Investigation of viscosity influence on transonic flutter

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ABSRTACT

The paper is devoted to computational study of transonic flutter when the viscosity can influence significantly on dynamic aeroelasticity characteristics of aircraft. The work has been done in the direction of development of methodology and software, which are used in ARGON (TsAGI) system for multidisciplinary analysis and optimization in airplane design. Considerable attention is paid to the validation of the proposed software. Experimental results of the NASA Common Research Model in the European Transonic Wind Tunnel (ETW) are used for comparison with computations. The results of flutter analysis are presented for the passenger middle range airplane with the high aspect ratio wing and the engine under the wing. Comparisons of aeroelasticity characteristics in transonic flow are carried out for cases of a set of Mach and Reynolds numbers. The computational results presented in the paper show the essential influence of transonic features on flutter characteristics.

KEYWORDS: *flutter, aeroelasticity, viscosity, Reynolds number*

1 INTRODUCTION

Modern airplane represents an elastic structure that is exposed to unsteady aerodynamic loadings. The increase in speed of flight entails increase of all aerodynamic loadings on lifting surfaces of the airplane that in turn, causes growth of elastic deformations. In this case angles of attack of a wing appear distinct from angles of attack at a rigid wing. Due to change of angles of attack there is the redistribution of aerodynamic loads caused by deformations of the airplane structure. Thus, at high speeds of flight it is natural to expect not only usual direct influence of loading on deformations, but also return influence of deformations on loads values. This correlation of loads and deformations at increase of flight speed is the reason of beginning of rather dangerous phenomenon of dynamic aeroelasticity-flutter of a wing or of a horizontal/vertical tail.
The types of the airplane configurations developed for different purposes in many cases bring into specific problems of aeroelasticity and require a development of new technologies for aeroelasticity analysis. For example, the supersonic airplanes with small aspect ratio wings are very different from transonic aircraft with high aspect ratio wings and thin supercritical airfoils.
The measurements of derivatives of aerodynamic forces and moments on vibrating wings and lifting surfaces, which are necessary for dynamic analysis and flutter computation, show their significant dependence from a scaling effect at transonic speeds, in particular, from Mach (M) and Reynolds (Re) numbers [1-4].

Numerical determination of unsteady transonic flow is far difficult then the computation of subsonic or supersonic flows. Firstly, the basic equations in partial derivatives are nonlinear, and it is necessary to modeling of the moving shock waves. Secondly, flow field represents a mixed type with local supersonic regions. Dimensions of supersonic regions depend on time because of moving shocks waves, which should be determined with the enough accuracy as the part of a solution. In some cases the local supersonic regions compress up to zero and vanish together with shock wave during the period of flutter vibrations. Accordingly shock waves move on the wing surface changing in strength. These moving shock waves play important role in arising of nonlinear transonic flutter at Mach number near one. There are a set of mechanisms of interaction of an airplane elastic structure with unsteady transonic flow that cause the structure vibrations. It is worth mentioning that the supercritical transonic airfoils are optimized for providing high lift to drag ratio in cruise regime of flight. On the upper surface of such wings the flow has rather small gradients of speed, density and Mach number on the bigger part of the airfoil chord. Therefore comparably small deviations of flow parameters from optimized value may lead to an essential flow reconstruction. For example, small change of the angle of attack or Mach number can generate big displacement of shock waves and separation zones on chord. These changes considerably change a distribution of the aerodynamic loads.

Interaction of the shock wave with the boundary layer influences significantly on nature of the shock motion on the wing surface. It is important to take into account this phenomenon in dynamic aeroelasticity problems. The shock movement in viscous flow considerably differs from the movement in the flow of an ideal gas when the angle of attack increases. When an airplane model is tested in wind tunnel at low Reynolds numbers, the boundary layer on the most of the streamline surface is laminar, while in flight at high Reynolds numbers the boundary layer is turbulent. This difference influences on the boundary layer thickness and on the conditions at which the separation of the boundary layer occurs. If the boundary layer is turbulent, the separation typically does not occur near the trailing edge of the wing, but if the boundary layer is laminar separation may occur in the adverse pressure gradient in the tail part of the profile. This may result in essential influence of the scale effects. Therefore, experimental results obtained in wind tunnels on small models with laminar boundary layer must have careful usage versus the flight conditions in which the turbulent flow is dominating.

The systematic study of an influence of the Reynolds number (so-called scaling effect) began in the 1950-th, when aircraft began to appear high transonic flight speeds [1-3]. A special impetus to the research was given by publication, in which comparison of the wind tunnel tests and flight experiments of C-141 aircraft, conducted by NASA in 1966 was given. These results demonstrated large differences between the results of the wind tunnel and flight tests [4]. The wind tunnel test of the model were carried out for a fixed transition point, located in the front part of the airfoil, in accordance with the position of the point of transition to full-scale flight of the aircraft. However, the thickness of the boundary layer on the wing of the airplane in flight is considerably less than in wind tunnel test. The thinner boundary layer causes the shock wave downstream movement toward the trailing edge of the wing and the flow separation area reduction. The experimental results [4-7] have shown that the Reynolds number variation from the full-scale test values to values in the wind tunnel tests causes a significant change of the shock wave position and the size of the separation region of the boundary layer. During computational research of aeroelasticity and loads the effects of viscosity and boundary layer should be included in consideration in order to analyze such aeroelasticity phenomena as transonic flutter and limit cycle oscillations. The comprehensive testing and verification should be provided for the used computational methods of unsteady aerodynamics by comparison with experimental data in analysis of static and dynamic aeroelasticity phenomena.

An original BLWF (Boundary-Layer-Wing-Fuselage) method of steady and unsteady aerodynamic forces computation in transonic flow has been developed in TsAGI on a basis of a finite difference solution of the unsteady Euler equations with a viscosity model [8]. This approach has been intended for quick determination of transonic flow over complex aerodynamic configuration taking into consideration the viscous effects on the wings including thin separation zones. It is possible to use this method in steady aerodynamic analysis and design, to accompany a wind tunnel test, to determine aerodynamic derivatives in tasks of flight dynamics, aeroelasticity and aeroservoelasticity.

In the current paper, some aspects of integration of the developed BLWF method for aeroelasticity applications in the frame of multidisciplinary system ARGON [8-10] are considered. Validation studies are carried out, elasticity and viscous roles are estimated on the basis of the comparison of

computational and experimental aerodynamic characteristics of the wind tunnel (WT) model CRM NASA [11].
Aerodynamic and flutter analysis have been carried out for medium range airplane (MRA) with the use of the developed transonic aerodynamic method in dependence of flow viscosity.
Unsteady time-harmonic flow is determined by the solution of finite difference system of the unsteady Euler equations linearized in the relevant field of steady flow, and converted to a linear system for the complex amplitudes of the oscillations of the flow parameters. The spatial disturbed fluxes are calculated on the basis of Euler fluxes linearization in the assumption that the local entropy does not change. The resulting system is conservative and linear one. The prescribed harmonic oscillations of an airplane are simulated by the corresponding flow transpiration on the undisturbed surface. An additional transpiration models the boundary layer response to the flow disturbance.

2 DYNAMIC AEROELASTICITY PROBLEM SOLUTION

The study of aeroelasticity characteristics of airplane is started from the modal analysis and preliminary flutter analysis by using ARGON linear aerodynamics (DLM). A set of reduced frequencies is also obtained on the basis of linear flutter analysis.
Modal shape is determined by the displacements of four corners of each panel for the lifting surfaces (wing, horizontal tail, vertical tail), and by the displacements of the nodes of central line for bodies (fuselage, nacelle) as beam deformations.
Finite difference solution of linearized unsteady Euler equations is performed for each mode and each reduced frequency, then the complex amplitudes of flow parameter oscillations are determined. Obtained distribution of the pressure difference is transformed to the same grid in which modal shapes were specified in order to aeroelasticity analysis could be conducted with the use of the same methods and computational procedure as for linear aerodynamics.

2.1 NASA Common Research Model in ETW

NASA Common Research Model (CRM) [11-13] is a good test case for validation and investigation of an influence of both structural elasticity and viscosity on aircraft aerodynamic characteristics. Here the results of experimental research of the CRM in the European transonic Wind Tunnel (ETW) in 2014 [13] were used. The CRM test configuration, mounted in the ETW is shown in Fig.1. The CRM configuration includes fuselage, wing (without pylon and engine), and horizontal tail. The set of experimental points consists of cryogenic regimes in order to use a possibility of variation the Reynolds number in a wide range including Re values for cruise flight of the full-scale airplane.

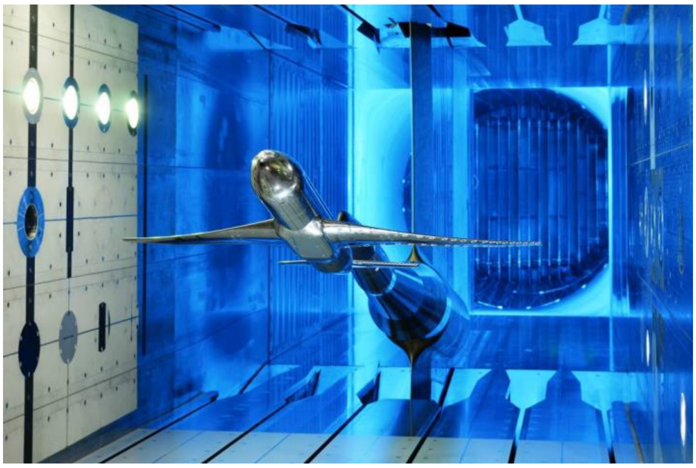


Figure 1: CRM model mounted in ETW

The developed computational model of the CRM for the BLWF solver is shown in Fig.2. The computational model consists of fuselage, wing and horizontal tail; the supporting device was not taken into consideration. Effectiveness of the developed approach and programs is provided by special procedures and additional tools some of them are listed below:

- conservative system of Euler equation is integrated by fast implicit method;

- 'Chimera' grid-embedding technique simplifies the problem of grid generation over complex configuration;
- second order finite volume cell centered Osher type flux difference scheme is used;
- effective Newton implicit solver based on approximate LU decomposition and GMRES algorithm provides very fast convergence;
- viscous wing wakes are calculated approximately by the two-dimensional Green's integral method;
- viscid-inviscid interaction including moderate separation regimes is determined by the quasi-simultaneous coupling scheme;

The calculation of steady flow is carried out within an iterative scheme viscous-inviscid interaction of the boundary layer theory. The calculation of the external inviscid flow is based on the finite difference Euler equations. Spatial grids for fuselage, nacelles and wing are generated automatically using algebraic techniques. The laminar and turbulent compressible three-dimensional boundary layers are computed by a finite difference time-marched method using a predictor-corrector scheme applied to the Keller formulation. The equilibrium algebraic turbulence model Cebesi-Smith is used. The boundary layer in the separated regions is determined by the inverse procedure. Jointing of the external and internal (in the boundary layer) solutions is made by viscous-inviscid iterations based on the quasi-simultaneous approach. The meaning of the approach consist in the fact that the calculation of the external inviscid flow is carried out taking into account the expected boundary layer response to the chordwise velocity variation and provides fast convergence of the process of viscous-inviscid iterations, including separation zones.
The computation time of the pressure distribution for each flow regime is approximately 2min (PC Core™ I5-2400 3.1 GHz) for the computational grids presented in Fig.2. Pressure distributions were mainly analyzed here, and also total aerodynamic forces of the complete configuration.

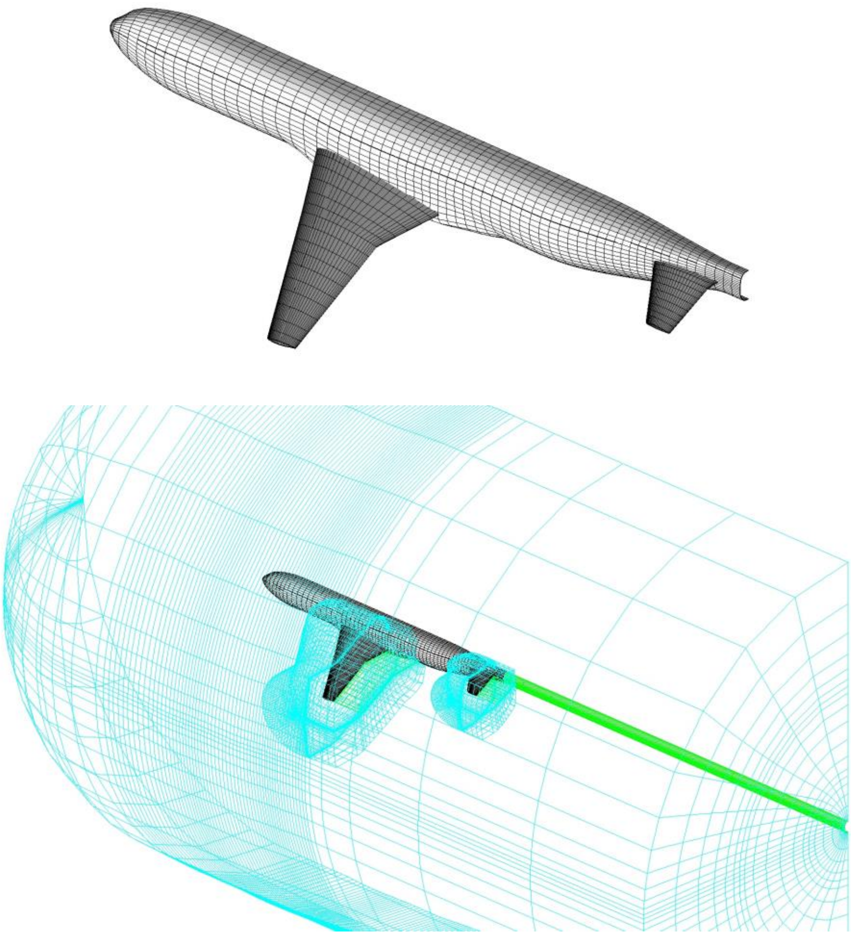


Figure 2: Aerodynamic model CRM and computational grids for the BLWF solver

For comparison analysis of experiment and computation two runs 182 and 227 have been chosen; the runs (also referred to as points) 182 and 227 are part of a larger set of simulations, their parameters are presented in Table 1.

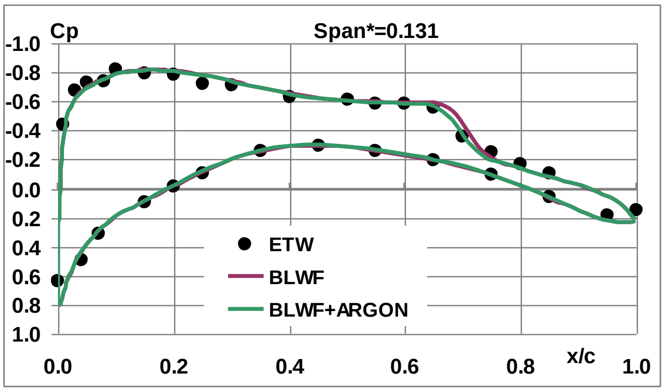
Table 1. Parameters of the two ETW runs

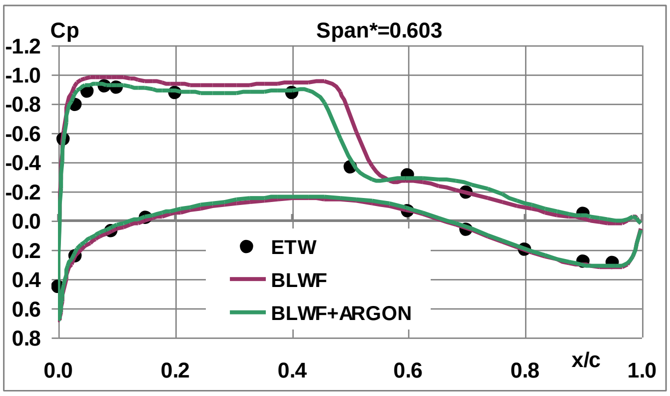
Point	Temp., K	Re, 10^6	M	Q, kPa
182	302	5	0.85	60.5
227	116	20	0.85	63.0

It is supposed that the regimes of these two runs have been chosen so that it will be possible to divide an influence of an elasticity and viscosity on aerodynamic characteristics. The two Mach numbers are equal, temperatures and dynamic pressures are chosen so that the Reynolds numbers are 5mln and 20mln; and relative flexibility of the structure are the same in these two runs. The last condition means that the difference in the dynamic pressure is in accordance with the change of the structural stiffness due to temperature, and ratio Q/E of the dynamic pressure Q to the Young's modulus E remains identical. For the considered CRM model, made of alloy VascoMax, ratio $Q/E=0.33{\cdot}10^{-6}$. If pressure distributions do not depend on the Reynolds number the elastic deformations will be the same for both regimes; for this reason, a difference of deformations characterizes an influence of viscosity.

2.2 Comparison of experimental and computational results

Numerical results of pressure distribution for rigid model (without taking into account elasticity) for the run 182 have agreed adequately with experimental data except for sections near the wing tip. For example, in Fig.3 the pressure distribution is shown for angle of attack $\alpha=3°$ (BLWF); typical transonic pressure distribution can be seen.





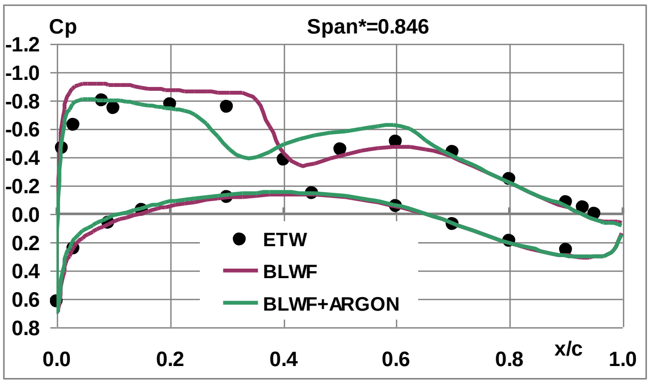


Figure 3: Pressure distribution in the wing sections, M=0.85, α=3°, q=60.5 kPa, Re=5 mln (run 182)

Joint iteration's solution of the coupled aerodynamic-aeroelasticity problem in most cases improves essentially the agreement between numerical and experimental results (Fig.3, BLWF+ARGON). Elasticity influence results in some reduction of the Cp on the wing upper surface and forward shift of the shock wave position due to decrease of the angle of attack. The lift coefficient C_L has decreased due to structural elasticity on 8% for α=3° (Fig.4).

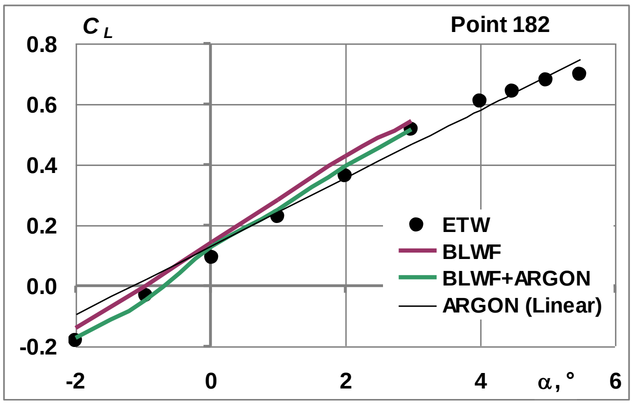


Figure 4: Comparison between computed and experimental dependence of lift coefficient on angle of attack

3 INVESTIGATION OF FLOW VISCOSITY INFLUENCE ON AERODYNAMIC CHARACTERISTICS OF MEDIUM RANGE AIRPLANE

Computation results of a viscosity influence on aeroelasticity characteristics have been obtained for the medium range passenger airplane (MRA) with transonic cruise speed at Mach number M=0.82. The airplane of traditional configuration with high aspect ratio wing AR=12.5, and two engines on pylons under the wing has been considered. The supercritical airfoils with thickness 15.8% in the wing root, 11% in the kink and 9% on the wing tip are applied.

Computation scheme of the MRA, developed for the BLWF solver, is presented in Fig.5.

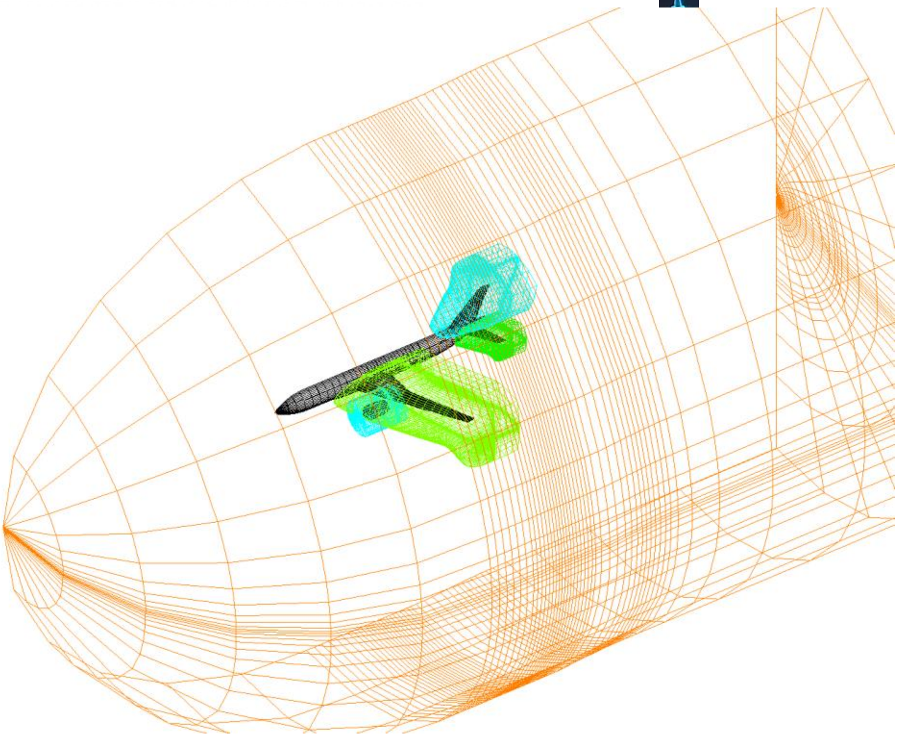


Figure 5: Computation grids for the BLWF solver

Preliminary computations of the aeroelasticity characteristics with linear aerodynamics have shown that they are in ordinary limits. Two flutter forms have been revealed in symmetrical motion. The first form with frequency about 4Hz is connected with interaction of the wing bending, the engine pitch vibrations and the wing tip twist. The dynamic pressure margins of this form are on the limit. The second flutter form with frequency about 6Hz is connected with the bend and twist of the wing tip; in this case the dynamic pressure margins are high. The main interest represents the first flutter form, and dependence of its characteristics on flow parameters and the airplane motion.
Parametrical studies of aerodynamic characteristics have shown that the pressure distribution and shock waves strength depend essentially on flow regime, and namely on Reynolds number (Fig.6). It can be seen that the shock wave has moved on about 4%-7% of the chord.

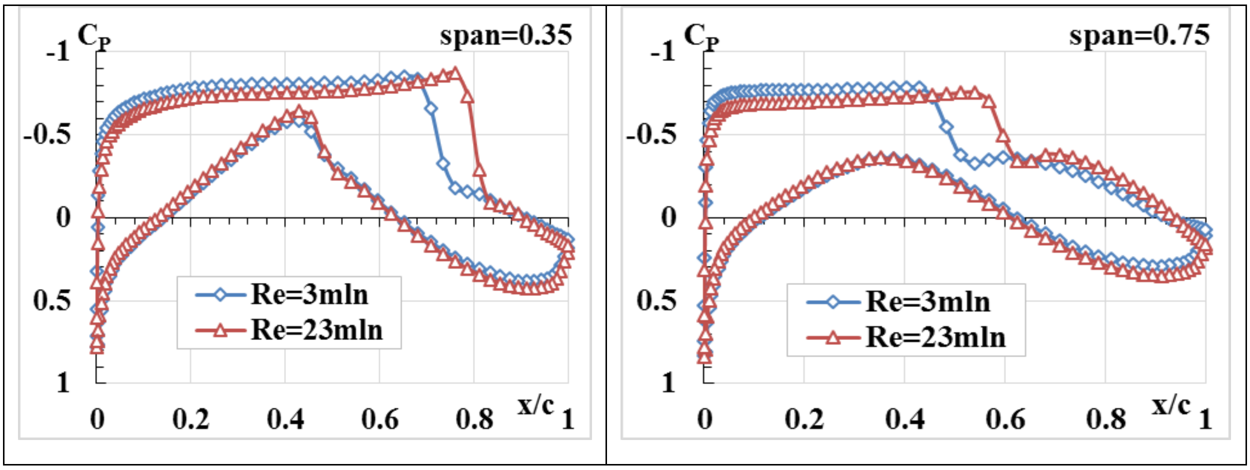


Figure 6: Comparison of pressure distributions for two flow regimes: CL =0.5, Re=3mln and Re=23mln, M=0.84

The main peculiarities of the total transonic aerodynamic characteristics of the MRA with viscosity taking into consideration in comparison to linear aerodynamics are shown in Fig.7, 8. The lift coefficient is higher considerably near cruise regime and decreases abruptly at Mach number increase above 0.85. Aerodynamic center position X_F^α moves essentially to the trailing edge.

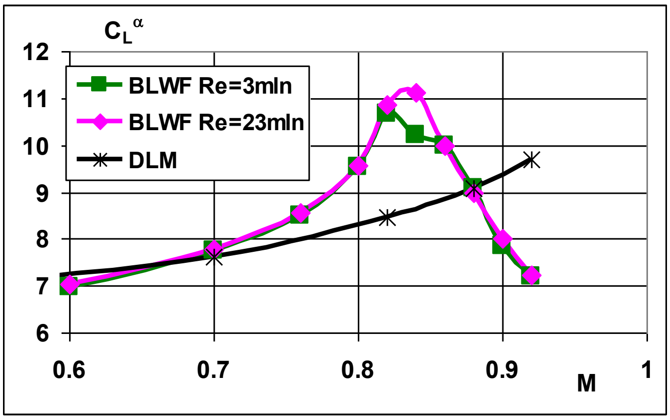


Figure 7: Influence of viscosity on lift coefficient for different Mach number, CL=0.5

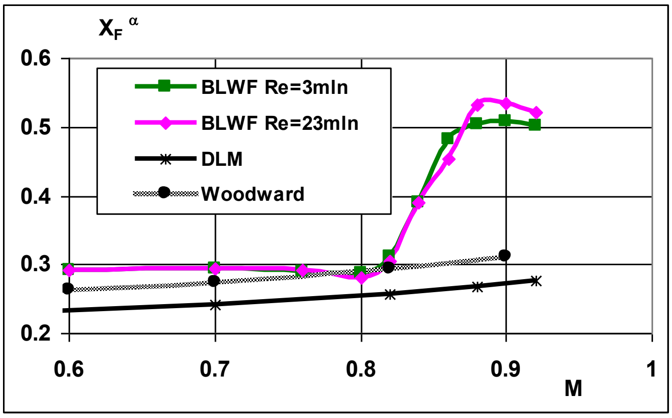


Figure 8: Comparison of the aerodynamic focus X_F^α position computed with the use of linear aerodynamic theory and the BLWF solver (with viscosity), CL=0.5

The most essential influence of viscosity on total aerodynamic characteristics is in transonic range of the Mach number from 0.8 up to 0.86 (Fig.7, 8). In the cruse regime M=0.82 the change of C_L^α due to viscosity achieves about 6%-8% (Fig.9) and 9%-13% for M=0.84. It is worth mentioning that increase of the wing lifting properties C_L^α in the case of viscosity decrease; usually result in decrease of flutter speed.

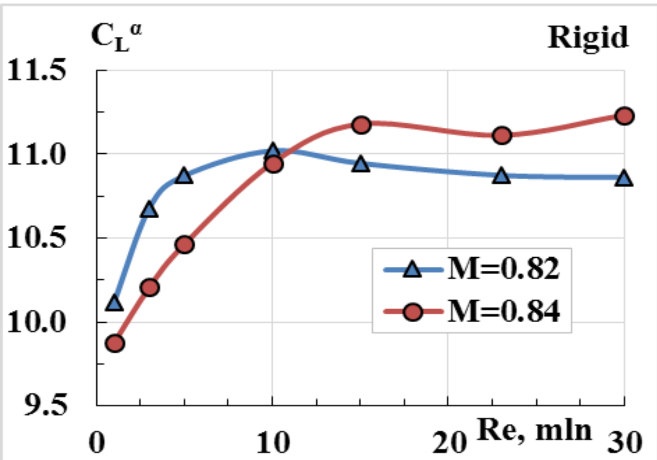


Figure 9: Influence of viscosity on lift coefficient for two Mach numbers

4 FLUTTER ANALYSIS

Viscosity influence on dynamic pressure of the lowest flutter form in dependence on Mach number is shown in Fig.10. The first regime (Re=3mln) is typical for a test of aeroelastic model in wind tunnel, the second (Re=23mln) for cruse flight. It can be seen that for the full-scale aircraft flight the dynamic pressure is lower on 8-10% than in the case of wing tunnel test.

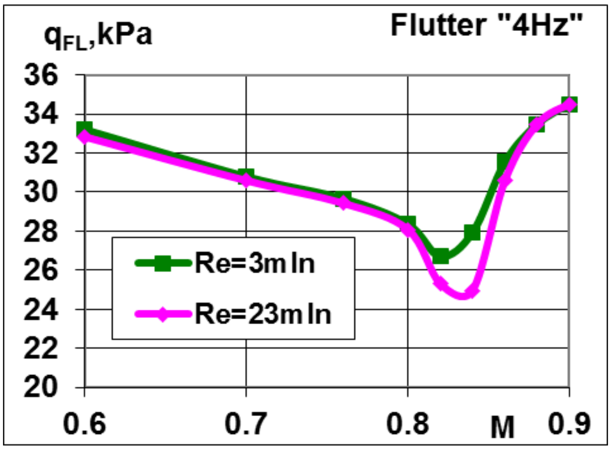


Figure 10: Influence of viscosity (Re number) on flutter dynamic pressure, CL=0.5

The influence of viscosity on flutter dynamic pressure and frequency is presented for wide range of Reynolds number in Fig.11, 12. It can be seen from the presented computational results that the changes of Re number in range above 10-15mln almost do not influence the flutter characteristics.

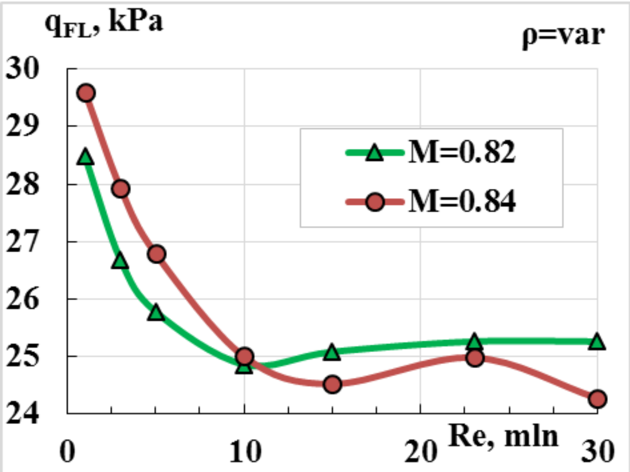


Figure 11: Influence of viscosity (Re number) on flutter dynamic pressure, CL=0.5

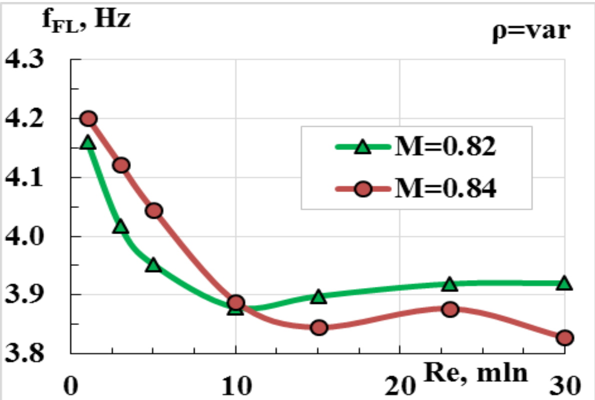


Figure 12: Influence of viscosity (Re number) on flutter frequency, CL=0.5

CONCLUSIONS

The paper describes the integration of the BLWF solver used for the computation of aerodynamic forces based on the Euler equations with viscosity in the ARGON multidisciplinary software for the analysis of dynamic aeroelasticity characteristics in transonic flow. Validation of the developed software is performed on the basis of comparison of the computed and experimental aerodynamic characteristics of the WT model CRM NASA:

– Numerical results of pressure distribution for rigid model (without taking into account elasticity) agreed adequately with experimental data except from some sections near the wing tip.
– Joint iteration's solution of the coupled aerodynamic-aeroelasticity problem improved essentially the agreement between numerical and experimental results. Elasticity influence results in a reduction of the pressure distribution C_p on an upper surface of the wing and a forward shift of the shock wave position due to decrease of the angle of attack. The lift coefficient C_L has decreased due to structural elasticity on 8% for angle of attack α=3°.

Computation results of aeroelasticity characteristics have been obtained for the medium range passenger airplane for transonic cruise regime. The influence of viscosity on flutter dynamic pressure and frequency is shown for wide range of Reynolds number.

The efficiency of the developed method for investigation of viscosity influence on flutter in transonic flow with reasonable accuracy is demonstrated. However, further unsteady validation test cases are required for a final assessment of availability of the new developed software for solving transonic aeroelasticity problems.

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