Preliminary Design of Movable Air-Turbo Ramjet Engine Intake

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Keywords: Movable Ramjet Intake, Throat Area, Capture area ratio, Total pressure recovery

Abstract

In this study, two types of ramjet intake were designed for the flight condition of Mach number 2 and 5 and numerical analysis was performed. In order to widen the flight envelope range (Mach number 2 ~ 6), movable intake concept was applied. The central body was designed so that the capture area ratio which is one of most important factors of ramjet intake design could be adjusted. And various types of cowl and movable insert part of shell were designed in order to control throat area which could increase total pressure recovery. The numerical results showed that the designed ramjet intake could be applied in various flights Mach number.

Introduction

The biggest difference between a ramjet engine and a rocket engine is air breathing system. Because the ramjet engine is an air-breathe propulsion system, the combustor of the ramjet engine is more complicate than that of the rocket engine. But, because of the ram effect, the configuration of the compressor of the ramjet engine is much simpler than that of the rocket engine. Simple compressor design and less weight of propellant make ramjet engine to have better performance. Thus, the performance of the intake of the ramjet engine has great effects on the performance of the engine.

In this paper, the detailed design of two types of movable ramjet intake is mentioned and the applicability of the intake is discussed.

General approach of Flow deceleration

The well known physical phenomenon of supersonic flow deceleration is realized due to the formation of the shock waves system. The simplest way to obtain rapid flow stagnation up to the subsonic velocity is the normal shock, but the total pressure drop in this case will be great enough and the lower total pressure recovery coefficient will be obtained. The more effective flow deceleration may be realized in the case of organization of the oblique shock waves system. The oblique shock wave system's interaction and configuration may give a quite different flow pattern and provide the variations of integral flow parameters such as recovery coefficient, capture ratio and drag.

If M is equal to M_p, the oblique shock waves are crossing in a fixed point and this point must coincide with the leading edge of the external envelope which are called cowl. If M is not equal to M_p, this point does not exist. This problem may be overcome by the flow pattern controlling which can be realized by leading cone or spike movement in axial direction. Theoretically, it is possible to make the capture ratio equal to unity at any M, but it can cause significant decrease of σ.

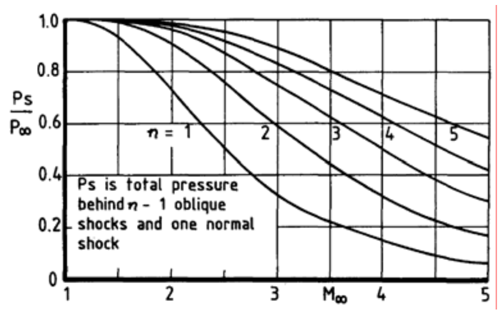

Fig. 1 Shock pressure recovery

The influence of m and M on the σ in case of the optimal system is presented at Fig. 1. One can see a strong dependence of m, especially at high Mach numbers. Theoretically, this increase may be even greater if m goes to infinite and the isentropic compression is realized. Practically, this result can't be realized due to the influence of the boundary layer. This increase causes the growth of the boundary layer thickness and its separation under the influence of the positive pressure gradient. This separation causes the additional inclination of the near body streamlines and formation of oblique shock wave in a region of separation. The result of viscous-inviscid interaction causes the additional flow drag and total pressure drop.

From this point of view and also taking into account some technological limitation in case of low Mach number of m is usually not greater than 2 or 3 and in case of high Mach number of m is usually not greater than 3 or 4. For the purpose of current investigation we shall assume this order as 3.

The optimal shock wave system may be characterized by ω. In case of m is 3, this angle coincide with ω_3 which is the third cone compression angle. A typical dependence of ω upon the M is presented at Fig. 2.

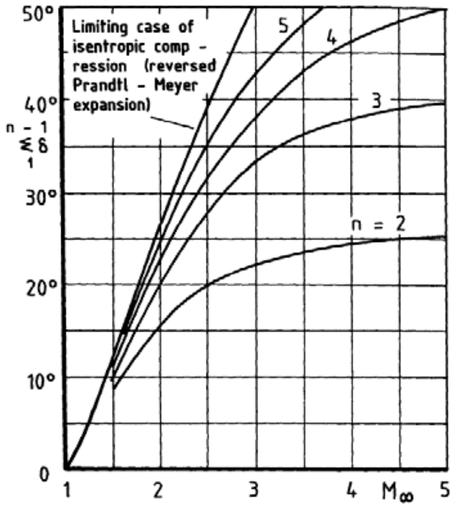

Fig. 2 Total compression angle with Mach number

Design of Movable Intake with M_p = 5

It is possible to estimate the limitation of the maximal compression angle as ω=35~40 degrees with m=3. Usually the maximal limit can't be realized because of the negative influence of the boundary layer. A rough estimation of this influence may be given in terms of boundary layer thickness and additional cone angle increase due to this thickness growth. Depending upon dimensions of central body and M the additional angle may be estimated as 3~4 degrees. So, based upon this conclusion which is approved by the available experimental data carried out in the supersonic conical flows we can limit ω to 35 degrees. This is the maximal level which may be realized with flow control. From the other hand it is useful to estimate this limit without control. This limit must correspond to the lowest M which is 2. Based upon the presented data, ω may be estimated as 25 degrees. It means that in the case of the absence of flow control the 25 degrees of ω provides the oblique shock wave system without it's transformation to the normal shock in a wide range of M from 2 to 6.

To configure the shock wave system, it is necessary to determine the current cones angles ω_i. Because the maximal level of σ can be obtained if each compression cone provides approximately the same total pressure drop, the step by step calculation give the cones angles distribution as ω_1=10 degrees, ω_2=17 degrees and ω_3=25 degrees. After this determination it is possible to find the length of each cone to provide the crossing of oblique shock waves in a fixed point corresponding to the M_p. The non-dimensional length of the first and the second cones are l_1=3.1 and l_2 = 4.05. The reference conditions calculations give σ is 0.16. The calculations of the flow pattern were performed in a full range of M and the typical pictures of shock wave systems are presented at Fig. 3 ~ Fig. 6. The calculation results are summarized in Table 1.

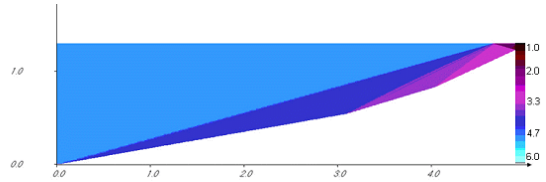

Fig. 3 Numerical result of M_p = 5 and M = 5

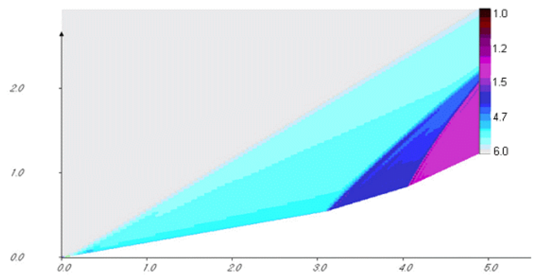

Fig. 4 Numerical result of M_p = 5 and M = 2

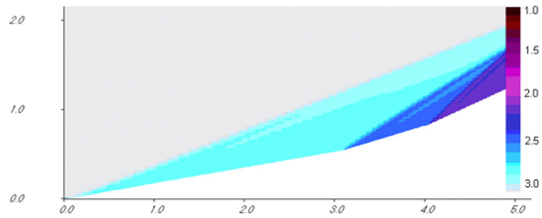

Fig. 5 Numerical result of M_p = 5 and M = 3

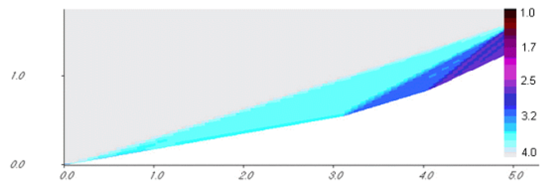

Fig. 6 Numerical result of M_p = 5 and M = 4

Table 1 Calculation results of M_p = 5

M	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
σ	0.86	0.75	0.61	0.47	0.34	0.23	0.16	0.13	0.1
φ	0.29	0.38	0.49	0.61	0.74	0.87	1.0	1.0	1.0

Because of the low level of ω which is 25 degrees, the values of σ are not great and they may be increased significantly only by means of ω and ω_i increasing. This way of flow control is the best one to realize the optimal shock wave system, but it can't be realized practically because of the complexity of controlling the cone shape.

From the other hand the numerical results show rather promising levels of φ which are greater than 0.3

for the full range of M variation. The additional increase of φ can be realized by the axial movement of cone. The axial movement of cone can move first shock wave to cowl and it will increase φ to 1.0. The general limitation of this displacement is the conservation of the oblique shocks interaction without un-start of intake.

The results of flow simulation corresponding to the different displacement of the central body is presented at Fig. 7 ~ Fig. 9. For the Fig. 8, the final normal shock formation is realized just before the throat. This configuration may be assumed as the critical one to realize the maximal φ. This pattern gives more sufficient decrease of σ which is estimated as 0.53. Nevertheless, it may be concluded that the decrease of σ is small enough in comparison with the increase of φ.

And these results show that M=3 is the lowest value when it is reasonable to obtain the maximal φ. The regular interaction and reflection of the shock waves cannot be realized in all flow domains if M is below 3. An example is showed at Fig. 7 for the case of M is 2. It is assumed that Δl is 1.9 which corresponds to the theoretical level of φ is 1. But the flow stagnation is realized just behind the second compression cone with formation of the λ-shape and normal shock wave. This problem may be solved in two ways.

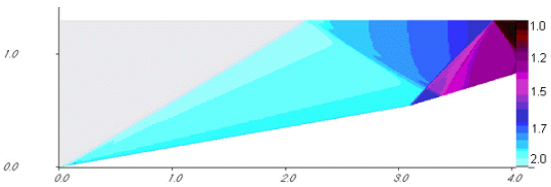

Fig. 7 M_p = 5 and M = 2 with Central body moving

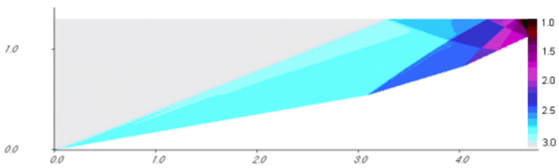

Fig. 8 M_p = 5 and M = 3 with Central body moving

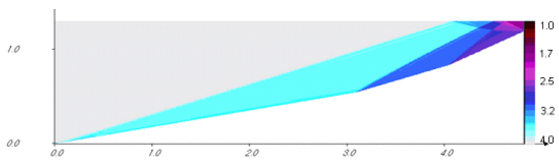

Fig. 9 M_p = 5 and M = 4 with Central body moving

The first way corresponds to the decreasing of Δl. The displacement limitation provides the flow conditions without crossing of the first oblique shock wave with the external envelope. As a result of this reduction, the reflected shock wave will be displaced in direction to the throat and its inclination will be reduced and the local Mach number will be increased. This way will provide the regular interaction of crossing shock waves and regular reflection of the waves on conical surface of central body and cylindrical surface of external envelope. An optimum shock wave system was obtained at Δl is 1.3, similar to the case of M is 3. It corresponds to the maximal φ is 0.59 and σ is 0.76. The results of this analysis are summarized in Table 2.

Table 2 M_p=5 with Central body moving

M	2.0	2.5	3.0	3.5	4.0	4.5	5.0
σ	0.76	0.65	0.53	0.44	0.325	0.22	0.16
φ	0.59	0.81	1.0	1.0	1.0	1.0	1.0
Δl	1.3	1.3	1.3	1.1	0.8	0.5	0

The second way to achieve the stable flow deceleration in the case of low M can be realized by controlling first cone movement. The flow pattern in this case is illustrated at Fig. 10.

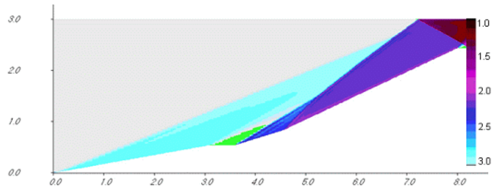

Fig. 10 M_p = 5, M = 3 with the first cone movement

The first cone displacement provides short cylindrical surface before the second compression cone. The flow expansion is realized on this cylindrical surface and additional increase of Mach number before the second cone is obtained. Due to this expansion, the flow can be accelerated up to the Mach number approximately the same as in the external flow's Mach number. The result of local Mach number increase can cause the reduction of the second and third shock waves inclination and the greater level of local Mach numbers. It means that the regular shock waves interaction and reflection will be obtained without the formation of the bow shock at the entrance at low Mach numbers. It is necessary to note that if the greater first cone displacement will be realized, the lower capture ratio will be obtained.

Envelope Shape Control

The most significant increase of φ may be obtained by the displacement of the spike, but it may be limited by a rapid formation of the bow-shock, especially in the case of low Mach number. To avoid this negative process, it is necessary to control the throat area. This control may be realized by an additional movable insert or by the changing of the external envelope shape. The simplest way to obtain the throat area control is to incline some part of the envelope.

A scheme of the envelope configuration which provides the throat area control is shown at Fig. 11. Central body position 1 corresponds to the reference flow conditions. Position 2 is realized when the central body is displaced inside the envelope and corresponds to minimal M. The relative throat increase may be estimated using the following equation.

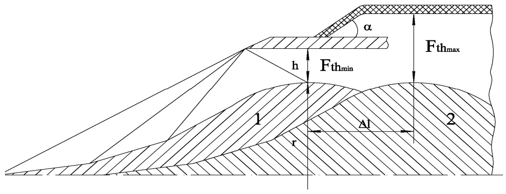

Fig. 11 Scheme of the envelope configuration

$$\frac{F_{\max}-F_{\min}}{F_{\min}}=\frac{\Delta l\cdot tg\alpha}{h}\left[\frac{1+\frac{h}{r}+\frac{\Delta l\cdot tg\alpha}{2r}}{1+\frac{h}{r}}\right] \quad (1)$$

If h<<r, then this equation can be simplified to the following equation.

$$F(\alpha)=\frac{F_{\max}-F_{\min}}{F_{\min}}=\frac{\Delta l\cdot tg\alpha}{h}\left[1+\frac{\Delta l\cdot tg\alpha}{2r}\right] \quad (2)$$

A strong dependence of F(α) provides a promising opportunity to control the throat area in case of variable Mach number. It is necessary to underline that there are also some limitation of α choice. It cannot be chosen very great, due to the increase of total drag of the envelope. So, from this point of view, α must be minimized.

And it cannot be very small to provide a perfect flow compression and regular shock wave pattern in vicinity of the throat. The examples of the flow pattern are presented at Fig. 12 ~ Fig. 14 respectively.

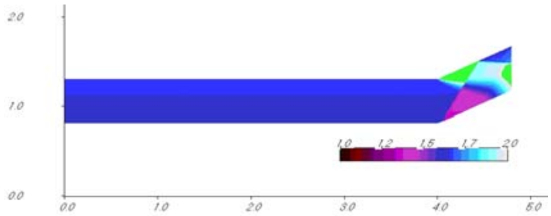

Fig. 12 α = 25 degrees

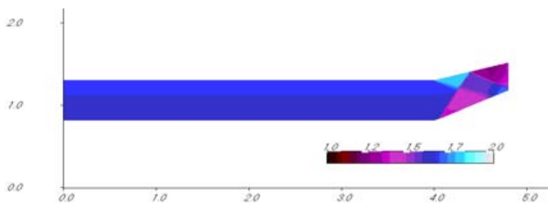

Fig. 13 α = 15 degrees

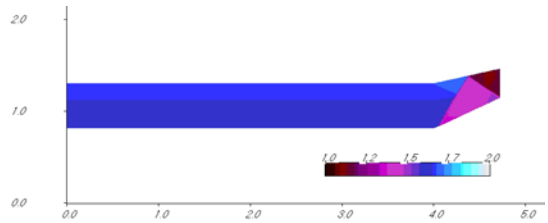

Fig. 14 α = 12.5 degrees

If α is 25 degrees, a strong flow acceleration is obtained up to the Mach number 2. This results show that α must be reduced. If α is 15 degrees, the regular flow interaction is obtained and the Mach number 1.3 is obtained before the throat. One can see that α of 15 degrees is big enough and may be reduced. The appropriate result may be obtained, if α is 12.5 degrees. The results are good enough to obtain the regular shock waves interaction without formation of the bow shock. The greater reduction of α is not reasonable.

Design of Movable Intake with M_p = 2

In order to have an opportunity to compare results, the total compression angle will be assumed as the same, taking into account the limitations which were described in previous parts. If we assume that the Mach number is a variable parameter, it is possible to determine a set of configurations, which will be optimal for each Mach number. The schemes of configurations for M_p is 2.0, 3.0 and 4.0 are presented at Fig. 15 ~ Fig. 17.

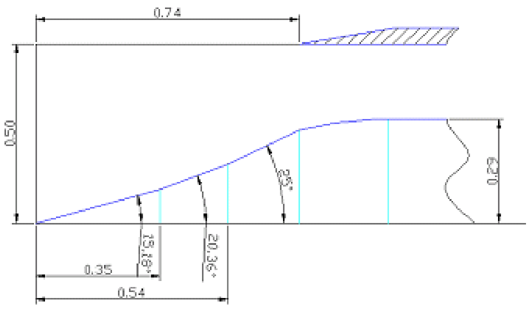

Fig. 15 Optimal Design of Intake with M_p=2

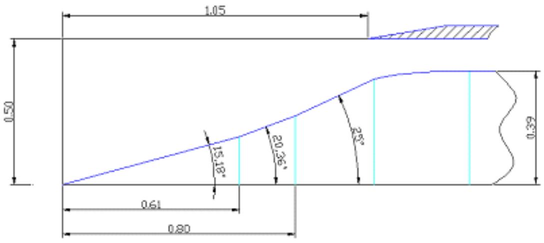

Fig. 16 Optimal Design of Intake with M_p=3

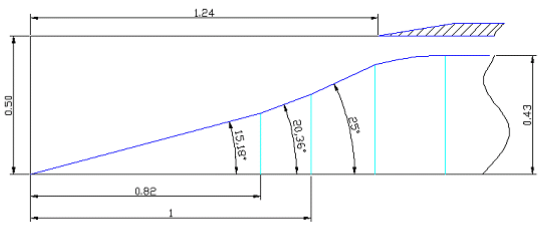

Fig. 17 Optimal Design of Intake with M_p=4

It is clear that the maximal throat area corresponds to the minimal Mach number and it may be assumed as the initial condition for the flow control. So this value may be suggested as the new reference Mach number.

The flow pattern in the described configuration is presented at Fig. 18. The oblique shock waves are crossing in a fixed point, which coincide with the leading edge of the cylindrical envelope.

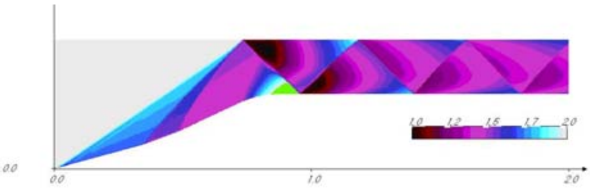

Fig. 18 Numerical Result of M_p=2, M=2

If the Mach number becomes greater than 2, then the oblique shock waves angles will be lower. Instead of a single reflected shock wave, system of reflected shock waves will be obtained. The reflected shock wave's interaction will lead to the formation of a strong oblique shock wave or normal shock and significant increase of total pressure loses.

In order to restrict the local Mach number in the throat region, it is possible to change the initial configuration by the displacement of the first cone, as it is shown at Fig. 19.

The displacement length corresponds to the flight Mach number and may be determined from the condition of fixing point of the first oblique shock wave crossing the leading edge of the envelope. The necessary displacement lengths are presented in Table 3.

Table 3 Displacement lengths of M_p=2

M	2.0	3.0	4.0	5.0	6.0
Δl	0	0.3	0.58	0.83	1.05

The flow patterns corresponding to different Mach number and Δl are shown at Fig. 19 ~ Fig. 21.

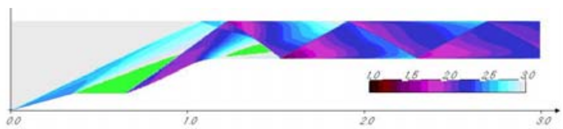

Fig. 19 Numerical Result of M_p=2, M=3

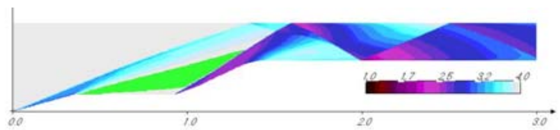

Fig. 20 Numerical Result of M_p=2, M=4

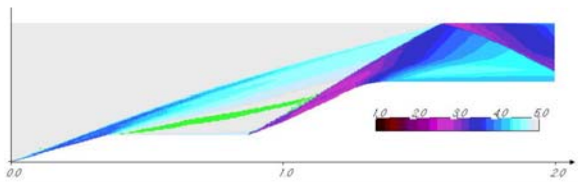

Fig. 21 Numerical Result of M_p=2, M=5

A set of the suggested configurations provides an opportunity to attain the maximal φ, but σ will become lower than the optimal ones. The possible method to control the throat area to satisfy the optimal condition is shown on the Fig. 22 ~ Fig. 24.

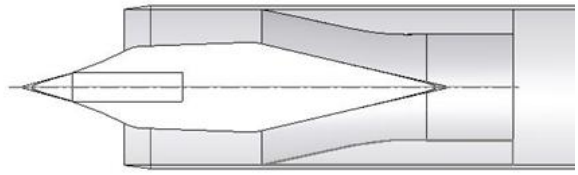

Fig. 22 Movable intake of M_p=2, M=2

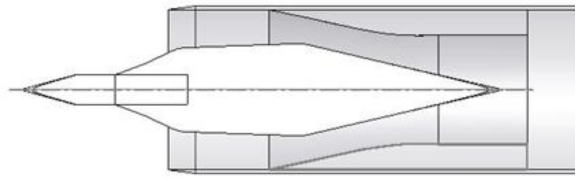

Fig. 23 Movable intake of M_p=2, M=4

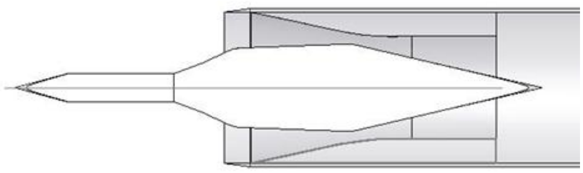

Fig. 24 Movable intake of M_p=2, M=5

The throat area control is realized by the displacement of the coaxial insert which is placed inside the cylindrical envelope behind the central body. The profiles of the insert and bottom part of the central body must be chosen in such a way which provides the possibility to decrease the area from maximal throat area to the minimal throat area. The insert width may be estimated from minimal value. In the case of the nearly conical profile of the insert, its axial displacement must be changed linearly and follows the relation,

$$\Delta l_i = (InsertWidth) \cdot ctg\beta \qquad (3)$$

If β is 8.3 degrees, then the maximal displacement length of the insert is 1.05. This value coincides with the maximal displacement length of the spike and the further development and design of the intake may be fulfilled assuming the application of the single actuator to displace spike and insert.

Conclusion

Based upon general consideration of the shock wave systems in high Mach number flows, two types of movable ramjet intake are designed.

The first type of movable ramjet intake is based upon notification of high enough reference Mach number and realized due to displacement of conical central body. The most significant limitation of this approach are discussed and illustrated by the results of numerical simulation of flow compression.

The second type of movable ramjet intake is based upon determination of the maximal throat area, corresponding to the minimal Mach number. The suggested flow control method intends the simultaneous displacement of spike and envelope insert to provide maximal capture ratio and throat area changing.

The flow compression numerical simulation is fulfilled in a wide range of Mach numbers and preliminary dimension of compression configurations and flow control parameters are determined.

Based on the results presented in this paper, another type of intake will be designed and compared with intakes presented in this paper. And real test with supersonic wind tunnel will be conducted in near future.

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Appendix

Nomenclature

M : Flight Mach number
M_p : Reference / Design Mach number
m : Shock wave system order, number of shock wave
ω : Total compression angle
σ : Total pressure recovery coefficient
φ : Capture Area Ratio
Δl : Cone / Spike Displacement
C_x : Additional drag coefficient
h : Height of the throat corresponding to M
α : Envelope / Cowl inclination angle
r : Central body radius
β : Inclination angle of insert