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WING ROCK OF LIFTING SYSTEMS

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Abstract

Experimental results on the wing rock of thin slender delta wings with a sharp leading edge at subsonic and transonic airspeeds are presented.

I. Introduction

At sufficiently high angles of attack modern high-performance aircraft become unstable and enter into an oscillatory, mainly rolling motion, which is known as wing rock. Such oscillations lead to a significant loss in the average lift which can cause a serious safety problems during a maneuver.

The source of oscillation in this case are vortical structures generated over the wing because of separation at the nose section or at the sharpened wing leading edge.

To study the general characteristics of the phenomenon, thin slender delta wings are used. Since roll oscillations predominate, it is possible to simulate wing rock regimes on lifting systems(1,2,8) having one or two degrees of freedom.

In spite of the multiple experimental and computational research efforts(1,2,5,6) it is generally acknowledged that the physical mechanism of the phenomenon(3,7) is not yet well understood.

This paper is directed toward the determination of the physical character of the phenomenon, the areas of its presence, and the that influence the motion parameters.

The approach relies extensively on experimental methods. The novel thing in this approach is that it tries to reveal the dependence of the wing rock onset and suppression on special types of vortical flows, to determine the trajectories of vortex cores during oscillation and to evaluate the effect of the air compressibility on the parameters of wing rock.

II. Models and Types of Tests

Various lifting system model (see Fig.1) were tested on a one-degree-of-freedom dynamic rig in a subsonic and transonic wind tunnels.

The models included delta, diamond-shaped and arrow wing planforms. The effects of the aspect ratio and the planform, the shape of the leading edge sharpening and the size of the upper fuselage, were studied. A wing-canard configuration model was also tested.

Delta wing having an aspect ratio of A = 0,71 were tested in a high - speed subsonic wind tunnel in the range of Mach number M = 0,3...1,0.

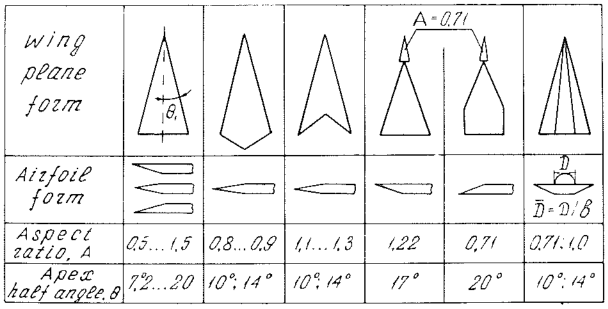

Figure 1. Wing planeforms

Except for the wing rock parameters (amplitude and frequency) some other characteristics including roll damping and dynamic pressures were determined on certain models. The vortex wake was visualized through the use of a net with tufts behind the trailing edge. The photographic data were analyzed to determine the vortex position in roll motion.

III. Experimental Results

Experimental analysis of transition processes preceding the stationary mode, as well as pressure measurements per cycle shows that the development of oscillation occurs without any external disturbance (soft excitation) and the establishment of a stabilized steady regime doesn't depend on the initial conditions.

The loopwise curves of the roll moment against the roll angle(4) having double self-crossing show the presence of negative and positive damping - the main symptom of self-induced oscillation, as well as an alternating function of damping against the angle of sideslip (roll) obtained independently through experimental research.

Let's consider the experimental results shown in Fig.1. They illustrate basic laws regulating wing rock amplitude variation. It is obvious that wing rock occurs only in a limited range of angle of attack, from 12 to 50 deg. and that an increase in the wing aspect ratio as well as the following modification of the planform, lead to a decrease in the oscillation amplitude. Also, the sharper the lower leading edge, the lower the oscillation amplitude. Note, that roll oscillation has a maximum amplitude of 60 deg. and a frequency of 2...3 Hz.

Fig.2 demonstrates also the effect of the upper fuselage mounting on the delta wing. The bigger the relative size of the upper fuselage, the less the amplitude. Moreover, in the case of a fuselage-semicone configuration D̄=0,5 there is no wing rock at all.

At last in Fig.2 illustrates the effect of self-induced oscillation generated on lifting systems with a slender delta wing as a canard. Note that no wing rock is generated on the main of those systems.

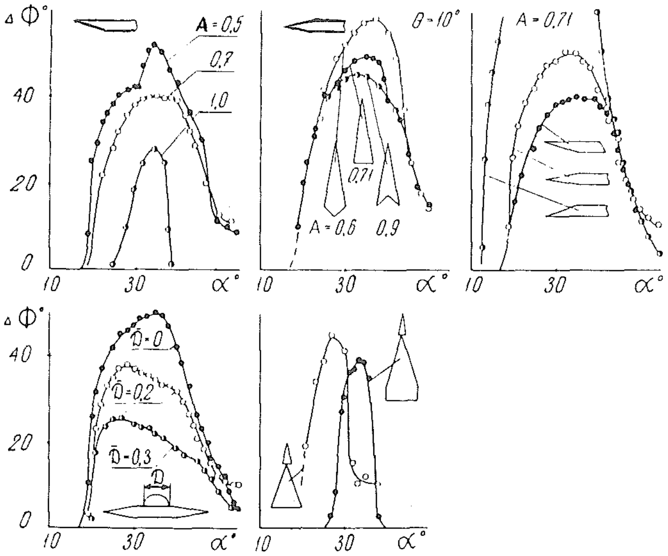

Figure 2. Influence of the main parameters of models on oscillation amplitude

The effect of the air compressibility is another factor that strongly influences the parameters of wing rock regimes.

Fig.3 shows examples of the oscillation amplitude curves against the angle of attack at various Mach numbers.

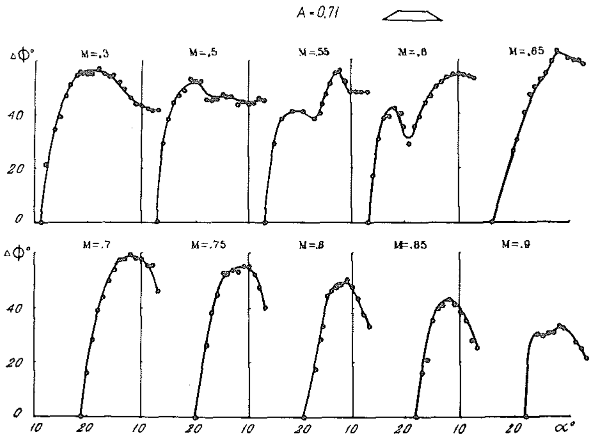

Figure 3. Dependences oscillation amplitudes versus angles of attack for several Mach number

It is obvious that the effect of the air compressibility shows in a decrease in the oscillation amplitudes and also in narrowing of the angle-of-attack range in which wing rock is excited.

Fig.4 shows typical examples curves of the oscillation amplitude dependences against the Mach number at fixed angles of attack for an isolated wing, wings with various shapes of the leading edge sharpening, and a wing with a fuselage-semicone above the upper surface.

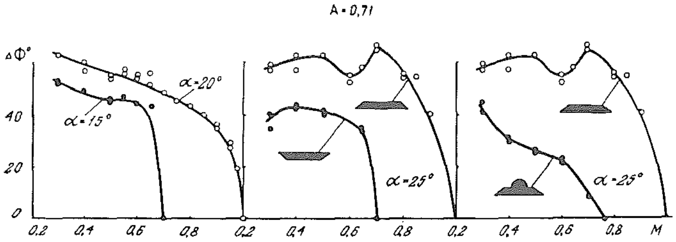

Figure 4. Effect of Mach number on oscillation amplitude

It is obvious that the effect of the upper fuselage and the shape of the leading edge sharpening is qualitatively the same as at low airspeeds.

In all the cases when the amplitude of oscillation is reduced, the wing rock is suppressed at lower Mach numbers. With an increase in the Mach number the amplitudes of wing rock are decreased. At M > 0.95 no wing rock is generated.

The assumptions concerning the physical mechanism of the air compressibility effect are discussed below.

Speaking of the physical aspects of the phenomenon, note that self-induced oscilltion of any system is based on balance of energy. Therefore, in the case of soft excitation, negative damping is generated at low roll amplitudes, but positive damping moments are generated at high amplitudes.

Since lifting systems never lose their damping qualities in attached flow, negative damping moments can only result from vortical components of the load.

In a flow with well-developed vortical structures the most interesting case presents itself when the attachment lines meet in the wing's plane of symmetry, and the vortices themselves remain unburst. According to Werle(10), this case is known as "connected vortices", as distinct from the foregoing case the vortices are "disconnected". It is meant that the vortices are connected to or separated from each other depending on the position of the attachment lines.

The authors have no a priori information on peculiar dynamic characteristics of such vortical structures.

The data discussed above allow to determine the conditions for the excitation or suppression of wing rock. To study the relation between the wing rock boundaries and special regimes of the flow over delta wings, Fig.5 compares a number of the curves for the characteristic angle of attack against the aspect ratio. Curve 1 determines the angles of attack for the case of attachment lines that meet in the wing's plane of symmetry. Curves 2 and 3 correspond to the first α_{1cr} and the second α_{2cr} critical angles of attack for the wing rock regime; at the angle of attack α_{1cr} the wing rock is excited, and at the α_{2cr} wing rock is suppressed. Curves 4 and 5 determine the angles corresponding to vortex breakdown regimes at the trailing edge (4) and the wing apex (5); $\alpha_{\Phi max}$ is the angle of attack corresponding to the maximum oscillation amplitude. Curve 6 determines the angles of attack corresponding, according to Ericsson's hypothesis, to vertical asymmetry of the vortex in steady regimes.

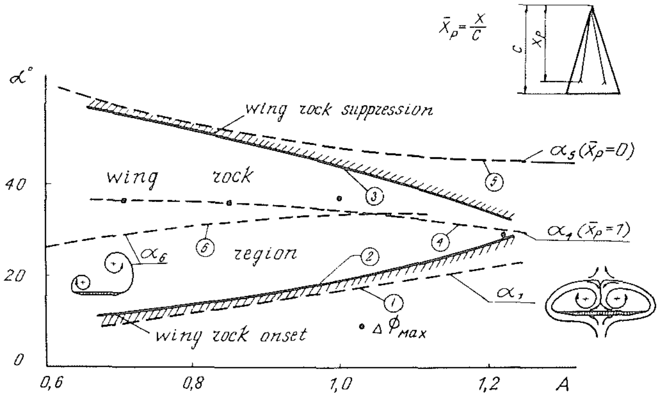

Figure 5. Wing rock boundaries

The analysis of those curves enables to reveal the following. The onset of wing rock is preceded by a certain flowfield structure with the attachment lines arranged in the wing's plane of symmetry. This regime occurs when the similarity parameter values for conical flows $\bar{\alpha}=\alpha/\theta\simeq1.2$ achieved (θ - is the half-angle at the wing apex). Wing rock is onset at angles of attack exceeding α_{1cr} under the condition of $\bar{\alpha}_{1cr}$ = const that reflects similarity of the flowfield over wings having various aspect ratios. The latter phenomenon testifies that the onset regime depends on a special type of the flow field structure with enhanced interaction between the vortices and reduced "attachment" of those to the upper wing surface. This assumption enables to understand the cause of the delay effect in the shifting of vortex cores under roll angle disturbances, which lead to oscillatory of the wing.

The similarity of the onset regimes determines the upper boundary for the aspect ratio range liable to wing rock. This boundary is given by $\alpha_{1cr} = \alpha_4$ which corresponds to a flowfield regime with the vortex breakdown front over the trailing edge. In this case, roll motion causes positive dampind moments resulting, as stated by Ericsson, from the longitudinal asymmetry of the vortex breakdown front. The limit aspect ratio for a flat-lower-surface delta wing having the considered parameters is A $\simeq$ 1,3.

At the angle of attack $\alpha > \alpha_4$ wing rock is maintained because negative damping effects due to vertical asymmetry of the vortices prevail over damping effects due to longitudinal asymmetry of the vortex breakdown fronts and the loads acting on the lower wing surface.

The narrowing of the angle-of-attack range of wing rock regimes with increasing the aspect ratio is due to the growing role of positive damping factors. Those physical mechanisms determine the upper wing-rock boundary α_{2cr} (curve 3).

Note that the boundary of asymmetry for vortical structures in steady regimes, assumed by Ericsson(9) as the wing rock boundary, is located within the range of wing rock regimes but actually has nothing to do with them.

More detailed information on this phenomenon determined by the dynamic characteristics of vortices under wing rock conditions, is presented by the trajectories of the vortex cores, obtained by means of means of filming the flow patterns at a cross-section behind the trailing edge.

Those data (Fig.6) show that in the wing rock regimes the vortex cores follow the wind's motion after a considerable time lay. The latter manifests itself in the loop-like character of these trajectories.

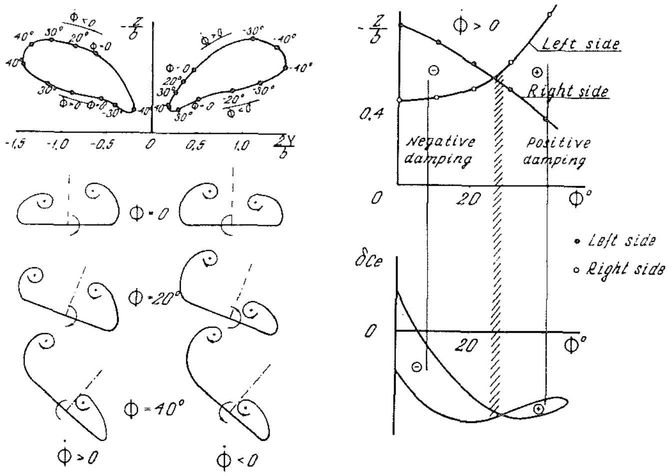

Figure 6. Vortex core trajectories. Sketch of vortex position at various roll angle

By comparing the coordinates of the vortex cores under static conditions and under wing rock , it is obvious that the wing's motion leads to additional dynamic asymmetry based on the inertial characteristics of the vortical structure.

The following characteristic of the vortex dynamics (see Fig.6) is essentially important for the understanding of the wing rock mechanism.

The analysis of the trajectories shows that because of the time lag every quarter of a cycle the type of vortex asymmetry is changed.

Actually, at low roll angles the asymmetry is of a type that generates a moment directed motionwise. At hing roll angles the moment is directed against the motion. It is this effect that determines alternation of positive and negative damping.

This can be illustrated also by schematic diagrams of vortical structure at various phases of motion (Fig.6). It can be seen that the time lag effects show in the asymmetry of the vortical structure. The type of the asymmetry depends on the direction of the wing's motion. The delay between the wing's motion and the motion of vortices is the main factor in the understanding of the phenomenon.

"Connected vortices" have greater freedom of motion and a considerable time lag. The resulting loads determine the alternating character of the damping function in the course of a half-cycle. The onset of wing rock is determined by the character of this function. The suppression of wing rock is bound to the regimes of final breakdown of the vortical structures.

No wing rock is generated on wings tailored so that the "connected vortices" flowfield is proceeded by the vortex breakdown regime.

It was mentioned above that one of the main characteristics for the wing rock regime is the damping function. The authors obtained experimental data accepted as a basis for a semi-empirical mathematical model to be developed for the phenomenon using Van-der-Paul equation.

As for the physical aspects of the phenomenon, there's still much to be thoroughly studied. For example, the cause for the reduced "attachment" of the vortices that strongly influences their dynamics, or the evolution of the vortical structure in a compressible flow in the presence of shock waves above the lifting surface.

The effect of the air compressibility on the oscillation amplitude are connected probably with variation of the vortical load components that are reduced with an increase in Mach number due to the decrease in the axial and radial velocity components in the vortex cores(5).

An increase in intensity of the process of vortex breakdown with increasing Mach number due to the growing pressure gradients may be considered another factor which possibly effects the angle - of - attack range liable to wing rock at high M.

Conclusions

The results allow to make the following conclusions on the mechanism of wing rock onset and formation of the limit cycle.

1. Wing rock arises under the condition of the attachment lines meeting in the wing's plane of symmetry with a vortical structure less "attached" to the wing surface, or "connected vortices".
2. the basic characteristic for "connected vortices" is a strong response to roll disturbances with a considerable delay.
3. As a consequence of the time lag effects in the vortex dynamics, even slidht disturbances lead to dynamic asymmetry of the cores relative to the wing. Therefore, small angles of deflection cause such vortical load components that generate a moment directed motionwise (negative damping), but high angles of roll lead to a moment in the opposite direction.
4. The limit cycle is formed at an amplitude providing the equality of work between the negative damping and the positive damping motion.
5. The suppression of wing rock occurs in the regimes dominated by positive damping due to the vortex breakdown.
6. In case, when vortex breakdown occur before the formation of "connected vortices" structure, wing rock are not arise.
7. The effect of the air compressibility shows in a decrease in the oscillation amplitudes mainly at high subsonic and transonic speeds. At Mach number $M > 0.95$ wing rock on wings with aspect ratio $A > 0.5$ are not excited.

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