LOADING PARAMETERS OF A LONG-RANGE AIRCRAFT WING IN WIND TUNNEL CLOSE TO BUFFET BOUNDARY

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Abstract:

The lift coefficient of buffet onset (CLb) or buffet boundaries is one of those limitations that should be taken into consideration when developing aerodynamic design of the subsonic aircraft wing, starting from the conceptual design stage. At cruising (transonic) Mach numbers pressure oscillations, leading to buffet load, are preconditioned by interacting shocks and the boundary layer of the wing. These oscillations are associated with fluctuations in flow separation zones, positions and shocks intensity.

A certain problem comes with predicting CLb value by results of models test in a wing tunnel and transferring results on to a full-sized aircraft. In most cases, WT tests of full scale models are conducted at Reynold's numbers (calculated by the average aerodynamic wing chord) no more than Re = (2.5-4.5) million. At these Reynold's numbers the wing with free transition of the boundary layer may include large segments of the laminar boundary layer which influence shocks position and buffet origination. With fixed transition of the boundary layer it becomes thicker if compared to real aircraft flight conditions. In this case buffet development will also differ from real conditions. This paper investigates peculiarities of influence of Reynold's number and of the boundary layer state on characteristics of flow about high aspect ratio wing at AoA up to buffet development.

1 NOMENCLATURE:

A	=	amplitude pressure oscillations
α, *AoA*	=	angle of attack
alpha	=	angle of attack
αn	=	angle of attack buffet onset according to criteria *n*
CD	=	drag coefficient
CL	=	lift coefficient
CL_b	=	lift coefficient buffet onset
CLcruise	=	lift coefficient cruse regime
CM	=	pitching moment coefficient
Cn	=	section normal force coefficient
CP	=	static pressure coefficient
$C\tau$	=	section tangential force coefficient
dP	=	pressure oscelations
M	=	Mach number
Re	=	Reynolds number
RMS	=	root mean square

RMS CP = root mean square static pressure coefficient
Xtr_{sec} – transition position of boundary layer in wing section
Xsw_{sec}- shock wave position on a chord in wing section

2 INTRODUCTION

When selecting design parameters of the aircraft, one faces problems with balancing numerous, and often contradicting requirements and limitations. One such problem is to achieve high lift-drag ratio and high cruising speed, while ensuring sufficient margin till the buffet boundary and loss of stability and controllability. Margins themselves must meet the regulatory requirements for the chosen geometric parameters of the aircraft. The lift coefficient of buffet onset (CLb) or buffet boundaries is one of those limitations that should be taken into consideration when creating aerodynamic design of the subsonic aircraft wing, starting from the conceptual design stage. At cruising (transonic) Mach numbers pressure oscillations, leading to buffet load, are preconditioned by interacting shocks and the boundary layer of the wing. These oscillations are associated with fluctuations in flow separation zones, positions and shocks intensity [1, 3, 4]. Buffet appearance and development is preconditioned by the impact of pressure oscillations on the elastic structure and its reaction. Most frequently, buffet intensity is assessed using the maximum values of additional overloads (Δn), acting in the aircraft center of mass. An overload of less than 0.05g is believed to generate no buffet; at $0.05<(\Delta n)<0.2$ there is ‘slight’ buffet; at $0.2<(\Delta n)<0.6$ – moderate buffet [1]. A long-range aircraft operation is allowed at slight buffet conditions, although it can cause slight deterioration in aircraft performance and affect passenger comfort. Slight buffet determines the upper limit of the AoA flight envelope. Another critical parameter, characterizing the operational AoA area, is buffet onset boundary by AoA. According to the Russian Aviation Regulations, at cruise and also at climb and descent on route, overload increment when reaching the buffet boundary should not be less than 0.3 (p. 25.251. Vibration and buffet (a^*). [2]. That is the margin between the lift coefficient CLcruise and the lift coefficient of the buffet onset (CLb) should match the following condition

$$CLb \,/\, CLcruise \geq 1.3. \qquad (1)$$

In other words, the buffet onset lift coefficient can determine the maximum of the cruise lift coefficient permitted. To get the maximum fuel efficiency of a transport aircraft, CLcruise should match the flight with the maximum lift-drag ratio. However, if CLb is not high enough, to fulfill requirement (1), the flight should be performed at decreased CLcruise lift coefficient. Nowadays, the problem of providing the specified lift margin has become especially essential. Firstly, it is connected with the rise in the wing aspect ratio (by 15-20%) for the advanced long-range aircraft due to ever-growing use of composite materials. Secondly, it goes with the trend towards higher cruising speed up to Mach number M =0.85-0.86 owing to improved aerodynamics and engines. The growth of the wing aspect ratio leads to rising CLcruise which corresponds to the maximum lift-drag ratio of the aircraft, whereas CLb is less dependent on aspect ratio and it only goes down with the Mach number going up, see Figure 1.

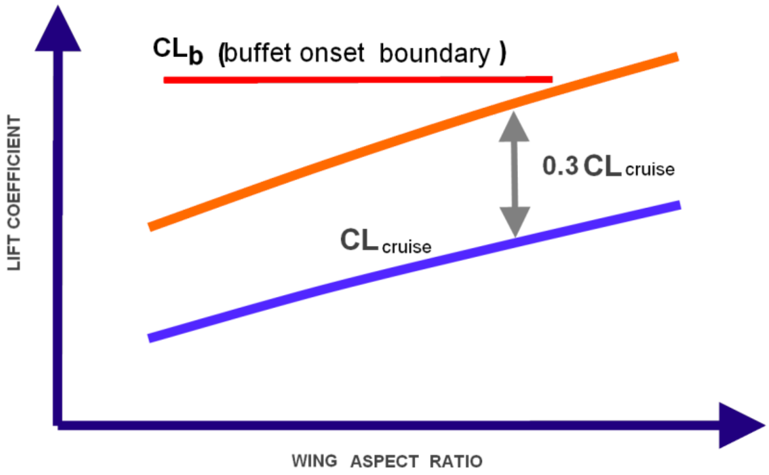


Figure 1: Flight envelope limitations

Obviously, to obtain the required lift margin between CLcruise and CLb for transonic wings of high and very high aspect ratio, it is necessary to try to increase CLb as well when enhancing efficiency of the wing. Normally, at low speeds the buffet onset lift coefficient CLb is caused by the flow separation development on the upper wing surface, as AoA grows. At cruise (transonic) Mach numbers, pressure oscillations are caused by the interaction of shocks and the wing boundary layer, leading to fluctuations of flow separation areas, intensity and the position of shocks [1, 3, 4, 11]. Increasing CLb is principally possible through removing or weakening the detached flow both at low and high subsonic speeds [6]. This however is a very difficult task, as far as the wing aerodynamic design development is mainly focused on the cruising flight regime, where the wing flow is nearly always without separation. So far, flow consideration at high AoA at multimode optimisation gives no sufficient effect with certain deterioration of lift-drag ratio at cruise. It is useful to highlight in this regard that high aspect ratio wing features higher flexibility. Accordingly, its optimisation should necessarily consider for deformations resulting from aerodynamic loads. There are various active and passive methods to resist buffet [5,13]. Attempts to apply special device to increase the buffet boundary are however still at design stage. Another way to solve the problem indicated above is to specify the procedure of CLb determination. More precise estimate of buffet boundaries allows to reduce additional margins when developing the aircraft design and thereby to increase CLcruise. The question of CLb reliable determination remains unresolved, since there is a variety of criteria, whose application produces different results [8, - 12]. The problem is that CLb is determined not as the definite beginning of the separation somewhere on the wing, but as its state after certain development which leads to changes in aerodynamic performances, and flow parametres. There is no clear objective line between normal flow and buffet condition. Moreover at early design stage there are data about elastic-mass characteristics of the aircraft, that does not allow to correctly evaluate the level of buffet oscillations amplitudes. Therefore at these stages buffet boundaries can be judged upon by buffet loads only.

For buffet delimitation based on results of experiments on ‘rigid’ aerodynamic models in a wind tunnel (WT) various criteria, including [14] can be applied: **criterion 1 -** beginning of deviation from curve linear section of the lift by AoA, or decrease of CL $^{\alpha}$ (α) derivative for both total CL (α) values and separate Cn(α) sections; **criterion 2 -** beginning of deviation from curve linear section of the pitch by mza (α) AoA, for both total and separate sections; **criterion 3 –** changes are opposite to those of the first type, both for total CL(CD) values and for Cn(Cτ) sections - beginning of deviation of Cn(Cτ) dependencies from a linear type by AoA; **criterion**

4 - change (fast fall) of pressure coefficient close to the trailing edge of the wing as AoA grows, witnessing separation flow development; **criterion 5 -** change (fast grow) of root-mean-square deviation of pressure coefficient in sections as AoA grows; **criterion 6** - change (fast grow) of pressure oscillations level in sections as AoA grows; **criterion 7** - change (fast grow) of amplitudes of frequency spectra of pressure oscillations in sections as AoA grows. Except for listed above, buffet delimitation can be undertaken with the help of other criteria [1]. A certain problem comes with predicting CLb value by results of models test in a wing tunnel and transferring results on to a full-sized aircraft. In most cases, WT tests of full scale models are conducted at Reynold's numbers (calculated by the average aerodynamic wing chord) no more than Re = (2.5-4.5) million. At these Reynold's numbers the wing with free transition of the boundary layer may include large segments of the laminar boundary layer which influence shocks position and buffet origination. With fixed transition of the boundary layer it becomes thicker if compared to real aircraft flight conditions. In this case buffet development will also differ from real conditions. This paper investigates peculiarities of influence of Reynold's number and of the boundary layer state on characteristics of flow about high aspect ratio wing at AoA up to buffet development.

3 TEST MODEL AND TECHNOLOGY DESCRIPTION

The experimental tests were carried out on a large-scale half model of the typical subsonic passenger aircraft with high aspect ratio swept wing in TsAGI’s T-128 transonic WT. The tests took place in WT free stream (without additional disturbance sources, like turbulising and oscillating grids, etc.) Reynolds number was ensured by selecting the chamber pressure value. The layout of the model under study is shown in Figure 2. The model was put on external five-component strain-gage balance, located outside the working section of the WT. At the first stage, total aerodynamic properties of the model were evaluated, as well as pressure distribution in 10 airfoil sections spanwise (more than 400 pressure points). Also defined was the position of the transition curve of the boundary layer on the wing upper surface with the help of liquid crystals [7]. In the test process, wing deformation was measured, and the wing sections twist angle alteration was estimated depending on impact air pressure and the model AoA. At this stage, the measurement of pressure oscillations was performed using the WT-128 standard measurement system. In all drain points measurements were taken simultaneously, with a sampling rate of 1000Hz. These tests have demonstrated that due to large length and volume of approach channels, pressure dynamic components, especially in high-frequency part of spectrum, were underrated. This has actually filtered off the 50-100Hz-plus frequency components, although the sampling rate of the gauges was high enough. This resulted in noticeable decrease of the measured pressure oscillation values and the estimable integral noise level [11]. Therefore, at stage two of the studies, the model has been partially equipped with pressure oscillation sensors (Kulite XCS-062-5D type) which were installed in measurement points with minimised lead ducts. It allowed to measure high-frequency components of pressures oscillations. Pressure oscillations sensors were placed starting from 30% of the local chord; Figure 2. The experimentswere performed with analogue-to-digital converter channels sampling rate of 54 kHz. The analogue filters of the measuring channels were set to 10 kHz, the operating frequency range of pressure sensors with pneumatic ducts was 0÷5kHz. For lowering the noise influence called by punching of WT walls and other sources, the frequency range of pressures oscillations 0÷2000Hz was considered As a rule, at cruise Mach numbers, for the high aspect ratio swept wing, the initial flow separation zone is formed on the wing outboard part, as a result of shock-boundary layer interaction. Therefore as an example we select the wing panel section, located at 59% of the wing semi-span, and coinciding with the section used for static pressure measurements at test stage one.

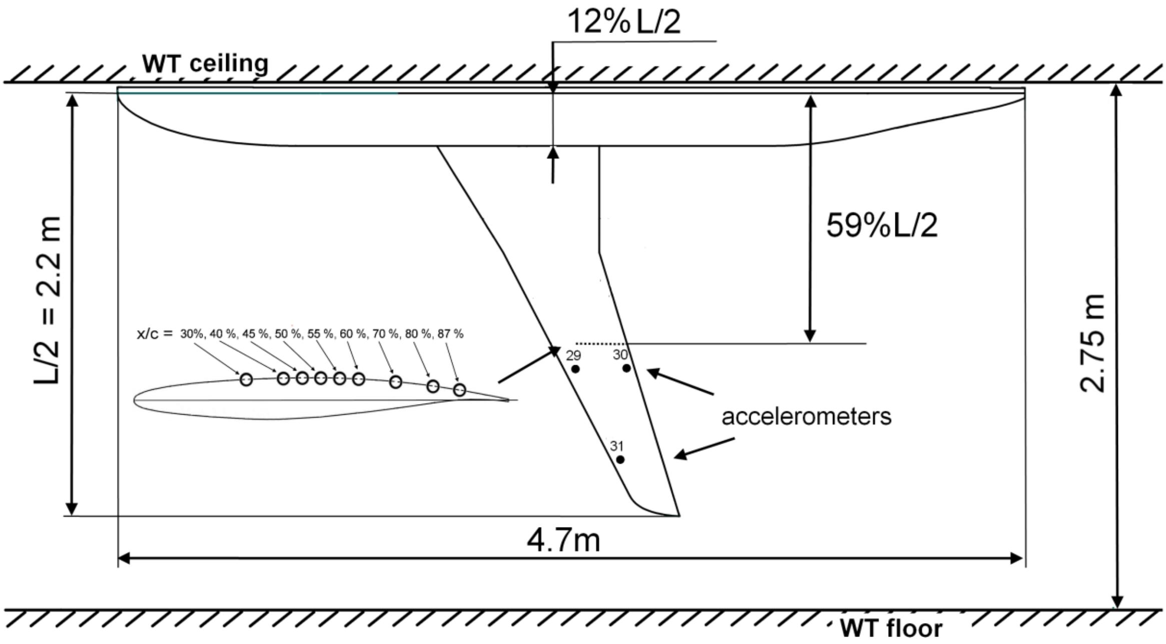


Figure 2: Layout of aircraft's model in WT

Investigations were made at M =0.78 and in a range of the Reynold's numbers evaluated on the average aerodynamic chord of the wing from Re = 3mill to Re = 9mill. Reynold's number in the section under study changed accordingly from Re = 2.5mill to Re = 7.4mill. The model was tested with free and fixed (Xtr = 5 %) boundary layer transition to the upper wing surface. On the bottom part of the wing in both cases boundary layer transition was fixed at Xtr = 5 %. The Reynold's number was increased by putting up WT pressure. It increased the wing twist as a result of a deflection of the wing of the model (picture 3). However with relatively higher stiffness of the wing the value of the additional angle of twist did not exceed $\Delta\alpha = 0.3$ ° at maximum Re =7.4mln, while difference in twist between tests was no more than $\Delta\alpha$ =0.15 °-0.2 °.

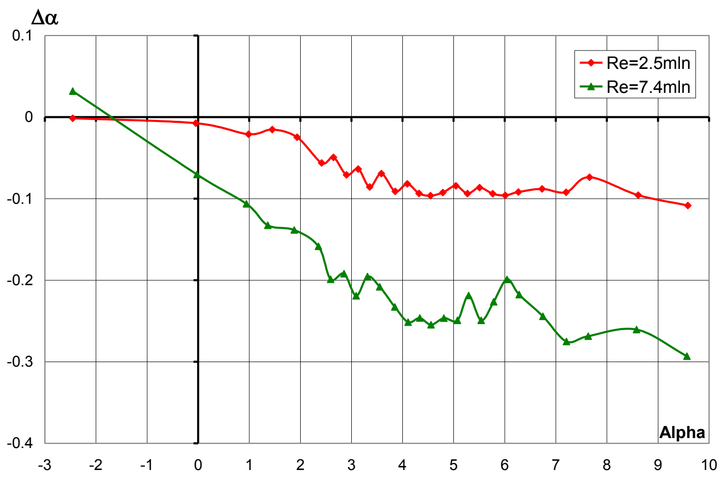
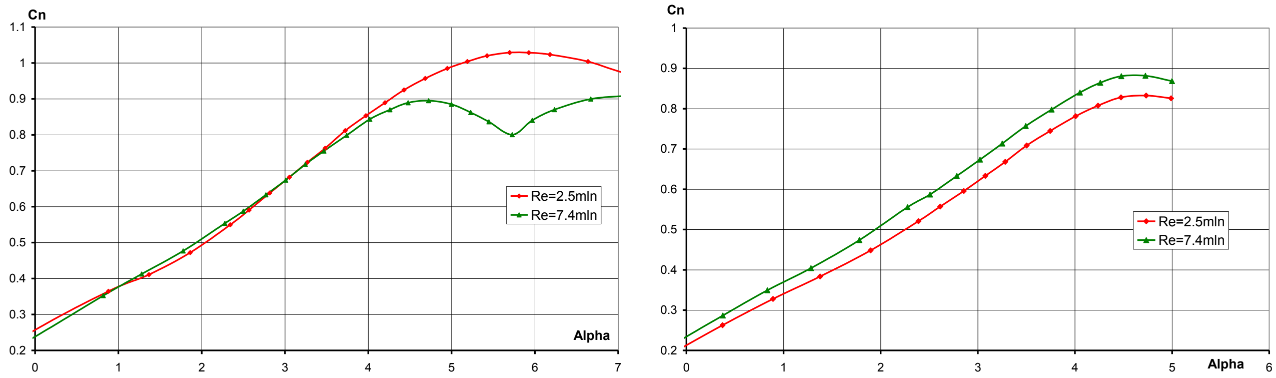


Figure 3: Additional twist angle of the wing in section Z=0.59

4 INVESTIGATIONS RESULTS

Figure 4 shows influence of Reynold's number on the change of carrying properties in wing section Z=0.59 at free and fixed positions of the boundary layer. Relations Cn (α) are obtained by pressure integration.



a) free transition   в) fixed transition

Figure 4: Influence of Reynolds number on Cn (Alpha)section Z=0.59

Attention should be given to the different character of influence of Reynold's number for free and fixed position of the boundary layer transition. In case of the fixed transition, the Reynold's number increase leads to the growth of carrying properties at all AoA. At the free transition, the Reynold's number increase practically does not influence carrying properties to AoA α ≈3.5 °. However, at α> 3.5° Reynold's number increase leads not to the growth but to a sensible drop of carrying properties of the section. With this, separation beginning α value feebly depends on Reynold's number and the boundary layer condition and equals α = 4.4 °-4.2 ° for free and α = 4.1 °-4.15 ° for the fixed transition.

Figure 5 shows position of the transition curve of the boundary layer, got with the help of liquid crystals method. It can be seen that Reynold's number increase from 2.5 million to 7.4mill materially (by 20-30 %) displaces the position of the boundary layer transition forward.

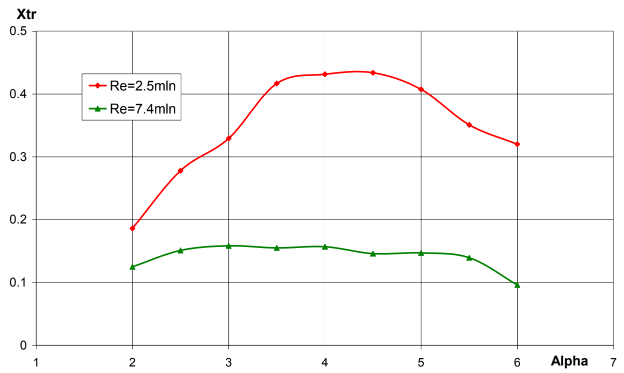
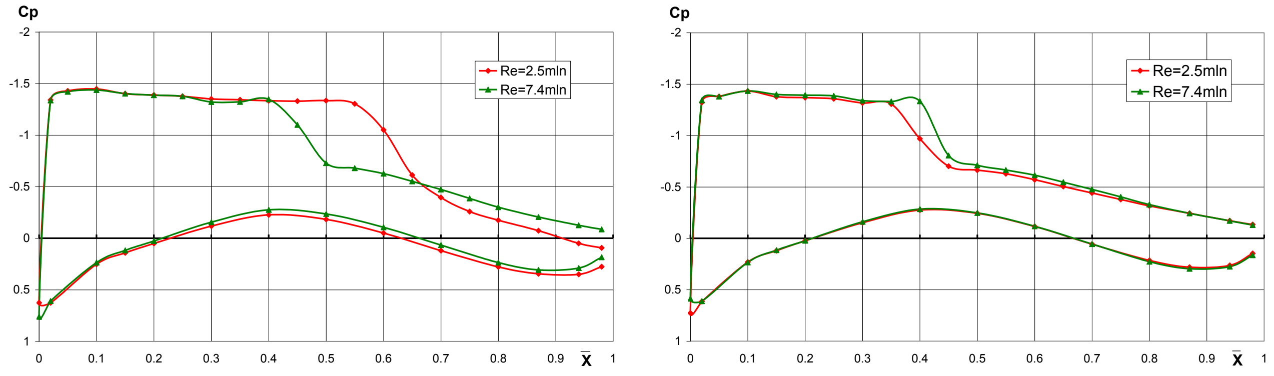


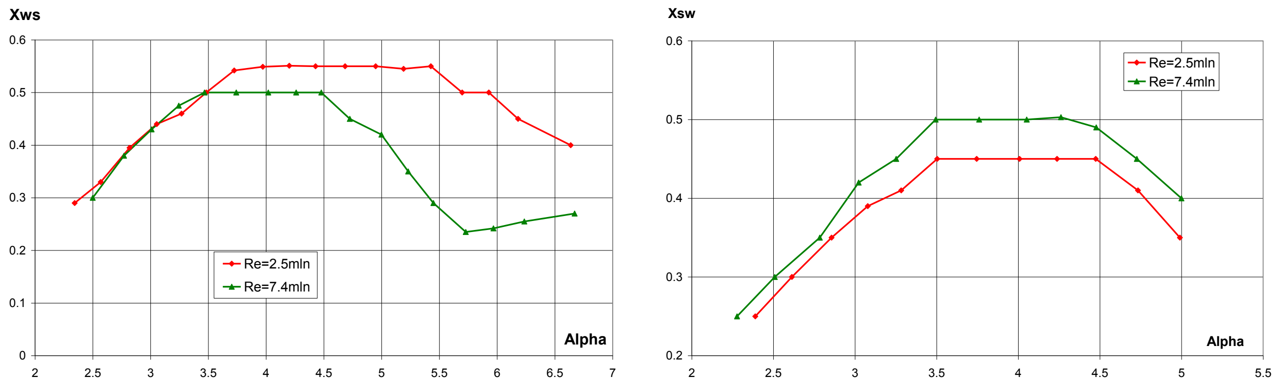
Figure 5: Influence of Reynolds number on boundary layer transition position in section Z=0.59



a) free transition   в) fixed transition

Figure 6: Influence of Reynolds number on Cp(x) section Z=0.59

With Reynold's number growing, the shock on the wing with the fixed transition moves down the chord (figure 6b), whereas on the wing with the free transition, Reynold's number growth leads to shock’s considerable move forward (picture 6a). The given effect is observed at all supercritical AoA (figure 7).

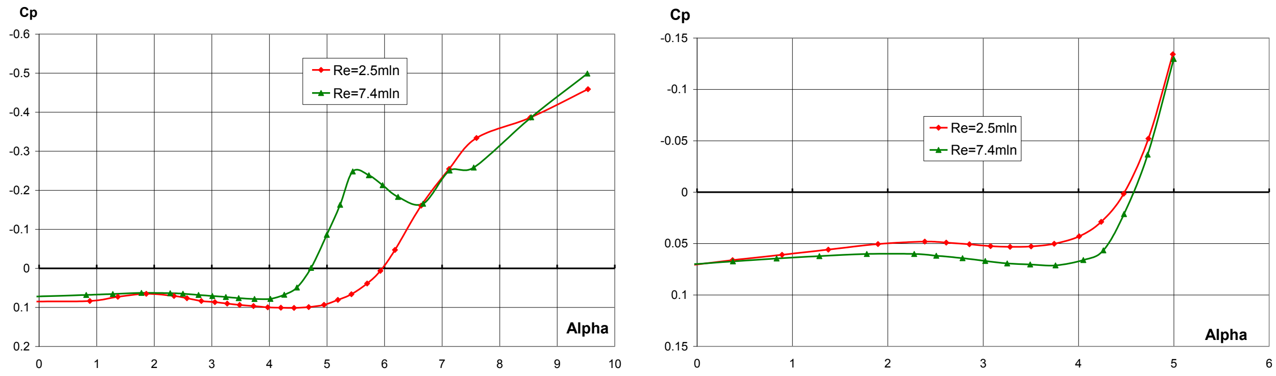


a) free transition   в) fixed transition

Figure 7: Influence of Reynolds number on shock position in section Z=0.59

Stabilisation of the shock position for both wings takes place starting AoA α≈ 3.5°÷3.75 °, that is to separation beginning α, and practically does not depend on Reynold's number change. Another thing is wave separation development and linked to it shock’s move forward [15]. In this case the boundary layer condition produces significant effect. For the wing with the free transition it takes place only with α ≈5.5 ° for Re=2.5 million and α ≈4.5 ° for Re=7.4 million. For the wing with the fixed transition it takes place from α ≈4.25°÷4.5 ° for all Reynold's numbers.

Let's consider the change of the pressure coefficient close to the trailing edge of the wing with the growth of AoA. Figure 8 shows dependencies of pressure coefficients Cp (x) close to the trailing edge (X=0.98). The character of these dependencies demonstrates development of diffuser separation. It can be observed that separation beginning on the wing with the free transition, moves with Reynold's number growing to smaller AoA from α ≈4.5 ° at Re=2.5 million to α ≈4.0 ° at Re=7.4 million



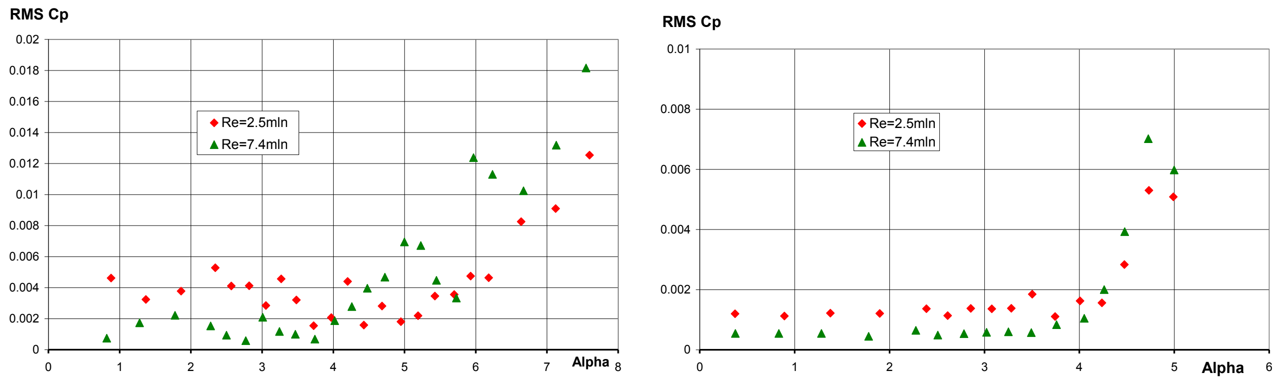
a) free transition

в) fixed transition

Figure 8: Influence of Reynolds number on Cp near to a trailing edge (X=0.98)

The Reynold's number increase at the wing with the free transition leads to appreciable growth of suction at α> 4.5 ° that testifies to amplification of diffuser separation. The Reynold's number growth at the wing with the fixed transition, on the contrary, improves flow at α> 4.0 °.

Figure 9 shows dependencies of RMS Cp for X=0.98. On the wing with the fixed transition appreciable growth of pressure oscillations is witnessed at α> 4.0 ° (picture 9в). In general it correlates with the data obtained earlier. However for the wing with the free transition, these is no such correlation detected (picture 9a). RMS Cp flow character by AoA feebly depends on Reynold's number. That is application of the regular measuring system owing to damp of drain tubes led to appreciable drop of measured values of pressure oscillations and the evaluated noise level.



a) free transition

в) fixed transition

Figure 9: Influence of Reynolds number on RMS Cp near to a trailing edge (X=0.98)

Therefore during the second stage of investigations the model was partially equipped with pressure oscillations sensors of Kulite XCS-062-5D type. Figure 10 shows dependencies of RMS Cp for X=0.87, obtained on the model with the free transition. It can be seen that the measurements made by oscillations sensors, give a more adequate impression of influence of Reynold's number on pressure oscillations close to the trailing edge.

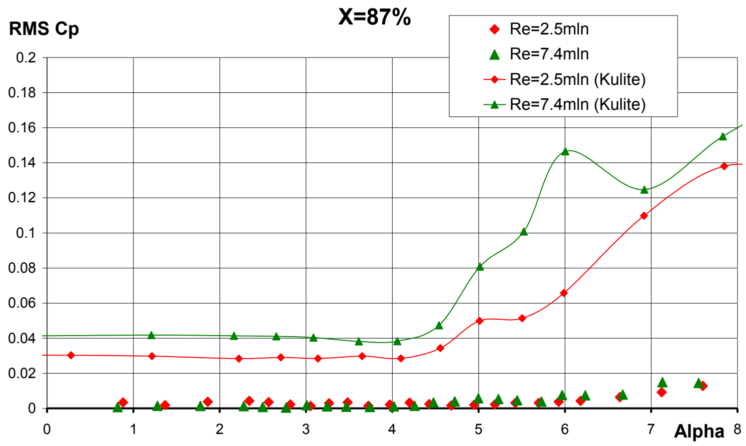


Figure 10: Influence of Reynolds number on RMS Cp near to a trailing edge (X=0.87)

RMS Cp intensive growth is detectable since as early as α> 4 °. With this, Reynold's number increase leads to rising pressure oscillations.

Figure 11 gives AoA values when the flow separation develops, as determined by above criteria.

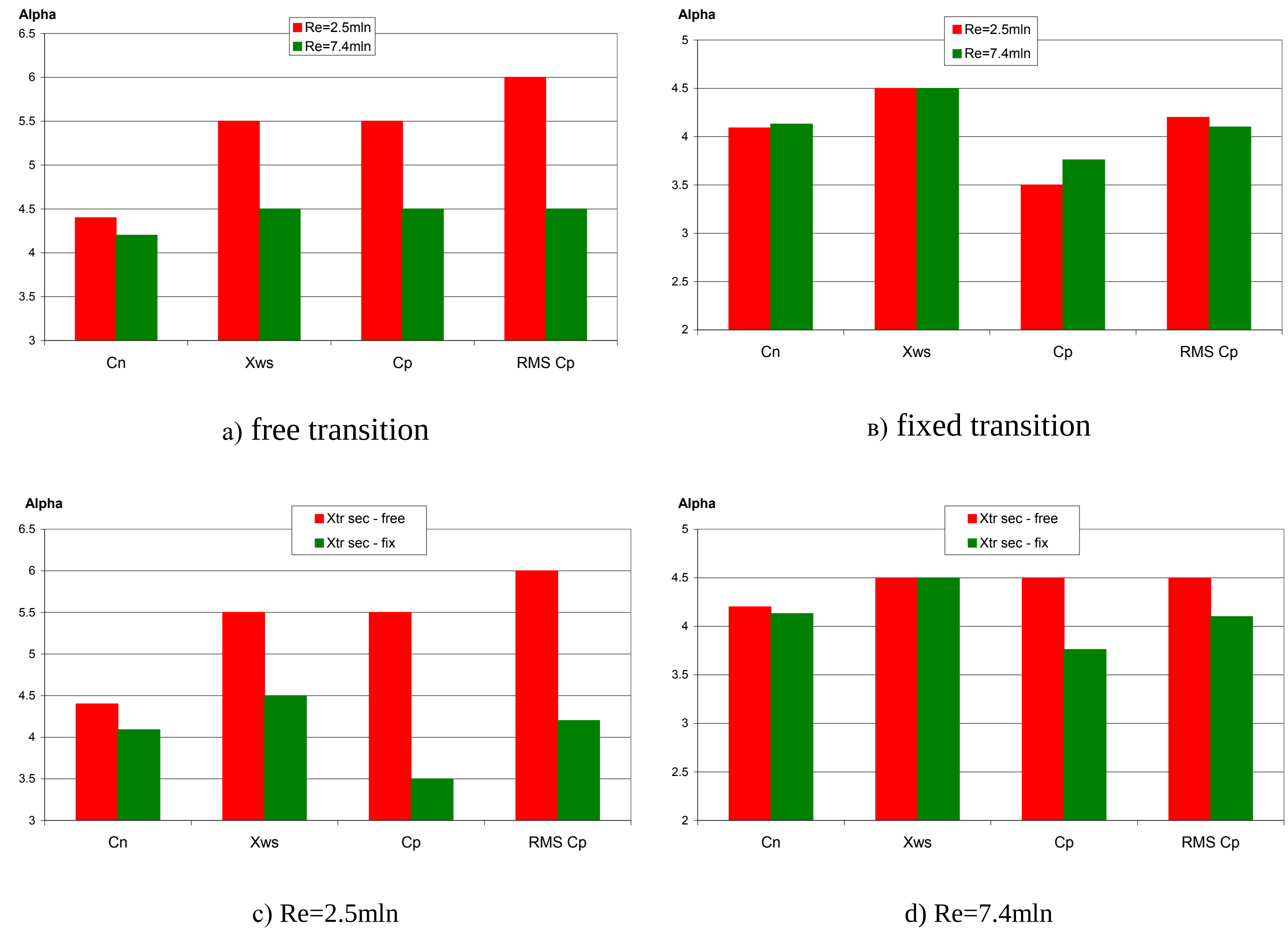
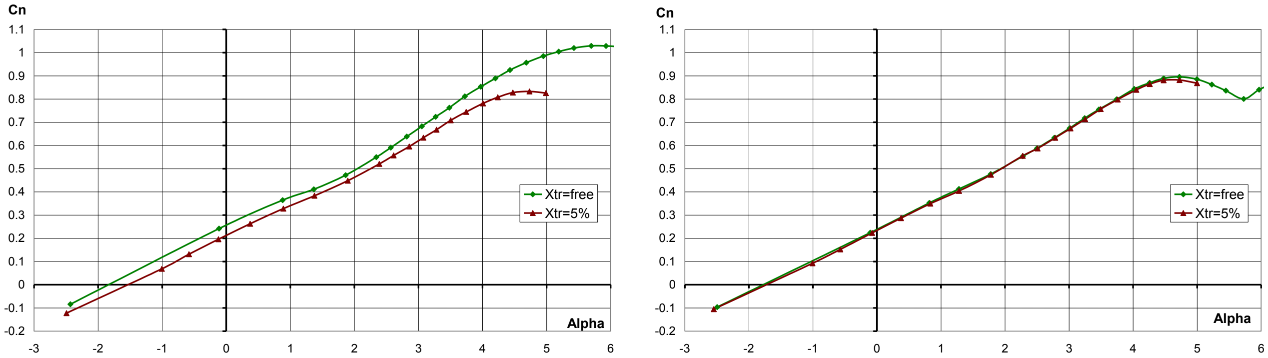


Figure 11: AoA when the flow separation develops, by different criteria

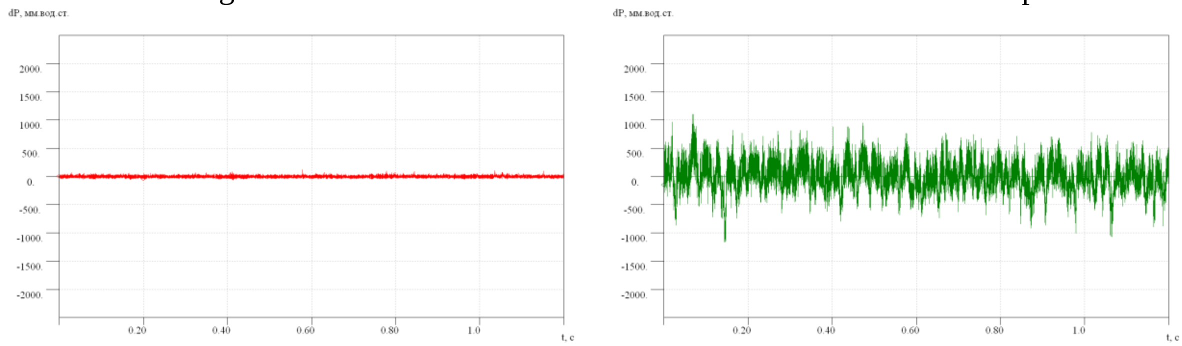
It can be seen that with Reynold's number growth there is a trend for characteristic AoA rapprochement, obtained on the model with the free and fixed transition.
It also demonstrates comparison of Cn (α) dependencies for the free and fixed transition (figure 12).



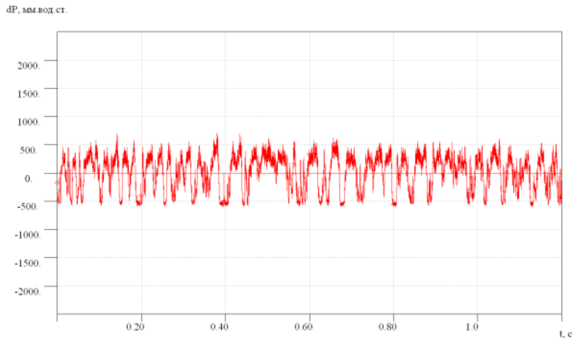
a) Re=2.5mln b) Re=7.4mln

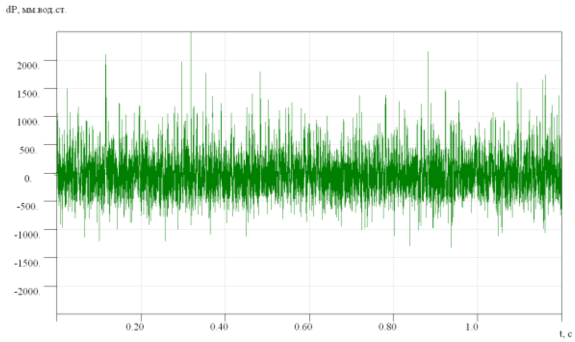
Figure 12: Influence of boundary layer transition at various Reynold's numbers on Cn(alpha) relation

Thus results of model tests with the free transition at Reynold's numbers (Re=2.5-3mln) which are typical for tests of the full models, give the uprated values of lift coefficient of the separation beginning. On the contrary, effects of model tests with front fixed transition show the underestimated values of lift coefficient of the flow separation beginning. Results of the model tests get accommodated the Reynold's number approximately reaching Re ≥ 7.4млн. To adequately evaluate the buffet onset, it is necessary to explore pressure oscillations in the characteristic points of section.
Influence of Reynold's number on pressure oscillations was examined on the model with the free transition. Figures 13 and 14 show changes of dP pressure oscillations with AoA growth in two characteristic points located at 50 % and 87 % of the chord. The first point is close to the shock position, second is near to the wing trailing edge, that is in the field of flow separation at high AoA. dP values of pressure oscillations themselves depend on parameters of the coming flow and are just an indirect sign of buffet development. However dP changes at AoA growing can serve as such a criterion for a particular model, especially in combination with other criteria. It can be seen that in both sections at X =87 % we have appreciable growth of pressure oscillations starting AoA α ≈5 °. A similar situation can be observed for X=50% point.



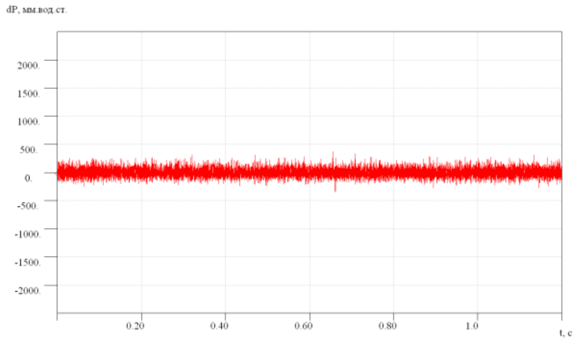
Re=2.5mln, Alpha=5° Re=7.4mln, Alpha=5°

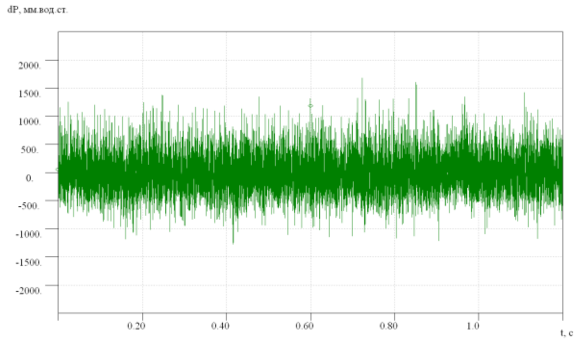




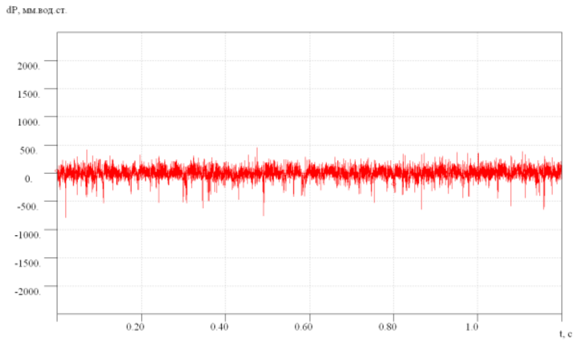
Re=2.5mln, Alpha=6°   Re=7.4mln, Alpha=6°

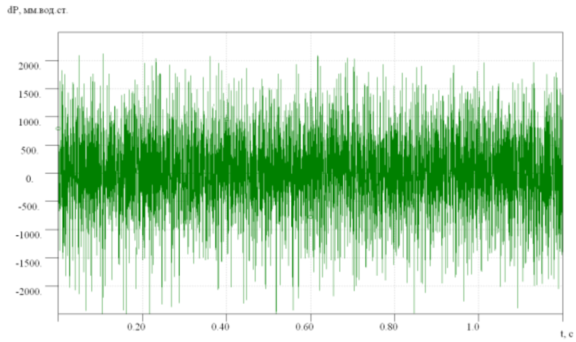
Figure 13: x=50%b





Re=2.5mln, Alpha=5°   Re=7.4mln, Alpha=5°





Re=2.5mln, Alpha=6°   Re=7.4mln, Alpha=5°

Figure 14: x=87%b

Starting from AoA α ≈5 °, dP values get practically a two-fold rise. Hence, the AoA of the buffet onset by pressure oscillations fast growth in sections can be adopted as equal α ≈5 °. The Reynold's number increase leads to appreciable increase of pressure oscillations. Accelerated growth of amplitudes of frequency spectra of pressure oscillations can also be a criterion of intensity of separation and, hence, criterion of the buffet onset. Data are given for the points located at 50 % and 87 % of the chord. These data show that amplification of nonstationarity of the model flow takes place starting AoA α ≈5 °. Hence, the buffet onset AoA by the criterion of high growth of amplitudes of pressures oscillations spectrum can be adopted equal α ≈5 °. Pressure oscillations spectra in the field of shock position are characterised by amplification of the low-frequency component caused by oscillations of shocks. Spectra of pressure oscillations close to the trailing edge have broad-band character. Reynold's number growth rise the amplitude of oscillations, however the spectra character does not change. At higher AoA under the influence of nonsteady aerodynamic loadings the buffet develops – that is oscillations of elastic configuration items of the aircraft. These oscillations were registered by means of acceleration sensors, located in check points of the test model. Location of acceleration sensors on the model wing is given in picture 2. As tests were conducted by means of a 'rigid' aerodynamic model of the aircraft, its elastic strains were insignificant. It allowed to reduce influence of elastic strains on effects of aerodynamic tests. Despite high stiffness and small structural deformations, its elastic oscillations were registered by indications of acceleration sensors. Picture 15 gives graphics of acceleration changes according to time, measured by accelerometers № 29, 30 and 31 at M=0.78 and Re ≈ 2.5 mln.

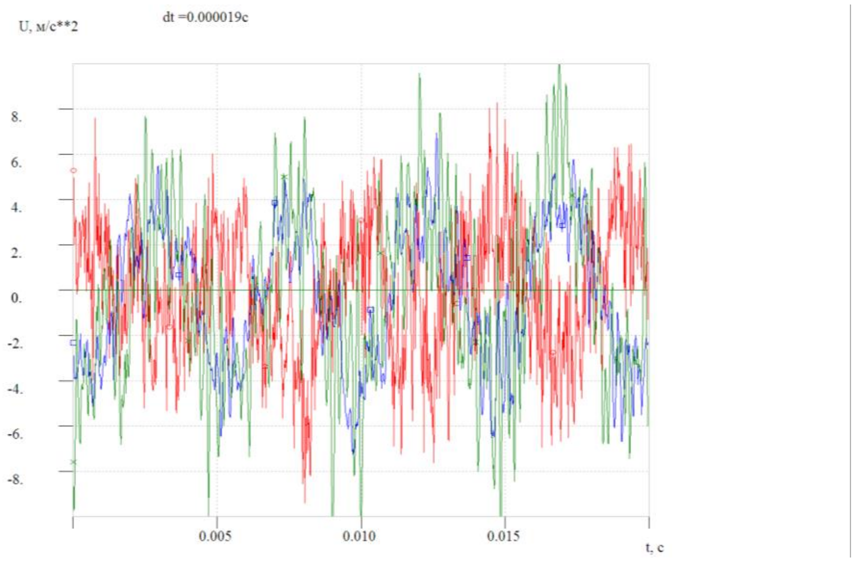


Figure 15: Acceleration of breakpoints of the wing model. Initial signal (M=0.78, Alpha=7.8°, blue – accelerometers №31, red – accelerometers №30, green - accelerometers №31)

Picture 16 shows smoothed according to time signals with easing of high-frequency harmonics.

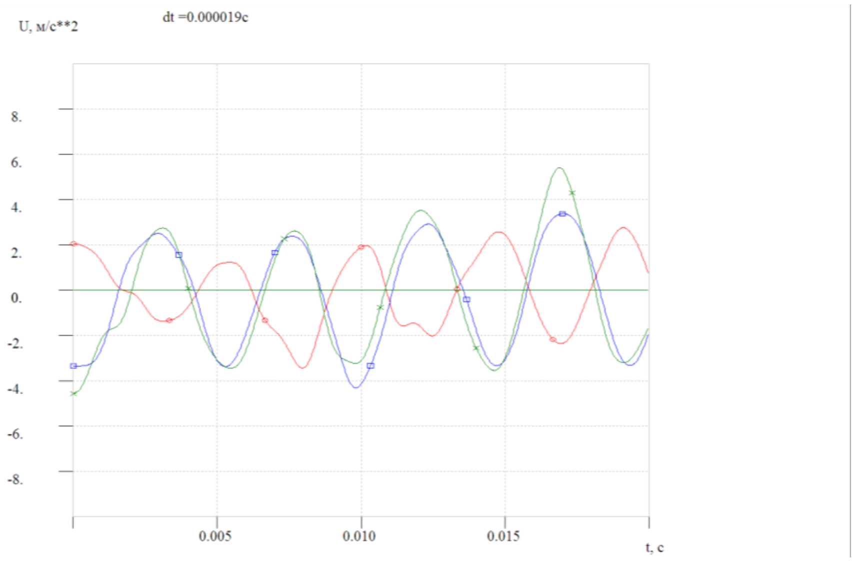


Figure 16: Acceleration of breakpoints of the wing model. A rounded signal (M=0.78, Alpha=7.8°, blue - line №31, red – line №30, green - line №31))

Pictures with acceleration graphics show that low-frequency twisting oscillations of the wing (accelerometers 29 and 30 data in an antiphase), on which high-frequency harmonics are superimposed, take place. Acceleration changes with AoA growth is shown in picture 17.

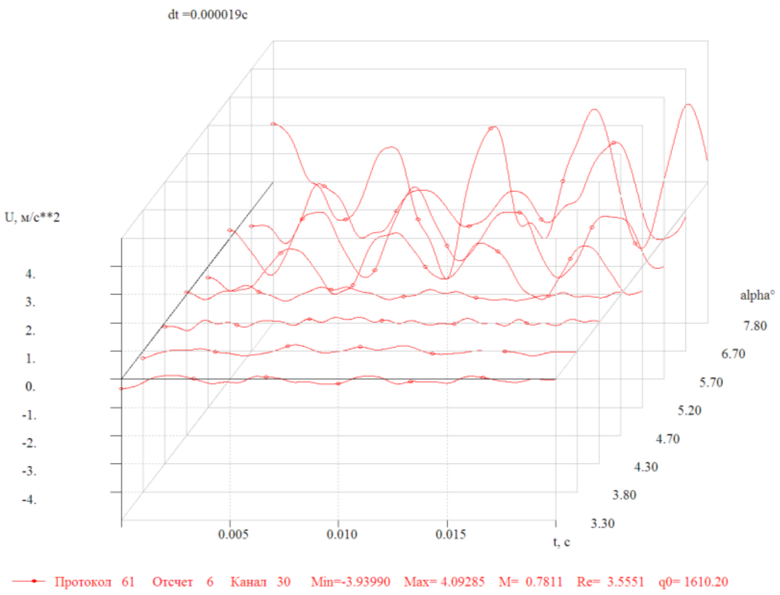


Figure 17: Changes of acceleration with AoA growth. accelerometers №30. A rounded signal (M=0.78)

Changes of amplitudes spectrums of the initial signal with AoA growth is shown in picture 18.

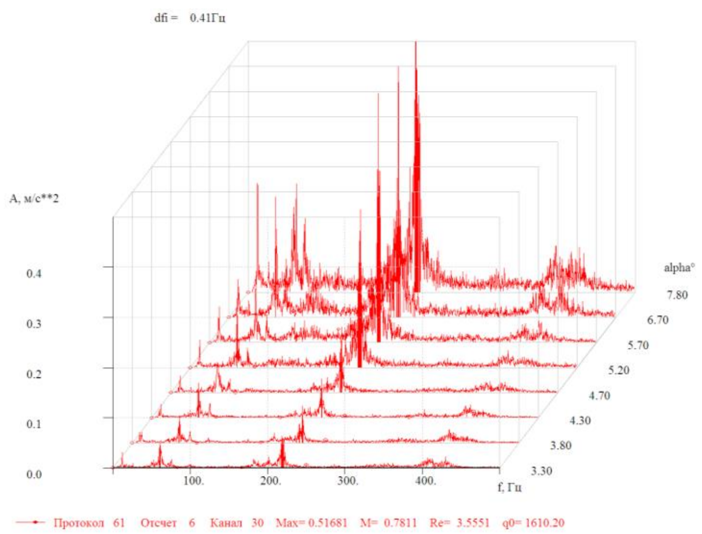


Figure 18: Change of acceleration amplitudes with AoA growth. Sensor №30 (M=0.78)

Picture 18 shows that the construction willingly responds to those harmonics of aerodynamic load which correspond to frequencies of the wing own oscillations. Influence of other harmonics of the load spectrum is less substantial. With AoA growth, amplitudes of dominating tones grow, while frequencies remain constant. Schemes show that starting from ~5 ° there is an accelerated growth of oscillation frequencies of the wind – the buffet develops. This estimate match the estimates of AoA of the buffet onset given above, obtained based on aerodynamic criteria. Thus, though aerodynamic criteria cannot be fully recognised to be the buffet objective criteria as they basically do not consider elastic-mass performances of the construction, nevertheless, in practice they can be used in the course of aerodynamic design, at stages when elastic-mass parameters of the aircraft are not determined yet.

5 CONCLUSION

The paper offers investigation of pressure and pressure oscillations distribution on the swept high aspect ratio wing at transonic flow regimes.
Investigation includes the response of the wing to aerodynamic loads oscillations.
It is shown that the elastic construction basically responds at the lowest tones of its own oscillations even in case of the broad-band spectrum of the effecting aerodynamic load.
Amplitudes of elastic oscillations of the construction increase with rising amplitudes of nonstationary aerodynamic loads when transiting to bigger AoA.
At identical values of Mach numbers and AoA the construction’s response is approximately proportional to impact air pressure.

6 REFERENCES

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