Fundamental Relations on Airframe/Propulsion Aerodynamic Integration for Supersonic Aircraft

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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 the intake performance appears in growth of both the intake mass flow rate and total pressure recovery. Enhancing the intake mass flow rate results from the 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 compared to 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 $M_\infty=4$ at angle-off-attack range $0<\alpha<6°$ as compared to 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 of supersonic flows.

Let's suppose that the external surfaces 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) by small angles, and disturbances of flow velocity in the external flow around a vehicle could be considered as asymptotically small 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-ordinates x, y, and z could be expressed by the potential derivatives φ_x, φ_y, and φ_z by the following formulae:

$V_x=V_\infty(1+\varphi_x)$;
$V_y=V_\infty\varphi_y$;
$V_z=V_\infty\varphi_z$,
V_∞ designates the free-stream flow velocity.

If the capture section of the intake having the capture area F_0 is located normally to longitudinal axis of the vehicle, the mass flow rate of the intake $f=F_\infty/F_0$ (F_∞ being the area of a free-stream flow tube entering the intake) could be calculated using the following formula:

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

It is seen from the formula (1) that the intake mass flow rate becomes more than 1 if the longitudinal flow velocity component in its location is lesser than the free-stream velocity. The latter corresponds to the compressed flow.

Theoretical study of the influence of the intake on the external aerodynamic forces acting on a vehicle was based on classical book-keeping principle of aerodynamic forces by external and internal ones similar to that presented, for instance, in the book [2]. Consideration shows that the intake's impact on the vehicle external drag force coefficient C_x could be expressed as follows [3]:

$$\Delta C_x = -\frac{1}{S_{ref}} \int_{F_0} \left[\left(M_\infty{}^2 - 1 \right) \varphi_x{}^2 + \varphi_y{}^2 + \varphi_z{}^2 \right] dS, \qquad (2)$$

S_{ref} is the reference area used for calculation of the drag force coefficient.

Several important qualitative relationships inherent in airframe/propulsion interference could be derived from consideration of the formula (2). The first of them is that if an intake is located in a disturbed flow, its impact on vehicle external aerodynamics is always favorable: the additional value of the vehicle external drag force coefficient representing the impact of the intake is obviously negative – with the negative sign, it consists of potential spatial derivatives squared. Together with this, more intense perturbation of the flow leads to more intense influence – proportionally to squared values of flow velocity perturbations. Additionally, the factor $\left(M_\infty{}^2 - 1 \right)$ in front of the term $\varphi_x{}^2$ shows that the growing Mach number leads to significantly more intense influence.

A set of practical examples shows that aerodynamic shapes providing more intense compression of the flow at an intake entrance location do really lead to improved aerodynamic efficiency. In particular, consideration of lifting bodies of different plan forms with flat bottom surfaces leads to conclusion that the rectangular shape used, for instance, in X-43A flight test vehicle, is preferable as compared to triangular shape with swept leading edges. Taking into account the mentioned above relationships, advantages of airframe components derived from classical shapes such as waveriders and Busemann biplane configurations also become evident.

References:

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