NUMERICAL STUDIES OF DYNAMIC STALL ON AIRFOILS USING VISCOUS-INVISCID METHOD

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Nomenclature

c	= chord
C_L	= lift coefficient
C_M	= pitching-moment coefficient
C_N	= normal force coefficient
k	= reduced frequency, $\omega c/2V$
q	= reduced angular velocity, $\omega_z c/V$
Re	= Reynolds number
V	= freestream velocity, m/s
$\bar{X}$	= dimensionless distance, X/c
$\bar{X}sep$	= dimensionless coordinate of separation point
$\bar{X}c$	= center of rotation
α	= angle of attack, deg
α_0	= mean angle of attack, deg
$\dot{\alpha}$	= reduced rate of change of angle of attack, $\dot{\alpha}$ c/V
θ	= amplitude of oscillation of α
τ	= dimensionless time, tV/c

ABSTRACT

Unsteady aerodynamic characteristics of airfoils oscillating in pitch and associated dynamic stall phenomena are investigated. The flow analysis is based on the viscous - inviscid method.

INTRODUCTION

At present, in spite of active studies of dynamic stall many details of this phenomena are not clear. For example, there are no systematic investigations of the effect of reduced frequency on a vortex formation mechanism at dynamic stall. The data for airfoil shape influence on unsteady aerodynamic characteristics at high angle of attack are not sufficient too.

A progress in computational methods permits to expand studies of vortical flows. Modern numerical investigations of viscous flow are based on Navier - Stokes equations /1/. But realization of these algorythms involves theoretical and technological difficulties, e.g. the development of adequate turbulence models. Besides, numerical investigation using Navier - Stokes equations requires significant computer resources, which limits the use of this method in engineering practice. Therefore alternative viscous - inviscid schemes are still actual /2,3/.

NUMERICAL STUDIES

In the present paper the airfoil contour where the no-flow conditions are valid, is replaced by panels with piecewise-linear vortex intensity distribution (Fig.1). The vortex wake is modelled by free discrete vortices. The boundary layer parameters are defined by means of the E.Truckenbrodt integral method /4/.

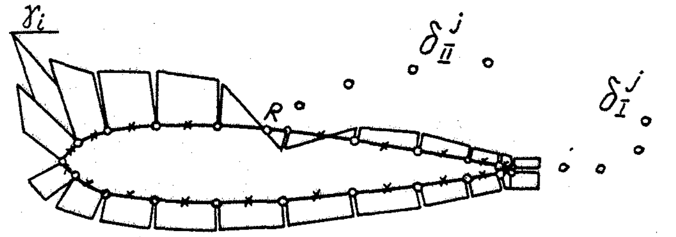

Fig.1 Viscous - inviscid scheme.
δ_I^j, δ_{II}^j - free discrete vortices;
γ_i - intensity of vortex distribution; × - control points;
R - separation point.

The ground of use of quasi-steady Truckenbrodt method is the known assumption that external flow is more inertial than boundary layer flow at dynamic stall /2,3/.

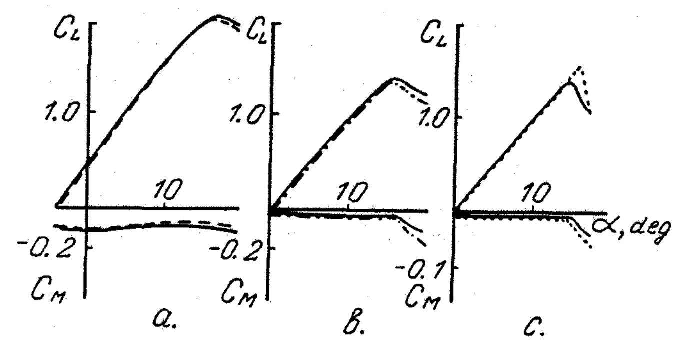

Fig.2 Comparison of calculation with wind tunel data (static).
a) GA(W)-1, Re=9200000;
b) NACA 0018, Re=2970000;
c) NACA 0012, Re=6000000.
——— presented numerical data;
- - - - experimental data /5/;
-·-·-·- /6/;
·········· /7/.

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A comparison of predicted and experimental data for GA(W)-1, NACA 0018, NACA 0012 airfoiles is presented in Fig.2. Numerical results were obtained with $\tau \to \infty$.

Simulated unsteady flowfields and computed aerodynamic loads are in good agreement with the available experimental /8/ and numerical /1/ data (Fig.3-6). Fig.3 shows the sequence of processes of flow over an oscillating airfoil, revealed by computation and an experiment /8/.

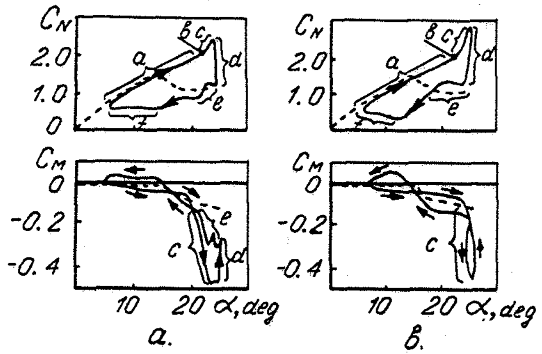

Fig.3 Events of dynamic stall on the NACA 0012 airfoil;
α_0= 15 deg ; θ = 10 deg; k = 0.15;
$\bar{X}c$=0.25; Re = 2500000.
a) presented numerical data;
b) experimental data /8/.

- - - static

At point (a) trailing-edge separation is gradually developing. At point (b) the leading - edge (dynamic) vortex is initiating. Rapid lift increasing at point (c) is connected with the effect of an already strong leading - edge vortex. A sharp reduction in lifting capacity of the airfoil is observed during deviation of the leading - edge vortex at point (d). Numerical modelling has revealed that except for the leading - edge vortex at pitch-up, a trailing - edge vortex at pitch-down is generated too (at point(e)). Lift peak in this stage (Fig.3) is created by the trailing- edge vortex.

Interaction between the leading and trailing - edge vortices is especially clear in the dependence of the moment coefficient versus angle of attack. It is known, that dynamic stall is accompanied by negative damping of pitch motion /8/. This phenomena is explained by inertia of the flow reversal point displacement and extra pitch - down moment of leading - edge vortex. But generation of trailing-edge vortex dramatically changes flow fields. Trailing - edge vortex forces out leading - edge vortex (points (d),(e)). In this situation the influences of given opposite rolling vortices are mutually compensated and the negative damping disappears in the neighbourhood of α max.

Point (f) corresponds to unstalled flow.

Fig.4-5 show a comparison between the presented computational data, experimental results /8/ and numerical data modelled by means of Navier - Stokes equations /1/. As it is seen, the present numerical method allows good modelling of qualitative effects in the considered frequency range. So, for k=0.1 and k=0.15 the peaks of C_L (α) in the vicinity of α max and the local peaks in pitch - down are reproduced correctly. During oscillation at k=0.25 the features of the C_L(α) loop in the neighbourhood of maximal angle of attack are also modelled adequately.

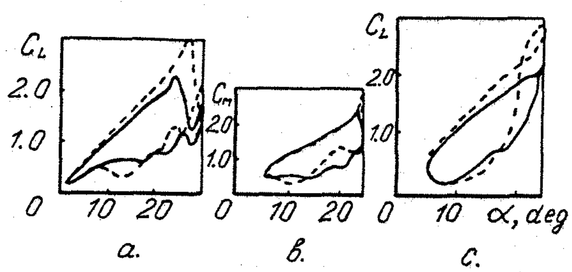

Fig.4 Unsteady aerodynamic characteristics of the NACA 0012 airfoil; α_0= 15 deg;
$\bar{X}c$=0.25; Re=2500000.
a) k = 0.1 ; θ = 14 deg;
b) k = 0.15; θ = 10 deg;
c) k = 0.25; θ = 10 deg.

——— presented numerical data;
- - - - experimental data /8/.

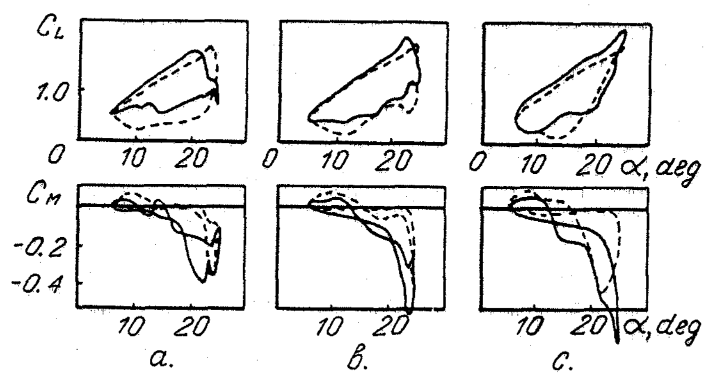

Fig.5 Unsteady aerodynamic characteristics of the NACA 0012 airfoil; α = 15 deg; θ = 10 deg;
$\bar{X}c$=0.25; Re=1000000.
a) k = 0.1; b) k = 0.15;
c) k = 0.25.

——— presented viscous - inviscid method;
- - - - modelling by means of Navier - Stokes equations /1/.

Fig.6 depicts the effect of reduced frequency on the dependences of the pitch moment coefficient on the angle of attack. It is obvious, that with frequency increasing a domain of positive damping in a vicinity of α max diminishes, and in frequency k=0.25 it is absent. In the presented numerical data this tendency is reproduced adequately.

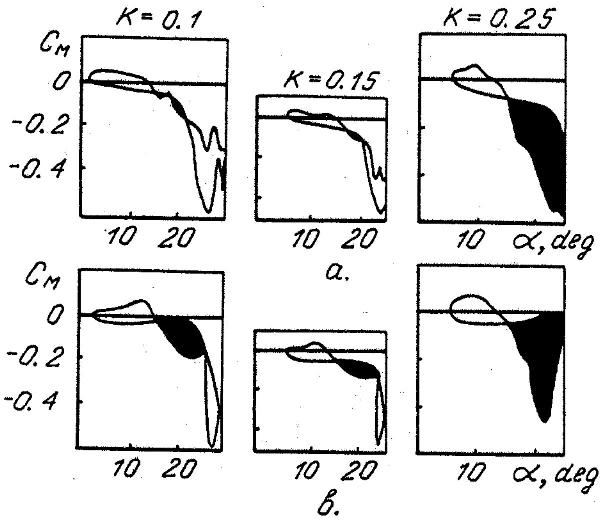

Fig.6 Effect of reduced frequency on the dependences of the pitch moment coefficient on the angle of attack. a) presented numerical data; b) experimental data /8/.

■ - negative damping;

□ - positive damping.

Mathematical modelling allowed to investigate unsteady aerodynamic characteristics in a wide range of Strouhal numbers. Fig.7 depicts characteristics of the NACA 0012 airfoil in a reduced frequency range from 0.15 to 1.5. The case for k= 0.15 (Fig.3) has already been discussed in detail. It has been established that the inertia of the motion of separation point and the leading - edge vortex initiation in pitch-up lead to an excess in dynamic lift for pitch - up stage above the lift value in pitch-down. This accounts for the clockwise passage direction of the loop $C_L(\alpha)$.

The oscillation in frequency k = 0.5 (Fig.7) are associated with significant change in the flowfield for the period. In this case the initiation and development of the leading - edge vortex are shifted to the pitch-down stage. As a result, lifting capacity in pitch-down is increased and the passage direction of a part of the loop $C_L(\alpha)$ changes to the opposite. The pitch moment coefficient versus angle of attack depicts prevalence of negative damping. Increasing of frequency (k=1.5) leads to a reduction of vortical components of unsteady aerodynamic characteristics. The oscillation amplitude of the separation point is reduced, non-linear effects are weakened, and the loops look like an ellipse.

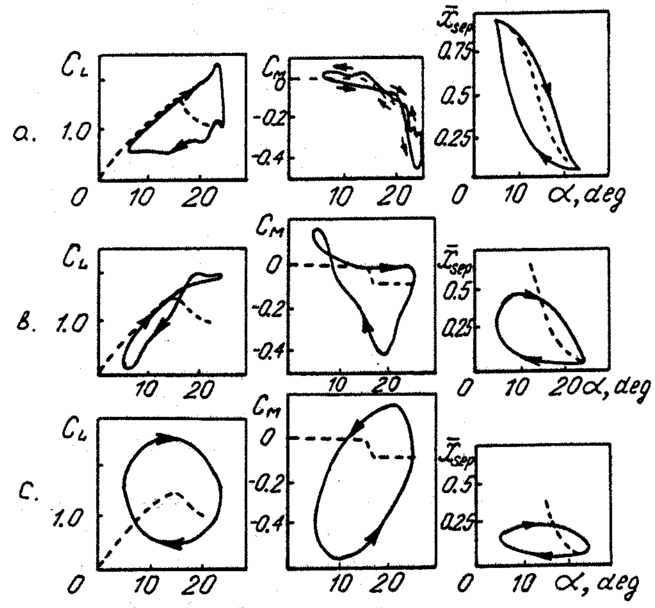

Fig.7 Effect of reduced frequency on the dynamic stall on the NACA 0012 airfoil; α_0 = 15 deg; θ = 10 deg; $\bar{X}c$ = 0.25; Re = 2500000. a) k=0.15 ; b) k=0.5 ; c) k=1.5.

Fig.8 depicts the frequency response - the dependence of damping factor $C_{Mq} + C_{M\dot{\alpha}}$ on oscillation frequency, which based on results of parametric investigations. The negative damping growth is apparently seen within the frequency range of k= 0.1 - 0.7, it is also observed in experimental data (Fig.6,b).

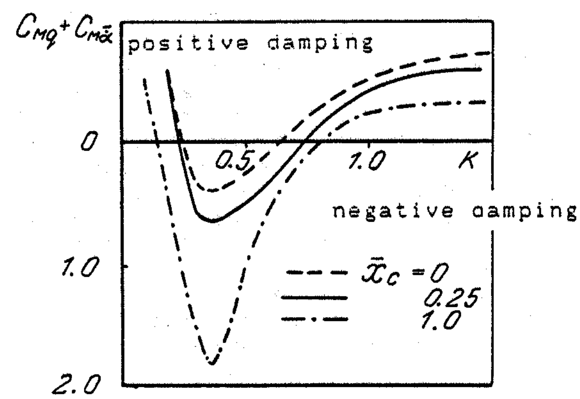

Fig.8 Frequency response of the NACA 0012 airfoil; α_0 = 15 deg; θ = 10 deg; Re = 2500000.

Investigations of the effect of rotation axis location on airfoil unsteady aerodynamic characteristics are of interest for solution of dynamic stall control problems. It is follows from data shown in Fig.8 that the negative damping is decreased when the rotation axis approaches to leading edge. This is caused by decreasing of dynamic stall vortex intensity.

Fig.9 shows the dependence of the damping factor on mean angle of attack calculated for constant frequency (k=0.7) and small amplitude oscillations of NACA 0012 airfoil. This data is demonstrated that damping factor practically coincides with theoretical value at small angles of attack and significant negative damping is observed at oscillations in the vicinity of the static stall angle of attack.

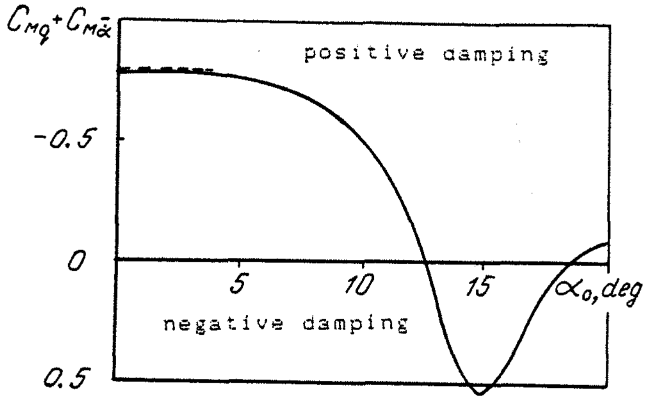

Fig.9 Effect of mean angle of attack on aerodynamic damping; θ = 4 deg; k=0.7 ; $\bar{X}c$=0.25; Re = 2500000.

- - - theoretical damping

The presented numerical investigations show that dynamic stall vortex and the original leading - edge vortex which is generated in impulsively started motion at high angle of attack have common features and similar effects on aerodynamic characteristics. This effect is qualitatively illustrated by means of a comparison of fragments of computed oscillograms $C_L(\tau)$ that are obtained for oscillation and impulsively started motion (Fig.10).

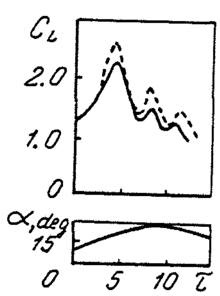

Fig.10 Lift coefficient versus time.

——— oscillation; α_o= 15 deg; θ = 14 deg; k = 0.1.

- - - - impulsively started motion; α = 29 deg.

The point of conjugation of these curves corresponds to the moment of leading - edge vortices initiation. It is also clear, that during pitch motion except for the powerful dynamic vortex, a series of Karman's vortices are generated as well.

The problem of searching a maximum possible airfoil lift value capable to be realized in incompressible fluid is of a large theoretical and practical interest. In connection with this, dynamic stall on airfoil pitching at a constant rate is investigated. In the present paper angle of attack was changed according to linear law from 0 to 35 deg. Comparison between the presented numerical and the available experimental /9/ data demonstrates a good agreement (Fig.11).

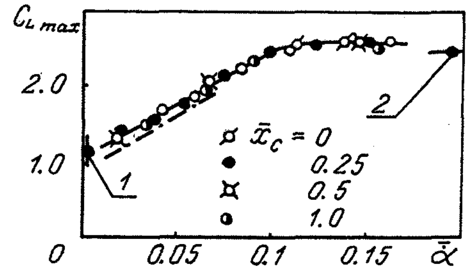

Fig.11 Effect of rate of change of angle of attack on dynamic lift of the NACA 0015 airfoil; Re=200000.

——— presented numerical data;
-·-·-·- experimental data ($\bar{X}c$=0.5) /10/.
1 - static;
2 - impulsively started motion.

Numerical experiment shows that coefficient C_{Lmax} is not practically dependnet upon values $\dot{\bar{\alpha}}$ > 0.12 and maximum possible lift on an airfoil pitching at a constant rate is close to the load occuring in impulsively started motion (Fig.11). It is accounted for by that leading - edge vortex is main factor determining the aerodynamic loading at rapid changing kinematic parameters (α and V respectively).

With chosen motion law, airfoil unsteady aerodynamic characteristics including C_L max will be determined by such kinematic parameters as $\dot{\bar{\alpha}}$ and q. It is known that components of unsteady aerodynamic characteristics proportional to q are dependent on location of the rotation axis, but components proportional to $\dot{\bar{\alpha}}$ are not. To analyse the formation of unsteady aerodynamic characteristics of an airfoil pitching at a constant rate the author made calculations at different centers of rotation. From presented data (Fig.11) it is seen that magnitude C_{Lmax} is low sensitive to a choice of the parameter $\bar{X}c$. It is an indication that the rate of change of angle of attack is the main factor determining unsteady lift.

Besides, components of aerodynamic loads proportional to reflect the effect of the vortical influence. The available experimental results /11/ obtained at harmonic lifting surface oscillations confirm this conclusion also.

Analysis of flow visualization shows that the inertia of the motion of separation point is the main factor of an lift increment for low rate of change of angle of attack ($\dot{\alpha} < 0.02$). In this case the dynamic stall vortex wasn't detected. But at high values of $\dot{\alpha}$ ($\dot{\alpha} > 0.02$) leading - edge vortex plays the significant role in increase of dynamic lift.

Airfoil shape influence on dynamic stall properties is studied. Fig.12 depicts the comparison between the frequency responses of the NACA 0012 airfoil having abrupt static stall and the GA(W)-1 airfoil with soft static stall.

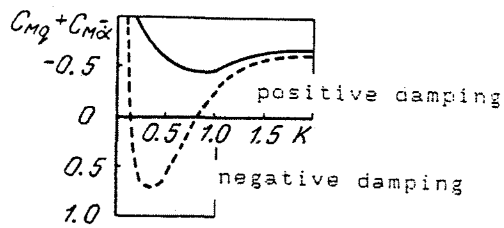

Fig.12 Effect of airfoil shape on frequency respons.

α_0 = 15 deg; θ = 10 deg; $\bar{X}c$ = 0.25; Re = 2500000.

- - - NACA 0012 airfoil
——— GA(W)-1 airfoil

A difference between given data is made clear by means a comparison between the sequences of processes of flow over NACA 0012 and over GA(W)-1 airfoils. The softer frequency response of the GA(W)-1 aifoil is due to weak dynamic vortex generating on trailing low-lift part of the airfoil. The discovered effect of airfoil shape may be very important for the designing of helicopter rotor blades, wind turbines and aircraft wing.

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