34. BOW SHOCK WAVES STRUCTURES DYNAMICS FOR PULSE-PERIODIC ENERGY INPUT INTO A SUPERSONIC FLOW

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Abstract. Basic principles of flow over bodies control by a localized energy input into an upstream flow are discussed. It is shown, that an optimization of an energy source shape with the purpose of continuous deceleration of a flow is necessary for a formation of a thin temperature wake with a low Mach numbers. Subsonic channels can be applied for the initialization of irregular regimes with front separating zones for flows over very different bodies. For a pulse-periodic energy input, the securing of quasi-stationary regime is critically important for irregular regimes realization and an effective wave drag reduction.

Initially, it was planned that the presentation would be concentrated on the possibility of heading shock wave structure control by a pulse periodic energy input into an upstream flow. However, in a view of recent discussion of plasma technologies application for wave drag reduction phenomena and a certain interest to this problem, the expanded variant is presented and some additional points are considered. Basic principles of flow over bodies control by a localized energy input into an upstream flow are under examination. Some results of previous investigations are summarized.

1. Formulation of the problem.

Unsteady axially symmetric motions of an ideal perfect gas are described by Euler equations:

\[
\begin{align*}
\frac{\partial}{\partial t} \left( \begin{array}{c}
\rho \\
\rho u \\
\rho v \\
\rho w \\
e
\end{array} \right) + \frac{\partial}{\partial r} \left( \begin{array}{c}
\rho u (e + p)u + \rho u^2 \\
\rho u u + \rho u v \\
\rho u v + \rho u w \\
\rho w \\
(e + p) u
\end{array} \right) + \frac{\partial}{\partial z} \left( \begin{array}{c}
\rho v (e + p)u + \rho v^2 \\
\rho u v + \rho v w \\
\rho v w + \rho v z \\
\rho z \\
(e + p) v
\end{array} \right) &= 0,
\end{align*}
\]

where \( e = \frac{p}{\gamma - 1} + \frac{\rho}{2} (u^2 + v^2) \).

The energy input into a mass unit per time unit \( Q \) is proposed to be a predetermined function of coordinates and time --“energy source” model.

\[
Q(r, z, t) = Q_0 f(t) \exp \left( -\left( \frac{r}{\Delta r} \right)^2 - \left( \frac{z - z_0}{\Delta z} \right)^2 \right)
\]

The condition of impermeability was postulated on the body surface, on the outside boundaries the flow supposed to be uniform and unperturbed. The unsteady MacCormac finite-difference explicit scheme of the second order accuracy with coordinates and time, without a special allocation of gasdynamic discontinuities was used for numerical simulations. The time marching procedure was applied to determine steady regimes \( f=1 \). The initial state \( t=0 \) for each numerical experiment is energy input free steady solution previously calculated by the same technique.

The efficiency of energy input for the wave drag reduction was determined as ratio of saved power to the spend one.

\[
k = \frac{\gamma^{3/2} M_\infty^3 S_m \Delta x}{2 W}, \quad W(t) = \int \rho Q \, dV
\]

where \( S_m \) – midsection area.

2. Basic principles of flow over bodies control by a localized energy input into the upstream flow.

In classical (non-viscous) gas dynamics different approaches for the flow over body problem are conceivable. Thus, for a sphere, along with unique “strong” solution with detached bow shock wave, the infinite amount of “weak” solutions with attached fluid cone, filled by stagnated gas, are theoretically allowable (Fig.1). The pressure in the fluid cone is equal to the one on its surface, so when moving the apex upstream and...
the flow turning angle decreases, the pressure tends to be equal to static pressure of the unperturbed flow $p_{f}$. This way, the wave drug, calculated as surface integral of extra pressure, tends to be equal to zero. This argumentation is correct both for blunt and sharpen bodies. On practice, as well as in numerical simulation, nevertheless, the strong solution is realized, which can be explained by real gas effects and, most of all, a viscosity (a numerical viscosity). The realization of weak regimes can be associated with creation of some artificial reason, some lack of uniformity in the upstream flow to determine the fluid cone apex position.

In the middle 50-ies in CIAM Institute the following experiment was set by V.Shulgin under the direction of G.Chernyi. The small ball was shooting from the stagnation point of a blunt body towards the flow. The thin layer was appeared behind the ball that was the reason for flow over body reconstruction; the shock wave structure typical for “weak” regime was clearly identified on photos. In 70-ies both in USSR and in USA some theoretical and experimental investigations for flow over bodies with a “needle” were carrying out. It was shown that even thin (asymptotically infinitely thin) needle is a reason for bow shock wave structure reconstruction, because of the boundary layer effect. In present times, the possibility of flow over body control and the wave drug reduction by plasma and hot-gas injection was determined in [1]. The comparison of different methods of irregular regimes initiation for blunt bodies can be found in [2].

The new principle for different bodies aerodynamic characteristics improvement is the guided action on the upstream flow by a localized energy input – “energy source” [3]. The high temperature wake with a reduced density, critical pressure, Mach numbers and increased longitudinal velocity is formed behind the energy source. For energy sources of size commensurable with the body one the quasi-uniform flow with reduced Mach numbers is occurred and, obviously, the wave drag decrease essentially. However, as it was shown in [4–9], such direct action is ineffective. The indirect action, when a small energy input into a small region becomes a reason for a bow shock wave structure reconstruction, is an effective method of wave drag reduction. This method is a key point for new “flow over body control” technology.

3. Formation of the temperature wake of “required” properties.

For an application of energy sources as bodies wave drag reduction instrument, parameters of great impotence are Mach numbers and critical pressure inside the temperature wake. However, in [3] the effect of “saturation of the flow with energy” was found. The essence of this effect is: for energy sources of fixed dimensions the increasing of intensity $Q_0$ over some critical value $Q_0^*$ results in the wake Mach numbers and critical pressure saturation. The “flow choking” is taking place that for two-dimensional flow appears as high-pressure region formation (Fig.2a – curve 1) with the bow shock wave ahead of it and results in gas acceleration in the wake [4–9]. Therefore, along with the temperature rise the increasing of longitudinal velocity is occurred. In particular, in [4,5] for spherical energy sources, the impossibility of subsonic wake formation was shown (Fig.2b – curve 1) and the approximation for the critical intensity $Q_0^*$ was proposed:

$$Q_0^* = \frac{J S M_0^2}{\sqrt{\pi (\gamma^2 - 1)}} \left(\frac{\gamma - 1}{M_0}\right)^{3/2}$$

Fig.1. The non-uniqueness of flow over body problem solution in classical gas dynamics: strong regime (upper), weak regime (down).
For the flow choking effect negotiation it is necessary to ensure the continuous, shocking-free deceleration of the flow, that can be obtained by the energy source elongation \([4–9]\). The numerical simulation for fixed \(\Delta r, Q_0\Delta z\) was carrying out (Fig.2). At increasing the elongation \(\Delta z\) the tendency to flattening the static pressure (Fig.2a) and monotonic Mach number decreasing (Fig.2b) are observed. The analytical model of quasi-one dimensional isobaric flows was applied \([9]\).

\[ q(z) = \int_{-\infty}^{z} Q(\zeta) \, d\zeta, \quad p = p_\infty, \quad v = v_{\infty} \]

\[ \frac{p_\infty}{p} = \frac{T}{T_\infty} = 1 + \frac{\gamma - 1}{\gamma} \frac{p_\infty}{p_0} q(z) \]

This model is conformed to the basis specific of the phenomenon – continuous deceleration of the flow by energy input (the higher is \(q\), the less is \(M\)). This way, the limitations of the flow choking effect are neglected.

Thus, a thin wake with predetermined properties and arbitrarily low Mach numbers can be formed in the supersonic flow by the energy input into a localized region.

### 4. The flow over different shape bodies control.

The temperature wake can be applied for aerodynamic characteristics improvement by the two different manners. In the first case, when the energy source and the body sizes are commensurable, the quasi-uniform flow with decreased Mach numbers (or even subsonic) is occurred, that is the reason for essential wave drug reduction. The subject of the present paper is the possibility of flow over bodies control as result of heading shock wave structure reconstruction by the energy input of a small portion of energy into a small region. For blunt bodies irregular regimes with front separating zones can be initiated by a simple decreasing of the spherical energy source size when supersonic temperature wakes are formed \([6,8,9]\). When decreasing the energy source radius, the total energy input decreases proportionally to the size in a square root while the wave drug gain remains finite, so that effectiveness of energy input is very high. However, for sharpen bodies the regular flows with the attached shock wave are realized for supersonic wakes. Correspondingly, the static pressure on the body surface is modified in the trace region only. The wave drug reduction is determined by the energy source size – when decreasing the radius, the wave drug gain disappear \([6,8,9]\). The effectiveness parameter is essentially less then one despite of energy source size, its intensity and sharpen body shape.

The establishing of the subsonic channel upstream of a body by the elongated energy source is a method for initiation of irregular regimes of flows over both blunt and sharpen bodies \([8,9]\) (Fig.3). In the wake paraxial region the continuous shock-less deceleration of the flow down to a subsonic speed is taking place. Even for thin
temperature wake, front shock wave structures are subjected to reconstruction and front separating zones filled by circulating gas are formed. The efficiency of the energy input increases multiply because of finite action of very small energy sources.

\[ f(t) = \begin{cases} 
1, \text{mod}(t,T) \leq \tau \\
0, \tau < \text{mod}(t,T) < T 
\end{cases} \]

Previously, it was mentioned, that depending on the period duration \( T \), different regimes of flows over energy sources could be realized \([4,5,7]\): single pulse regime, pulsing regime and quasi-stationary regime. For a single energy pulse the ellipsoidal cloud of heating gas is formed, that later is drifted downstream by the flow. The elongation of the cloud is occurred due to injection of hot gas particles downstream of the energy source with a velocity equal to that one of the steady temperature wake. For energy sources of high elongation the wake velocity is closed to the unperturbed one, so that the cloud size could be easily estimated depending on pulse duration \( \tau \). For pulsing regime the unsteady shock waves structure is formed: every new pulse provides explosion-similar effect and generates shock waves in the supersonic flow. In \([10]\) experimentally and in \([4]\) theoretically the qualitative new quasi-stationary regime was found. In this case, the flow structure similar to the steady one is formed with typical attributes – bow shock wave and temperature wake. The parameters distribution depends on the total energy input during the period only but not pulse form or duration. The condition of realization of such regime: every new pulse must be pumped unless the high temperature cloud of the previous one is drifted downstream the energy source – that is in the manner ensuring the “continuity” of the wake. Supposing the effective length of the energy source \( 2\Delta z \), the approximation for dimensionless period can be proposed:

\[ T = \frac{2\Delta z}{\sqrt{\gamma M_{\infty}}} \]

Physical model for laser-induced spike in the supersonic flow and more accurate estimations can be found in \([11]\).

Let us consider an action of pulsing and quasi-stationary “non-choking” energy sources of high elongation on the flow over sharpen body – \( \theta = 25^\circ \) cone, in a comparison with a power-equivalent steady source (Fig.4). For the steady irregular flow (Fig.4a) – the shock-less paraxial region and hanging shock wave on the periphery can be distinctly identified. For the quasi-stationary regime (Fig.4b), the situation is much closed, with the difference that hanging shock wave is broken, and every new pulse generates shock waves, spreading from the symmetry axes to the periphery, just like for the cylindrical explosion. For unsteady pulsing regime (Fig.4c), the high temperature cloud is drifted downstream by the flow before the next
pulse is pumped. The attached shock wave is disappeared every time the subsonic cloud is formed in the oncoming flow and is appeared on the cone apex just when parameters of an ambient flow are recovered.

The attached shock wave is disappeared every time the subsonic cloud is formed in the oncoming flow and is appeared on the cone apex just when parameters of an ambient flow are recovered. For pulsing regime, the formation of a front separation zone is destroyed every time when parameters of the ambient flow are recovered. The wave drug coefficient is periodically changing with time, but the average value is higher than that one for quasi-stationary regime. Thus, the securing of quasi-stationary regime of an energy input is necessary condition for initiation of irregular flows over sharpen bodies.

Fig.4 Different steady and unsteady regimes for the flow over $\theta=25^\circ$ cone for $M_f=2$ and "non-choking" energy sources $\Delta r=0.1, \Delta z=0.5$ (pressure isolines).

The analysis for the wave drug reduction dependence vs. time enables to make some additional conclusions concerning the dynamics of an action of a pulse-periodic energy input on a flow over cone (Fig.5). Even for steady regime, the noticeable time $T_s=5$ is necessary for the relaxation process to be finished and for the front separation zone stabilization. Within this time, the wave drug is permanently decreasing to the new value (about 50% of initial). For the quasi-stationary regime,

every new pulse pumps a portion of an energy into the flow, ensuring an integral action equivalent to the steady energy source - the curve for dependence of wave drag vs. time oscillates near steady curve. For pulsing regime, the formation of a front separation zone is destroyed every time when parameters of the ambient flow are recovered. The wave drag coefficient is periodically changing with time, but the average value is higher than that one for quasi-stationary regime. Thus, the securing of quasi-stationary regime of an energy input is necessary condition for initiation of irregular flows over sharpen bodies.

Therefore, both steady and pulse-periodic energy input into a supersonic flow can be applied to initiate low Mach numbers channels, to control the bow shock wave structure over bodies and to decrease the wave drug.

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