

# The impact of unilateral vibrations on aerodynamic characteristics of airfoils in transonic flow

V Zamuraev and A Kalinina

Khristianovich Institute of Theoretical and Applied Mechanics of SB RAS, Russia

E-mail: zamuraev@itam.nsc.ru, kalinina@itam.nsc.ru

**Abstract.** The work is devoted to the mathematical modeling of the influence of forced vibrations of a surface element on one side of the airfoil on the shock-wave structure of transonic flow around. The influence of parameters of oscillations on the airfoil wave drag and the lift force were qualitatively and quantitatively investigated for constant maximum velocity amplitude, which is close in magnitude to the sound velocity in the incoming flow, and for a wide range of frequencies. The arising of additional lift force is shown.

## 1. Introduction

The oscillations of the airfoil surface element at transonic streamline is possible to examine from different points of view. In the first place is necessary to understand the buffeting of aircraft [1, 2]. From another perspective, the forced oscillations as a means of streamline control is of interest. The author's study which concerns the management of transonic flow around airfoils with the aid of pulsed-periodic energy supply has shown significant favourable changes in the aerodynamic characteristics of profiles. Generalization of these results is presented in [3]. The initial results of the study of the impact of high-frequency oscillations of an airfoil surface element on transonic streamline were presented in [4], and the similarity of shock wave structure with the case of energy supply allows a conclusion to be drawn about the possibility of achieving similar effects. Transonic flow around an airfoil even without oscillations is a complex problem because it involves the viscous and thermal phenomena which are characterized by complex physical models [5]. The introduction of oscillations into the formulation greatly increases the computational complexity of the problem. Direct numerical simulation of the oscillations based on the Navier – Stokes equations contains certain difficulties, which manifest themselves as numerical oscillations. These oscillations are completely impossible to suppress even by non-reflecting boundary conditions [1]. As a result the search of regimes with the occurrence of buffeting was performed using the SST-turbulence model within ANSYS CFX [1, 2]. The present paper examines the oscillations of a small portion of the surface, an order of magnitude less than the chord of the profile. This issue was partially explored for high frequency symmetrical fluctuations of the symmetric profile which is streamlined by transonic flow at zero angle of attack [4]. Unlike of [4] here we consider the case of oscillations of the surface element on one side of the airfoil in a wide range of frequencies. The studied case is an airfoil NACA 0012 which is streamlined at zero angle of attack with the Mach number in the incoming flow of  $M = 0.85$  (there is no flow separation). Numerical simulation is based on the solution of two-dimensional unsteady Euler equations with oscillations of the surface element. This formulation allows us to



estimate the maximum values of all effects, because consideration of the dissipative phenomena reduces the magnitude of the oscillation effect in the flow in comparison with a case without these phenomena.

## 2. Mathematical formulation

As a mathematical model to describe planar unsteady flow of non-viscous gas the Euler equations in conservative form are used. The system of equations is supplemented with boundary conditions on boundaries of two-dimensional rectangular area of a rectangle with an inner border corresponding to the contour of the considered airfoil. On the left, top and bottom boundaries of this area undisturbed flow conditions are used. On the right boundary "soft" conditions are used. The condition of impermeability is used on the airfoil contour. On the part of the contour with the boundaries  $x_1$  and  $x_2$  the geometry changes according to the following dependence  $y = f_0(x)$ :

$$f(x, t) = f_0(x) + A \sin(2\pi t/\Delta t) \sin(\pi(x - x_1)/(x_2 - x_1)).$$

Here all the spatial sizes are related to the chord length of the profile  $b$ ; the  $x$ -coordinate is directed along the chord,  $y$  is the transverse coordinate; the profile is localized at  $0 \leq x \leq 1$ . Time  $t$  and the oscillation period  $\Delta t$  are measured in units of  $b/a_\infty$ , where  $a_\infty$  is the sound velocity in the incoming flow. In detail the problem formulation is presented in [4]. For the numerical solution of the formulated problem the finite-volume scheme is used which reduces the total variation with taking into account the fluctuations of the surface profile.

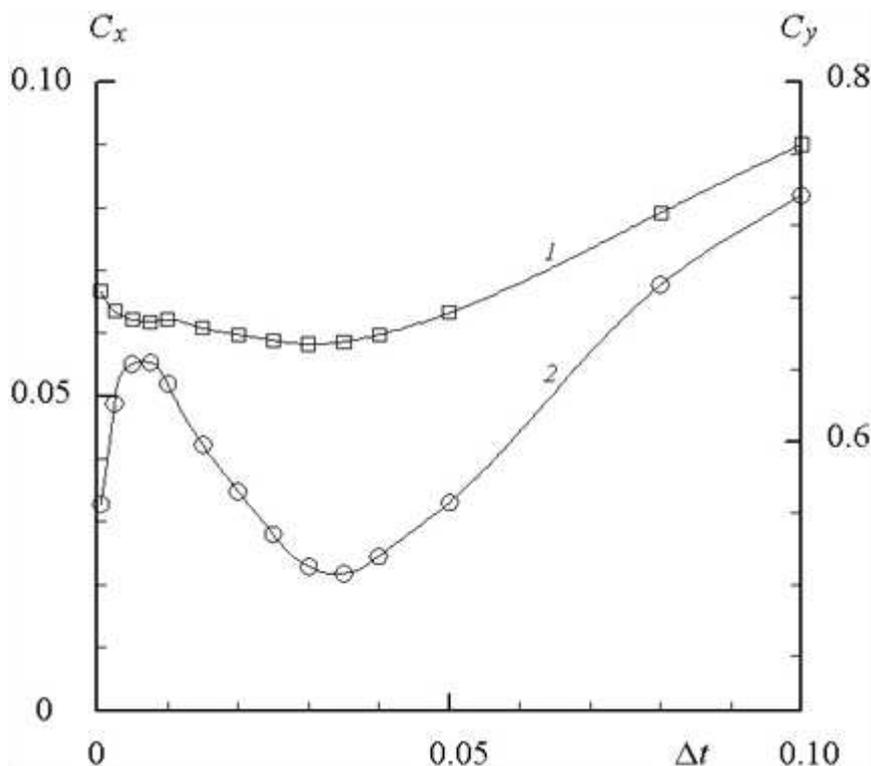
## 3. The results

The results were obtained for airfoil NACA 0012 which is streamlined at zero attack angle by the ideal gas with the heat ratio  $\gamma = 1.4$  and the Mach number  $M_\infty = 0.85$ . The oscillations amplitude and the period were varied for fixed localization of the moving surface element and its size  $x_1 = 0.600$ ,  $\Delta x = x_2 - x_1 = 0.096$ , respectively. In Figure 1 for the relation  $A/\Delta t = 0.2$  the dependence of the wave drag coefficients  $C_x$  (curve 1) and the lifting force  $C_y$  (curve 2) from the period are presented.

A given value of the ratio  $A/\Delta t = 0.2$  corresponds to the maximum amplitude of the velocity oscillations which has a ratio to the speed of sound of incoming flow of 1.26. The character of the  $C_y$  dependence changes significantly with  $\Delta t$ . A rather sharp maximum at  $\Delta t = 0.0075$  and a minimum at  $\Delta t = 0.035$  are observed. The ratio of the oscillations amplitude of the profile element to the period specifies the amplitude of the velocity oscillations. For all points of the curves in Figure 1 the ratio  $A/\Delta t = 0.2$  is characterized by the same value. Therefore, the flow gets the same energy for each period. However, its distribution in the streamline region depends on the period value. For small values of the period (high frequency oscillations) each portion of gas gets energy repeatedly, and this process leads to increasing of  $C_y$ . As a result the quasi-stationary regime of the airfoil streamline is observed. Such a regime takes place, in particular, for the period  $\Delta t = 0.0075$ . In this case, the reciprocal of the homochronicity number which is calculated along the length of oscillating region of the profile [3], consists of

$$1/Ho = 1/(\Delta t/(\Delta x/u)) = 11 \gg 1.$$

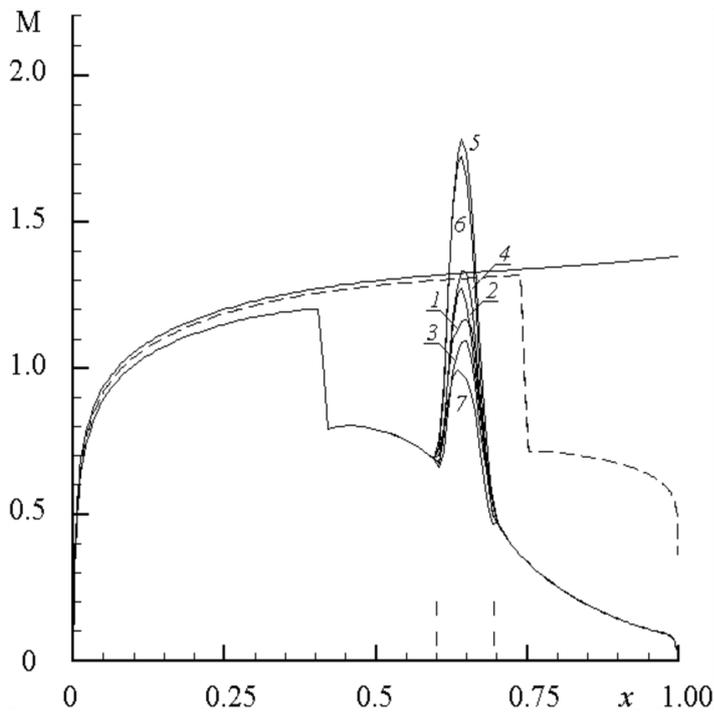
This value indicates the number of energy portions which is received by one portion of gas, and its magnitude corresponds to the quasi-stationary regime of the flow (here  $u$  is the velocity component along the  $x$ -axis). However, for very small values of the profile surface displacement, the spatial dispersion of energy is significant. The amplitude of the surface displacement increases with the increase of the oscillation period in accordance with condition  $A/\Delta t = const$ .



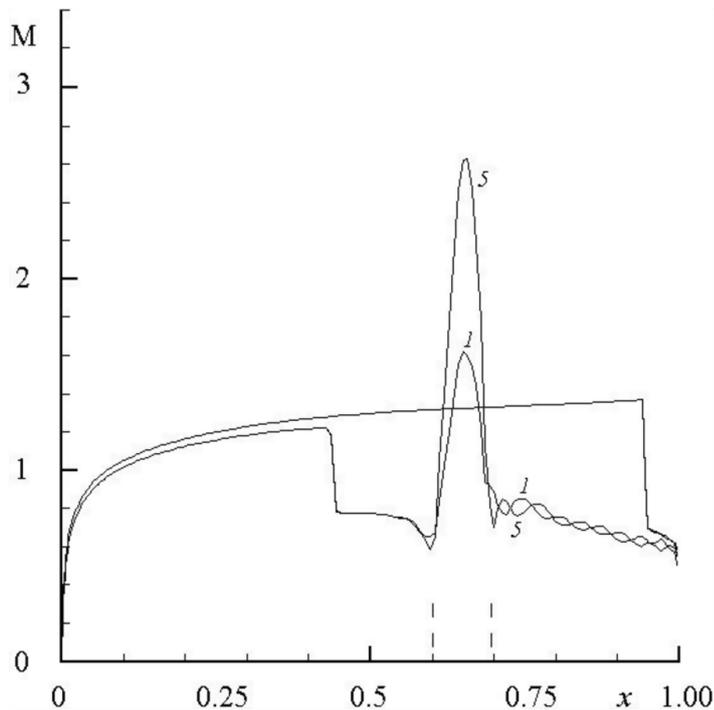
**Figure 1.** The wave drag coefficient  $C_x$  and the lifting force coefficient  $C_y$  depending on the period  $\Delta t$  at  $A/\Delta t = 0.2$ .

The absolute value of the spatial attenuation decreases with increasing of the magnitude  $A$ , but simultaneously reduces the energy which is received by the portion of gas when that portion passes the oscillations zone. The first peak on the graph arises due to these two competing processes. The closed shock wave which is localized on the profile side with the undisturbed surface goes on until the trailing edge. On the opposite side (perturbed surface) is displaced upstream. The shift of the closed shock waves is qualitatively similar to the case of unilateral energy supply [3]. The distributions of Mach number  $M$  along the contour profile in different phases of oscillation at  $\Delta t = 0.0075$  is shown in Figure 2 for various oscillations phases. For comparison, the dashed line shows the distribution  $M$  in the absence of oscillations. Streams flowing down from both sides of the profile are separated by a contact discontinuity. The pressure on both sides of the contact discontinuity must be the same (as well as the Mach number and other values characterized by the discontinuity solution). After closing the shock wave on the bottom (disturbed) side of the profile the flow becomes subsonic. It is inhibited when approaching the trailing edge, and the pressure increases. To balance the pressures at the trailing edge, the closing shock wave on the top (undisturbed) surface should be displaced downstream. In the present case, it stops at the trailing edge. Vertical dashed lines near the  $x$ -axis in Figure 2 indicate the zone of oscillations on the profile. The change of the Mach number  $M$  within the period happen in essence in this zone too. The smooth nature of the distribution after the peak indicates a quasi-stationary mode.

For  $\Delta t > 0.01$  the character of the streamline is changed. The traveling wave extends from the oscillating zone. In Figure 3, this wave is shown after half of the period (curves 1 and 5 for phase 0 and  $\pi$  respectively). The closing shock wave on the upper side of the profile is not displaced to the trailing edge; on the underside the offset of the closing shock wave is less



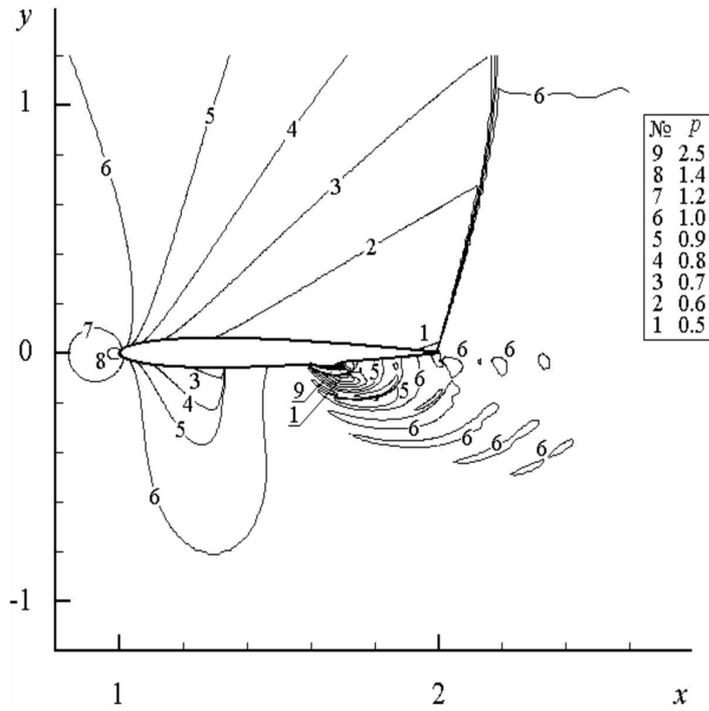
**Figure 2.** The Mach number at  $\Delta t = 0.0075$  (1 – phase 0, 2 –  $\pi/4$ , 3 –  $\pi/2$ , 4 –  $3\pi/4$ , 5 –  $\pi$ , 6 –  $5\pi/4$ , 7 –  $7\pi/4$ ).



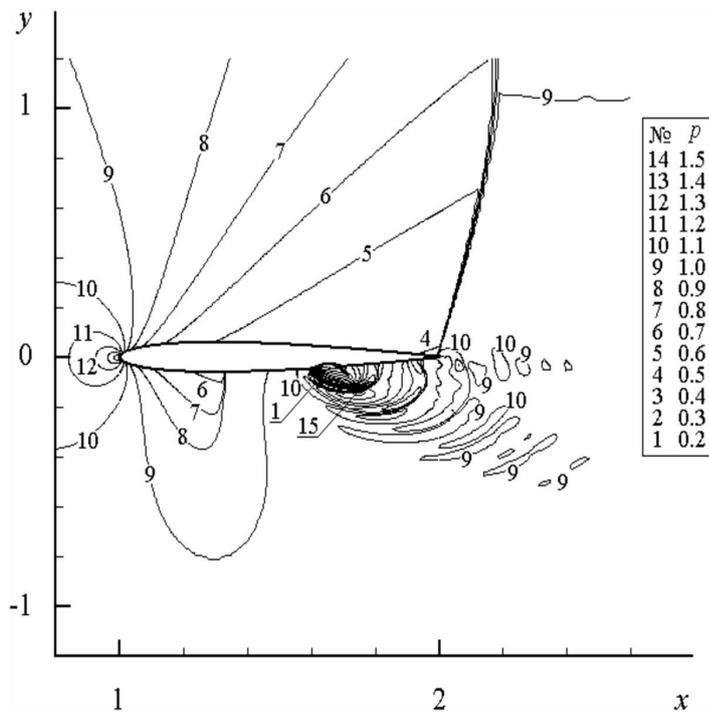
**Figure 3.** The Mach number at  $\Delta t = 0.0075$  (1 – phase 0, 5 –  $\pi$ ).

than the data from Figure 2. All these factors lead to a significant reduction in additional lift force. With further increase of the period  $\Delta t$  the oscillation amplitude  $A$  increases, and, as a result, the spatial and temporal scale of the emerging wave structures increases. In Figure 4 and Figure 5 for the period  $\Delta t = 0.08$  the formation of wave structures at the maximum deviation of the surface profile outside (Figure 4) and inside (Figure 5) is shown. In the first case the shock wave departs from the surface of the profile, and behind it a rarefaction wave runs; in the

second case, the region of rarefaction wave after the shock wave which detaches from the profile is characterized by the more extending area.



**Figure 4.** The pressure distribution at  $\Delta t = 0.08$  and phase  $\pi/2$ .



**Figure 5.** The pressure distribution at  $\Delta t = 0.08$  and phase  $3\pi/2$ .

In the considered case, the ratio between the period of oscillation, the distance to the trailing edge and the flow parameters has such magnitudes that three "semi-cylindrical" shock waves appear which are localized between the oscillation surface and the trailing edge, and high pressure

for the last wave leads to a shift of the closing shock wave on the upper side of the profile to the trailing edge. The effect is mostly caused by the fact that with increasing amplitude of the oscillation the value of the absolute attenuation decreases. As a result the lifting force is growing again, which explains the behavior of  $C_y$  in Figure 1 after the minimum. Neither in this case nor for other values of the oscillation period for the selected values of the velocity amplitude the formation of vortex structures with their detaching from the trailing edge or flow separation are observed. This is the fundamental difference between the force impact from the surface and the energy supply to the flow, which is sometimes characterized by the formation of the vortex structures due to the instability of the thermal track.

#### 4. Conclusion

Thus, it was found that when unilateral force action on transonic airfoil (forced oscillations of a surface element) takes place, the airfoil aerodynamic characteristics have a non-monotonic dependence on frequency. The study has revealed the occurrence of the additional lifting force. For a constant value of the velocity amplitude which is close to the speed of the incoming flow, the dependence of lift force coefficient on the period of the oscillations is nonmonotonic. The relationship of these effects with the transformation of shock-wave structure of the flow is shown. Shift of the shock waves is qualitatively similar to the case of unilateral energy supply. The observed effects may be used to control the flow around airfoils at the corresponding regimes.

#### Acknowledgments

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