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REALIZATION OF A CONTINUOUS BALANCE TESTING PROCEDURE IN A COMPRESSOR-DRIVEN TRANSONIC WIND TUNNEL

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Abstract

The ways of efficiency and information density of the experimental research in transonic wind tunnels increase are revised; in particular, optimization of the wind tunnel control systems for realization of the continuous balance testing mode is described. The problem of the Mach number stabilization in the test section of a large transonic compressor-driven wind tunnel at subsonic flow conditions with continuous aircraft model pitch angle variation based on an example of TsAGI T-128 wind tunnel is solved by implementing an additional adjusting controlling impact on the base of the forecast of Mach number disturbances caused by the model pitch angle variation to the control system. Examples of the system practical realization are given.

Settings of T-128 wind tunnel Data Acquisition and Control System (DACS) measurement channels' filters are optimized. It minimizes signals' dynamic deviations and, at the same time, provides noise suppress within main frequency range. Evaluation of pitch/pause and continuous balance modes convergence in T-128 wind tunnel (Mach number M=0.4) for two pitch angle variation rates of aircraft model is given.

1 Introduction

Increasing efficiency and information density of the experimental research while testing aircraft models is an actual problem, especially for high-power industrial wind tunnels (WT). One of the ways of solving this problem together with complex automation of the aircraft model testing is development and implementation of the continuous test method.

Continuous test method means continuous change of the parameter under control (Mach number, aircraft model's pitch or slip angles, etc.) with simultaneous continuous measurement of the researched parameters (forces, moments, angles, flow parameters, etc.). Usage of the continuous test method allows reducing the test time by several times comparing with the pitch/pause (traditional) test mode during which measurement is performed at steady values of the parameters under control and, correspondingly, it allows reducing power expenses on tests.

While performing tests by the continuous method the problem of Mach number stabilization in the wind tunnel test section with a definite accuracy (about ±0.001) with continuous variation of the angular position of the aircraft model appears. This is an important condition of performing balance tests as aerodynamic coefficients considerably depend on Mach number, especially close to its sonic value [1].

As a rule, Mach number control systems are created for pitch/pause test mode. This method implies stepped changing of the model position and does not provide the needed accuracy of Mach number stabilization for continuous tests due to presence of the transporting lag of the control impact in compressor-driven wind tunnels. Deviations of Mach number from the required value in this case can reach the values of about ±0.005 and higher and are not acceptable.

2 Mach number stabilization at continuous pitch angle variation

Solving the problem of Mach number stabilization for a continuous testing mode is presented by the example of the industrial T-128 wind tunnel (TsAGI) [2], which is a transonic compressor-driven wind tunnel with 100 MW electric drive power. It provides conduction of a wide range of experimental researches while creating new models of aviation technique. The range of the Mach number variation is from 0.15 up to 1.4, the range of Reynolds number per 1 meter is up to $40 \cdot 10^6$, the cross section size of the test section is 2.75 × 2.75 m. Figure 1 presents a photo of the T-128 WT, figure 2 presents the scheme of the WT.

Mach number control in the wind tunnel test section is performed by variation of the angular position of the compressor stator blades at fixed compressor rotor rpm.

Mach number stabilization with the required accuracy is achieved by implementing an additional adjusting control impact on the base of the forecast of M number disturbances caused by the model pitch angle $\alpha(t)$ variation to the control system. While performing continuous tests it can be performed on the base of agreed control of the aircraft model pitch (slip) mechanism and M number.

Based on the conditions of performing tests in the wind tunnel the aircraft model pitch angle control system should provide continuous variation of the pitch angle with the required rate in the range of 0.2…0.5 °/sec in positive and negative directions within the pitch angle operation range. In this case Mach number control system should provide stabilization of the required value of the Mach number at subsonic velocity range with the accuracy not worse than ±0.002.

As a rule, Mach number control system designed for pitch/pause tests does not provide the required accuracy of Mach number stabilization at continuous variation of the aircraft model pitch angle due to the transporting lag of the control impact because of the space remoteness of the Mach number controllers (compressor stator blades) and the wind tunnel test section. The value of the lag for T-128 wind tunnel is about 0.5–0.6 sec. During this time period Mach number deviates from the set value on a considerable value due to variation of the test section aerodynamic drag when the aircraft model position changes. Deviation value depends on the dimensions and configuration of the aircraft model and on the rate of its position variation, too.

Mach number digital control system designed for pitch/pause tests is optimized by operating rate on the base of the Pontrjagin maxi-

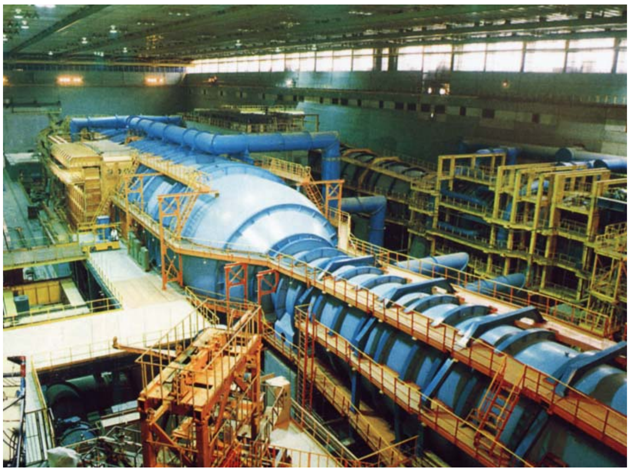

Fig. 1. Layout of T-128 wind tunnel

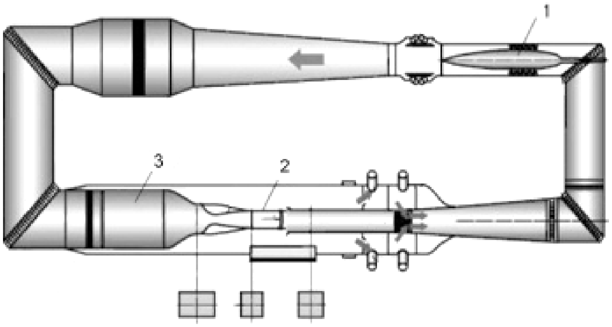

Fig. 2. Scheme of T-128 WT:
1 – compressor blades,
2 – wind tunnel test section,
3 – settling chamber

mum principle [3]. Synthesis of the Mach number control algorithm is based on the wind tunnel mathematical model as an object under control by the controlling impact — the stator blades' angle Δφ setting [4] which is the following in a small area of M number:

$$W_{\varphi}(s)=\frac{\Delta M(s)}{\Delta\varphi(s)}=\frac{K_{\varphi}}{Ts+1}e^{-\tau s}, \tag{1}$$

WT mathematical model as an object under control by the controlling impact — the model pitch angle Δα variation is the following [3]:

$$W_{\alpha}(s)=\frac{\Delta M(s)}{\Delta\alpha(s)}=\frac{K_{\alpha}}{Ts+1}, \tag{2}$$

Here T —the time constant for given Mach number; s — Laplace operator; τ — transporting lag of the control impact due to remoteness of the compressor and the wind tunnel test section which is equal to 0.5…0.6 sec; K_{φ} — transfer coefficient of the control impact; K_{α} — transfer coefficient of the disturbing impact:

$$K_{\alpha}(M_{set},\alpha)=\left.\frac{\Delta M}{\Delta\alpha}\right|_{\varphi=const}=-K_{\varphi}\left.\frac{\Delta\varphi}{\Delta\alpha}\right|_{M=const} \tag{3}$$

Time constant T is a function of the Mach number and it varies in the range of 0.5…5 seconds while Mach number varies from low velocities to transonic modes. Coefficient K_{α} is a function of the aircraft model pitch angle at the fixed Mach number. Shape of this function is defined by the geometry of the aircraft model and is individual for each model.

Adjustment of the control system for disturbance compensation needs preliminary knowledge of the K_{α} coefficient value within pitch angle operation range for each specific aircraft model. These values can be determined from the preliminary performed pitch/pause tests for the required range of the pitch angle variation or from calculations. Obtained K_{α} values provide adjustment of the control system for performing all series of tests of the model by the continuous mode.

Coefficient K_{α} is determined by the relation given above, where Δφ is the change of the compressor stator blades' angles in the T-128 wind tunnel at the Δα pitch angle variation at constant Mach number.

Figure 3 shows dependencies Δφ(α) for Mach numbers 0.6 and 0.8 for the reference aircraft model. These dependencies are determined from the pitch/pause tests and are implemented to the Mach number digital control system.

Mach number stabilization is provided by implementing an additional circuit by the dis-

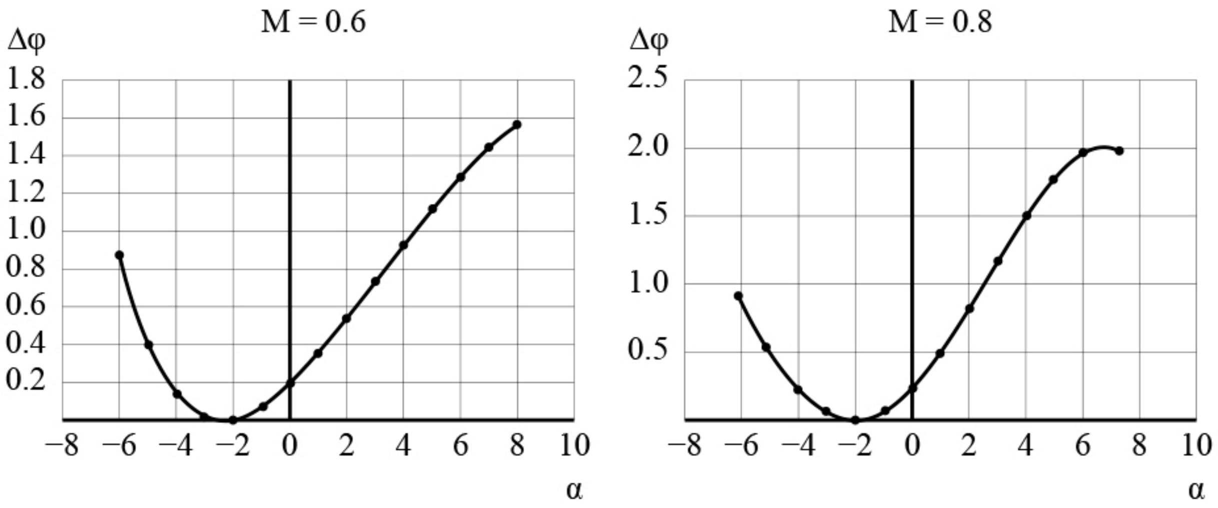

Fig. 3. Dependence Δφ(α) for the reference aircraft model for Mach numbers 0.6 (a) and 0.8 (b)

turbing impact which takes place due to aircraft model pitch angle variation. This circuit provides forecast of the disturbance of Mach number from the lag interval τ which is compensated by the control system. As a result Mach number is stabilized with the required accuracy.

Figure 4 presents block diagram of the control system with the forecast of the disturbing impact; here W_{cont} — is the transfer function of the controller, W_{CD} — is the transfer function of the compressor stator blades system.

Figure 5 shows the graphs of the Mach number change for T-128 wind tunnel at the continuous aircraft model pitch angle variation with compensation and without compensation of the disturbing impact. These graphs were obtained in real experiment (at the pitch rate 0.5 °/sec). Implementation of the information about the disturbances provides Mach number stabilization with the accuracy of about ±0.002.

Operation of the Mach number control system with the forecast of the disturbing impact for continuous tests was verified during testing of the reference model.

Figure 6 presents the time graphs for the pitch angle rates 0.2 and 0.5 °/sec and for Mach number during the continuous tests at Mach number $M_{\text{set}} = 0.8$ within pitch angle range −1…+6°. As it is seen from the graphs, Mach number stabilization is provided with the accuracy not worse than ±0.0015 for both rates.

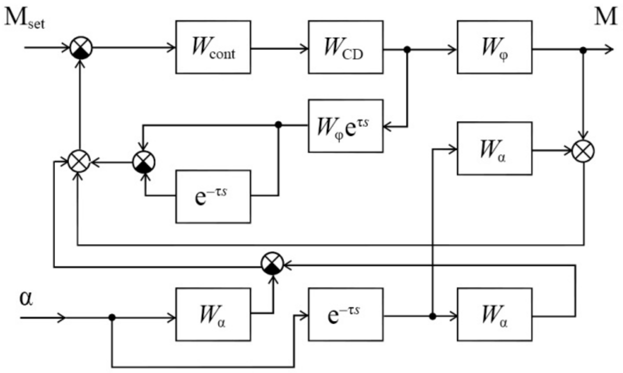

Fig. 4. Block diagram of Mach number control system for T-128 wind tunnel with compensation of the disturbing impact by α

Figure 7 shows time graphs of the reference model (Fig. 8) pitch angle variation for continuous mode with pitch rates of 0.2 and 0.5 °/sec and for pitch/pause test for Mach number = 0.8 in the angle range of −1…+5°. As it is seen from the presented graphs, duration of tests was 12, 28 and 72 seconds correspondingly.

Therefore Mach number stabilization with the maximal deviation of ±0.0015 from the set value was achieved. Duration of experiment for continuous tests at the speed of the pitch rate 0.2 °/sec was decreased by three times in comparison with the pitch/pause test.

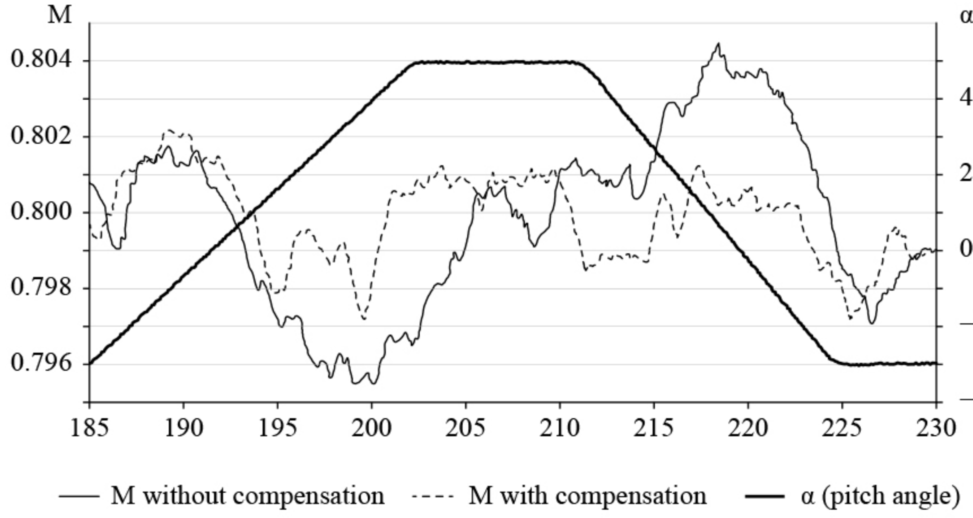

Fig. 5. M number stabilization in T-128 wind tunnel at the continuous variation of the aircraft model pitch angle with compensation and without compensation of the disturbing impact; α – pitch angle

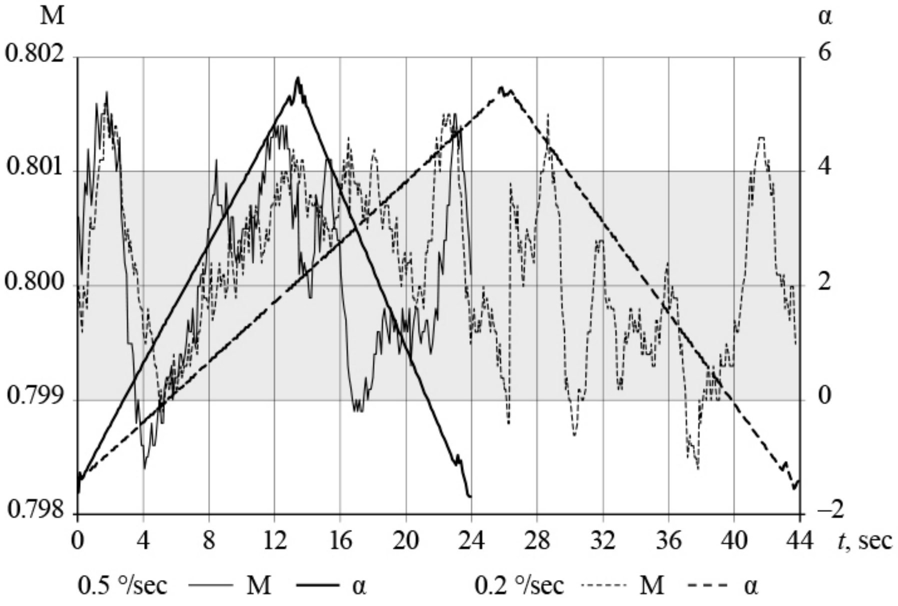

Fig. 6. M number stabilization in T-128 wind tunnel for continuous tests: for α = 0.5 °/sec and for α = 0.2 °/sec

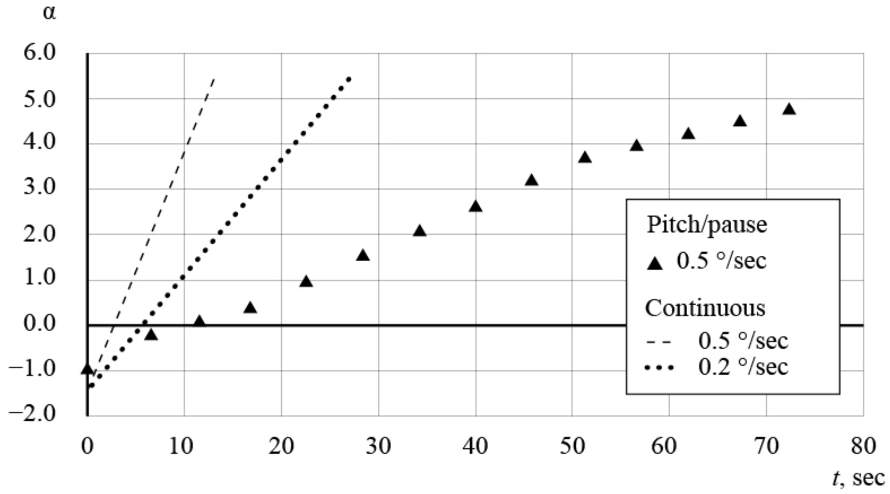

Fig. 7. Duration of the continuous and pitch/pause tests: pitch/pause; continuous: 0.5 °/sec; 0.2 °/sec

Fig. 8. Reference model in T-128 wind tunnel

3 Evaluation of pitch/pause and continuous balance experiment convergence in T-128 wind tunnel

During continuous experiment conduction dynamic deviations of signals in measurement channels of a wind tunnel Data Acquisition and Control System (DACS) evaluation and taking into account is necessary. T-128 wind tunnel balance experiment DACS is based on a MGC plus measurement equipment of HBM company. Signals from strain gauge balance (aerodynamic forces and moments) are measured by ML38 amplifiers, aircraft model pitch angle — by ML01 amplifier (Fig. 9).

These amplifiers include integrated Bessel and Butterwort low frequency filters with wide cutoff frequencies ajustment range. For these amplifiers, amplitude and phase frequency performances, allowing dynamic deviations and measurement channels signals transporting lag evaluations acquisition are experimentally determined.

In experiments without a flow settings of measurement channels filters were determined, minimizing signal dynamic deviations and simultaneously providing satisfactory noise suppress. In these settings Butterwort filters with cutoff frequency 5 Hz having smooth amplitude and linear phase frequency performances within low frequency range providing good noise suppress above the cutoff frequency are used. For these settings value of signals transporting lag between ML01 and ML38 amplifiers is determined, making about 30–34 msec due to various orders of filters. Transporting lag, introduced by strain gauge balance and pitch angle sensors, is considerably larger and makes few milliseconds.

Obtained evaluation of balance channels signals' transporting lag relatively to pitch angle α measurement channel allows evaluation and account of dynamic errors of aerodynamic coefficients measurement during continuous displacement of aircraft model compared to results of a pitch/pause experiment. At pitch rate 0.5 °/sec, transporting lag of 30 msec causes advancing of angle measurement relatively to force measurement channels beyond $\Delta\alpha = 0.015°$. For T-128 wind tunnel reference model in the vicinity of maximum lift to drag ratio angle of attack measurement error $\Delta\alpha = 0.015°$ results in deviation from pitch/pause mode for example for C_D for

$$\Delta C_D = \frac{dC_D}{d\alpha}\Delta\alpha \cong 0.00005 \tag{4}$$

and for C_L – for

$$\Delta C_L = \frac{dC_L}{d\alpha}\Delta\alpha \cong 0.0015 \tag{5}$$

comparable with requirements of C_D and C_L measurement precision at cruise flight regimes. Thus, determination of transporting lag in measurement channels is an essential problem during continuous experiment mode development.

For pitch/pause and continuous balance experiment convergence evaluation in T-128 wind tunnel a set of tests of a transport aircraft model for M = 0.4 (stabilization accuracy ±0.0015) and two different pitch rates 0.3 °/sec and 0.5 °/sec was carried out (prescribed DACS filters'settings, Butterwort filters, cutoff frequency 5Hz).

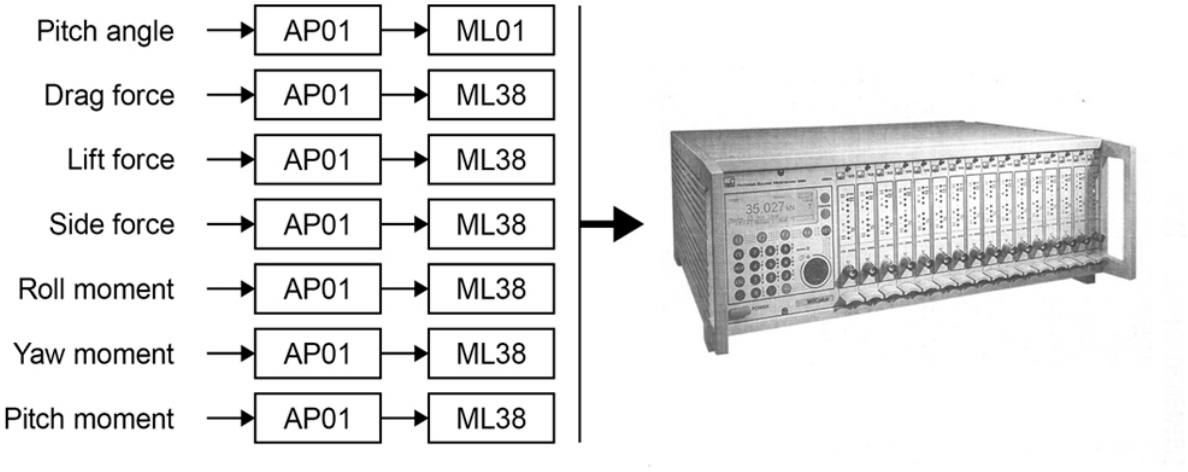

Fig. 9. MGC plus measurement equipment

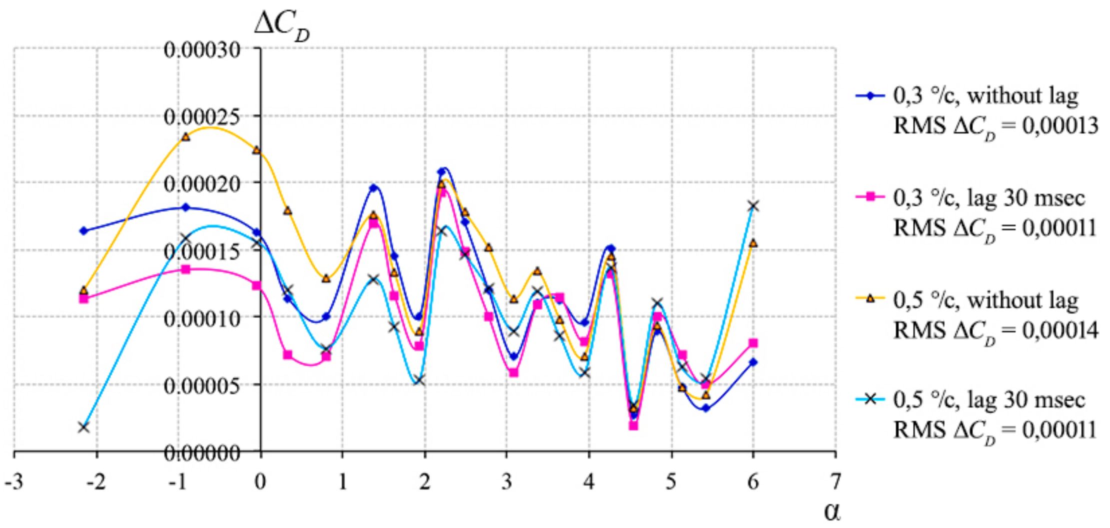

Fig. 10. C_D deviations between continuous and pitch/pause modes

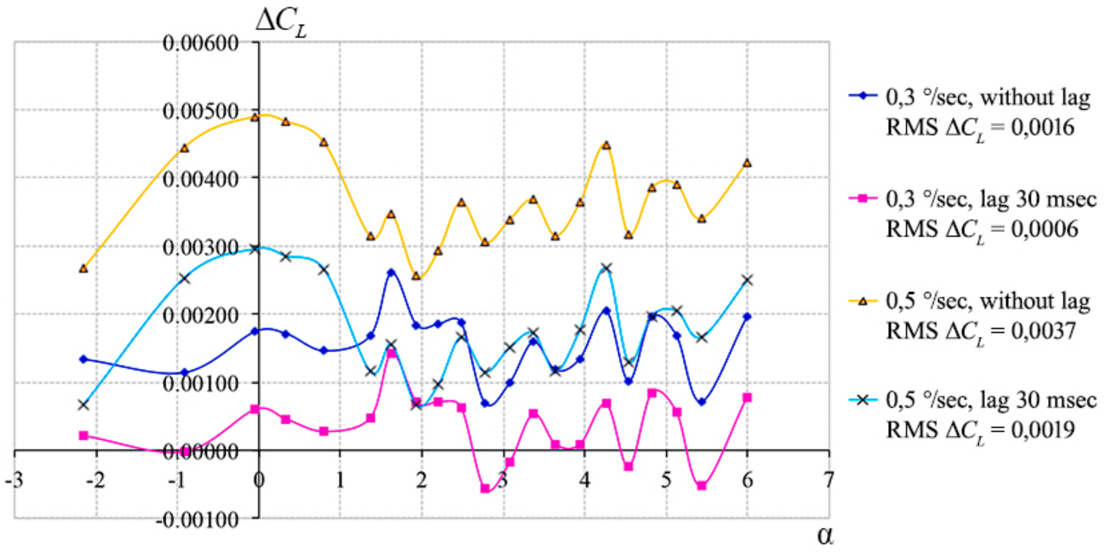

Fig. 11. C_L deviations between continuous and pitch/pause modes

Figure 10 represents average values of C_D deviations of continuous experiment from pitch/pause one with and without signal transporting lag of 30 ms account between channels for pitch rates 0.3 °/sec and 0.5 °/sec correspondingly. From these results one might conclude that account of dynamics allows improve convergence of pitch/pause and continuous experiments for 0.00003 in average.

Figure 11 shows average values of C_L deviations between continuous and pitch/pause experiments with and without signal transporting lag account between channels for pitch angle variation ranges 0.3 °/sec and 0.5 °/sec correspondingly. Account of dynamics allows increase of convergence of pitch/pause and continuous experiments of C_L determination by 0.0018 in average.

In general, good convergence of pitch/pause and continuous experiments' results is obtained.

4 Software for continuous tests

Tests in T-128 wind tunnel were performed on the base of the system of complex automation realized on the base of the real-time local network, digital data acquisition system and Potok software package [5, 6].

Unified software package Potok provides automated preparation and centralized control of tests in automatic mode, synchronization of operation of data acquisition and control subsystems, multi-mode data acquisition from the measuring equipment of different types with the required measurement frequency, effective processing and presentation of information in graphic form, complete processing and presentation of test results. Potok software package has an open architecture and it allows flexible adjustment on the required number of data acquisition and measurement equipment; it supports measurement equipment for different interfaces (VME/VXI, PCI, ISA, Ethernet, RS-232/485, etc.) and allows usage of measurement equipment supplied by Russian and foreign producers in data acquisition and control systems of new generation.

Potok software package provides realization of the continuous test mode in T-128 wind tunnel including the stages of preparation, test performing, processing and data presentation.

Operation of Mach number control system is realized and approved at subsonic modes with the forecast of the aircraft model disturbing impact.

It is experimentally approved that the control system provides Mach number stabilization not worse than 0.0015 at pitch angle variation rates 0.2 and 0.5 °/sec.

Balance tests of the reference model are performed in the test section of T-128 wind tunnel for pitch/pause and continuous tests. Acceptable agreement of test results is obtained.

WT runtime while performing continuous tests is reduced by 2–6 times in comparison with the pitch/pause test method with the simultaneous increase of test information density.

The results obtained can be extended for other compressor-driven wind tunnels.

References

[1] Loytsyansky L.G. *Liquid and gas mechanics*. Nauka, 1978.

[2] Petronevich V.V. Much number stabilization in transonic wind tunnel test section during aircraft model pitch angle continuous variation. *Sensors and systems*. No. 8, pp. 2–6, 2013.

[3] Petronevich V.V., and Kudrin N.A. Quasi-optimal operating speed of M number control in a compressor-type wind tunnel. *Uchenie zapiski TsAGI*. Vol. XXIV, no. 3, pp. 108–120, 1993.

[4] Petronevich V.V., and Kudrin N.A. Identification of mathematical model of a compressor-type wind tunnel as an object under control. *Uchenie zapiski TsAGI*. Vol. XXIV, no. 2, pp. 102–106, 1993.

[5] Petronevich V.V., Blokin-Mechtalin Yu.K., and Chumachenko E.K. Complex automation of aerodynamic tests. *Polet*. No. 6, pp. 46–49, 2009.

[6] Petronevich V.V. Organization principles and functional capabilities of Potok software package for automated aerodynamic tests. *Sensors and systems*. No. 5, pp. 3–7, 2010.

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