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by

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Aerodynamic Design Research of the Gas Vane of a Solid Rocket

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Abstract: Several issues involved in the aerodynamic design of the gas vane of a solid rocket, such as jet flowfield analysis, material selection and property analysis, theoretical configuration and aerodynamic characteristics design, as well as wind tunnel tests of the gas vane model and force measurement tests of a full-scale vane during rocket engine firing, etc., are presented. Integration of aerodynamic characteristics with strength, stiffness, as well as ablation value of the vane will make development of gas vanes more smooth.

Key Words: Solid propellant rocket, Control system, Gas vane, Aerodynamic design

1. General Description

The gas vane is a special kind of wing functioning in a rocket jet flow designed to control the missile thrust vector. When applied in the earlier liquid middle-range ground-to-ground missiles and carrier rockets, the gas vane was made of graphite material, which, while functioning in normal conditions in flight tests and applied flights, was accepted as the simplest and reliable thrust vector control mode.

Afterwards, however, with the gradual development of large carrier rockets and long-range ground-to-ground missiles, such a gas vane could no longer meet the control requirements due to its inadequate lift and therefore was replaced by some new technologies, including an oscillating jet pipe.

In recent years, due to its many advantages with regards to control, the gas vane was selected by designers for use in newly developed vertically launched solid missiles such as ground-to-ground missiles, ground-to-air missiles, ship-to-ship missiles and anti-submarine missiles. Nevertheless, the jet flow in solid rockets not only produces extremely high temperatures and strong corrosiveness, but also contains high speed Al_2O_3 particles which can create an extremely powerful eroding force. Under such a scenario, graphite material may easily be destroyed at one fell swoop, and melt-resistant alloy materials have to be thought of as a replacement, which can self-protect against being ablated and eroded.

As a matter of fact, a tungsten-molybdenum gas vane, made from 85% tungsten and 15% sintered molybdenum, was already successfully applied in several solid models like Pension, which was developed in the United States. In the eighties, an even newer tungsten-copper gas vane was invented and used in ship-borne missiles, including the Harpoon, a ship-to-ship missile and ASROC, an anti-submarine rocket..

Since the aerodynamic design for a graphite vane is not applicable to the melt-resistant alloy vane and besides, related design data are hardly available in our country, many technical difficulties have to be overcome before an aerodynamic design can be worked out with an immediate success for the latter.

Aerodynamic design for a gas vane involves three principal aspects: (1) designing the vane configuration dimensions and vane axis location map; (2) determining the vane mount location and (3) determining its permitted areal ablation rate and calculating its aerodynamic characteristics. Among other things, the vane configuration design is the key element, because such design requires that the vane must not only satisfy the missile control force (moment) requirements, but also have adequate strength, stiffness and the ability to resist ablation and erosion. Otherwise, once designed and constructed, the vane may break, bend and undergo excessive ablation during an engine test run. Moreover, an inadequate control force (moment) or an over-large hinge moment are likely to appear during a force measurement test. As a result, the aerodynamic design will be renewed and the development period will be prolonged.

2. Jet Flowfield Analysis

Some significant parameters of gas vanes, such as aerodynamic characteristics, strength, stiffness and ablation value, are closely associated with the nature of a jet flowfield. Thereby, a flowfield analysis is necessary before the vane configuration dimension can be designed.

2.1 Jet Flowfield Nonuniformity

A cone-shaped jet pipe is commonly used in a solid rocket engine. Fig. 1 shows that Mach number distribution in the radial direction appears basically uniform at the exit section of a cone-shaped jet pipe. However, the gas vane is located beyond the jet pipe exit, where the jet flowfield is nonuniform and parameters like Mach number, static pressure, etc. vary with their different radial and axial locations. the Mach number increases in the axial downstream direction, while static pressure and dynamic pressure rapidly decrease along the axial direction, which must be taken into full consideration in determining the vane mount location and its turning-axis location as well as in calculating aerodynamic characteristics. Fig. 2 displays theoretical calculations of Mach number distribution and wind tunnel test results.

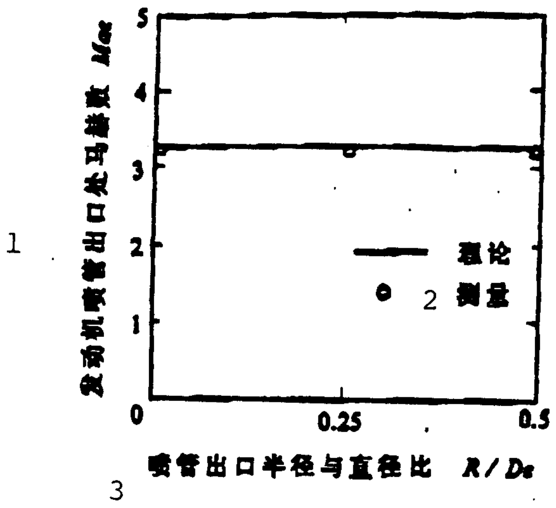

Fig. 1. Radial distribution of the Mach numbers at the cone-shaped jet pipe exit

Key: 1. Mach numbers at engine jet pipe exit; 2. Theoretical measurement; 3. Radius and diameter ratio at jet pipe exit R/De

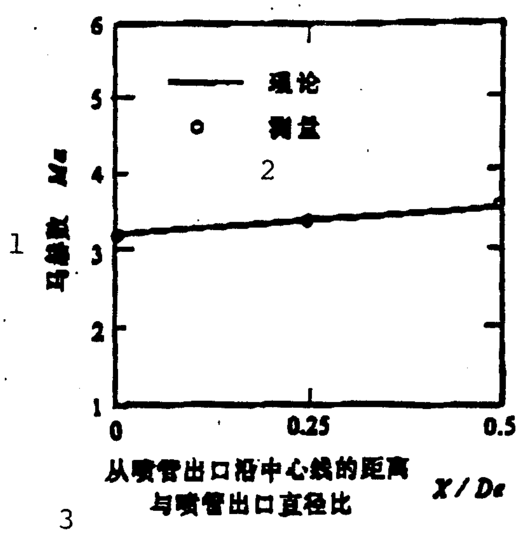

Fig. 2 Axial distribution of the Mach numbers beyond the cone-shaped jet pipe exit

Key: 1. Mach number; 2. Theoretical measurement; 3. Ratio between distance along central line from jet pipe exit and jet pipe exit diameter X/De

2.2 Shock Waves and Expansion Waves at Jet Pipe Exit

Shock waves are formed at the jet pipe exit in the initial stage of missile flight, when environmental pressure is larger than the air-flow static pressure at the pipe exit, whereas expansion waves appear at the jet pipe exit at a high flight altitude when environmental pressure decreases to such a degree that it becomes lower than the static pressure at the pipe exit. While operating in the shock wave or expansion wave region, the vane body offers a decreasing lift effect. Therefore, it is needed to minimize as much as possible the shock wave or expansion wave interference regions in locating the vane body.

2.3 Particle Current

To eliminate combustion oscillation and boost the engine, the general practice is to add a large amount of metallic powder in the solid propulsive agent. For instance, the content of aluminum powder in some engines reaches as high as 16.5% or more. Data [1] show that the content of Al_2O_3 particles in the combustion product of such propulsive agent accounts for 10-25% of the combustion product. Working in such particle currents, the vane body undergoes severe corrosion as well as erosion. This should be taken into serious consideration during the vane body geometric design so as to propose a practical goal for the vane areal loss rate.

A solid rocket jet flow is a kind of multiphase current which contains gas, liquid and solid particles. Therefore, when the wing surface theory is applied to such multiphase current, in-depth studies must be made to determine the effect of the solid particles. The author's initiative research indicates that such current can be regarded approximately as a pure air-flow as long as the diameter of solid particles is less than 15μm.

2.4 Instantaneity of Flowfield

The nonuniformity of parameters at different points of the flowfield at a particular instant of engine operation has already been discussed in sections 2.1 and 2.2. In a solid rocket engine, due to the variation of powder charge and powder core shape, the pressure inside a combustion chamber constantly changes with time; in addition, the jet pipe area ratio also changes continuously with constant ablation of the jet pipe and its throat, both resulting in instantaneous nature of the flowfield where the gas vane is located.

Calculations of diameters at the jet pipe throat and its exit, which were made after an engine ground test run, suggested that the jet pipe area ratio slightly decreased, while the increase of Mach number at the jet pipe exit slightly diminished with time. Practice has proved that pressure inside the combustion chamber of a solid engine rise and fall to a considerable degree with time. Fig.3 shows the variation of air-flow dynamic pressure at the vane surface with the change of pressure inside the combustion chamber. Consequently, calculations of the gas flow dynamic pressure can by no means rely on the average air-flow parameter at the jet pipe exit, but on the instantaneous combustion chamber pressure or thrust of the engine.

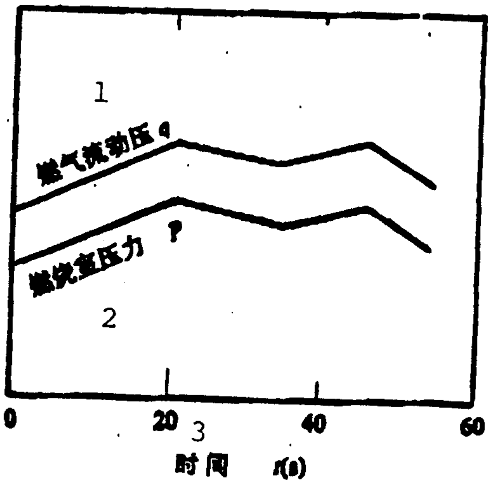

Fig. 3. Schematic diagram showing variation of gas flow dynamic pressure with combustion chamber pressure

Key: 1. Gas flow dynamic pressure q;
2. Combustion chamber pressure P;
3. Time t(s)

3. Analysis of Vane Material Selection and Its Working Properties

3.1 Vane Material Selection

An aerodynamic designer must first select appropriate vane material before starting his vane aerodynamic configuration design. Generally, for a gas vane with a larger plane area and longer working time, material capable of resisting ablation and erosion is regarded as the best choice because it can reduce the areal ablation rate. As for the gas vane with a shorter working time, it would be wise to select material with a poorer ability to resist ablation and erosion since this is favorable for material development. Besides, material production capability is also regarded as a consideration.

Generally, tungsten-molybdenum and tungsten-copper materials appeal to designers in designing a solid missile gas vane because they enjoy excellent ablation-resistant properties as well as high strength under high temperatures, and also because the manufacturing techniques of these two materials are well developed, suitable for mass production. For example, the United States has successfully constructed tungsten-molybdenum and tungsten-copper vanes, and applied them in the "Pension" and other models.

3.2 Analysis on Material Working Properties

Understanding and grasping the mechanical and thermophysical properties of a particular vane material are vital to an immediate success in designing the gas vane geometric dimensions. If the design is based on aerodynamics alone without considering the material tensile strength and shear strength as well as the vane stiffness and ablation-resistance, the vane designed may undergo breakage, bending and over-ablation during an engine test run.

A tungsten-molybdenum alloy vane has several advantages including high melting point, great strength, and high ability to resist ablation and erosion. Reference 1 suggests that a gas vane made from 85% tungsten and 15% molybdenum powder sintered shows around 9% area loss after the test run, and that areal loss increases from 1% to 9% when its leading-edge radius decreases from 12.7mm to 3.4mm. Nevertheless, the tungsten-molybdenum alloy vane also has many disadvantages, such as aluminum in the air flow may form an alloy with either tungsten or molybdenum to reduce the melting point at the vane surface; precipitation of low-melting-point carbides may cause tungsten and molybdenum particles to melt or even shed at the vane surface; aluminum particles, while colliding with the vane surface, can release enough energy to raise its temperature. Another even more serious disadvantage is that due to its low temperature during blank preparation, sintering may not be complete and secondary sintering may happen when the vane is operating in the high temperature jet flow. This can give rise to a density difference in different sections of the vane body because of its different temperatures. As a result, extremely powerful internal stress will be generated, which can lead to cracking and thus, restrict the application of tungsten-molybdenum alloy material.

Tungsten-copper is a new-generation material, which was developed and put to use later in the United States. While working in a high temperature and high speed particle current released from a solid rocket engine, copper inside the tungsten skeleton of a tungsten-copper gas vane may be melted, gasified and escape from the tungsten skeleton, which, by absorbing a large amount of heat during phase variation, can decrease the temperature of the vane body and maintain a smaller area ablation loss rate. Test data prove that this vane has the same ablation-resistant ability as tungsten-molybdenum alloy. The remarkable advantage of tungsten-copper is its excellent thermal shock resistance, because of which there will not be the above-mentioned cracking caused by secondary sintering. Apparently, the tungsten-copper material serves as an ideal vane material.

4. Gas Vane Dimension Design

4.1 Requirements for Gas Vane Aerodynamic Configuration Design

Design of the gas vane configuration dimensions should meet the following requirements:

a. The maximum lift generated by the gas vane should not be lower than the maximum control force proposed during an attitude control analysis;

b. The hinge moment should not surpass the maximum moment permitted by the servo mechanism;

c. Reduce the resistance force as much as possible;

d. The Vane designed must have enough strength and stiffness so as not to generate any deformation that may affect aerodynamic force or even cause a breakage;

e. Its root part must maintain a lower temperature, favorable for connecting structure design; and

f. The gas vane must have a simple configuration, convenient for processing and production.

4.2 Plane Area Ablation Loss Rate

To make the vane designed meet the lift requirement, the areal ablation rate should be restricted. Determination of the vane area loss rate should be designed on the basis of a number of factors, such as: the working conditions of the vane; the ablation resistance of the vane material; the working time corresponding to the required maximum lift; the vane plane area, the leading-edge radius and sweep angle; data collected from actual design practice and experience at home and abroad. For a gas vane with a larger area and longer working time, the rate can be selected as 10%, because if it is too high, its lift will considerably decrease, while for a gas vane with a shorter working time, the rate can be selected as 10-20% or even 30%, which can lower the material requirement and the development period can be shortened.

4.3 Vane Mount Location

In determining the vane mount location, the following factors must be considered:

(a) Minimize the shock wave and the expansion wave affecting the region at the jet pipe exit so as to increase the lift effect;

(b) Locate the vane close to the jet pipe exit so as to reduce the effect of the decreasing gas flow dynamic pressure along the axial direction; and

(c) Simplify connecting structure design.

Based on the foregoing principles, it is wise to mount the vane beyond the jet pipe exit, with its root chord parallel to the axial line of the jet pipe (or missile body) and the leading-edge point of root chord close to the jet pipe exit plane (approximately 35-40mm) as shown in Fig. 4.

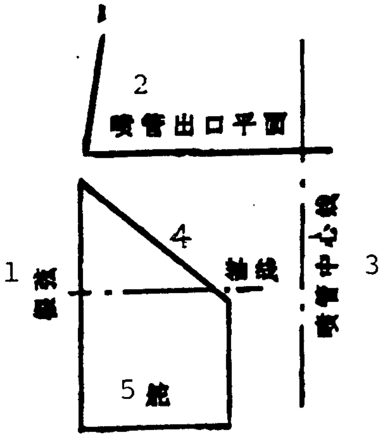

Fig. 4. Gas Vane Mount Location

Key: 1. Root chord; 2. Jet pipe exit plane;
3. Jet pipe central line; 4. Axial line;
5. Vane

4.4 Determination of Maximum Vane Edge Angle

The maximum vane edge angle should be determined on the principle that the vane surface can generate the required lift without bringing too much induced drag. Generally speaking, the maximum vane edge angle should not exceed 20°. If it has already reached 20°, but the total lift still can not meet requirements, the vane plane area has to be enlarged.

4.5 Vane Geometric Dimension Design

Apart from requirements proposed in section 4.1, the vane geometric dimensions should not surpass the blank dimensions attained in the sintering furnace so as to decrease the cost and shorten the development period.

4.5.1 Vane Planform Design

The vane planform should be selected according to the supersonic wing surface theory, along with its stiffness, strength, ablation and erosion resistance. The general choice is a trapezoidal wing with a larger leading-edge sweep angle (Λ), smaller aspect ratio (A) and end-root ratio (λ). With the foregoing plane parameters, a vane can acquire larger lift, smaller zero-edge angle resistance and smaller hinge moment. Also, such a vane can reduce its leading-edge area ablation loss, make its lift center close to the root chord, decrease load stress at the root and increase its strength. Fig. 5 shows the variation of the pressure center with the edge angle under two extremal conditions of a trapezoidal wing. It can be seen then that the increasing leading-edge sweep angle can lead to the decrease of hinge moment.

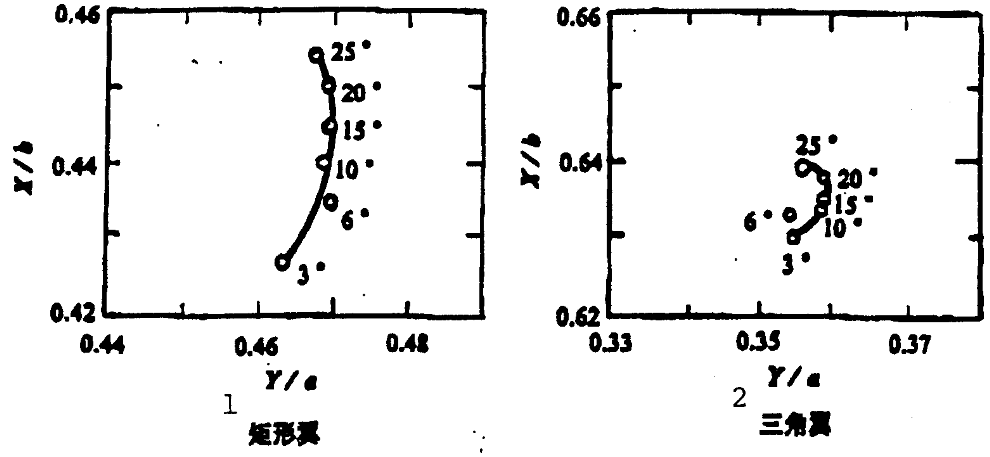

Fig. 5 Relationship between the Pressure Center and the Edge Angle in Vanes of Different Shapes

X--Distance between pressure center and root chord leading-edge point; Y--Distance between pressure center and root chord; a--spread length; b--chord length

Key: 1. Rectangle wing; 2. Triangle wing

4.5.2 Vane Plane Area Design

The vane plane area (S) is determined on the basis of the following equation:

$$S = L_{\max} / [C_{L_\delta} \dot{\delta}_{\max} q \ (1 - \xi)] \tag{1}$$

where $L_{\max}$ is the maximum lift suggested by the attitude control system; C_{L_δ} is wing surface lift coefficient derivative; is gas flow dynamic pressure; $\delta_{\max}$ is the maximum vane edge angle; q is the nondimensional vane surface area loss rate.

4.5.3 Wing Type Design

The vane section is designed as a hexagonal wing type with a small relative thickness, and small front and back wedge angles. Such design of wing type enjoys the following advantages: small resistance and light weight; no considerable backward movement of the pressure center; the use of sections of equal relative thickness leads to the increase of root thickness and therefore root strength; the increase of thermal capacity at the root causes root temperature to decrease and provides excellent conditions for connector design.

4.6 Design of the Gas Vane Turning Axis Location

The turning axis of the gas vane is designed so that it is vertical to the root chord, and the distance between its central line and the root chord leading-edge point (X_j) is calculated from the following equation:

$$X_j = X_{cp} - \xi M_h / N \qquad (2)$$

where X_{cp} is the distance between the pressure center and the root chord leading-edge point, which can be measured on the basis of theoretical calculations and wind tunnel test results, along with the pressure center backward movement quantity caused by area ablation loss; $\dot{M}_j$ is the maximum hinge moment permitted by servo mechanism; N is the gas vane normal force; ξ is the empirical coefficient, given as 0.8.

4.7 Guard Plate Configuration and Dimensions

The guard plate is usually mounted at the root chord of the gas vane. Apart from protecting the vane axis and the supporter from being burnt, it can also restrict the gas flow from spilling out over the root chord, overcome the three-dimensional effect, prevent or decrease the effect of shock and expansion waves on the vane body at the jet pipe exit, which is caused by the change of environmental pressure. All these may eventually increase the lift effect of the vane. Noticeably, if the guard plate area is too large, it can possibly bring about higher friction resistance. Experience has proved that a straight guard plate (Fig. 6) will contribute to a compact structure and light weight.

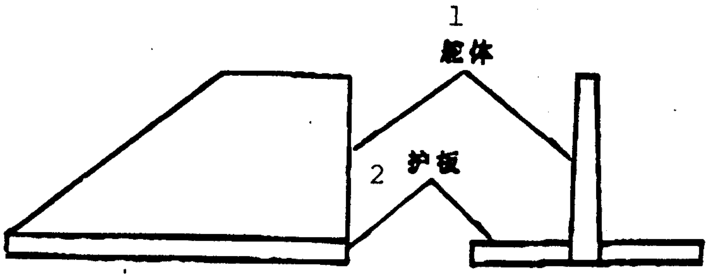

Fig. 6 Guard Plate Shape

Key: 1. Vane body; 2. Guard plate

5. Aerodynamic Characteristics of the Gas Vane

5. 1 Normal Force Gradient (N_δ) Calculations

$$N_\delta = k_1 C_{N_\delta} q S \tag{3}$$

where K_1 is the correction coefficient over dynamic pressure attenuation, wing type thickness, limited wingspan, shock waves and expansion waves at the jet pipe exit, the guard plate shape and vane area ablation loss; C_{N_δ} is the derivative of normal force coefficient; q is the dynamic pressure of gas flow; S is vane plane area.

The derivative of normal force can be calculated through the flat wing linearization theory as follows:

$$C_{N_\delta}=4/(57.3\sqrt{M_{\infty l}^{2}-1})\qquad(4)$$

Fig. 7 shows a comparison between the measurement value and the theoretical value of the normal force coefficient of a particular trapezoidal wing. It can be seen from the figure that the two values are well in agreement when the edge angle is less than 10°, yet when the angle is larger than 10°, the measurement value becomes slightly larger than the linearization theoretical value. This difference can be corrected with K_1 selection method.

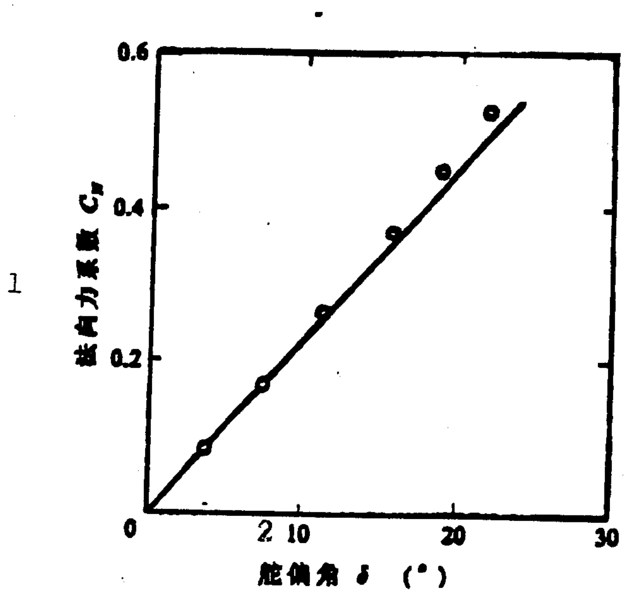

Fig. 7 Variation of Normal Force coefficient with Edge angle in a particular trapezoidal wing

Key: 1. Normal force coefficient; 2. Vane edge angle

5.2 Circumferential Force (T) Calculations

$$T = k_2 C_1 q S \tag{5}$$

where K_2 is the correction coefficient; C_1 is the circumferential force coefficient. Considering the additional circumferential force caused by the leading-edge being passive due to ablation, the circumferential force coefficient can be calculated from the following equation

$$C_1 = C_{1_0} + \Delta C_1(t)$$

where C_{1_0} is the circumferential force coefficient of the unablated vane; $\Delta C_1(t)$ is the circumferential force coefficient increment varying with flight time.

5.3 Pressure Center Location Calculations

Considering the backward movement of the pressure center caused by the ablation-induced passive leading-edge, the distance between the pressure center and the root chord leading-edge (X_{cp}) can be calculated from the following equation:

$$X_{cp} = X_{cp_0} + \Delta X_{cp}(t) \tag{6}$$

where X_{cp_0} is the distance between the pressure center of an unablated vane and the root chord leading-edge; $\Delta X_{cp}(t)$ is the backward movement quantity of pressure center caused by vane ablation.

5.4 Hinge Moment Gradient (M_{h_δ}) Calculations

$$M_{h_\delta} = N_\delta (X_{cp} - X_h) \tag{7}$$

5.5 Gas Flow Dynamic Pressure (q) Calculations

In a solid engine, unlike in the liquid engine, the pressure inside the combustion chamber varies greatly with the passage of flight time, the jet pipe throat is subject to severe ablation, and the gas flow dynamic pressure at the engine exit varies considerably with flight time. Thereby, the method of calculating dynamic pressure with exit air-flow average parameters, which is generally used for the liquid engine, is not applicable to the solid engine. However, the engine design department cannot provide the variation of the engine exit parameters with flight time. This imposes much difficulty in calculating aerodynamic characteristics. Research suggests that the air-flow dynamic pressure at the jet pipe exit of the solid rocket can be written as the coefficient to parameters including the engine thrust as follows:

$$q = f(F, D_e, \theta, p_{ej}, p_a) \tag{8}$$

where F is the engine thrust; D_e, θ, p_{ej}, respectively are jet pipe exit diameter, half angle and air-flow static pressure; p_a is the atmospheric pressure at a given flight altitude.

5.6 Vane Temperature Calculations and Strength Checking

It is necessary to constantly estimate the maximum stress of the vane throughout the design of its dimensions until it can still meet, even after putting in the safety coefficient, the maximum stress requirement tolerated by the material. Only in this way, is it possible to avoid such a situation that the strength and stiffness of the vane are found inadequate following the vane structure design and the design has to be renewed. Additionally, this procedure can ensure the immediate success of the vane design. Prior to strength checking, it is needed to carry out the vane temperature calculations first. The calculation method is described in Reference 3.

6. Testing

6.1 Wind Tunnel Test

The wind tunnel test on an unablated vane model must be advanced and completed after the gas vane geometric dimension and aerodynamic characteristics have been designed. In designing the wind tunnel jet pipe and model, the following requirements must be satisfied: the wind tunnel jet pipe exit diameter and the vane geometric dimensions should be minimized in the same proportion (i.e. to ensure geometric approximation); the wind tunnel jet pipe half angle should be identical to the actual jet pipe half angle; the area ratio of the wind tunnel jet pipe exit (and its throat) should be designed so that the Mach number at the wind tunnel jet pipe exit is equivalent to the the Mach number at the actual wind tunnel jet pipe exit. When the ratio between the jet pipe exit pressure and environmental pressure exceeds 2.5, the variation of environmental pressure no longer affects the vane aerodynamic characteristics and therefore, pressure ratio can be designed as 2.5. Theoretical calculations indicate that when the vane is close to the jet pipe, deviation of aerodynamic characteristics caused by medium difference can be ignored. Obviously, wind tunnel test turns out to be an economical and reliable method in calculating the gas vane aerodynamic characteristics.

6.2 Full-scale Gas Vane Ablation and Force Measurement Test

It is an economical and effective way to conduct a gas vane ablation and force measurement test during the ground test run of the solid engine. The gas vane must be mounted strictly in accordance with design requirements, and starts turning according to design procedures. To increase measurement accuracy, a suspended tube type force measurement scales must be applied [4]. Prior to the test, the scales must be carefully debugged and calibrated plus some heat protection measures, while in the course of the test, the scale must be cooled. Noticeably, sometimes it is difficult to acquire convincing data because there are only few test runs, the vibrational environment is poor and scales calibration may not be adequate. In any case, scales calibration is vitally important.

7. Conclusions

Development of the melting-resistant alloy gas vane is a new technique. The gas vane aerodynamic configuration design is an optimum design, i.e. two kinds of requirements must be taken into account during the design: aerodynamic characteristics requirements on one hand, and requirements over the vane strength, stiffness, ablation quantity and connecting structure on the other. To reach an immediate success for a vane configuration design, designers must first understand and grasp the mechanical and thermophysical properties of the material selected and also, they must investigate the solid rocket jet flowfield characteristics, as well as study and improve the calculating method on aerodynamic characteristics.

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CONVENING OF THE SECOND MICROGRAVITY SYMPOSIUM

The second microgravity science symposium was convened in Chongqing University from May 22 through May 28, 1995. This meeting was co-sponsored by the Chinese Academy of Sciences, the State Science and Technology Committee, the State Natural Sciences Foundation Committee and the State High-tech Aerospace Experts Committee. The meeting was intended to exchange the newest achievements acquired in microgravity science and its applications, develop academic exchanges among scientists specializing in different microgravity areas, and promote the development of microgravity science by investigating and analyzing the prospects of microgravity science. Delegates from China, the United States, Germany, France, Japan and Chinese Taiwan province attended the meeting and presented a total of 85 papers. These presentations covered a large diversity of subjects, including microgravity fluid physics, microgravity combustion, solidification process, crystal growth, space material science, space biological science and technology, microgravity experimentation and diagnosis technology, etc. All these papers reflect the newest research achievements, achieved in microgravity at home and abroad in recent years. Through academic exchange and discussion, delegates gained a good insight into issues, such as setting up and upgrading microgravity ground test facilities in China, strengthening research on basic microgravity theories, promoting engineering application research on spacecraft microgravity environments, facilitating research on manned spacecraft fire prevention and microgravity combustion, etc.

(Reported by Chun Hui)

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