LOOK ACADEMIC PUBLISHERS
OPEN ACCESS

INTERNATIONAL JOURNAL OF ENVIRONMENTAL & SCIENCE EDUCATION
2016, VOL. 11, NO. 12, 4976-4984

Shock Waves Oscillations in the Interaction of Supersonic Flows with the Head of the Aircraft

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ABSTRACT

In this article we reviewed the shock wave oscillation that occurs when supersonic flows interact with conic, blunt or flat nose of aircraft, taking into account the aerospike attached to it. The main attention was paid to the problem of numerical modeling of such oscillation, flow regime classification, and cases where aerospike attachment can lead to drag reduction. It is established that the effective computation methods, that allow acquisition and recreation of their oscillation, are based on either technique with pre-allocation on gas-dynamic discontinuities or high accuracy difference schemes. Moreover, the application of standard straight-through methods leads to appearance of non-physical artifacts in solution: solution's oscillation on shock waves, weak rarefaction waves and instability streets of Kelvin-Helmholtz type. The practical value is that the research findings may be useful for future investigations on the problem of numerical modeling of shock wave oscillation.

KEYWORDS
Bow shock wave, shock wave structure, oscillation of shock wave structures, interaction of supersonic flows, aircraft's nose cone

ARTICLE HISTORY
Received 02 June 2016
Revised 29 June 2016
Accepted 07 July 2016

Introduction

The modeling of oscillation on spiked body is one of the most difficult problems for numerical methods (Hankey & Shang, 1980). Till the end of 90's it was studies by using model of an ideal gas or integral methods (Glotov, 1992). The integral methods were most developed in works of B. S. Auduyevsky in 60's (Avduevsky & Medvedev, 1967). During long time it was impossible to acquire periodical solution by using model of inviscid gas. The reason was a presence of "numerical" viscosity for numerical first-order methods and solution's instability on compression shocks for second-order methods (Bailey & Calarese, 1981).

The mechanism of "inviscid-viscous" interaction and detachment of boundary layer is the key for expendable oscillation excitement. "Numerical" viscosity can be compared with real turbulent viscosity and adds considerable corrections to the solution and suppresses oscillation. Schemes with high degree of approximation are used in order to overcome flaws of difference schemes with artificial viscosity (Zapryagaev & Mironov, 1991).

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Classic second-order schemes lead to non-monotonic solution in compression shock region and require fitting of dissipative member to suppress non-physical oscillation. Such flaws are well known in mathematics as Gibbs phenomenon. The phenomenon appears during Fourier expansion of discontinuous function (Shang & Hankey, 1980). This problem is related to the calculation of the convective terms of the Euler and Navier-Stokes equations at high Reynolds numbers: it is not possible resolution of the internal structure of the shock wave (acquisition of a smooth solution, defined by physical viscosity). The TVD (Total Variation Diminishing) schemes, are based on principle of non-increasing total variation, and do not possess the flaw in question.

Calculation using scheme of laminar viscous gas ignoring turbulence, became next step in the development of mathematical modeling. Amongst native works, it worth pointing out the article (Antonov et al., 1989), which served as starting point for this research, amongst foreign – (Feszty et al., 2000), a work that demonstrated a highest development level of calculation technology utilizing model with laminar viscous gas. It was showed that calculation error of frequency response rises depending on Mach number, and reaches 60% at M=6.

Usage of turbulence modules for oscillation modes calculation requires additional verification of calculation methods, because Navier-Stokes equations with averaged time can only be used for quasi-stationary calculations (Bulat & Bulat, 2013).

Aim of the study

The aim of this work is to review the history of the research on shock wave oscillation in supersonic flow over nose cone. The main attention is paid to the development of method that allows calculation of such flow types.

Research questions

What are the main methods used in order to explore the shock waves oscillations in the interaction of supersonic flows with the head of the aircraft?

Method

The study is based on the method of historical-comparative analysis of existing approaches to numerical modeling of shock wave oscillation that occurs when supersonic flows interact with conic, blunt or flat nose of aircraft.

Data, Analyses, and Results

The diagram of flow around conic, blunt or flat nose, taking into account the attached spike, is show on Fig. 1. The classification of such flows, including oscillating flows, was made by C.J. Wood (1962). According to said classification there are four flow type (A, B, C, D Fig. 1). Type A shows attached flow at low cone angle. With increase of cone angle, at some point, a region of separated flow Z appears.

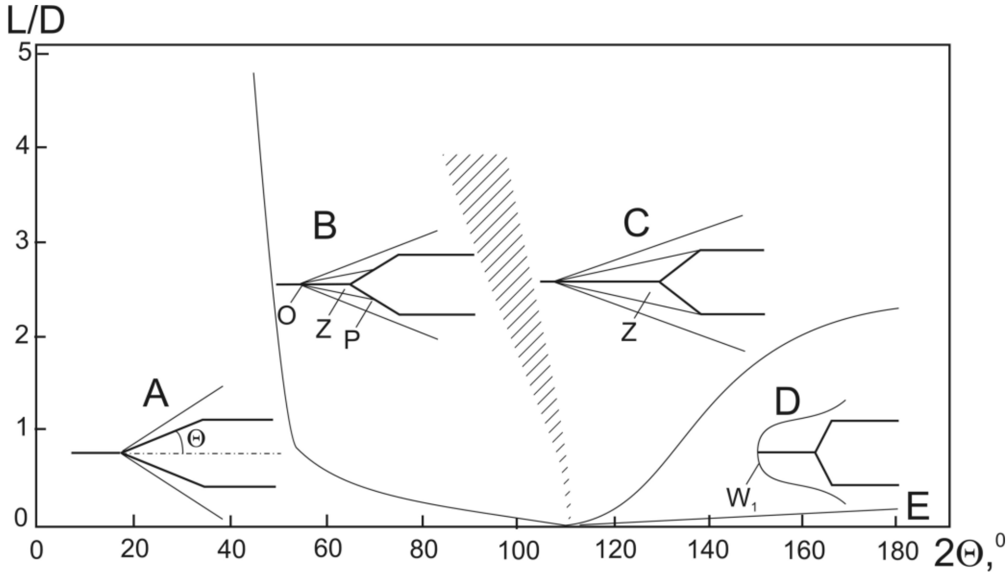

Figure 1. Wood's classification of flow types over spiked cone bodies.
A-attached flow, B-flow with detached region Z and attachment flow point P on cone's face, C- flow with detached region Z and attachment flow point P on cone's face, D-oscillatory flow, E - spike's length is small compared to cone's size and has no influence on drag, dashes – a border between regions B and C, precise position of which is dependent on value of Re.

The stagnation region is bounded by tangential discontinuity line OP. Point of supersonic flow attachment P is located on the nose cone. With further increase of cone's angle the attachment point shifts to the body's shoulder, which leads to flow type C. Next is a flow type D with detached shock wave. This type is characterized by intense shock wave oscillation.

Experimental research of nose spiked body

Type B demonstrates the lowest drag, and oscillation occurring in type D poses the most thread to aircraft's integrity. Oscillating type D, which has reoccurring frontal detached region, was discovered by H.M. McMahon (1958). And name for it was proposed by H. Kabelitz (1971). This flow type is characterized by high frequency of self-oscillation, and significant amplitude of pressure oscillation (an averaged non-square value of oscillation reaches the value of impact pressure or higher).

One of the first models that describes such flows was proposed by D.J. Maull (1960). Later experimental research, carried out by A.G. Panaras (1981), showed, that irregular distribution of parameter on nose's surface and dynamic shock wave processes, are key to maintain self-oscillation. The experimental data acquired during 80's in and outside of USSR, was generalized in N.F. Krasnov's monograph (Krasnov, Koshevoy & Kalugin, 1988). The mechanism of oscillation's appearance and maintenance is mainly expendable in its nature, as shown in A.N. Antonov's monograph (Antonov, Kuptshov & Komarov, 1990). The works of and I.N. Kavun, V.F. Chikareshko and Yu.N. Yudintsev (1976) show, that spike can be changed to under-expanded supersonic jet directed against supersonic flow (Yudintsev & Chirkashenko, 1979). The altered flow mode is similar to that with an aerospike.

Around same time J. S. Shang's works have been published (Shang & Hankey, 1980; Hankey & Shang, 1980), which had generalized experimental and theoretical research data on frontal detached region. V.I. Zapryagaev and S.G. Mironov (1991) at the Instiute of Theoretical and Applied Mechanics n.a. Christanovich (ITAM Novosibirsk) have put a lot of effort to study spiked bodies during 80's of past century. The main goal of the experiment was to create a detailed sequence of frames of the flow (a set of photos describing the development of self-oscillation cycle in time). Comparison of the acquired photos with phases of process and measured oscillation on cylinder's face, allowed analyzing the flow's shock wave structure changes in time. It was determined that oscillation can be non-periodic like a strange attractor. The oscillations can also have symmetrical or azimuhtal modulation (Bailey & Calarese, 1981). The researches, conducted at ITAM are generalized in three of his articles (Azarova, Grudnitskii & Kolesnichenko, 2006; Farnaz et al., 2008; Azarova, 2008).

Numerical research

The problem of non-stationery flow over step in channel, was used as a model (Fig. 2). The problem was formed in A.F. Emery's (1968) work, and was popularized by work of R.P. Woodward (1984). The problem was later used by S.A. Isaev, and D.A. Lysenko (2004) in order to determine the precision of Fluent and CFX commercial computational packages. The solution of this problem found in Woodwork's is taken as a standard.

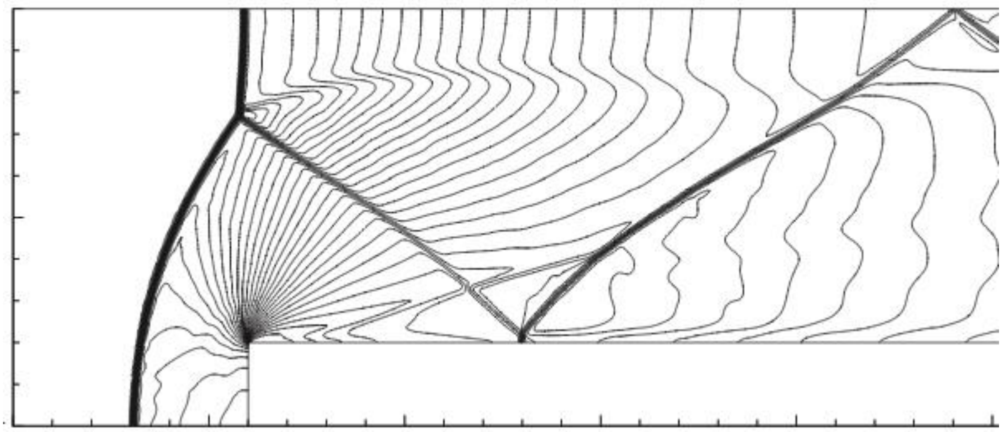

Figure 2. Model problem of flow over step in channel

Criterions of accuracy are: position of triple point (the intersection point of Mach disc and bow shock), length of upper Mach's stem, and structure of interaction between shock waves and solid structures.

In work by W.R. Wolf & J.L. Azevedo (2007) during computational course nonphysical flows singularities have been found. They appear because of numerical errors and are independent of difference schemes and numerical algorithms applied. The singularities are:

– weak rarefaction wave, that appears during rarefaction wave fan interaction, which propagates from the angle of a step, with its upper wall.

– the development of Kelvin–Helmholtz instability, that propagates from triple point alongside channel's upper wall.

The averaged discrepancy of shock wave's position between numerical and standard method doesn't exceed 3%.

The shock wave interaction with boundary layer on body's surface can cause the detachment of the latter and formation of circulation flow detached region, which is perquisite to appearance of oscillation.

The computational scheme is shown on Fig. 3.

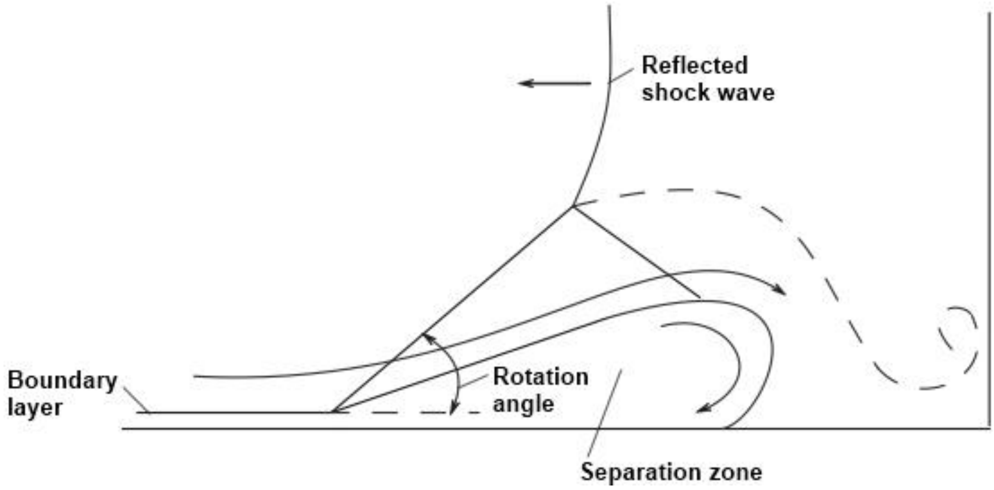

Figure 3. The problem of shock wave and boundary layer interaction

At the initial time, the virtual membrane on the left "breaks", and shock wave moves to the right, creating boundary layer on the wall. Interaction of reflected shock wave with boundary layer forms λ-like SWS. It appears, that standard MUSCL difference scheme, doesn't allow to solve this λ-like structure at high Reynolds number. As a result of research, the following universal solutions were designed:

– Third-order Runge-Kutte scheme is used for time sampling,

– Second-order MUSCL, third and 6th-order WENO schemes are used for inviscid flow sampling

– Second-order central differences for viscous flow sampling.

With these parameters on small grids, the satisfactory solution was acquired (Fig. 4).

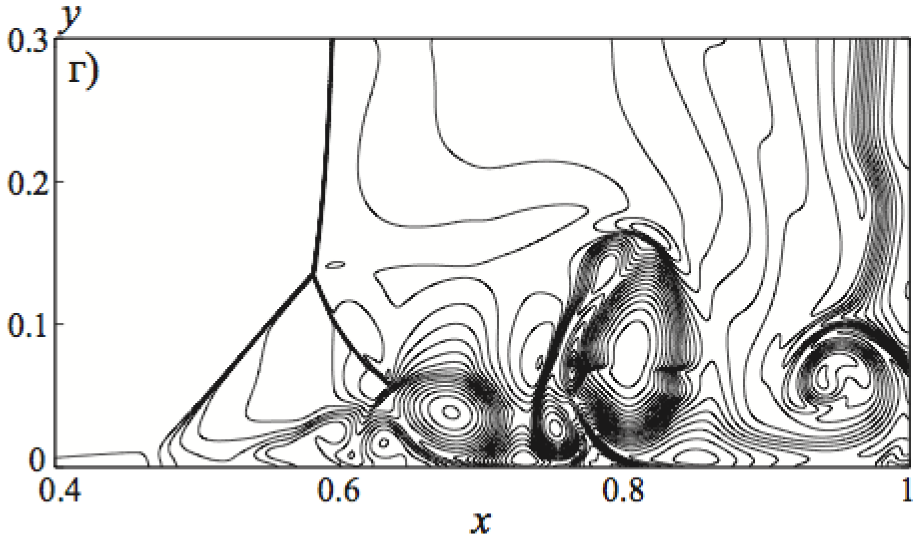

Figure 4. The result of model problem solution

The works, carried out by O.A. Azarova in 2000-2010 (Azarova, Grudnitskii & Kolesnichenko, 2006), can serve as a showcase of development level for computational technology of non-stationary supersonic flow over body problem. The way to reduce resistance of cylinder and a cone by creation of a low density thin channel in between them has been investigated. It can be achieved, for instance, by microwave radiation. The method with emphasis on gas-dynamic discontinuities was developed. The stationary cases of such flows were studied first (Azarova, Grudnitskii & Kolesnichenko, 2006). The flow modes of supersonic flow over cylinder's face, were acquired later. The said modes are characterized by their tendency to establish sustainable longitudinal flow oscillation. The streets of plane-stratified vortexes were also studied (Farnaz et al., 2008). They accompany the appearance of Kelvin-Helmholtz shear instabilities in shock layer. These instabilities are typical for problems related to interaction of heat irregularity with shock layer. It has been shown that dynamics of vortex initiation before body, and formation dynamics straight vortex streets, are cyclic in nature (Fig. 5). This nature is regulated by mass-scale flow oscillation (Azarova, 2008).

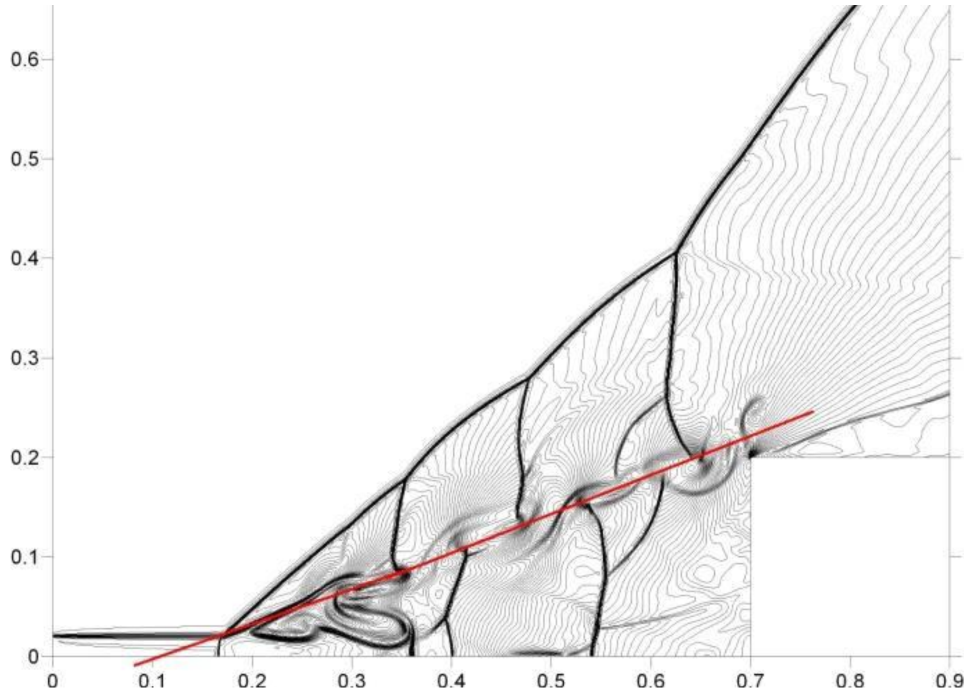

Figure 5. Development of Kelvin-Helmholtz shear instabilities in shock layer during interaction of heat irregularity with shock layer

Discussion and Conclusion

The series of works, written by K.V. Babarykin et al. (2000, 2001, 2003) during 2000's, demonstrate modern development level of numerical methods based on ideal gas model, and acquisition of solution for Euler's equation via TVD schemes.

Can add that the expendable nature of oscillation was proven as well, B.S. Albazarov (1991) acquired same result by using TVD schemes. Generalization, theoretical justification and verification by model problem with high accuracy difference scheme, was done by K.N. Volkov (2005, 2006).

A different approach was being developed under leadership of A.N. Krayko at ITAM. It's based on S.K. Godunov's (1959) method utilizing model of an ideal gas, with explicit emphasis on shock waves, front of which is built during calculation (Emery, 1968). This method allowed for directly model of quasi-stationary shock wave oscillation.

In summary, we reviewed the shock wave structure oscillations that occur during supersonic flow over conic, blunt or flat nose with attached spike. The main attention was paid to the numerical modeling problem of such oscillation.

The effective computation methods, that allow acquisition and recreation of their oscillation, are based on either technique with pre-allocation on gas-dynamic discontinuities or high accuracy difference schemes.

It is established that the application of standard straight-through methods leads to appearance of non-physical artifacts in solution: solution's oscillation on shock waves, weak rarefaction waves and instability streets of Kelvin-Helmholtz type.

Implications and Recommendations

The research doesn't exhaust the current scientific problem. Thus, the submissions may be useful for future investigations on the problem of numerical modeling of shock wave oscillation that occurs when supersonic flows interact with conic, blunt or flat nose of aircraft.

Acknowledgements

This study was financially supported by the Ministry of Education and Science of the Russian Federation (the Agreement No. 14.575.21.0057), a unique identifier for Applied Scientific Research (project) RFMEFI57514X0057

Disclosure statement

No potential conflict of interest was reported by the authors.

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