acting on a liquid is smaller than the saturated vapor pressure of the liquid at the particular temperature, the liquid evaporates into gas and gas bubbles are produced. When the carrier rocket conducts an accelerated flight with a thrust, the pressure at the pump opening (if the pressure loss is neglected) is equal to the sum of the inertial force of the liquid columm above and the increased pressure in the fuel tank. Once the thrust becomes zero and the propellant leaves the bottom of the fuel tank, this portion of the pressure is lost. For a low temperature propellant with very low boiling temperature, the pressure will be lower than the saturated vapor pressure at the particular temperature. Then the low temperature propellant evaporates, producing gas bubbles along with the phenomenon of "gas corrosion." Since the operation time is very short for a liquid fuel rocket engine, most likely the turbine pump will not be damaged due to gas corrosion. However, it is very obvious that under the situation of gas corrosion, and especially in the case when the vapor bubbles are so numerous that they are unable to condensate in the pump during the limited time span, then the pressure head of the liquid and the conveyance quantity of propellant delivered by the pump are considerably reduced. Thus, the vapor bubbles may block the passage, causing interruption in conveyance of propellants, and malfunctions develop in the combustion chamber due to an abnormal combustion process; this also may cause engine explosion.

In order to solve this problem, auxiliary force solid fuel rockets can be added to the upper stage to overcome the air resistance; the rockets give an acceleration to the upper stage and prevent propellants from leaving the bottom of the fuel tank. This is the cold separation (auxiliary force separation) method mentioned above. Or, the upper stage engine begins to ignite when two stages have not yet separated and the lower stage engine is still in accelerated motion, since the engine is still under the action of aftereffect thrust following ignition cutoff of the lower stage engine. This is the hot separation method, also an effective measure.

From the above, we can see that in the interstage separation (during the transitional instant of concluding one stage operation and beginning another stage) consideration should be given to many interrelated factors and mutually contradictory requirements, and the coordination problem between systems is relatively complex. Flight failure will be the result with only a little deviation. Therefore, the reliability problem should be especially stressed. How will the reliability of interstage separation be increased?

First, beginning with design, deliberate analyses of unreliable factors should be conducted to reserve sufficient safety excess amounts during design. For example, on pondering collision problems, not only the normal separation but also possible malfunctions should be calculated in determining the "collision area." For problems affecting reliability, solutions or remedies should be thought out in advance. For example, dual detonator parallel circuits are used for separation mechanism. Thus, in the case of failure of one detonator and one circuit, another one can still function to accomplish the task. At the same time, various tests should be conducted, such as the aerodynamic test of interstage separation, and ground simulation test of the separation mechanism. In addition, destructive tests of components should be conducted, and reliable data should be accumulated by inspecting qualities during design and production.

In short, the reliability of interstage separation, and the reliability of the entire carrier rocket, require thorough cooperation of design, production and operation teams for longterm consistency, and a great deal of work to maintain a high reliability.