Fundamental relations on airframe/propulsion aerodynamic integration for supersonic aircraft

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Abstract
Fundamental features of aerodynamic interference and integration of airframes and air-breathing jet engines for supersonic aircraft are studied within the frame of small perturbation theory. Both the influence of airframe components on intake performance and influence of the intakes on vehicle external aerodynamics have been considered. Analytical relations and specific examples show that significant favorable interference between airframes and air intakes could be realized at flight Mach numbers exceeding approximately 3 due to preliminary compression of the flow before intakes by airframe components.

1. Introduction

Effective airframe/propulsion integration should be considered as one of the principal features of advanced aerodynamic configurations for supersonic flight vehicles with air-breathing jet engines, especially for high supersonic speeds. Its effects are significant for both engine thrust performance and vehicle external aerodynamics.

If some of the vehicle airframe components are used as preliminary stages of flow compression in front of the intakes, their effects on intake performance appears in growth of both the intake mass flow rate and total pressure recovery. Enhancing the intake mass flow rate results from growth of flow density. It allows to use the intakes of lesser size and, correspondingly, of lesser weight for engine providing the appropriate thrust-to-drag balance of the vehicle. Preliminary compression of the flow leads also to diminution of the flow Mach number at intake entrance as compared to the Mach number in the free-stream. The latter results in higher total pressure recovery of the intake comparing with the case of an intake located in the undisturbed free-stream flow. As a result, growth of total pressure recovery can considerably improve specific impulse of the engine and the needed fuel consumption. The example presented in Paper [1] shows that due to appropriate shaping of the forward part of the vehicle fuselage making preliminary compression more intense both the intake mass flow rate and pressure recovery factor could be enhanced by 30% at Mach number M_∞=7 at angle-off-attack range $0\leq\alpha\leq6°$ as compared to the conventional shape of the nose part having the axial symmetry.

From the other hand, if the intake is located in a disturbed flow, significant part of the drag force acting on the airframe surfaces providing flow preliminary compression before intakes could be eliminated from external aerodynamic forces acting on an aircraft and devoted to internal forces which act on the flow stream-tube passing through an engine. These forces could be regarded as ones taking part in engine thrust generation.

In order to investigate principal relationships inherent in airframe/propulsion integration for supersonic vehicles it is reasonable to use simplified theories such as, for instance, the linear theory for supersonic flows. Though the current stage of development CFD methods based on Euler and Navier – Stokes equations allows rather reliable investigating aerodynamics of complex configurations, simplified theories haven't lost their significance due to ability of giving clear analytical relationships helping to understand principal features of aerodynamics. Consideration of airframe/propulsion aerodynamic interference and integration within the framework of supersonic small perturbation theory gives possibility to understand a set of important trends and ways of improvement.

2. Description of the theoretical approach

The general theoretical approach used had been described earlier in Paper [2].

Let's suppose that all the elements of the external surface of a vehicle flying with supersonic velocity at small angle-of-attack are inclined to the free-stream direction coinciding with the x-axis of the Cartesian co-ordinate system x, y, z (y-axis being directed laterally in horizontal plane, and z-axis upwards) by small angles, and disturbances of flow velocity in the external flow around a vehicle could be considered as having asymptotically small values as compared to the free-stream velocity. Then it is possible to use the disturbed flow potential φ to describe the external flow, and the flow velocity components V_x, V_y, and V_z along the co-ordinate axes x, y, and z could be expressed with the potential spatial derivatives φ_x, φ_y, and φ_z by the following formulas:

$$\begin{aligned} V_x &= V_\infty(1+\varphi_x); \\ V_y &= V_\infty \varphi_y; \\ V_z &= V_\infty \varphi_z, \end{aligned} \qquad \textbf{(1)}$$

V_∞ designates the free-stream flow velocity.

In order to calculate the intake mass flow rate $f=F_\infty/F_0$ (F_∞ being the area of a free-stream flow tube entering the intake, F_0 is the intake capture area), it is necessary to integrate the mass flow across a stream-tube entering the intake on some its cross-section S_1. If this section is located in the plane normal to the longitudinal axis of the vehicle or it is inclined to this plane at asymptotically small angle, taking into account that density of the disturbed flow ρ could be expressed as $\rho=\rho_\infty(1-M_\infty{}^2\varphi_x)$, the value of f could be calculated using the formula:

$$f = 1 - \frac{1}{F_0}(M_\infty{}^2 - 1)\int_{S_1} \varphi_x dS. \qquad \textbf{(2)}$$

Consideration of airframe/propulsion integration of a vehicle with air-breathing jet engine in terms of external aerodynamics is based on the well-known momentum theorem and the book-keeping principle described, for instance, in Ref. [3].

From the momentum theorem it follows that epy formula for the resulting force acting on a vehicle (or on its model incorporating an internal duct simulating the influence of an engine), $\vec{R}_\Sigma$ could be expressed in the following manner (see Figure 1):

$$\vec{R}_\Sigma = \int_{S_W} [-(p-p_\infty)\vec{n}_W + \vec{\tau}_W] dS + \vec{I}_1 - \vec{I}_N. \qquad \textbf{(3)}$$

Here S_W means the external surface of a vehicle, p – static pressure in the corresponding point, p_∞ – value of static pressure in the free-stream, $\vec{n}_W$ is a vector directed normally to the surface S_W outwards, and having the length of unity, $\vec{\tau}_W$ is a vector of local tangential stress on the external surface, $\vec{I}_1$ is a vector of intake entrance momentum defined by the formula

$$\vec{I}_1 = \int_{S_1} [(p-p_\infty)\vec{n}_1 + \rho(\vec{V}\cdot\vec{n}_1)\vec{V}] dS \qquad \textbf{(4)}$$

(S_1 being the surface located at the entrance section of the intake connecting around its perimeter with the vehicle external surface, $\vec{n}_1$ is the vector directed normally to the surface S_1 and having the length of unity, $\vec{V}$ is the local flow velocity vector), $\vec{I}_N$ is the vector of flow momentum exerting from the engine exit nozzle and defined similarly to $\vec{I}_1$ by integrating over surface crossing the exit stream-tube, S_N. In order to satisfy properly to conditions of using the momentum theorem, the surfaces S_1 and S_N should be chosen so that the entire control surface S_1+S_N+S_W is closed.

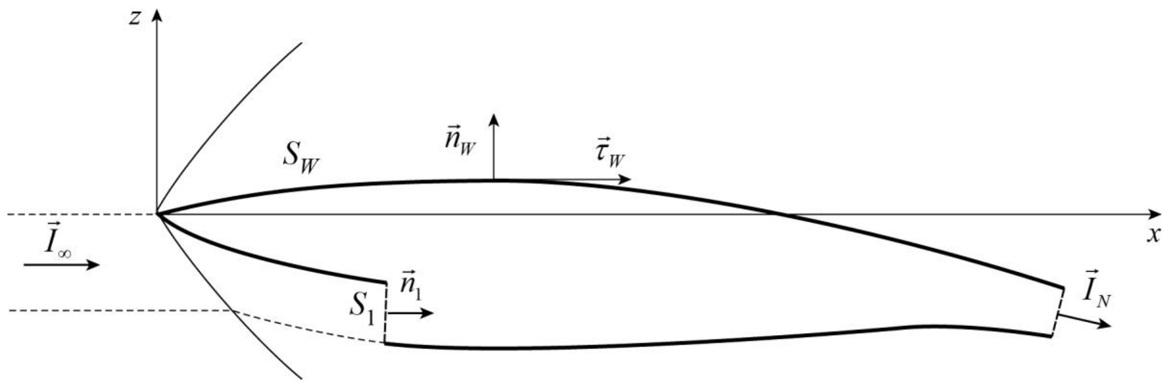


Figure 1: The scheme representing definition of the external aerodynamic force of a vehicle

According to the above mentioned book-keeping principle, the thrust of an air-breathing jet engine (or internal force related to the model duct), $\vec{T}$ equals to the difference between the exit flow momentum, $\vec{I}_N$ and the initial momentum, $\vec{I}_\infty$ of the stream-tube captured by the intake defined at the free-stream condition, that is $\vec{T} = \vec{I}_N - \vec{I}_\infty$.

Then, taking into account that the resulting force of a vehicle, $\vec{R}_\Sigma$ should be equal to the sum of the external aerodynamic force, $\vec{R}_E$ and the engine thrust $\vec{T}$, vector of the external aerodynamic force acting on a vehicle could be presented by the following expression:

$$\vec{R}_E = \vec{R}_\Sigma - \vec{T} = \int_{S_W} [-(p - p_\infty)\vec{n}_W + \vec{\tau}_W] dS + \vec{I}_1 - \vec{I}_\infty. \quad \textbf{(5)}$$

Omitting the term related to viscosity in the Formula (5) and substituting the exact values of flow parameters in it by their approximate values obtained within the frame of supersonic small perturbation theory, the following formula for external drag force coefficient C_D could be derived as follows:

$$C_D = C_{DW} - \frac{1}{S_{REF}} \int_{S_1} [(M_\infty{}^2 - 1)\varphi_x{}^2 + \varphi_y{}^2 + \varphi_z{}^2] dS. \quad \textbf{(6)}$$

Here C_{DW} represents the impact of pressure distribution over the vehicle external surface, S_{REF} is the reference area used for definition of aerodynamic force coefficients. Similarly to the case considered earlier in deriving the Formula (2), it is supposed that the surface S_1 is located approximately at the lateral plane normal to the longitudinal axis of the vehicle so that the vector $\vec{n}_1$ has longitudinal component $n_{1x} \approx 1$ and asymptotically small lateral components n_{1y} and n_{1z}.

Similarly, the formula for external lift force coefficient takes the form:

$$C_L = C_{LW} + \frac{2}{S_{REF}} \int_{S_1} \varphi_z dS. \quad \textbf{(7)}$$

The analytical Formulas (2), (6), and (7) allow us to understand a set of important relationships inherent in airframe/propulsion integration for supersonic flight vehicles.

3. Influence of vehicle airframe on intake performance

As it is seen from the Formula (2), the intake mass flow rate becomes more than 1 if the longitudinal flow velocity component in its location becomes lesser than the free-stream velocity. The latter corresponds to the preliminarily compressed flow capturing by the intake. Enhancement of the mass flow rate increases with growing intensity of the preliminary compression. It is rather well-known effect. The formula helps to understand dependence of the effect from Mach number. The factor $(M_\infty{}^2-1)$ containing in the formula shows that the effect of flow preliminary compression on intake performance grows significantly with Mach number increase. For instance, in the case of an intake located in the compressed flow under a flat plate inclined at an angle-of-attack α to the free-stream, intensity of flow deceleration and compression could be characterised by the Ackeret's formula:

$$\varphi_x = -\alpha / (M_\infty{}^2 - 1)^{1/2}. \quad \textbf{(8)}$$

Substituting this expression into the Formula (2) and assuming that the flow at the intake location is uniform, the formula for the intake mass flow rate becomes as follows:

$$f = 1 + \alpha (M_\infty{}^2 - 1)^{1/2}. \quad \textbf{(9)}$$

It means that if angle-of-attack α is fixed, the mass flow rate coefficient grows significantly with increasing Mach number.

The Formula (9) is asymptotic. It means that theoretically it is valid just for the cases if perturbations of flow parameters are small. Nevertheless, it worth to be mentioned that the practical range of its possible use is rather wide, because really relationships of the intake mass flow rate from angle-of-attack at fixed supersonic Mach numbers are close to linear ones. Relationships $f(\alpha)$ corresponding to the considering case obtained both from the Formula (9) and from exact solution for compressible supersonic flows at fixed Mach numbers are depicted on Figure 2.

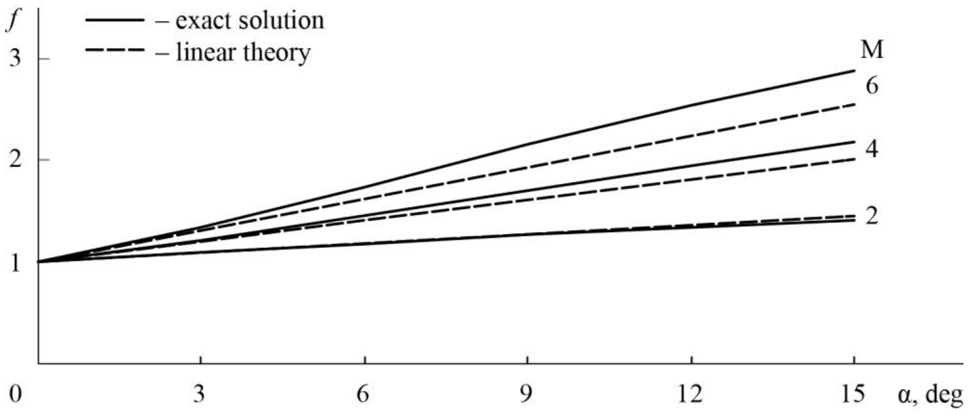


Figure 2: Mass flow rate for intake under a flat plate: linear theory (dotted lines), and the exact solution (solid lines)

It is seen from the figure that linear theory gives rather appropriate approximation for the intake mass flow rate at $M_\infty \leq 4$ in the whole considering range of angle-of-attack $\alpha \leq 15°$. If $M_\infty=6$, significant discrepancies exceeding 10% occur at $\alpha \geq 6°$.

4. Airframe/propulsion integration in terms of external aerodynamics

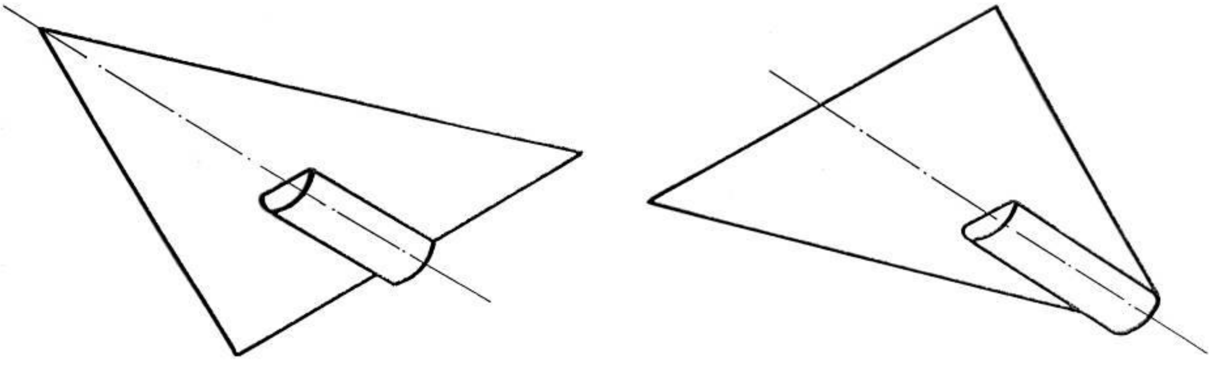
In practical cases, if the intake is designed properly, the shock-waves causing by its own compression ramps at the most important parts of flight trajectory of a vehicle should not lead to considerable spillage of the compressed flow and the influence of these ramps on vehicle external aerodynamics shouldn't be significant. In such cases, vehicle external aerodynamics could be considered without taking into account components of an intake which influence just on internal flow. Exclusion of the intake compression ramps from consideration in external aerodynamics analysis of a vehicle allows us to evaluate the pure effects of airframe/propulsion integration related to mutual arrangement of airframe components and intakes, not mixed with the influence related to particular intake design.

Both interesting and practically important relationships follow from qualitative consideration of Formulas (6) and (7) for external drag and lift force coefficients.

First of all, it should be noted that, following from the Formula (6), if an intake is located in a disturbed flow, it always leads to diminution of vehicle external drag. Really, the additional term in the Formula (6) related to influence of airframe/propulsion interference includes the terms of flow velocity disturbances squared with the 'minus' sign. It means that the external drag force of the whole vehicle is always lesser than the corresponding component of force acting on its external surface, no matter what kind of flow disturbance at the intake entrance location is: deceleration or acceleration. Of course, in order to improve both external aerodynamics and intake performance, it is reasonable to use preliminary deceleration (and compression) of the flow.

Another important issue occurs from the factor $(M_\infty^2 - 1)$ in the term containing $\varphi_x^{\ 2}$. Due to this factor, the influence of this term on the external drag grows sharply with increasing Mach number. Considering again the above mentioned case of an intake located under a flat plate, φ_x being expressed by the Formula (8), one can see that this term for this case does not depend from Mach number. Taking into account that values of aerodynamic coefficients usually diminish with increasing Mach number in the supersonic range, proportionally to $(M_\infty^2 - 1)^{-1/2}$, relative growth of the considering effect of airframe/propulsion interference becomes evident.

Remarkable example of airframe/propulsion integration influence on rational shaping of airframe components had been considered in the Paper [2]. The example includes consideration of the two different simplified schemes of vehicles with air-breathing engines shown on Figure 3. Each of the considering vehicles consists of a triangular wing with 'sonic' side edges, and air-breathing jet engine having cylindrical external surface. The difference is that the wing of the 1st vehicle (Version 1) meets the flow by its apex, and the wing of the 2nd one (Version 2) by its bottom. Intakes are supposed to be rather small so that the flow parameters at the intake entrance in the 1st case could be considered as uniform. Both vehicles are considering as flying at the same angle-of-attack α.



Version 1 Version 2

Figure 3: The simplest configurations of wing and air-breathing engine

According to the reverse flow theorem, aerodynamic forces acting on isolated wings of the two versions are similar: $C_{DW1} = C_{DW2} = C_{DW}$; $C_{LW1} = C_{LW2} = C_{LW}$ in terms of Formulas (6) and (7). Application of the linear theory to study of flow-fields around the considering configurations gives the expressions for longitudinal velocity disturbances φ_x for both cases as follows:

$$\varphi_{x1} = -2\alpha / \pi(M_\infty^{\ 2} - 1)^{1/2};$$
$$\varphi_{x2} = -\alpha / (M_\infty^{\ 2} - 1)^{1/2}. \qquad \textbf{(10)}$$

In the 2nd case the flow preliminary compression is stronger, and it gives stronger its impact on the external drag. The vertical component of the disturbed flow velocity φ_z, according to the boundary conditions on the wings surfaces, for both cases equals to angle-of-attack with the ‘minus’ sign: $\varphi_{z1} = \varphi_{z2} = -\alpha$.

Using the Formula (6), the external drag force coefficients could be expressed as:

$$C_{D1} = C_{DW} - [1 + (2/\pi)^2]\alpha^2 F_0 / S_{REF};$$
$$C_{D2} = C_{DW} - 2\alpha^2 F_0 / S_{REF}. \qquad \textbf{(11)}$$

The corresponding expression for the lift force coefficients is the following:

$$C_{L1} = C_{L2} = C_{LW} - 2\alpha F_0 / S_{REF}. \qquad \textbf{(12)}$$

As it is seen from the Formulas (11) and (12), the external drag force of the 2nd vehicle is less as compared to that of the1st one, the lift force of both vehicles being equal. The absolute value of the negative additional term related to airframe/propulsion integration in the 2nd expression of (11) for C_{D2} is larger than that in the 1st one for C_{D1}, and the difference between them exceeds 40 %. It means that airframe/propulsion interference in the 2nd case is more favourable, and the lift-to-drag ratio of the 2nd version of a vehicle is higher as compared to that of the 1st one.

The latter conclusion could be generalized so that airframe/propulsion integration leads to significant change of conventional ideas on choice of the rational aerodynamic shapes: according to reverse flow theorem, the considering isolated wings have the same aerodynamic force coefficients, while their characteristics in combinations with engines become different.

5. Examples of the integrated aerodynamic schemes

As it is evident from the considered above relationships, the advanced aerodynamic configurations of high-speed vehicles with air-breathing jet engines could be based on the concept of providing the intense preliminary compression of the flow before intakes. The most well-known configurations of such vehicles include American flight test vehicles X-43A and X-51A. These vehicles use their nose parts having flat bottom surfaces to provide flow preliminary compression.

The other possible integrated aerodynamic schemes of vehicles studied both theoretically and experimentally in the Central Aerodynamic Institute named after Professor N.E. Zhukovsky (TsAGI) include those based on using the classical waverider and Busemann biplane configurations. The author of this paper provided computational end experimental investigations of the schemes in cooperation with TsAGI specialists M.F. Pritulo, V.M. Ruch’ev, V.V. Kovalenko, V.V. Khlevnoy, and D.Yu. Gusev.

The first of the configurations is based on the concept of waverider [4] which is studying widely as promising one for obtaining high lift-to-drag ratio. Its nose part consists of the two combined caret lifting elements providing intense preliminary compression of the flow before the two intakes. This configuration was designed for cruise Mach number 5. The scheme of possible vehicle configuration and the photo of its model which has been tested in the TsAGI wind tunnel T-116 are presented on Figure 4 (the part of the configuration simulating by the model is designated on the figure by letter L).

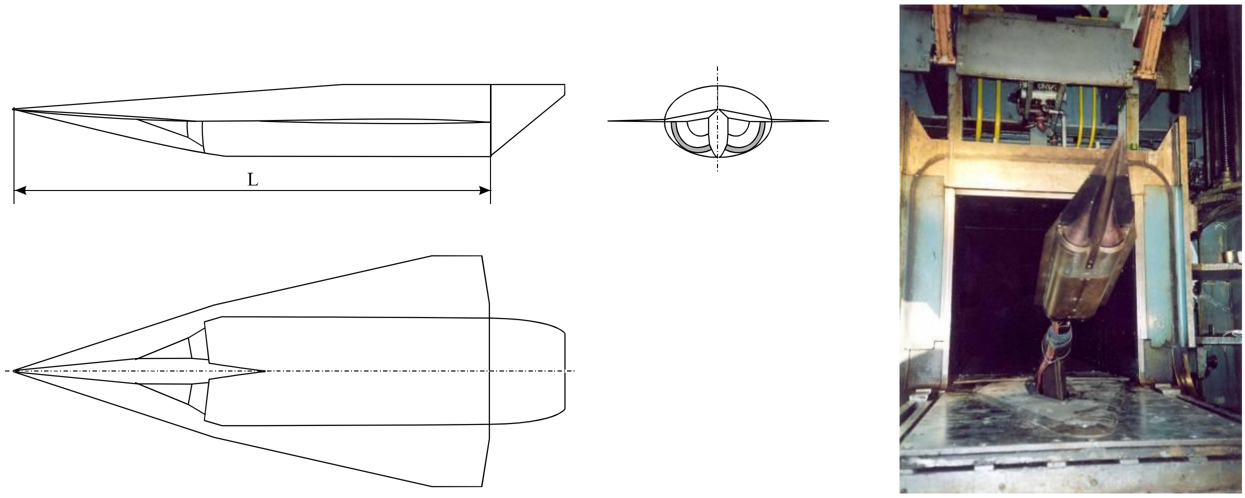


Figure 4: Configuration of vehicle based on waverider concept

The second configuration was based on the Busemann biplane concept. This concept is known from 1936 [5]. The advantage of the Busemann biplane is that theoretically it has a volume and doesn't produce a wave drag. But, as compared to conventional aerodynamic shapes, the biplane configurations have approximately doubled area of the external surface, and it leads to doubled skin friction drag. It is the reason why the Busemann biplane configuration hadn't found practical application until now. If used in the design of vehicles with air-breathing jet engines, the Busemann biplane configuration acquires additional advantage of forming the areas of efficiently compressed flow passing through the two oblique shock waves. These areas could be extremely comfortable for positioning of the air intakes. The latter circumstance allows us to reconsider the question on possible use of the concept.

Configuration of possible vehicle developed and tested in TsAGI is presented on Figure 5. It has been designed for cruise Mach number 4. Preliminary compression of the flow before conventional 2D intake is provided by the two surfaces: the upper surface of the nose part of vehicle fuselage, and the flat cover installed on the side walls preventing spillage of the compressed flow. The slots in front of the leading edges of the intake shown at the picture are necessary to ensure starting of the supersonic flow inside of the biplane configuration.

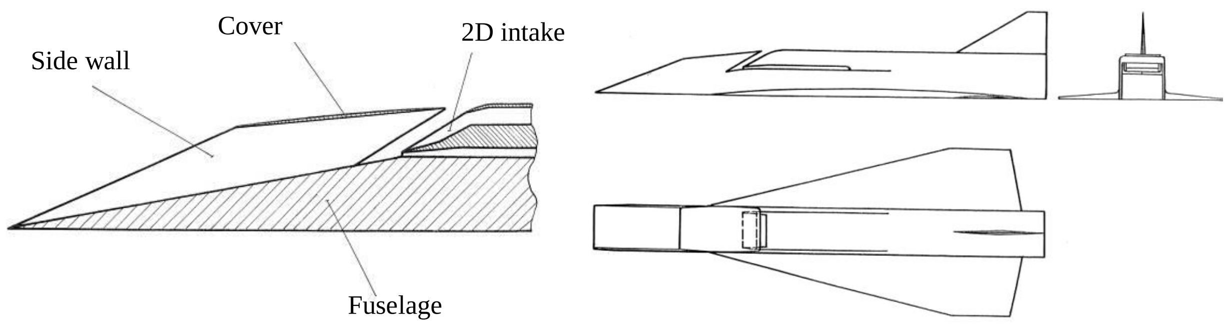


Figure 5: Configuration of vehicle based on Busemann biplane concept

Promising experimental results have been obtained from tests of the two configurations on lift-to-drag ratio, intake mass flow rate, and pressure recovery.

6. Conclusion

1. The study has confirmed ability of using theoretical approaches based on small perturbation theory to assist researchers in the study of fundamental relationships inherent in airframe/propulsion aerodynamic interference and integration.
2. As follows from the analytical relations derived, aerodynamic interference of vehicle airframe with air intakes becomes stronger with increasing Mach number.
3. Analytical study supports the expedience of use the intense preliminary compression of the flow before air intakes by airframe components. As a result of its use, both intake performance and vehicle external aerodynamics could be improved significantly.
4. Analysis of the simplest combinations of wing and air-breathing jet engine shows that airframe/propulsion integration leads to significant change of the conventional ideas on aerodynamic optimization.
5. Consideration of aerodynamic configurations based on classical concepts of waverider and Busemann biplane shows that their use allows reaching high values of lift-to-drag ratio, mass flow rate, and total pressure recovery.

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