UDC 533.6.011.72

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Triple configurations of pursuit shock waves in conditions of ambiguity of the solution

The article studies triple configurations of shock waves in supersonic flows of a perfect gas in view of the fact that it is not always possible to determine unambiguously the parameters of the remaining shocks in the configuration by specifying the properties of the oncoming flow and the branching shock wave. The values of the parameters of triple configurations with maximum relations of the parameters of the flow on the sides of the outgoing tangential discontinuity (extremal configurations) in conditions of the ambiguity of the physically realizable solution are found analytically and numerically.

Keywords: triple configurations, shock waves, supersonic flow.

Introduction

Triple configurations of shock waves, present in stream and nozzle gas flows implemented in jet aviation and rocketry technologies, affect the performance of supersonic air intakes and other equipment based on jet flow technologies.

At the present time, developers keep on searching for effective solutions for ramjet, rotating, and pulse detonation engines, so the problem of analysing interaction between compression shocks, shock and explosive waves is especially relevant. To solve this problem, it is necessary to analyse all triple configurations that may form in given conditions, depending on device parameters. It is also important to analyse a variety of possible solutions to the problems regarding development of explosive-proof equipment, determination of damage effect caused by condensed substance explosion associated with irregular interaction of air shock waves and their Mach reflection.

This paper briefly reviews the properties of optimal triple configurations that correspond to the maximum variations in the parameters of flows after them and are inherent to the basic and alternative solutions within the framework of the local triple shock theory. In this respect, when searching for the optimal flow conditions in triple configurations, we must consider the ambiguity in solution to the constitutive system of equations.

General information on triple configurations

A triple configuration of compression shocks is a shock-wave structure consisting of three shock waves with a common triple point (point T in Fig. 1). Triple configurations of shock waves, being stationary within a selected coordinate system (compression shocks), are present in stream and nozzle gas flows implemented in jet aviation and rocketry technologies [1–3]. They affect the performance of supersonic air intakes and other equipment based on jet flow technologies [4, 5]. Triple configurations of moving (travelling) shock waves appear under their Mach reflection and irregular interaction [6–10], affecting the efficiency of the mechanical impact of an explosion, as well as the performance of explosion-proof devices intended to suppress the high-explosive effect [11–13], in particular, in case of multiple interaction of shock waves in confined volumes [14–16]. Gas flows having passed through different compression shock wave systems (sequence of shocks 1 and 2 or single shock 3) are separated by tangential discontinuity τ. The parameters of shocks are connected by the conditions of consistency on tangential discontinuity, written in the form [17–19]:

$$J_1 J_2 = J_3 ; \quad (1)$$

$$\beta_1 + \beta_2 = \beta_3 . \quad (2)$$

Here, $J_i (i = 1...3)$ – intensity of the i-th shock (ratio of static pressures after and before the shock);

β_i – flow turn angle on the surface of the i-th shock.

Angles β_i and Mach numbers M_i after the i-th shock are associated with shock intensity and Mach number M_k before the shock by the known [1] classic relationships.

Depending on the direction of flow turn on shocks 1–3, three types of triple configurations are

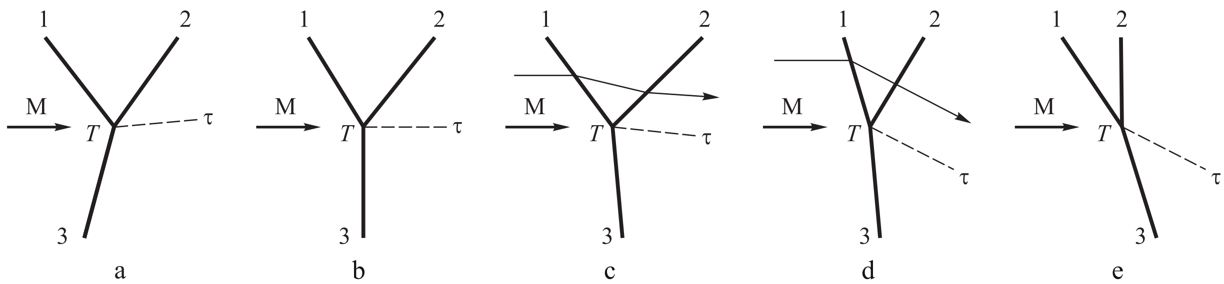

Fig. 1. Types of triple configurations:
a – TC-1; b – TC-2; c – TC-3; d – SMC; e – TTC-2-3

distinguished. In configurations of the first type (TC-1, Fig. 1, a), flow turn on shock 1 occurs in a direction different from that on shocks 2 and 3. For example, at $\beta_1 < 0$, angles $\beta_2 > 0$, $\beta_3 > 0$. In configurations of the second type (TC-2, Fig. 1, b), the direction of turn on shock 2 is different from the others, and in configurations of the third type (TC-3, Fig. 1, c), flow turn occurs in the same direction on all the shocks. The stationary Mach configuration (SMC, Fig. 1, d) with direct main shock ($\beta_3 = 0$) and configuration TTC-2-3 (Fig. 1, e) with direct shock 2 ($\beta_2 = 0$) are transient.

Setting adiabatic index γ, Mach number M of flow before the triple point, and branching shock intensity J_1 does not always allow to explicitly define the properties of other shocks in the system of equations (1)–(2). The same parameters γ, M, and J_1 are matched by up to three physically based solutions with different values of β_2 and β_3. The basic solution to the system of equations (1)–(2) is defined in the widest area of parameter space $(\gamma, \mathrm{M}, J_1)$, and two alternative solutions – only at subsets of the region of the basic solution definition. Triple configurations corresponding to the basic solution may belong to all three types, as well as to the transient configurations SMC and TTC-2-3. Alternative triple configurations (ATC) relate to the third type (see Fig. 1, c), and the flow after shock 2 is supersonic at that. They are formed as a result of interaction between pursuit shocks.

Many parameters of gas flows after triple configurations have substantial differences. Those of interest are the differences in stagnation pressures p_0, velocities V, flow rate functions $q = \rho V$, flow strength $d = \rho V^2$, flow pulses $j = p + \rho V^2$ after the triple point. The measure of difference here are their ratios on the tangential discontinuity sides. Triple configurations with extremal values of such ratios are called optimal configurations. Investigation of the optimal configurations may have practical importance in analysing the origin of self-oscillation regimes of flows in free and impact supersonic jets [20], when designing the equipment generating pulsating gas flows.

Further, we shall analyse the properties of optimal triple configurations corresponding to both the basic and alternative solutions. The numerical results are given for $\gamma = 1{,}4$.

Optimal configurations corresponding to the basic solution

The properties of triple configurations of compression shock waves are analysed on the plane of parameters M and σ_1 (Fig. 2), where σ_1 – angle of shock 1 to the direction of flow before the shock. Angle σ_1 correlates with shock intensity J_1 as

$$J_1 = (1+\varepsilon)\mathrm{M}^2 \sin^2 \sigma_1 - \varepsilon,$$

where $\varepsilon = (\gamma - 1)/(\gamma + 1)$.

The range of angles σ_1 variation is limited from below by curve 1, which corresponds to shock transformation into a weak discontinuity ($\sigma_1 = \alpha(\mathrm{M}) = \arcsin(1/\mathrm{M})$, $J_1 = 1$). The values σ_1 are limited from above as well, at least by the requirement that shock 2 must exist in the supersonic flow after the branching shock. This requirement is conformed to by the region under curve 2, which is plotted proceeding from condition $\mathrm{M}_1 = 1$ after shock 1.

For the existence of triple configuration, presence of a supersonic flow after shock 1 is insufficient. A solution to the system (1)–(2) exists only in the region between curves 1 и f_1 therefore curve f_1 is the exact upper boundary of the region under consideration and is defined by the equation common for curves $f_i (i = 1, 2)$:

$$\mathrm{M} = \Big\{\Big[(1 - 2\varepsilon - \varepsilon^2)J_1^2 + (1 - 5\varepsilon^2)J_1 + 2\varepsilon \times \\ \times(1 - 2\varepsilon^2) \mp 2(1 + \varepsilon J_1)\sqrt{\varepsilon(1 + \varepsilon J_1)(J_1 + \varepsilon)}\Big] / \\ /\Big[(1 + \varepsilon)\big((1 - 3\varepsilon)J_1 - 4\varepsilon^2\big)\Big]\Big\}^{1/2}. \quad (3)$$

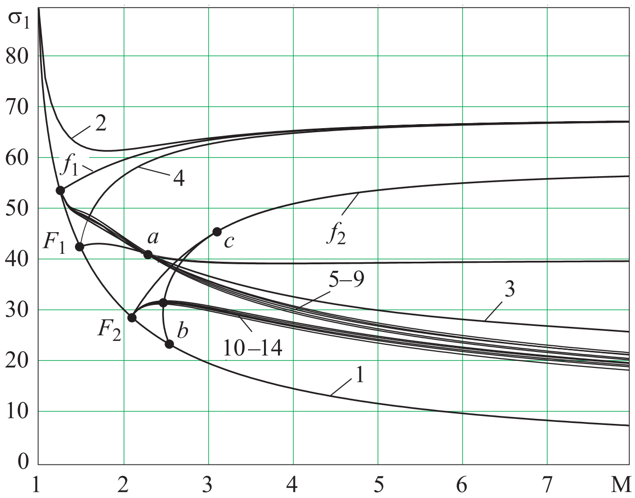

Fig. 2. Parameters of triple configurations

Curve f_1 starts in point F_1 on curve 1, where $\mathrm{M}_{F_1} = 1.245$, $\mathrm{M}_{F_2} = 2.54$.

Solutions to the system (1)–(2) in the region under consideration may correspond to configurations of different types. In the subregion between curves 1 and 3, configurations of TC-1 type are implemented; between curves 3 and 4 – TC-2, and between curves 4 and f_1 – TC-3. Curve 3 corresponds to the stationary Mach configuration and is plotted from solution to the equation

$$aJ_m^2 + bJ_m + c = 0,$$

where $a = (1 - \varepsilon)(1 + \varepsilon J_1)$;

J_m – intensity of direct shock, formed in the flow with a given Mach number,

$J_m = (1 + \varepsilon)\mathrm{M}^2 - \varepsilon$;

$b = -\left[(1 + \varepsilon - \varepsilon^2 + \varepsilon^3)J_1^2 + \varepsilon(1 + \varepsilon)J_1 + (1 - \varepsilon)\right]$;

$c = J_1\left((1 - \varepsilon^2)J_1^2 - (1 + \varepsilon^2)J_1 - 2\varepsilon\right)$.

Transient configurations TTC-2-3 (curve 4) are determined analytically as well [18, 19].

Intensities and other parameters of compression shock waves across the entire region of basic solution existence are changing continuously. The parameters of individual shocks take extremal and specific values (e.g., shocks 2 and 3 may correspond to the maximum deviation points, Crocco points, constant pressure points, and sonic point [19]).

The properties of flows after the triple configuration are determined from the system (1)–(2) and ratios on the compression shocks. For example, the ratios between total pressures p_0, velocities V, flow rate functions q, flow strengths d, flow pulses j at tangential discontinuity are as follows:

$$I_{p_0} \equiv \frac{p_{02}}{p_{03}} = \left(\frac{E_3}{E_1E_2}\right)^{\frac{1+\varepsilon}{2\varepsilon}}, \quad I_V = \frac{\mathrm{M}_2}{\mathrm{M}_3}\sqrt{\frac{E_1E_2}{E_3}},$$

$$I_q = \frac{\mathrm{M}_2}{\mathrm{M}_3}\sqrt{\frac{E_3}{E_1E_2}}, \quad I_d = \frac{\mathrm{M}_2^2}{\mathrm{M}_3^2}, \quad I_j = \frac{1 + \gamma\mathrm{M}_2^2}{1 + \gamma\mathrm{M}_3^2}, \quad (4)$$

where $E_i = \dfrac{(1 + \varepsilon J_i)}{(J_i + \varepsilon)}$ – inverse ratio of densities on the shock.

The lower boundary of the region of solution existence (curve 1) corresponds to transformation of shock 1 and the upper boundary (curve f_1), of shock 2 – into a weak discontinuity. In these cases, all the considered parameter ratios after the triple point are equal to unity. At fixed Mach number M, the only extremum point of the considered functions in a range between the definition region boundaries is the maximum point. The configurations corresponding to these maxima are optimal at fixed Mach number.

The parameters of configurations optimal with respect to the target functions (4) are shown in Fig. 2 by curves 5–9, respectively. At low Mach numbers, these configurations belong to the third type. The intersections of curves 5–9 with curve 4 corresponds to the optimal transient configurations. In this case, the optimal ratios of parameters ($I_{p_0} = 1.076$; $I_V = 1.085$; $I_q = 1.107$; $I_d = 1.201$; $I_j = 1.090$) are low, and the ratios of Mach numbers ($\mathrm{M} = 1.596$; $\mathrm{M} = 1.567$; $\mathrm{M} = 1.571$; $\mathrm{M} = 1.569$; $\mathrm{M} = 1.584$) are very close.

With an increase of Mach numbers, the optimal curves 5–9 come close and intersect in one point a, which corresponds to the stationary Mach

| ISSN 2542-0542 Journal of "Almaz – Antey" Air and Space Defence Corporation | No. 4, 2017

configuration (SMC) with Mach number $M = \frac{\sqrt{4-3\varepsilon+\varepsilon^2}}{(1-\varepsilon)} = 2.254$. The intensities of incident shock 1 and reflected shock 2 of the compression shock waves in such SMC are equal to: $J_1 = J_2 = \frac{2}{(1-\varepsilon)} = 2.4$. It is proved [21, 22] that equality of the shock wave intensities leads to the total pressure maximum after the shock-wave system if the product of those intensities is a fixed value. It can be shown that in the SMC such a product (J_3 intensity), even though it is not a fixed value, obeys the above theorem, therefore it is exactly the Mach configuration with equal shock intensities that is the optimal one. The parameter ratios after the optimal SMC:

$$I_{p_0} = 1.448,\ I_V = 1.649,\ I_q = 1.833,\ I_d = 3.024,$$

$$I_j = 1.587.$$

At greater Mach numbers, configurations of the first type are optimal. The optimal values of target functions increase monotonically but in a limited way, while the optimal intensities of shocks 1 and 3 at $M \to \infty$ tend to infinity. The configurations optimal in terms of I_{p_0} have the following finite limits:

$$\frac{J_3}{M^2} \to C_1,\ \frac{J_1}{M} \to \sqrt{C_1},\ \frac{J_2}{M} \to \sqrt{C_1},$$

where $C_1 = \frac{\left(1+\varepsilon-\sqrt{(1-\varepsilon)^2+4\varepsilon^3}\right)}{\left[2\varepsilon(1-\varepsilon)\right]}$.

The Mach number after shock 1 tends to the infinite limit (order $\sqrt{M}$) and after shocks 2 and 3 – to finite limits. Ratio I_{p_0} itself tends to the value

$$I_{p_0} \to \varepsilon^{-(1+\varepsilon)/2\varepsilon} = 529.1. \quad (5)$$

The limit values of other functions in configurations optimal in terms of I_{p_0}, are as follows:

$$I_V \to \sqrt{\frac{1-\varepsilon+\varepsilon^2+\sqrt{(1-\varepsilon)^2+4\varepsilon^3}}{2\varepsilon^2}} = 4.007,$$

$$I_d \to \frac{1-\varepsilon+\varepsilon^2+\sqrt{(1-\varepsilon)^2+4\varepsilon^3}}{2\varepsilon^3} = 152,$$

$$I_q \to \frac{1-\varepsilon+\sqrt{(1-\varepsilon)^2+4\varepsilon^3}}{2\varepsilon^2} = 30.2,$$

$$I_j \to \frac{1-\varepsilon+\sqrt{(1-\varepsilon)^2+4\varepsilon^3}}{2\varepsilon^2} = 30.2$$

and, as a rule, they are close to the optimal values reached on curves 6–9 (see Fig. 2): $I_V \to 5.261$, $I_d \to 155.8$, $I_q \to 30.41$, $I_j \to 30.22$; therefore, optimisation of configurations with respect to these parameters is sometimes substituted for optimisation as per I_{p_0} [18]. In configurations optimal with respect to these four parameters, intensity J_1 has order M^2, and values M_1 and J_2 tend to high finite values. The angle of shock 1 tends to a low finite value at that, rather than to zero.

The optimal values (especially, the total pressure ratios) tend to their limits slowly: at $M = 8$, optimal $I_{p_0} = 19.36$, and at $M = 200$, $I_{p_0} = 439.2$. The optimisation of configurations leads to notable increase of the target functions. Thus, at $M \to \infty$, optimal $I_{p_0} \to 529.1$, while $I_{p_0} \to 69.72$ in the SMC and $I_{p_0} \to 1$ in TTC-2-3.

Alternative triple configurations

Starting from certain Mach number ($M = 2.542$ in optimisation as per the ratio of total pressures), parameters (M, σ_1) of the optimal basic configurations determine two more solutions, and at $M > 2.61$ – one solution that describes ATC of the third type corresponding to one of the alternative solutions, which exist along with the basic one at the same Mach numbers of the intensity flow of shock 1 (branching) and gas adiabat.

The alternative solutions to the system (1)–(2) appear on curve bc (see Fig. 2) as a result of decomposition of shock isomachs [13]. There are two different ATCs in curvilinear triangle F_2cb. One of the solutions in segment F_2c of curve f_2 corresponds to value $J_1 < 1$, due to which it stops being implemented. At the same time, a new and the only possible solution for ATC appears on curve f_2, after point c. Curve f_2 and point F_2 are defined by relationship (3), and points b

(M_b = 2.089) and c (M_c = 3.117) – by high-degree (for point b – eighth) algebraic equations.

The maxima of equations (4) can be achieved in the ATCs corresponding to the solution which is continuous across the entire region beyond curves bc and f_2 (curves 10–14). At $M \to \infty$, the optimal value of I_{p0} tends to the limit (5) and can be achieved at $J_3/M^2 \to C_1$, $J_1/M \to \sqrt{C_1}$, $J_2/M \to \sqrt{C_1}$. The flow turn angle on shock 3 in an optimal asymptotic ATC is opposite to its value in the "basic" configuration.

The limits of other parameter ratios in the optimal ATCs are at least comparable to the "basic" configurations: in the ATC, at $M = 199.3$, maximal $I_V = 4.858$, $I_d = 133.1$, $I_q = 27.47$, $I_j = 28$, and in the "basic" configurations, $I_V = 5.257$, $I_d = 151$, $I_q = 29.23$, $I_j = 28.56$. The relative position (from bottom to top) of the optimal curves 10–14 is opposite to the position of curves 5–9 at high Mach numbers.

With parameter γ increased, Mach numbers at which the ATCs are formed increase substantially and tend to infinity at $\gamma \to 5/3$. At $\gamma \geq 5/3$, the system of equations (1)–(2) has no more than one physically based solution.

Conclusion

The conducted calculation and parametric analysis of triple configurations forming under all theoretically feasible flow parameters before them serve for optimisation of systems and devices that employ the effects of interaction and reflection of compression shock waves, blast shock waves, and detonation waves.

The study demonstrates that triple configurations corresponding to different physically feasible solutions can be optimal: after such configurations, the maximum and quite high ratios of total pressures, velocities, flow strengths, and other flow parameters can be achieved on different sides of tangential discontinuity originating from the triple point. This statement holds true both for the basic (traditionally considered) and additional (alternative) solutions defining triple configurations, therefore, when searching for the optimal flow conditions in triple configurations, it is necessary to consider the ambiguity of solution to the defining system of equations.

The results obtained using theoretical and numerical methods can be used in various applications of gas dynamics. For instance, high total differential pressures in a supersonic gas jet initiate self-oscillation regimes when a jet interacts with obstacles, and lead to extreme acoustic and force loads when executing starting tasks. The different translational (transferred) impact of blast shock waves on bodies located above and below the triple point is achieved due to a considerable difference between flow strengths on the opposite sides of tangential discontinuity. This phenomenon can be used in design of explosion-proof devices and in an analysis of blast effect (especially in confined spaces with inevitable multiple reflection of shock waves and their irregular interaction). Moreover, high values of flow parameters after triple configurations hamper initiation of detonation in aircraft and rocket engines of appropriate type and shall be eliminated at the development phase of such devices.

This study has been conducted under financial support of the Foundation for Assistance to Small Innovative Enterprises in Science and Technology (Innovation Promotion Fund) (Agreement No. 11206ГУ/2016 dated 13.03.2017) and by the Ministry of Science and Higher Education of the Russian Federation (Agreement No. 14.577.21.0277, unique project number RFMEFI57717X0277).

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Submitted on 30.11.2017

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Тройные конфигурации догоняющих скачков уплотнения в условиях неоднозначности решения

Рассмотрены тройные конфигурации скачков уплотнения в сверхзвуковых потоках совершенного невязкого газа с учетом того, что с помощью задания свойств набегающего потока и ветвящегося скачка уплотнения не всегда однозначно можно определить параметры остальных скачков конфигурации. Аналитически и численно найдены значения параметров тройных конфигураций с максимальными отношениями параметров течения на сторонах исходящего тангенциального разрыва (экстремальных конфигураций) в условиях неоднозначности физически реализуемого решения.

Ключевые слова: тройные конфигурации, скачки уплотнения, сверхзвуковой поток.

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Область интересов: газовая динамика, ударные и взрывные волны, взаимодействие газодинамических разрывов, взрывозащита.

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