Transonic streamline of symmetric wing under the influence of unilateral oscillations characterized by the spectrum of two frequencies

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Abstract. Forced high-frequency vibrations of the airfoil surface part with the amplitude almost equal to the sound velocity can change significantly the lift force of the symmetric profile streamlined at zero angle of attack. The oscillation consists of two harmonics. The ratio of harmonics frequencies values is equal to 2. The present work shows that the aerodynamic properties depend significantly on the specific energy contribution of each frequency.

1. Introduction

The influence of energy supply on the transonic flow around airfoils can be used to improve their aerodynamic characteristics [1, 2] and to reduce flutter [3, 4]. The appearance of spontaneous and forced oscillations connected with the phenomena of flutter and buffeting influences the flow around the airfoils. The possibility of development of these phenomena was investigated in [3-5], but the streamline of the airfoil was not considered. The study in [1] concerns controlling the transonic flow around the profiles with the help of pulse periodic supply of heat energy. The possibility of significant influence of such effects on shock-wave structure and significant changes in aerodynamic properties was shown. However, formation of near surface high-temperature zone resulting from energy supply can be an obstacle for using this method for control. High frequency forced oscillations of the surface element of the profile were investigated in [2]. The effectiveness of such a method for controlling transonic flow around wing was shown. The influence of forced oscillations on the transonic streamline requires more detailed parametric studies.

When studying flutter or buffeting [3-5], the development of these processes is usually simulated only in the very beginning. The result of the studies is the answer to the question whether these phenomena occur. The numerical simulation is carried out by using the unsteady Euler equations [3] or Navier – Stokes [4, 5] ones. Obtaining the periodic solution is not the goal of these studies. Even in the absence of oscillations, the transonic streamline of the profile is a complex task including the modeling of viscous and thermal phenomena. It should be noted that the physical models for this phenomena are constantly being improved [6]. The computational complexity increases when considering the oscillations. For example, using the direct numerical simulation based on unsteady Navier – Stokes equations could lead to the numerical oscillations [5]. Therefore search of modes with occurrence of buffeting is performed by means of turbulence models [4, 5] without analyzing the streamline of the airfoil.
The parametric study of the influence of the forced oscillation on the transonic streamline of the profile based on the unsteady Euler equations was performed in [7]. The calculation was carried out until obtaining the periodic solution. It was assumed that the oscillations do not cause any flutter or buffeting. It is shown that in case of certain parameters of single-mode vibration in the form of a standing wave, it is possible to improve of the aerodynamic characteristics (see the Figure 1).

![Figure 1. The coefficients of the lifting force $C_y$ (1) and the wave drag $C_x$ (2) depending on the time period $\Delta t$](image)

The curves in Figure 1 are obtained at constant amplitude of velocity oscillations, which is close in magnitude to the flow velocity. The aerodynamic characteristics dependences on the period of oscillation are not monotonic.

However, the question about affect of the multimode oscillation on the profile streamline arises. This paper presents the results of parametric study of the influence of two-mode oscillation localized in a zone of the profile surface.

2. The problem formulation

The airfoil NACA 0012 streamlined by ideal gas with the adiabatic index $\gamma = 1.4$ and the Mach number of the incident flow $M_\infty = 0.85$ and zero angle of attack (the streamline without separation zones) is considered. A small section of the surface profile with one of its sides makes an oscillatory motion. The two-frequency oscillations are considered. Use was made of two-dimensional Euler equations in conservative form as a mathematical model to describe the unsteady planar flow of inviscid gas. This approach allows evaluating the max value of the effect of oscillation, because the dissipative phenomena aids in decreasing of this effect. The calculation region is a rectangle with an inner border corresponding to the contour under consideration. On the left, upper and lower boundaries of this region are the conditions of undisturbed flow; the extrapolation is used on the right boundary.

The change of the initial geometry $f_0(x)$ on the contour part with the boundaries $x_1$ and $x_2$ is described by the formula:

$$f(x, t) = f_0(x) + (A_1 \sin(\omega_1 t) + A_2 \sin(\omega_2 t)) \sin\left(\pi \frac{x-x_1}{x_2-x_1}\right).$$

Here $A_i$ and $\omega_i$ ($i = 1, 2$) are the amplitude and frequency of the i harmonic; all the dimensions are related to the chord length of the profile $b$, $x$ coordinate is directed along the chord of the profile ($0 \leq x \leq 1$); the time $t$ is related to $b/a_\infty$ ($a_\infty$ is the sound velocity in the incoming flow). The oscillation frequency $\omega_i$ is associated with a period of $\Delta t_i$ by the ratio $\omega_i = 2\pi/\Delta t_i$, $i = 1, 2$. In the case of single-
mode oscillation the second amplitude $A_2$ was supposed equal to zero: $A_2 = 0$. The formulation of the problem for single mode oscillations is presented in [7]. The finite-volume scheme of the third order reducing the total variation of the flow parameters considering the surface motion is used.

3. Results

The simulation is performed for two-harmonic oscillation with frequencies $\omega_1$ and $\omega_2$. The total energy was assumed equal to the energy of single-mode oscillations with amplitude $A$ and frequency $\omega_1$ [7]. The following equality takes place

$$A_1^2 \omega_1^2 + A_2^2 \omega_2^2 = A^2 \omega_1^2.$$ 

The frequency values differ in twofold:

$$\omega_2 = 2 \omega_1.$$ 

The low frequency is equal to the frequency of the single-harmonic oscillation. The choice of the ratio between the frequencies is determined by the possibility of resonant excitation of multiple frequencies. The ratio of the contribution to the total energy of the individual harmonics is following:

$$\frac{A_2^2 \omega_2^2}{A_1^2 \omega_1^2} = k, \quad k = 1, 0.5, 0.1.$$ 

Figure 2 shows the dependence of the wave drag coefficient $C_x$ and the lift force coefficient $C_y$ from the period $\Delta t = \Delta t_1$ for all values of $k$.

![Figure 2](image)

**Figure 2.** The coefficients of the wave drag $C_x$ (a) and the lift force $C_y$ (b) depending on the period $\Delta t$: curves 1, 2 and 3 correspond to $k = 1, 0.5, 0.1$ respectively.

The case with the same specific contribution to the total energy of the individual harmonics ($k = 1$, curves 1) at low frequency gives almost the same values for the aerodynamic coefficients as the single-harmonic oscillations [7]. Both of coefficients change non-monotonically in dependence of the oscillation period for each value of relative contribution of the harmonics. The coefficient of wave drag varies much less than the lift force coefficient. The change of $k$ from 1.0 to 0.5 for $C_y$ gives an increase in minimum (at $\Delta t \approx 0.03$) for 24% and increase $C_x$ for 12%. The value of the aerodynamic quality of the profile increases.
The distribution of pressure coefficient and the Mach number for one- and two-harmonic oscillations in the zero phase for relatively large oscillation period $\Delta t = 0.08$ are shown in Figure 3. The positions of the shock waves almost coincide. The differences in aerodynamic characteristics in this case are insignificant and do not exceed 5%.

![Figure 3. Distribution of the pressure coefficient (a) and the Mach number (b): the dashed line is the oscillation with a single frequency, the solid line corresponds to two-harmonic oscillation.](image)

The distribution of the Mach number for one- and two-harmonic oscillation in the zero phase for the period $\Delta t = 0.03$ and $\Delta t = 0.015$ are shown in Figure 4. These periods correspond to the local minimum (Figure 4a, $\Delta t_1 = 0.03$, $\Delta t_2 = 0.015$, $k = 1$) and the maximum of $C_y$ (Figure 4b, $\Delta t_1 = 0.015$, $\Delta t_2 = 0.0075$; $k = 1$). In the first of these cases ($\Delta t_1 = 0.03$) the closing shock localized on the side profile without oscillations does not achieve the trailing edge. Differences in shock-wave flow structure between the single-harmonic and two-harmonic oscillations for sufficiently small period ($\Delta t_1 = 0.015$) is relatively small. The differences in aerodynamic characteristics are also small.

![Figure 4. The distribution of the Mach number along the contour of the profile: (a) $- \Delta t = 0.015$, (b) $- \Delta t = 0.015$; the dashed line for the oscillation with a single-harmonic oscillation, solid line for the two-harmonic oscillation.](image)
However, there is no difference in the flow structure of fluctuations. This can be seen in Figure 3 and Figure 4, and Figure 5, that shows the distribution the Mach number for the variant in Figure 4b.

![Figure 5](image5.png)

Figure 5. The part of the Mach number distribution at $\Delta t = 0.015$.

The closing shock wave on the upper part of the picture is localized on the back edge of the profile. On the lower side the shock wave is shifted upstream. This increases the lift force. Attention must be paid to the fact that shocks practically don’t change their position within the period (see Figure 6 taken from [8]).

![Figure 6](image6.png)

Figure 6. A fragment of the pressure distribution for the phase $\pi/2$ (a) and $3\pi/2$ (b) at $\Delta t = 0.08$.

It can be seen in Figure 6 that the positions of shock waves in opposite phase at relatively low frequencies of oscillations remain constant.

4. Conclusion

Thus, the studies show that the impact of two-harmonic oscillations on the transonic flow around a wing profile is determined by the total power, if both of frequencies correspond to the monotonic part of the dependence of aerodynamic characteristics on the period of oscillations. In the other case the lift force coefficient depends significantly from the relative energy contribution of the individual harmonics.
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