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Some aspects of transonic flutter of aircraft with laminar wings

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Abstract
The work is devoted to investigation of aircraft aeroelasticity characteristics in transonic flow in a presence of transition from laminar to turbulent boundary layer. In the paper a method developed for numerical study of aeroelasticity of laminar wings, based on joint application of software codes BLFW and ARGON (TsAGI) is presented. Computational results are compared with experimental data of the TWG test of a model with laminar supercritical airfoil CAST10-2. The results of flutter analysis of modern transport aircraft are discussed. The variant of a wing with a swept angle of 20 degrees and supercritical airfoils is considered.

1. Introduction

Promising technologies for the near future include the design of laminar wings, with research aimed at creating a laminar boundary layer on the most extended area of the wing surface by shifting the transition point from the laminar to the turbulent state to the trailing edge of the wing. It is known that the change in flight conditions leads to displacement of shock waves and change in the position of the transition point/line. In a free transition there is a nonlinear dependence of the lift on the angle of attack. In this case, the derivatives of aerodynamic forces are changed with the parameters of flow, which in turn can lead to a change in the characteristics of aeroelasticity. Therefore, the study of the flutter characteristics of such laminar wings requires special consideration.
Laminarization is currently one of the most promising technologies in aerodynamic design, which will provide a significant reduction in fuel consumption. Despite the rather long development of this technology [1-3], it is still waiting for active implementation in the design of the aircraft. Today, laminar airfoils are widely used in the structures of gliders, unmanned flying vehicles and light aircraft. Laminarization can be achieved passively (naturally laminar flow) at an average sweep angle and with the use of laminar wing airfoils with a maximum thickness near the trailing edge. Active laminarization methods include boundary layer suction systems or a combination of both technologies (hybrid laminar flow control). In any case, on the wings of aircraft there is a transition of laminar boundary layer in turbulent. In contrast to conventional turbulent airfoils, laminar airfoils exhibit laminar bucket in the polar because the flow can remain laminar only at small angles of attack. In this case, there is a nonlinear dependence of the lift on the angle of attack, which is associated with different thickness of displacement of the laminar and turbulent boundary layer.
Almost all applications of laminar flow technology put into operation so far are limited to straight wings flying at low Reynolds and Mach numbers. The situation is complicated for transonic swept wings. To prevent early transition a sweep of the leading edge of the wing should be no higher than 18-20 degrees. It is supposed that because of this limitation the cruise Mach number reduction to about 0.75 will be inevitable [4-7]. However, such a small cruise speed does not meet the modern requirements of air transportation, served by high-speed (M=0.78-0.8) regional and short-and medium-range aircraft type A-320 and B-737. To achieve the necessary cruise speed at a small sweep angle of the leading edge DLR, for example, proposed to use forward swept wings [7], but their features lead to other significant problems that outweigh its advantages.

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2. Computational method for aeroelastic analysis of laminar wing

In the paper the numerical method for aeroelasticity analysis of laminar wings is presented. The method is based on joint application of the BLFW and ARGON (TsAGI) programs. The BLFW program is developed for the computation of aerodynamic forces in transonic flow with taking into consideration viscosity. An iterative procedure is used to obtain the transition line. Determination of the aeroelasticity characteristics is carried out using the multidisciplinary software package ARGON.
TsAGI has been researching various aspects of laminarization for many years, and in recent years these studies have obtained new impact. The airplanes with NLF considered in TsAGI have wings with a small sweep of the leading edge, but can reach high Mach numbers of about M = 0.78 due to the use of advanced supercritical airfoils along the span. A special multi-criteria procedure for optimization the aerodynamic design of laminar wings was created [5, 7]. When designing such wings, it is necessary to take into account the need for a compromise between the laminar and turbulent flow regime, between the values of viscous and wave drag at subsonic speeds, as well as between the characteristics of natural laminarization (small radius of curvature of the leading edge) and a high lift coefficient. The natural laminar flow around the wings of small sweep was developed for advanced regional and short-range aircraft without reducing the cruise Mach number characteristic of advanced aircraft.
The key to the success of the aerodynamic design process is a fast direct method for computation of the transonic flow– the BLWF code [5] program created in TsAGI. This program is developed for prompt comprehensive analysis of transonic flow of the wing-fuselage combination and actually more complex configurations based on the iterative procedure of computation the strong viscous-inviscid interaction of the external potential flow and the boundary layer on the lifting surfaces of the airplane. The solution to the problem of transonic flow around the complex airplane is provided in a matter of seconds on a modern personal computer. Due to the low cost of CPU time, as well as the built-in automatic grid generation procedure, the BLWF code is widely used in the world's aviation centers for aerodynamic design. TsAGI also developed and applied an original method for computing the unsteady aerodynamic forces in transonic flow, based on the Euler equations taking into account the viscosity [13]. This approach is developed for fast calculation of both stationary and non-stationary (time-harmonic) flow and evaluation of aerodynamic characteristics of multi-element configurations. The method is used for computations in problems of aerodynamic analysis, for support of a wind tunnel experiment, for determination of aerodynamic derivatives in problems of flight dynamics, aeroelasticity and aeroservoelasticity. The computation of the external inviscid steady-state flow is carried out by numerically integration of the conservative form of the finite-difference analogue of the Euler equation system (version BLWF100 code), based on a fast implicit algorithm using the technique of intersecting computational grids (the so-called Chimera approach). The use of the technique of intersecting computational grids basically removes the traditional problem of generating a single computational grid near a complex configuration. Creation of simpler intersecting computational grids near the elements of the airplane structure is carried out automatically by the program. Calculation of unsteady time-harmonically perturbed flow is performed by BLWF120 code. In the framework of the linear approach, small perturbations of the flow with respect to a certain known stationary regime are described by an unsteady linear system, which can be obtained by the linearization of the equations of motion on a known stationary solution.
Initially, only a fixed transition regime was available in the BLWF code for computations. Several attempts have been done to include the possibility of predicting the transition, for example, based on the semi-empirical eN method. The use of a simple two-dimensional empirical Granville criterion was found to be adequate for a wing with a small sweep [14]. The position of the transition line on the small sweep wing that was calculated using this criterion, is in satisfactory agreement with the experimental data obtained on the base of the liquid crystal imaging technique [14]. The initial wing pressure distribution is obtained for the originally specified transition point. The position of the new transition line is determined based on the analysis of a number of pressure distributions along the wingspan, then the following computation of the pressure distribution and the new position of the transition line is performed, and so on until convergence.

3. Computational results

When developing new computational methods, it is necessary constantly to test them. The best approach for validation is to compare the computational experiment data with the wind tunnel experiment. This paper describes an example of such data comparison.

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3.1 CAST model

The comparison of numerical results with experiments in the wind tunnel TWG, Goettingen, of a two-dimensional model with laminar airfoil CAST10-2 was carried out for several transonic regimes at different Mach and Reynolds numbers [9-12]. Schematic picture of the CAST model is shown in fig.1.

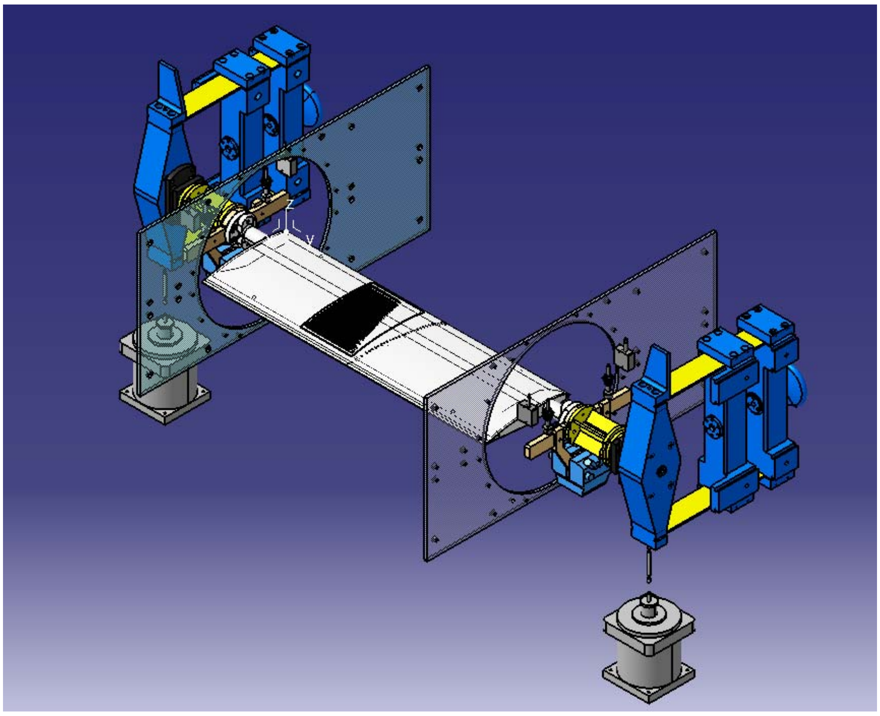

Figure 1: Two-dimensional CAST model in transonic WT TWG [11].

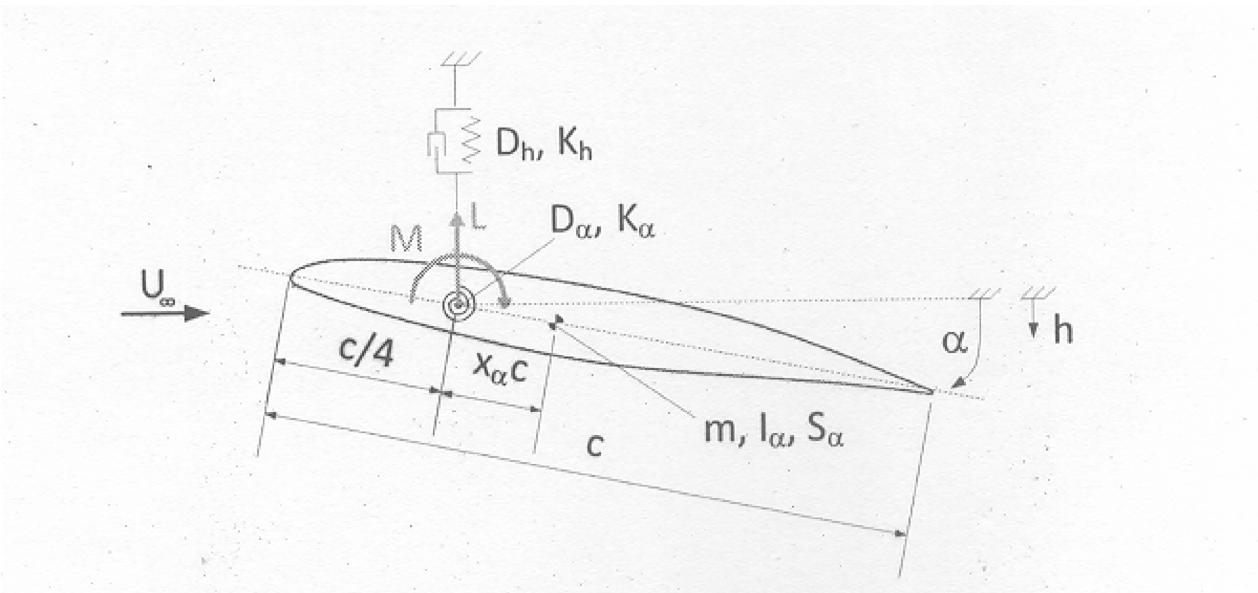

Figure 2: Computational CAST model for flutter analysis from [11].

Description of the CAST model, some details of its installation in WT, flow parameters and experimental results are presented in [6, 9-11].

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Some basic parameters of the model and flow are:

- Mach Number 0.5 <M< 0.85
- Static pressure in ADT 40 kPa <Ps< 90 kPa
- Reynolds number 1mln < Re < 3.5mln
- Wingspan 1m
- Chord c=0.3 m.

Figure 2 shows computational CAST model for flutter analysis used in [11]. Two types of research were carried out in TWG:

– Free transition of the boundary layer,
– Fixed transition (Re = 2mln) at a given position of the transition point Xt = 0.075.

3.2 Aerodynamic analysis of the CAST model

In process of computation the following aerodynamic and aeroelasticity characteristics were obtained: the pressure distribution on the model at a fixed and free transition from laminar to turbulent state, the dependence of the lift on the position of the transition point at different Mach and Reynolds numbers. Flutter analysis of the elastic wind tunnel CAST model with a laminar wing was carried out.
In the case of a fixed transition with the use of the BLWF code the position of the transition point was set at the leading edge of the straight wing Xt =0.01. The influence of the Reynolds number on the lift coefficient for the Mach number M=0.75 is shown in Fig. 3. It can be seen that with an increase of the Reynolds number, the value of the lift increases. At a given transition point located on the leading edge of the wing, the linear dependence of the lift on the angle of attack (AoA, deg) is obtained (Fig. 3).

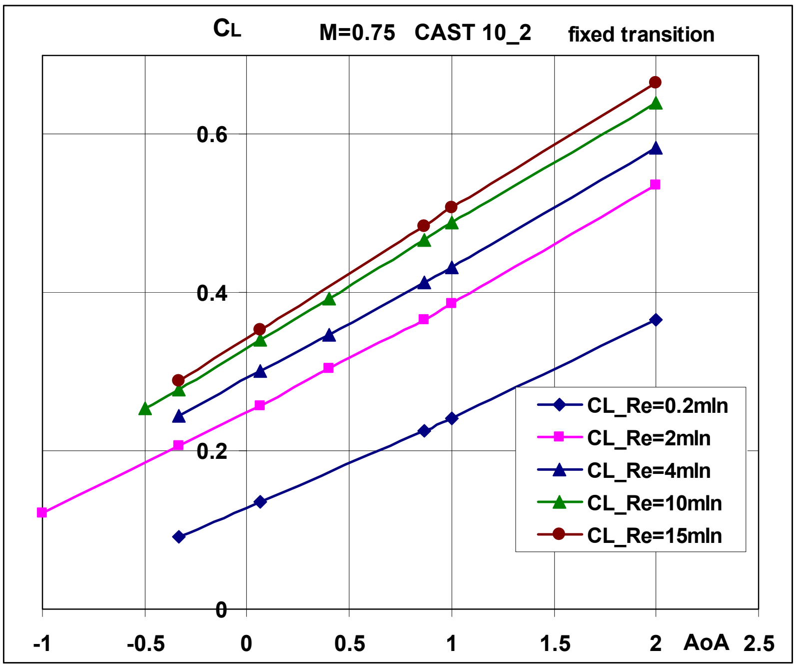

Figure 3: Results of the BLWF program computation. CAST model. Fixed point of transition. Effect of Reynolds number on lift coefficient at M=0.75.

Experimental data (Fig.4) and computational results (Fig. 5) are presented for comparative analysis. For example, figure 4 shows pictures taken from [9]. The dependence of the lift coefficient on the angle of attack (a) and polar (b) at M=0.75 measured in WT TWG for a fixed and free transition is shown.

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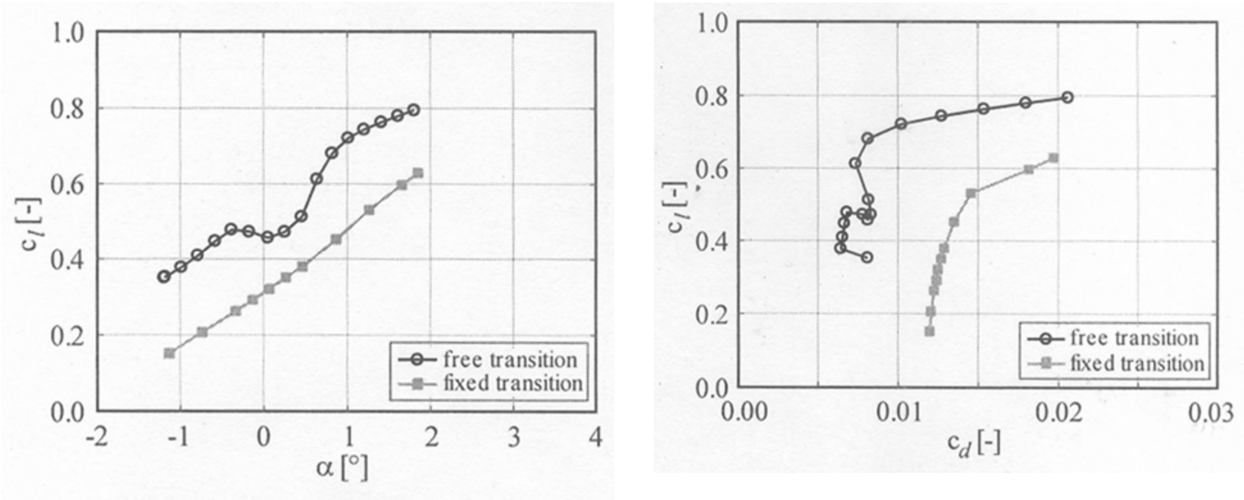

Figure 4: Experimental results from [9]. Lift curve (a) and drag polar (b) for M=0.75 at fixed and free transition.

In Figure 5 the computational results are presented. The position of the transition point from the laminar to turbulent state in the case of a free transition in the BLWF program is determined by an iterative procedure. The qualitative agreement of computational and experimental results is obtained.

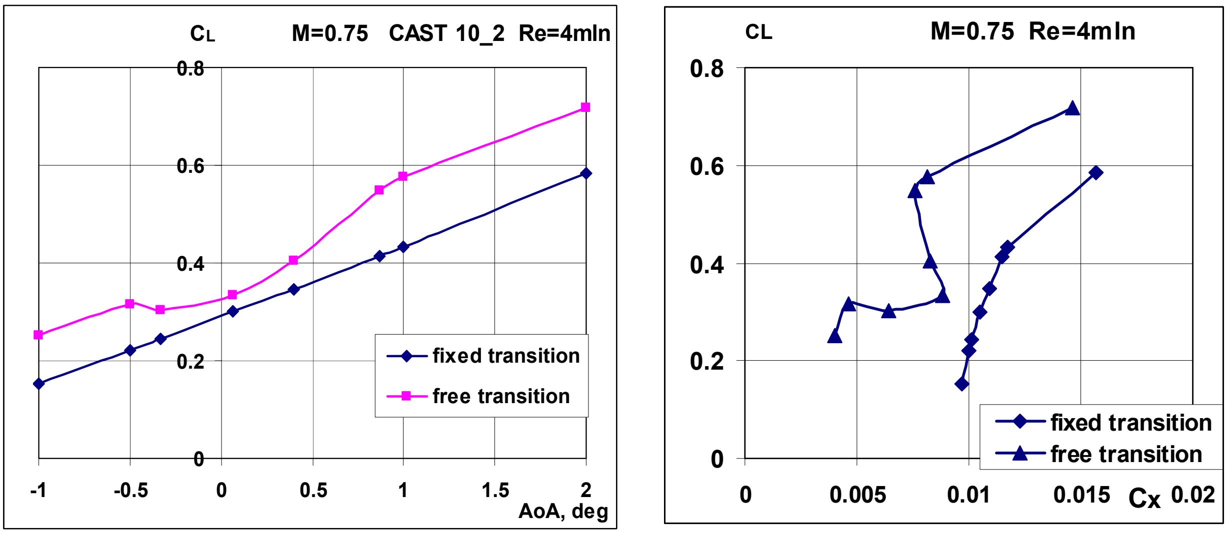

Figure 5: Computational results of the BLWF solver. Dependence of lift coefficient on angle of attack (a) and drag polar (b) at M=0.75 for fixed and free transition.

The computation of the pressure distribution for fixed and free transition from the laminar to turbulent state is performed for various Mach and Reynolds numbers, and lift coefficient. The angles of attack are determined at the same time from the condition of compliance with a given lift coefficient. For example, the results of computations of pressure distribution at Mach number M=0.75 are presented in Figure 6 for fixed and free transition: a) Re=4mln, CL=0.48, b) Re=2mln, CL=0.42.

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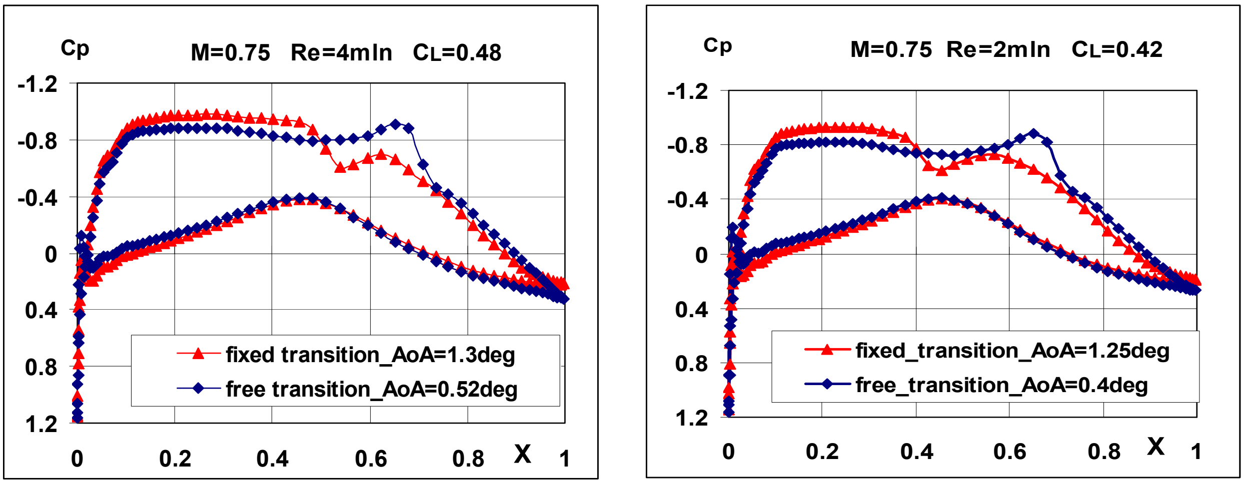

a) b)

Figure 6: Pressure distribution at Mach number M=0.75 for fixed and free transition for two different flow regime:
a) Re=4mln, CL=0.48, b) Re=2mln, CL=0.42.

Numerical research of the influence of the transition point $\mathbf{x_t}$ on the pressure distribution of the CAST model was performed. It can be seen that the lift value depends significantly on the length of the laminar boundary layer. Figure 7 shows computational results for the following flow parameters: M=0.79, Re=4 mln, angle of attack AoA=0.

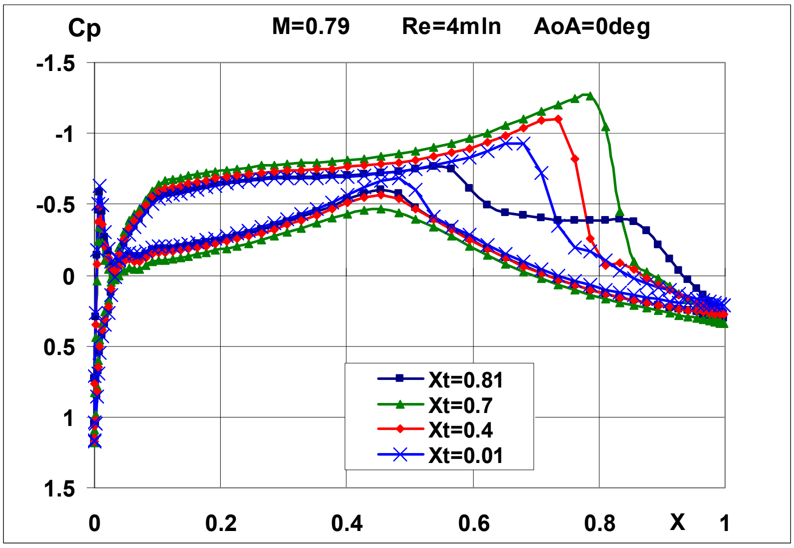

Figure 7: Influence of transition point xt on the pressure distribution of the wing CAST. M=0.79, Re=4mln, angle of attack AoA=0.

3.3 Validation study

The comparison of the numerical results with experiments in the wind tunnel TWG of the CAST model was carried out for several regimes: 0.5 <M< 0.85, 1mln< Re <3.5 mln. The results of the comparison of the pressure distributions for a fixed and free transition from a laminar to a turbulent state are presented in figures 8 and 9. The computational results were obtained with the use of BLWF solver. The dependence of the pressure distribution on the transition point is shown. It can be seen that the agreement between the compared results is good.

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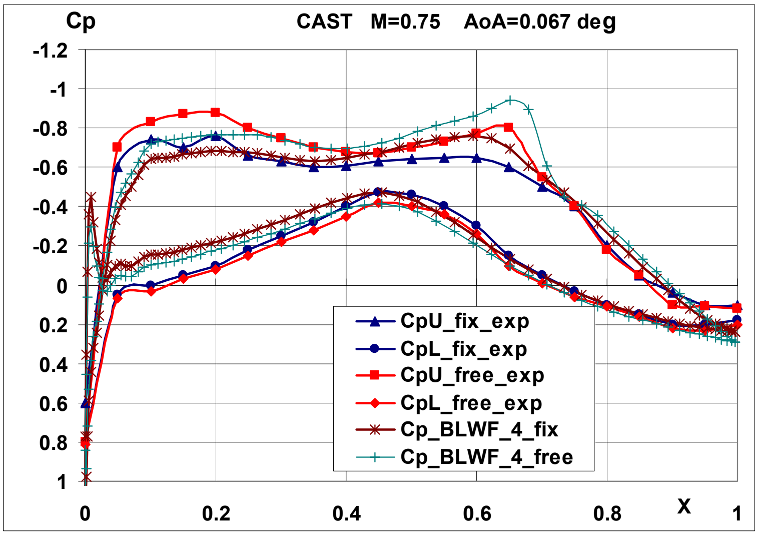

Figure 8: Pressure distribution on the CAST 10-2 airfoil for free and fixed transition. Comparison of analysis and experiment [6, 9-11].

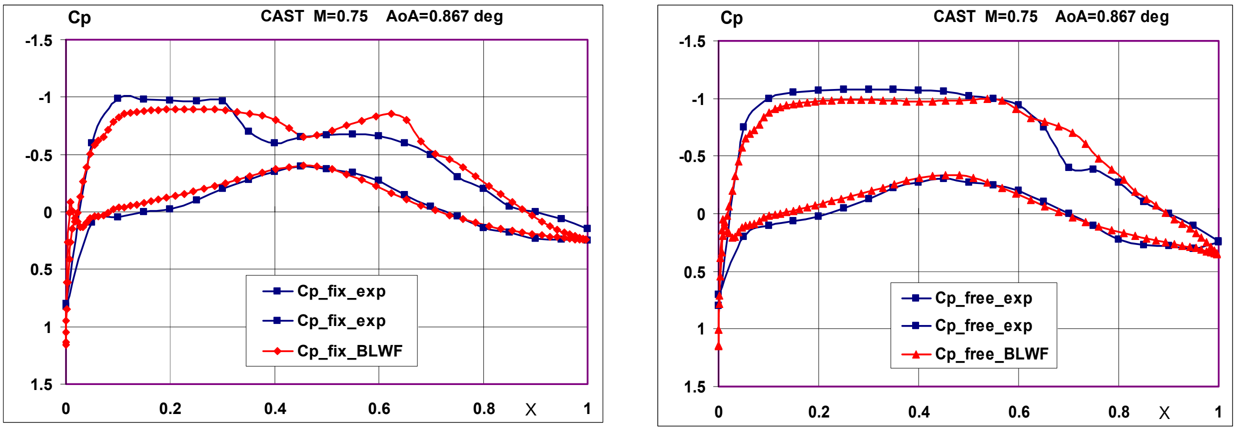

Figure 9: Comparison of pressure distribution on the CAST 10-2 airfoil for free and fixed transition. Results of analysis and experiment [6, 9-11].

3.4 Flutter analysis

The study of aeroelasticity characteristics of the CAST model begins with a modal analysis and preliminary calculation of flutter by the ARGON program using linear aerodynamics doublet lattice method (DLM). On the basis of linear calculation, a set of reduce frequencies (Sh numbers) is also determined, which allows us to represent with sufficient accuracy the derivatives of unsteady aerodynamic forces in the wide range of frequencies and velocities of interest.

Modal shape is determined by the displacements of four corners of each panel for the lifting surfaces, and by the displacements of the nodes of central line for bodies 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 performed with the use of the same methods and computational procedure as for linear aerodynamics DLM.

The flutter analysis of the CAST model was carried out based on a simple two-degree-of-freedom system shown in Fig.2 and on the structural model given in [11-12]. The torsion flutter form with the frequency of 39 Hz was

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obtained. The position of the transition point was determined by preliminary calculations of aerodynamic coefficients for the set of Mach and Reynolds numbers.
For example, the effect of boundary layer transition on flutter dynamic pressure in the transonic range of the Mach numbers is shown in figure 10 for Reynolds number Re=4mln.

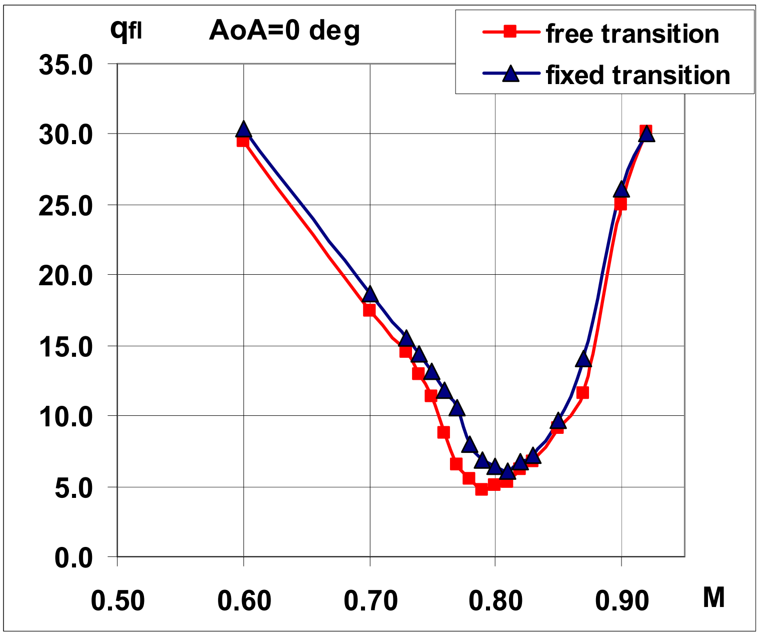

Figure 10: Dependence of flutter dynamic pressure on Mach numbers for two flow regimes.

The first regime (fixed transition) corresponds to a flow with a fully turbulent boundary layer when the transition point is located on the leading edge of the wing. The second regime (free transition) is typical for supercritical laminar airfoils, when the transition point from a laminar boundary layer to turbulent is on the upper surface of the wing near the shock wave. It can be seen that in the flow regime corresponding to the free transition of the boundary layer, the flutter dynamic pressure is lower on 10-15% of the value corresponding to the flow conditions of the completely turbulent boundary layer. In this case, the minimum flutter dynamic pressure in the flow with free transition corresponds to less Mach numbers than in the flow with the turbulent boundary layer, i.e. for the fixed transition.

4. LCO of the CAST model

The results obtained by A. Hebler on the CAST model in Transonic Wind Tunnel Goettingen (TWG) and presented in the IFASD-2017-089 paper, demonstrate a presence of several regions of flutter and LCO in transonic flow in dependence on Mach number and angle of attack. For aeroelastic analysis of these phenomena in the current paper, numerical solutions of nonlinear Euler equations were obtained with use of the Godunov method [13]. The pitch motions are given by a simple harmonica of varying frequency with an amplitude Ao and a mean angle of attack AoA. The oscillations are considered around straight axis at a quarter of an airfoil chord. Calculations were carried out in time domain over several periods for pitch oscillation. Imaginary part of the moment coefficient response to pitch (damping coefficient), which is proportional to the work of aerodynamic forces over one period for pitch oscillations was obtained for various Mach numbers, angles of attack and amplitudes. According to the damping coefficient value, several instability points are found. For examples, the effects of oscillation frequency (left picture) and amplitude (right) on damping coefficient value are presented in fig. 11 for the angle of attack AoA=0.8 deg. The model performs the limit cycle oscillations (LCO) at M=0.75. This LCO is composed of a large pitching oscillation with amplitude Ao=1.25 degree and frequency 52 Hz. The wind tunnel model carries out a similar LCO [11] with the frequency 43.5 Hz. Figure 12 shows time domain results of lift coefficient for pitch motion at M=0.75 and at the amplitude of the LCO for the two frequency values. It can be seen that at frequency less than LCO's the lift is behind the wing pitch motion.

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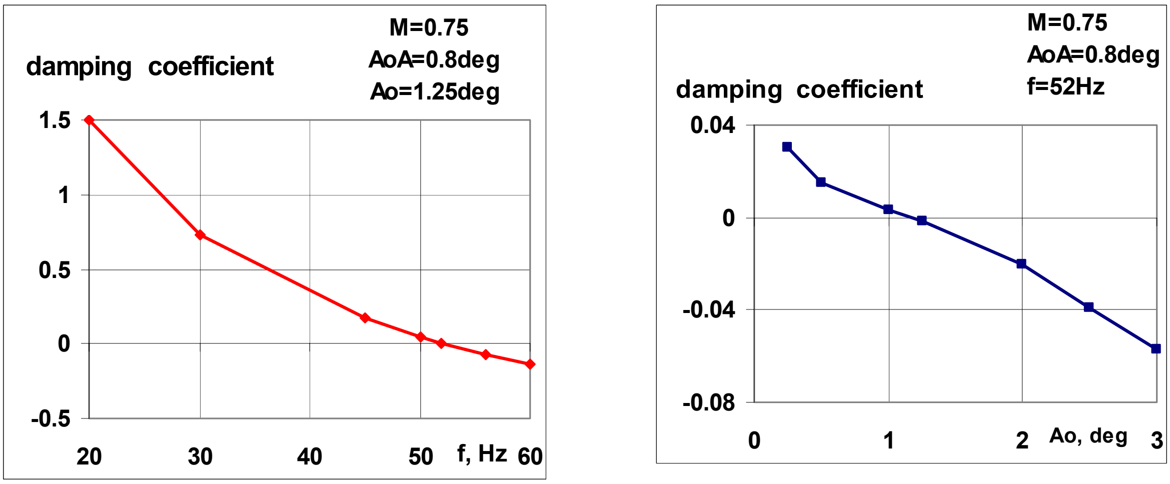
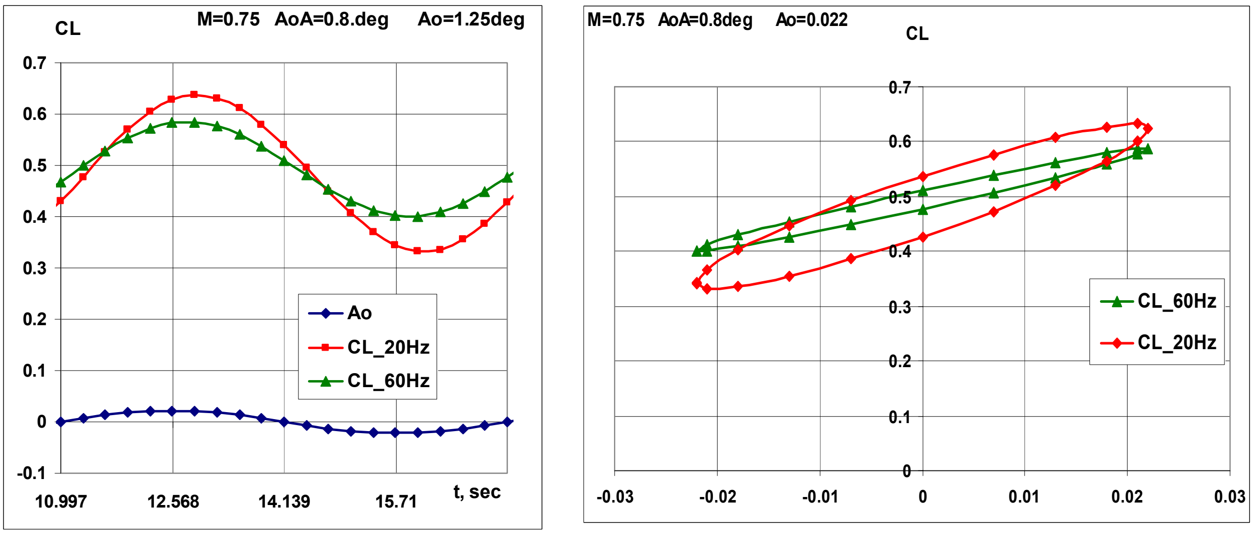


Effect of oscillations frequency

Effect of oscillations amplitude

Figure 11: CAST model pitch motions. Dependence of damping coefficient on frequency (a) and amplitude (b) at M=0.75, AoA=0.8 degree.



Ao=1.25 deg

Ao=0.022

Figure 12: Change in the lift coefficient over one period for pitch motion at M=0.75, AoA=0.8 degree, LCO amplitude Ao=1.25 degree.

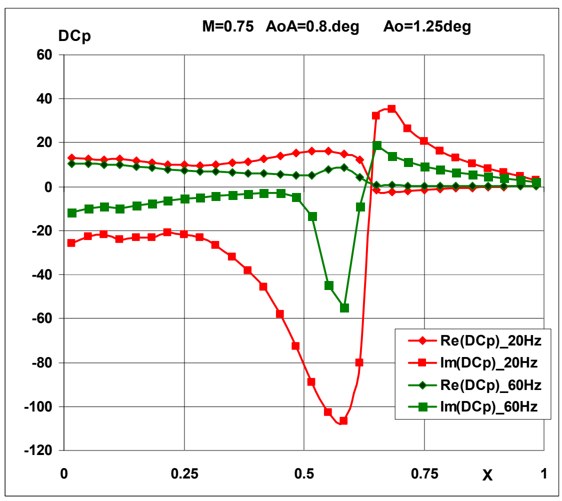


Figure13: Real and imaginary parts of the lift coefficient response to pitch motion.

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Figure 13 shows real and imaginary parts of the lift coefficient response to pitch motion for two oscillation frequencies at M=0.75, AoA=0.8 degree, Ao=1.25 degree.

5. Flutter of aircraft with laminar wing

Computational results of a viscosity influence on aeroelasticity characteristics have been obtained for the modern transport airplane with transonic cruise speed. The airplane of traditional configuration with high aspect ratio wing with sweep angle of 20 degrees along the leading edge and laminar supercritical airfoils was considered. Aerodynamic model of the airplane and computation grids, developed for the BLWF solver, are shown in fig.14.

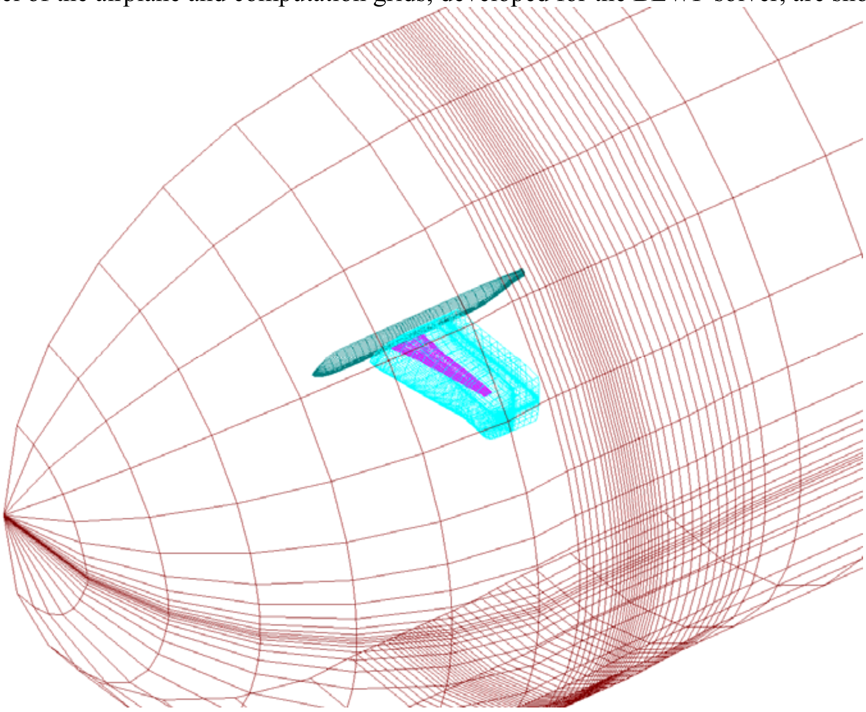
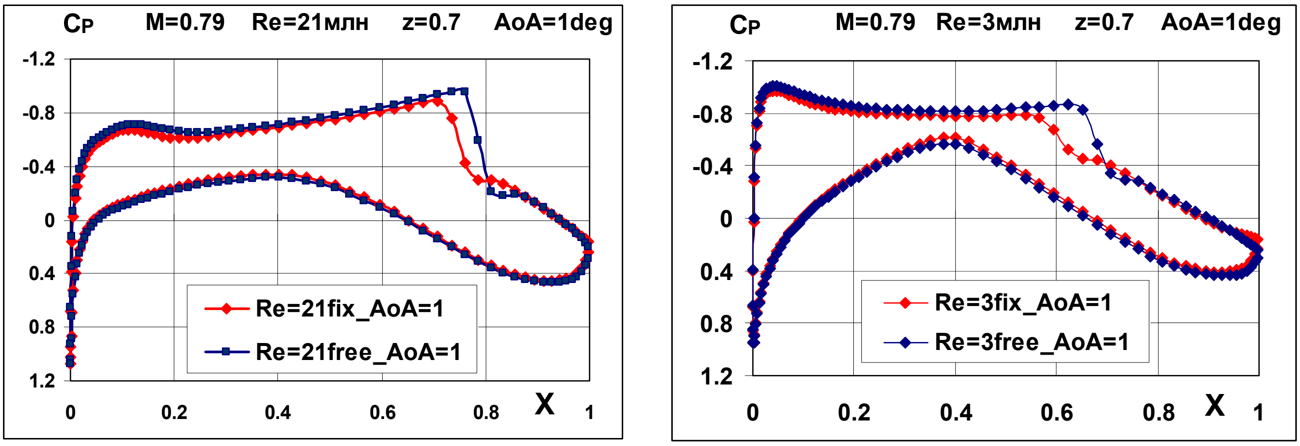


Figure14: Aerodynamic model and computation grids for the BLWF solver

Parametrical studies of aerodynamic characteristics based on the BLWF solver have shown that the pressure distribution and shock waves strength depend essentially on flow regime, and namely on the Reynolds number and on the boundary layer transition (Fig.15). It can be seen that the shock wave has moved ahead on about 10% of the chord when Reynolds number decreased from 21 mln to 3 mln.



Re=21 mln Re=3mln

Figure 15: Comparison of pressure distributions for two flow regimes: Re=3mln and Re=23mln, turbulent and transitional flow at M=0.79 for wing section z=0.7.

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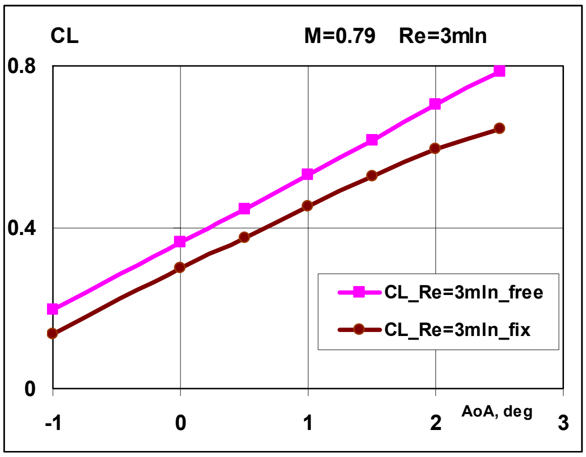
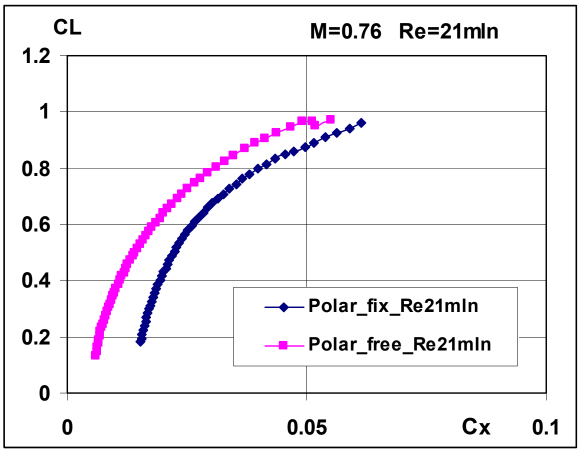
Computational results show that in transonic region for various considered Mach and Reynolds numbers, the lift coefficient is bigger in laminar (transitional) flow than in turbulent (fixed transition). In Fig.16 the lift and drag coefficients are presented for turbulent and transitional flow.



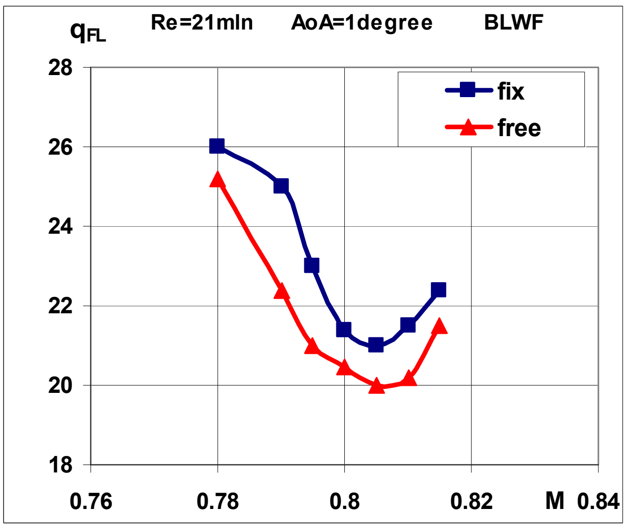
M=0.79



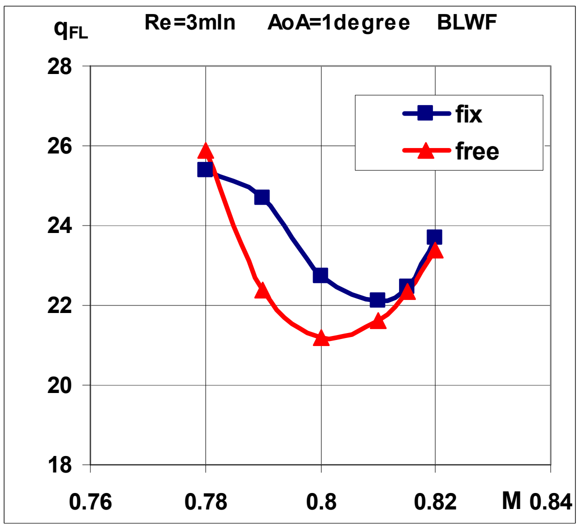
M=0.76

Figure 16: Lift coefficient and drag polar for turbulent and transitional flows.

Influence of viscosity and flow transition on flutter dynamic pressure in dependence on Mach number is presented in Fig.17. It can be seen that for the transitional flow flutter dynamic pressure is lower on 10-12% than in the case of fully turbulent flow. Besides, computational results show that for the full-scale aircraft flight the flutter dynamic pressure is lower on 8-10% than in the case of wing tunnel test.



Re=21 mln



Re=3 mln

Figure 17: Effects of viscosity and flow transition on flutter dynamic pressure.

Conclusion

The paper describes a method of computational study of aeroelasticity of laminar wings in transonic flight regime based on the joint application of software codes BLFW and ARGON (TsAGI).

Validation of the developed software BLFW code is performed on the basis of comparison of computational and experimental aerodynamic characteristics of two-dimensional model with laminar airfoil CAST10-2 in TWG.

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For the CAST model the results of comparison of pressure distributions at the fixed and free transition from laminar to turbulent state are presented. The results of flutter analysis in the considered range of Mach and Reynolds numbers are shown depending on the position of the transition point of the boundary layer.

The results of the analysis demonstrate an efficiency of the developed approach and the presence of the peculiarities in flutter characteristics of laminar wings in transonic flow. However, a further validation of unsteady test cases is required for a final assessment of availability of the new developed software for solving transonic aeroelasticity problems.

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