PAPER • OPEN ACCESS

The influence of an oscillating wall on the position of oblique shocks in a 2D channel

IOP ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

The influence of an oscillating wall on the position of oblique shocks in a 2D channel

E V Perchatkina, L L Minkov

Tomsk State University, 36 Lenin Avenue, Tomsk, 634050 Russian Federation

E-mail: perchatkinae@mail.ru

Abstract. In the paper we solve the problem of supersonic gas flow in a two-dimensional channel with the moving upper wall making oscillations according to the harmonic law. In order to obtain a numerical solution for gas dynamics equations we have implemented two difference schemes: the scheme with the space and time approximation of the first order and the scheme with the space approximation of the second order. The fluxes were computed using Van Leer's method. A special form of fluxes in the gas dynamics equations is given, which enables to calculate fluxes on cell faces of difference mesh using Van Leer's method. Depending on a type of the harmonic law and initial gas inflow conditions, the peculiarities of oblique-shock wave propagation in moving curvilinear domains have been investigated. It has been determined that under a particular oscillation frequency the presence of wall oscillation practically doesn't have an effect on the flow regime inside the domain. The convergence of the obtained solution is shown by calculations using difference grids with different numbers of cells. While comparing the numerical solution obtained due to our program with the one obtained with Ansys Fluent solver we found that the constructed code operates correctly.

1. Introduction

These days the investigation of peculiarities of scramjet flight is very important. Hypersonic speed flight can significantly increase the flying range, furthermore, hypersonic ramjet engines have a simpler concept of operation than other types of propulsion system of aircraft. Coincidently, their elaboration deals with significant technical difficulties caused by large thermal and dynamic loads on the body, as well as unstable engine operating conditions [1].The operation of these devices is always accompanied by the formation of various systems of shock waves in the air scoops, air flow ducts and nozzles of propulsion system. Another promising direction of research in the field of aerodynamics is the study of waveriders. The principle of their operation is based on the use of a special aerodynamic form, which allows one to improve the aerodynamic characteristics using high pressure behind the shock waves [2, 3].

With the development of industry, aviation, rocket and missile engineering, the question of a detailed study of the influence of oscillatory processes (or vibrations) on the characteristics of gas flow in limited domains began to arise. Vibrations can be a part of technological processes, such as mixing fuel components inside engines in order to improve its energy performance, as well as clarification of liquids from the unwanted impurities. In these cases, the oscillatory processes are initiated intentionally and aimed at achieving the desired result. But there is also a negative side of the question, when the occurrence of vibrations is a side effect of any processes, such as the oscillations associated with the work of jet engines and aerodynamic features of the flight. For example, the strongest vibrations occur during the launch of rocket engines, separation of stages and other impulse loads, as well as the vibrations arise during flight under certain external conditions (the so-called "flutter" phenomenon) [4-6]. A thorough study of these issues should help reduce the number of emergency situations during the flights of the space rockets and the civil aviation.

Nowadays there are three main approaches to solving gas dynamics problems in the domains with time-varying boundaries: solving equations on re-arranged grids [7]; the free boundary method in which the presence of a solid wall is modeled through the source terms in the conservation equations [8]; solving equations in curvilinear coordinates, in which the region and the grid do not change their topology [4-6, 9].

The purpose of this paper is to investigate the features of the formation and propagation of oblique shock waves and rarefaction waves in curvilinear regions with moving boundaries using equations in a curvilinear coordinate system. This allows the usage of a simpler grid with rectangular cells oriented along coordinate axes.

2. Problem formulation

We consider the supersonic flow within the domain with time-varying geometry. As a result of the interaction of a supersonic flow with a solid wall of the region, a system of oblique shock waves appears. We consider the domain formed by the upper and lower solid boundaries, figure 1. Gas flows into the domain through the left boundary AB with a supersonic velocity $\vec{V}$, which is inclined at an angle α, and flows out through the boundary CD.
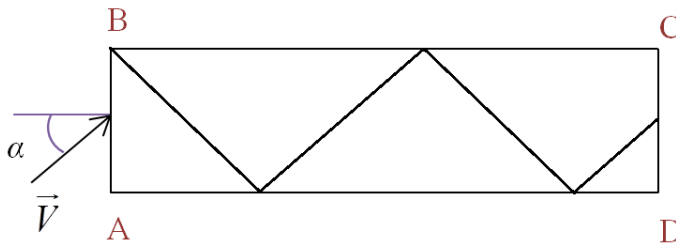

Figure 1. Computational domain.

The upper wall BC makes oscillations along a vertical axis according to the harmonic law $y = |DC| + A \cdot |AD|^{-1} \cdot x \cdot \sin(\omega t)$, wherein point B supposed to be fixed. On initial time we suggest the value of the domain inlet and outlet height is AB=DC=1, the domain length is AD=4.

Using the latter approach, we performed a preliminary transformation of the original system of equations into a curvilinear coordinate system, which allows the use of a simpler grid with rectangular cells oriented along coordinate axes.

Gas flow is governed by the system of nondimensional Euler equations in a curvilinear coordinate system (1) [10, 11, 12].

$$\frac{\partial \tilde{\mathbf{U}}}{\partial \tau} + \frac{\partial \tilde{\mathbf{F}}}{\partial \xi} + \frac{\partial \tilde{\mathbf{G}}}{\partial \eta} = 0,$$
(1)

where

$$\tilde{\mathbf{U}} = \begin{pmatrix} \rho J \\ \rho J u \\ \rho J v \\ \rho J E \end{pmatrix}, \quad \tilde{\mathbf{F}} = \begin{pmatrix} \rho(\alpha - \gamma) \\ \rho u(\alpha - \gamma) + p \cdot y_\eta \\ \rho v(\alpha - \gamma) - p \cdot x_\eta \\ \rho H(\alpha - \gamma) + p \cdot \gamma \end{pmatrix}, \quad \tilde{\mathbf{G}} = \begin{pmatrix} \rho(\beta - \sigma) \\ \rho u(\beta - \sigma) - p \cdot y_\xi \\ \rho v(\beta - \sigma) + p \cdot x_\xi \\ \rho H(\beta - \sigma) + p \cdot \sigma \end{pmatrix},$$

u, v – components of velocity vector V, directed along x, y axes in Cartesian coordinate system; ρ – density; p – pressure; H – enthalpy, $E + p \cdot \rho^{-1}$; E – total energy, $p \cdot \rho^{-1} \cdot (k-1)^{-1} + 0.5(u^2 + v^2)$; k – heat capacity ratio, 1.4; $\alpha = u \cdot y_\eta - v \cdot x_\eta$; $\gamma = x_\tau \cdot y_\eta - y_\tau \cdot x_\eta$; $\beta = v \cdot x_\xi - u \cdot y_\xi$; $\sigma = y_\tau \cdot x_\xi - x_\tau \cdot y_\xi$.

Initial and boundary conditions at the domain inlet are set in the form (2).

$$\rho = 1; u = 2; v = 0.5; P = 1$$
(2)

The boundary conditions at the exit are specified basing on the value of the gas flow rate in the last cells. For supersonic flow, $u > c$ (where c is a speed of sound), the boundary conditions at the exit are not specified, otherwise, when the flow is not supersonic, at the right boundary we set the pressure. To obtain a solution to this problem, the finite volume method is applied. The determination of flows through the faces of the computational cells was carried out using the Van Lear method.

3. Implementation of Van Leer method

To carry out the splitting procedure in a curvilinear coordinate system, the vector $\tilde{\mathbf{F}}$ (according to [6], [7]) will be represented as:

$$\tilde{\tilde{\mathbf{F}}} = \begin{pmatrix} \rho U_\eta \\ \rho U_\eta^2 + p \\ \rho v_\eta U_\eta \\ \rho H U_\eta \end{pmatrix} + \begin{pmatrix} 0 \\ \rho U_\eta \cdot W_t \\ 0 \\ p \cdot W_t \end{pmatrix},$$

where

$$U_\eta = \left(y_\eta \left(u - x_\tau \right) - x_\eta \left(v - y_\tau \right) \right) \cdot \left(x_\eta^2 + y_\eta^2 \right)^{-1/2}; \ u_\eta = \left(u \cdot y_\eta - v \cdot x_\eta \right) \cdot \left(x_\eta^2 + y_\eta^2 \right)^{-1/2};$$

$$v_\eta = \left(u \cdot x_\eta + v \cdot y_\eta \right) \cdot \left(x_\eta^2 + y_\eta^2 \right)^{-1/2}; \ W_t = \gamma \cdot \left(x_\eta^2 + y_\eta^2 \right)^{-1/2}$$

Vector $\tilde{\mathbf{G}}$ splitting should be carried out in a similar way.

4. The Ansys Fluent results

To verify the simulation results, we calculated the pressure fields and Mach numbers using the Ansys Fluent software. Here are the simulation results for gas flowing into the domain at an angle $\alpha = 14°$, (figures 3, 5).
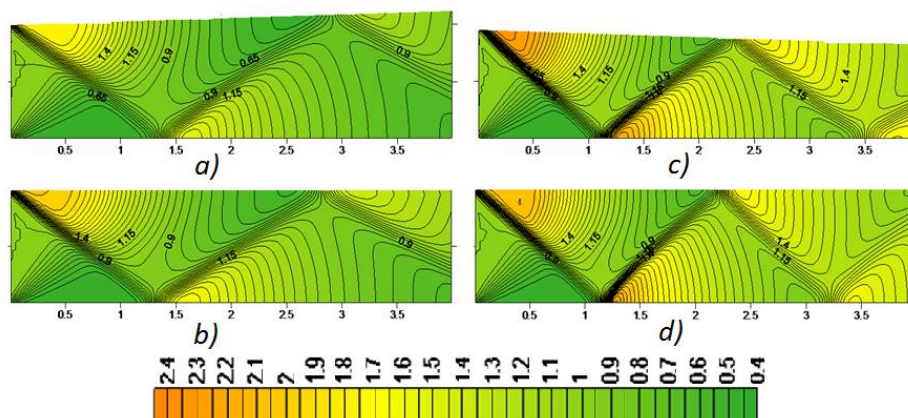

Figure 2. Pressure field
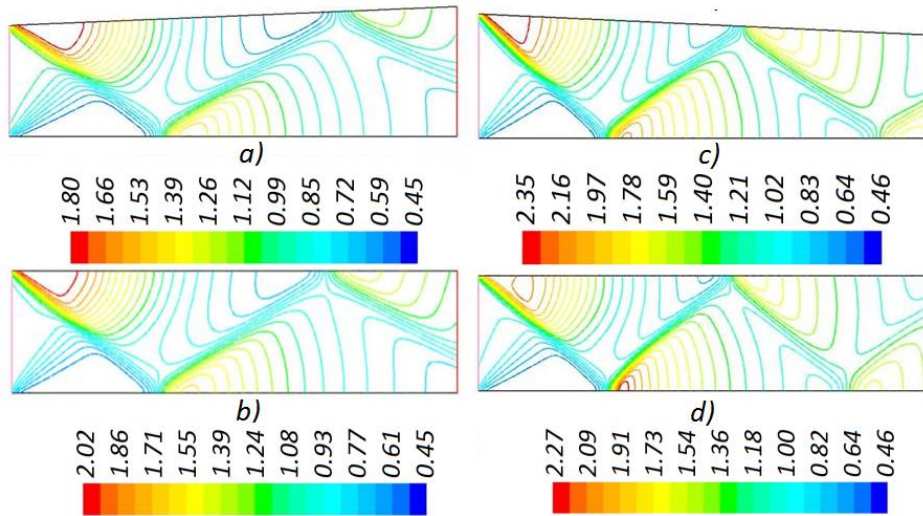a) $- t \cdot T^{-1} = \pi$, b) $- 2\pi$, c) $- 3\pi$, d) $- 4\pi$.

Figure 3. Pressure field as per Ansys Fluent

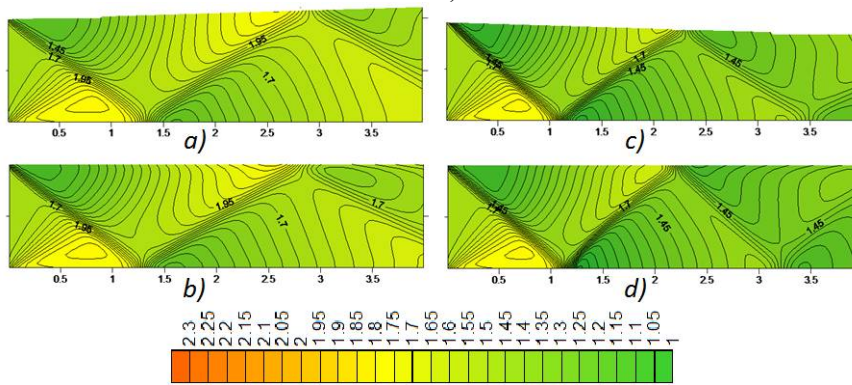a) $- t \cdot T^{-1} = \pi$, b) $- 2\pi$, c) $- 3\pi$, d) $- 4\pi$.

b)

Figure 4. Mach-number distribution

a) $- t \cdot T^{-1} = \pi$, b) $- 2\pi$,c) $- 3\pi$,d) $- 4\pi$.
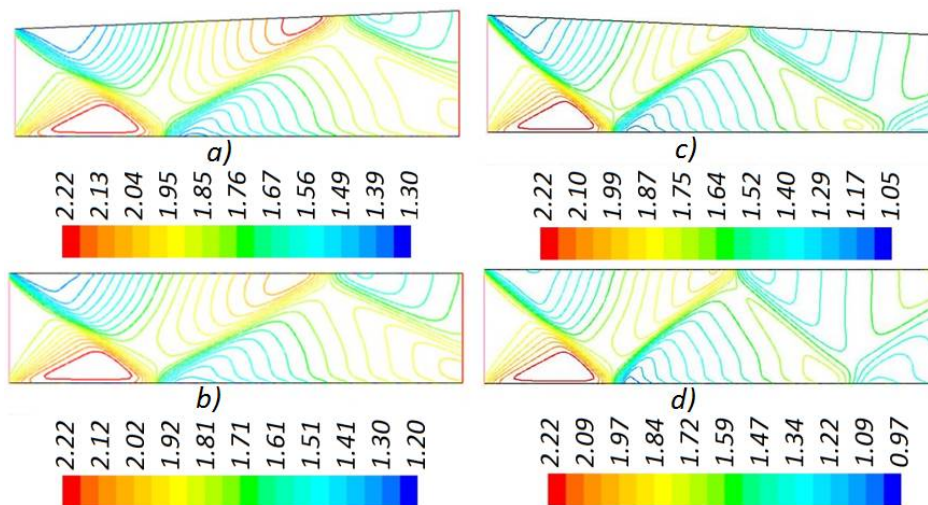

Figure 5. Mach-number distribution as per Ansys Fluent

a) $- t \cdot T^{-1} = \pi$, b) $- 2\pi$, c) $- 3\pi$, d) $- 4\pi$.

The law of motion of the upper wall is $y = 1 + 0.17 \cdot 0.25x \cdot \sin(t)$. Comparison of the flow pattern, position and intensity of shock waves in figures 2 and 3, 4 and 5 shows that the created procedure of calculating gas flow in a curvilinear region with moving boundaries allows us to obtain a physically correct numerical solution.

5. Convergence control

To check the convergence of the solution, the calculation was carried out using differential grids containing 50, 100, 200 and 400 cells in the longitudinal direction and 12, 25, 50 and 100 in the transverse direction, respectively. The resulting graphs of the average nondimensional pressure value versus nondimensional time for various difference grids demonstrate the convergence of the numerical solution of the problem (figures 6, 7).
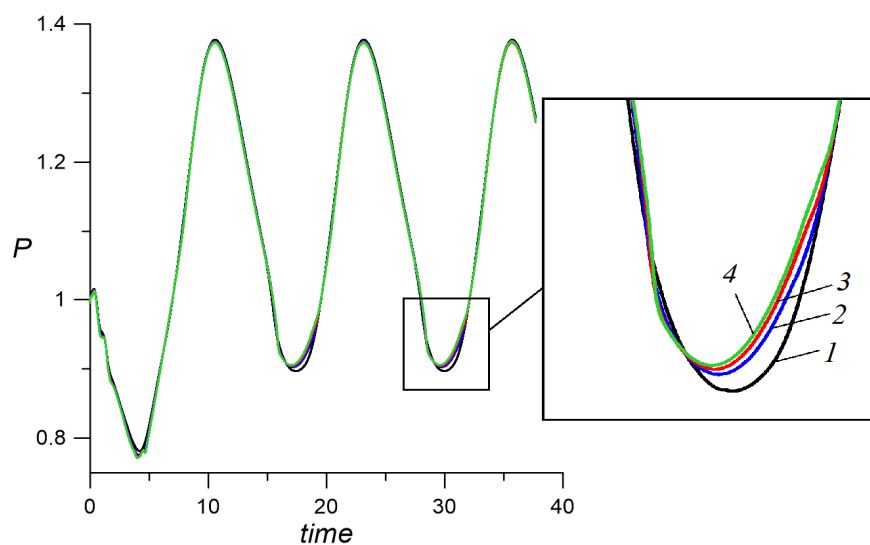

Figure 6. The dependence of the average pressure at the region outlet on time. Number of cells:
1 – 50×12,
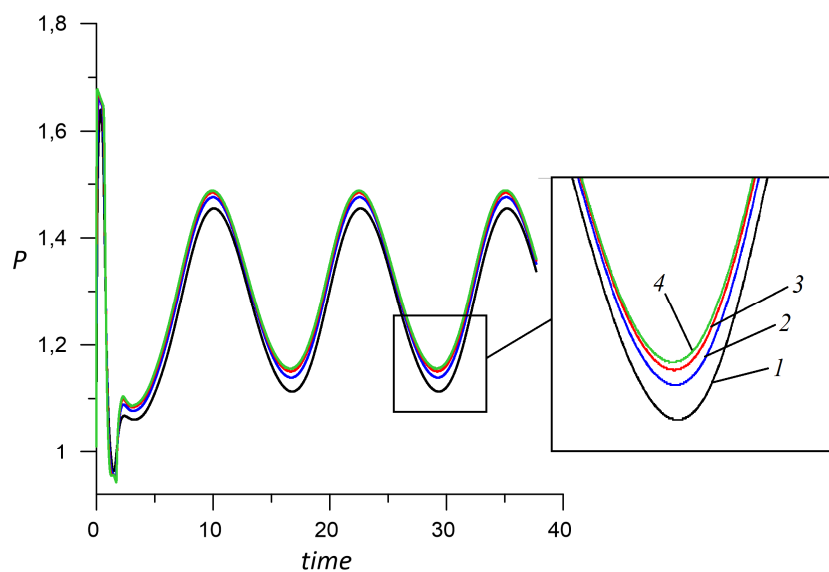2 – 100×25,
3 – 200×50,
4 – 400×100.

Figure 7. The dependence of the average pressure on the upper wall of time. Number of cells:
1 – 50×12, 2 – 100×25,
3 – 200×50, 4 – 400×100.

6. The results of the numerical simulation

To verify algorithm and methodology of calculation we compare numerical solution obtained using our program with the exact solution [13] obtained using the equation (3).

$$ctg(\alpha) = \left[1 + M^2\left(0.5(k+1) - \sin^2\beta\right)tg(\beta)\right]\left(M^2\sin^2\beta - 1\right)^{-1} \qquad (3)$$

where

$M = \left(u^2 + v^2\right)^{1/2} c^{-1}$ – Mach number; $c = \left(kp\rho^{-1}\right)^{-1/2}$ – local speed of sound; α – angle of velocity inclination; β – angle between the flow velocity and the shock wave front.

Taking into account that $\alpha = 14°$ and using (3) we derived the angle between the wall and the shock wave is approximately equal to 38°. The result obtained using numerical simulation showed a similar result, at which the angle is approximately equal to 37 °.

The similar results, but with different values of the angle α, were obtained in the articles [14, 15].

The numerical simulation results of supersonic gas flow in a region with a time-varying geometry were obtained using a difference scheme with the second order of approximation in spatial variables and first order in time variables (Kolgan scheme [16]) on a difference mesh 200 × 50 and are presented using isobars and Mach isolines.

In the considered task, there are two characteristic times of the process: the oscillation period of the domain upper wall and the time of propagation of the sound wave along the region. Firstly, we give the consideration of the first case, when $t_{os} \; \square \; t_{gd}$. Here $t_{gd} = L \cdot c^{-1}$ – gasdynamic characteristic time; L – characteristic dimension of the domain; $t_{os} = \omega^{-1}$ – characteristic oscillation period; ω – oscillation frequency.

In order to clarify the case when this condition is met, the flow pattern does not depend mainly on the presence of oscillations of the domain upper wall, calculations have been made when the gas flows in at an angle $\alpha = 14°$ for the flow in the region with a fixed upper wall (figure 8) and the flow when the upper wall moves according to the law $y = 1 + 0.17 \cdot 0.25x \cdot \sin(0.5t)$, (figures 9, 10). Comparison of the position and intensity of oblique shock waves shows that a change in the position of the upper wall with time has virtually no effect on the overall flow pattern.
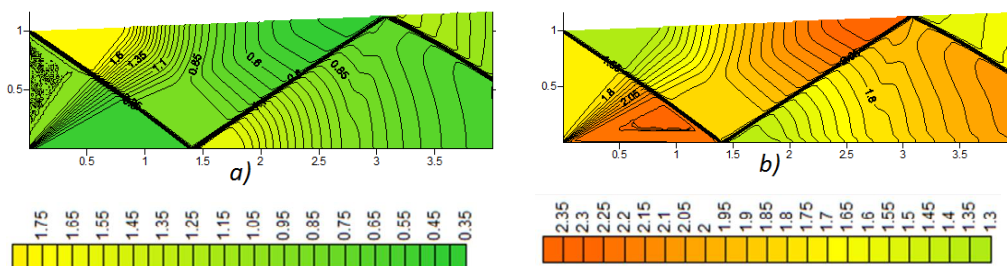

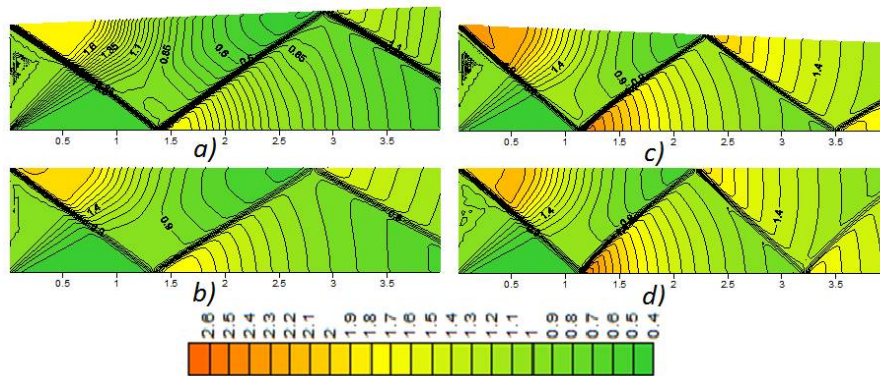**Figure 8.** Isolines of a) – pressure, b) – Mach number.

Figure 9. Pressure field
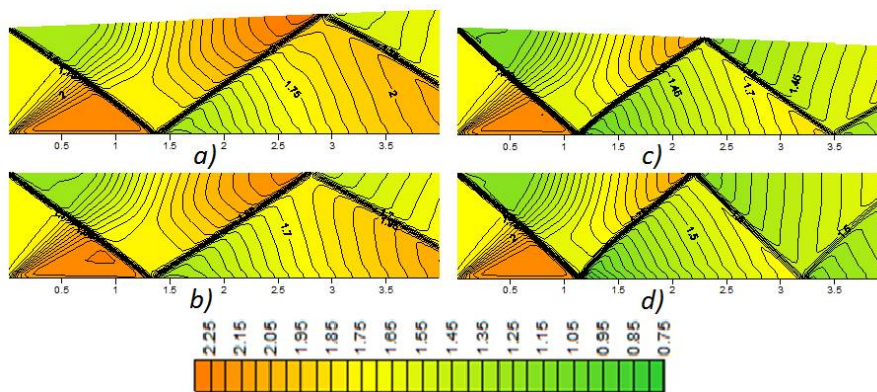
a) $-t \cdot T^{-1} = \pi$, b) -2π, c) -3π, d) -4π.

Figure 10. Mach-number distribution

a) $-t \cdot T^{-1} = \pi$, b) -2π, c) -3π, d) -4π.

Let us consider the following case $t_{os} \approx t_{gd}$. This case corresponds to the gas flow in the domain with the upper wall position, changing according to the law $y = 1 + 0.17 \cdot 0.25x \cdot \sin(t)$. The calculation results of the pressure fields and the Mach numbers for gas flowing into the region at an angle $\alpha = 0°$ for the one period of time T are presented in figures 11, 12, respectively. Figure 11 (a) clearly demonstrates that the rise of the upper wall causes the formation of rarefaction wave at the beginning of the region. On the contrary, when the wall moves down - a compression wave forms, figure 11 (c).

In order to establish the dependence of the intensity of shock waves on the law of wall displacement, we carried out a calculation in presence of a direct gas inflow (i.e. $\alpha = 0°$) for a region with the upper wall moving according to the law $y = 1 + 0.51 \cdot 0.25x \cdot \sin(t)$.

The results of this simulation are presented in figures 13, 14. A comparison of figures 13 and 11 allows us to conclude that with an increase in the swing amplitude of the upper wall, the intensity of generated rarefaction waves (figures 11 (a), 13 (a)) and compression waves (figures 11 (c), 13 (c)) also increases.
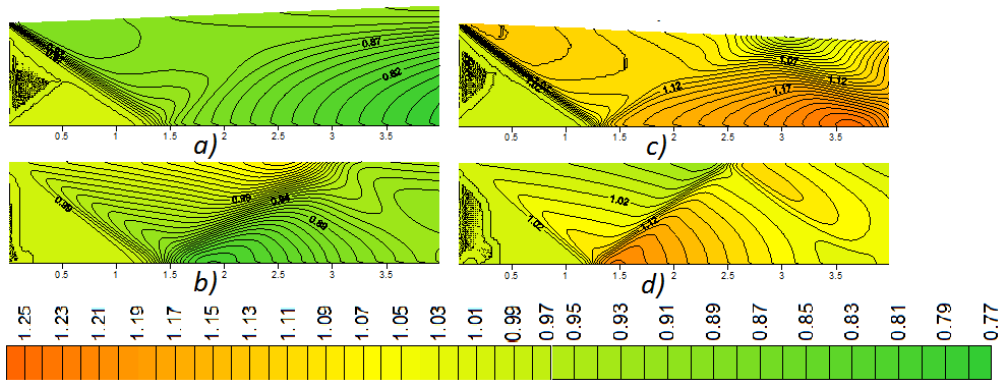
Figure 11. Pressure field
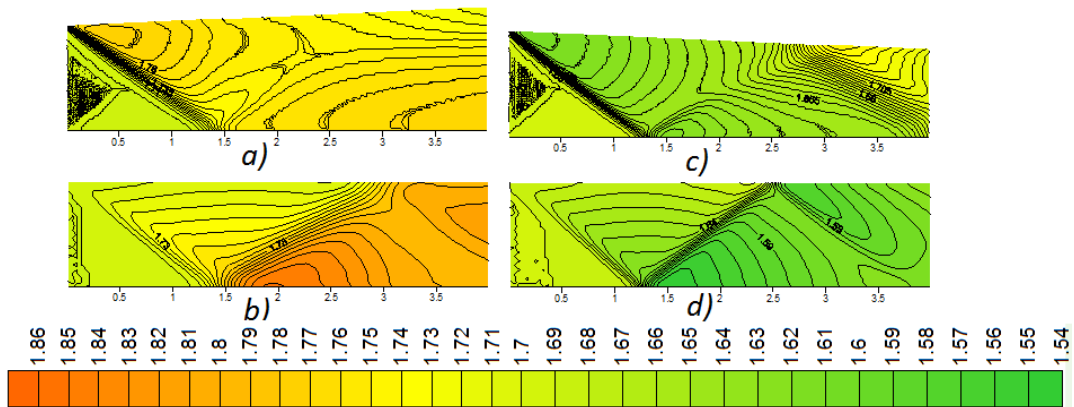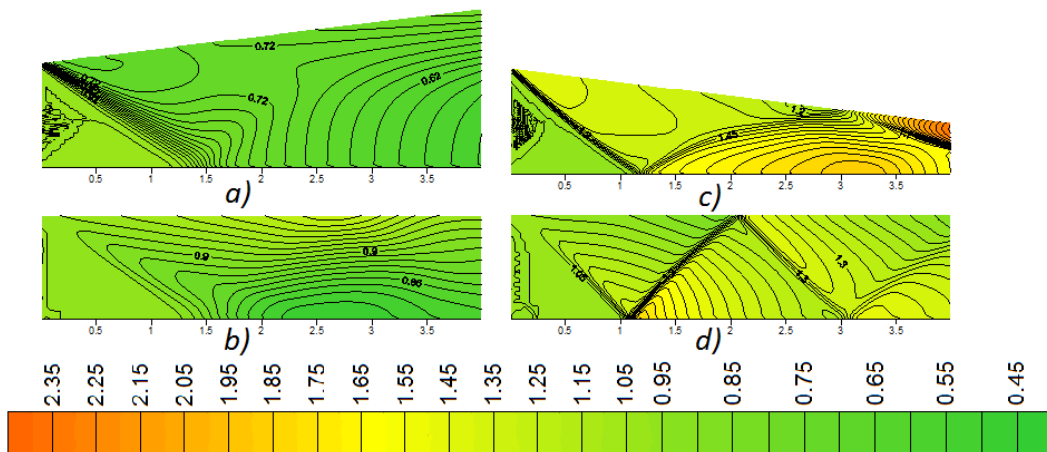a) $-t \cdot T^{-1} = 0.5\pi$, b) $-\pi$, c) -1.5π , d) -2π .

Figure 12. Mach-number distribution
a) $-t \cdot T^{-1} = 0.5\pi$, b) $-\pi$, c) -1.5π , d) -2π .

Figure 13. Pressure field
a) $-t \cdot T^{-1} = 0.5\pi$, b) $-\pi$, c) -1.5π , d) -2π .
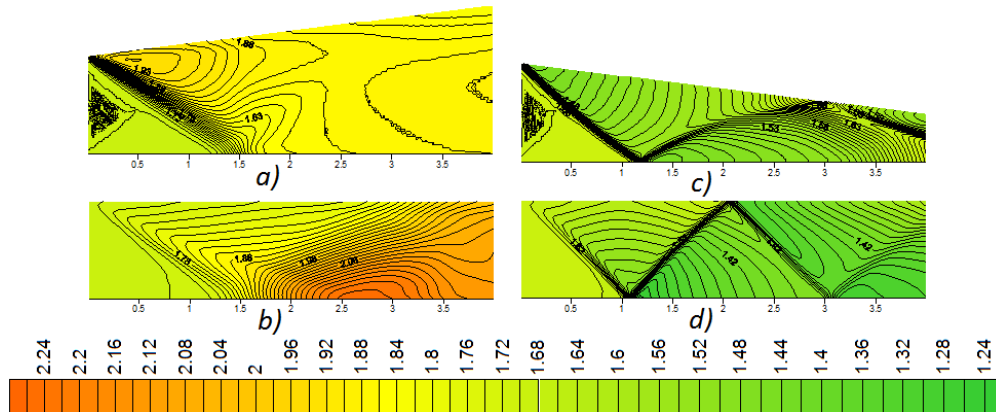
Figure 14. Mach-number distribution
a) $- t \cdot T^{-1} = 0.5\pi$, b) $- \pi$, c) $- 1.5\pi$, d) $- 2\pi$.

Figures 15, 16 show the calculation results for the case when gas flows into the region at an angle $\alpha = 14°$. The movement of the upper wall is described by the law $y = 1 + 0.17 \cdot 0.25 x \cdot \sin(t)$. A comparison of figure 15 with figure 9 shows that with an increase in the upper wall oscillation frequency, the intensity of the resulting oblique shock waves weakens. In addition to the above, at the time 0.5π, when the upper wall reaches the maximum point (figure 15a) the shock waves do not have enough time to propagate along the entire length of the region.
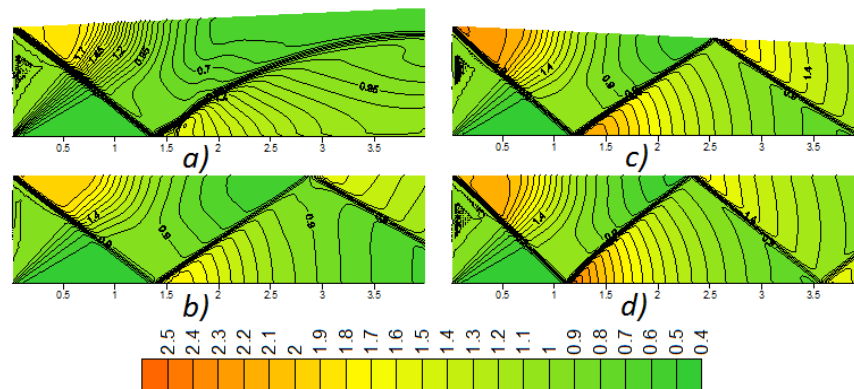

Figure 15. Pressure field
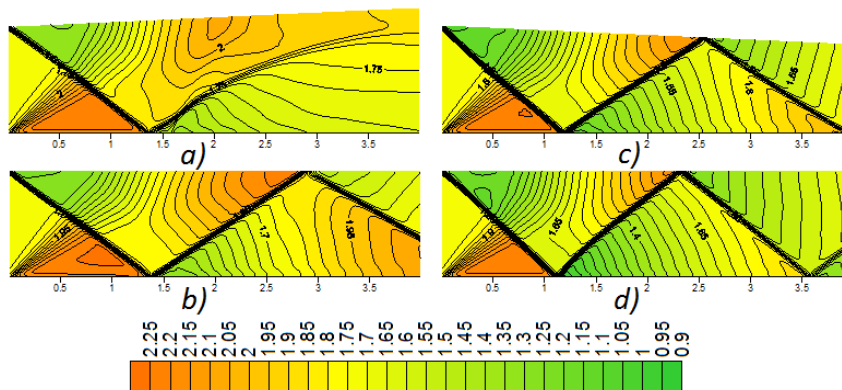b) $- t \cdot T^{-1} = 0.5\pi$, b) $- \pi$, c) $- 1.5\pi$, d) $- 2\pi$.

Figure 16. Mach-number distribution
a) $- t \cdot T^{-1} = 0.5\pi$, b) $- \pi$, c) $- 1.5\pi$, d) $- 2\pi$.

The graph shown in figure 17 illustrates the dependence of the average pressure at the outlet of the region on time. Thus, the greatest change in pressure occurs when the upper wall moves with an increased amplitude, i.e. in the case when the wall moves according to the law: $y = 1 + 0.51 \cdot 0.25 x \cdot \sin(t)$. In addition, it was found that the increase in the initial velocity angle of inclination practically does not affect the value of the pressure at the outlet. The smallest change in pressure is observed in the case of a direct gas inflow into the region ($\alpha = 0°$) with the upper wall, which oscillates according to the law $y = 1 + 0.17 \cdot 0.25 x \cdot \sin(t)$.
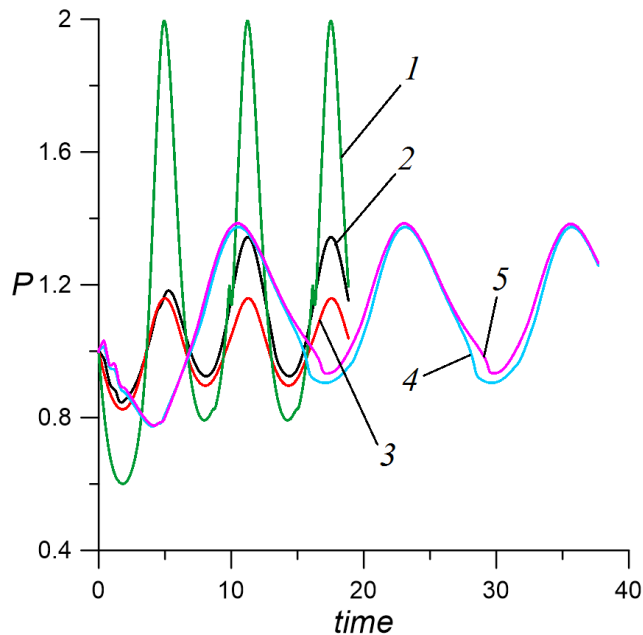

Figure 17. The dependence of the average pressure at the region outlet on time.
The wall motion law and the velocity angle of inclination:

$1 - y = 1 + 0.51 \cdot 0.25 x \cdot \sin(t)$, $\alpha = 0°$,

$2 - y = 1 + 0.17 \cdot 0.25 x \cdot \sin(t)$, $\alpha = 14°$,

$3 - y = 1 + 0.17 \cdot 0.25 x \cdot \sin(t)$, $\alpha = 0°$,

$4 - y = 1 + 0.17 \cdot 0.25 x \cdot \sin(0.5t)$, $\alpha = 14°$,

$5 - y = 1 + 0.17 \cdot 0.25 x \cdot \sin(0.5t)$, $\alpha = 16.7°$.

7. Conclusion

We have studied the features of the oblique shock wave propagation in the region in the presence of an oscillation of the upper boundary depending on the type of the harmonic law basing on which this oscillation is carried out.

It was found that at a certain amplitude, the oscillation of the wall practically does not affect the nature of the flow in the considered region.

It is shown that an increase in the initial inclination angle of the gas velocity in reality does not affect the character of the flow in this region.

A comparison of the numerical solution obtained by the created program with the numerical solution obtained with the Ansys Fluent solver showed the correctness of the created program at work.

References

[1]   Vasenin I M, Shrager E R, Glazunov A A, Krainov A Yu and Krainov D A 2013 *Russ. Phys. J.* **56** 908-13

[2]   Bulat P V Stacionarnye gazodinamicheskie razryvy i udarno-volnovye struktury [Stationary gas dynamic jumps and shockwave structures] Doctoral thesis in Phys.-Mat. Science. St-Petersburg, 2017, 361 p.

[3]   Seleznev R K 2018 *J. Phys.: Conf. Ser.* **1009** 012028

[4]   Shuvaev N V Metodika chislennogo modelirovaniya aehrouprugogo vzaimodejstviya

kompressornyh lopatok gazoturbinnogo dvigatelya s dozvukovym nabegayushchim potokom vozduha [The technique of numerical simulation of aeroelastic interaction of compressor blades of gas turbine engine with subsonic air flow]. Ph.D. thesis in Phys.-Mat. Science. Perm, 2014, 133 p.

[5]   Tukmakov A L 2003 J. Appl. Mech. Tech. Phys. **44** 77-82

[6]   Zagovalov G B, Khodirev V V, Chumakov A G, Karpov V N Reguliruemoe soplo gazoturbinnogo dvigatelya [Adjustable gas turbine engine nozzle]. Patent for an invention. № 2183282, 07.03.2001

[7]   Zaycev D K Chislennoe reshenie zadach gidrogazodinamiki i teploobmena s ispol'zovaniem blochno-strukturirovannyh setok [Numerical solution of problems of fluid dynamics and heat transfer using block-structured grids]. Doctoral thesis in Phys.-Mat. Science. St-Petersburg, 2016, 261 p.

[8]   Menshov I S, Kornev M A 2014 *Math. Models. Comput. Simul.* **6** 612-21

[9]   Egorov M Yu, Parfenov A Yu 2014 *PNRPU Aerospace Engineering Bulletin* **36** 165-75

[10]   Vinokur M 1974 *J. Comput. Phys.* **14** 105–25

[11]   Godunov S K 1976 *Numerical Solution of Multidimensional Problems of Gas Dynamics* (Moscow: Nauka)

[12]   Minkov L L, Shrager E R, Kiryushkin A E 2016 *Key. Eng. Mat.* **685** 114-8

[13]   Abramovich G N 1976 Applied Gas Dynamics (Moscow: Nauka)

[14]   Kostyushin K V, Kotonogov V A Kagenov A M, Tyryshkin I M, Glazunov A A, Eremin I V, Zhiltsov K N 2019 *J. Phys.: Conf. Ser.* **1145** 0120487

[15]   Kostyushin K, Kagenov A, Eremin I, Zhiltsov K, Shuvarikov V 2017 *AIP Conference Proceedings* **1899** 060012

[16]   Minkov L L, Shrager E R 2016 *The Main Approaches to the Numerical Solution of One-Dimensional Gas Dynamics Equations* (Tomsk: SST)