TECHNICAL NOTE

The influence of Reynolds and Mach numbers on two-dimensional wind-tunnel testing: An experience

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ABSTRACT

In this note, the experimental results of wind-tunnel measurements of lift coefficient and lift-curve slope for aerofoil NACA 0012 obtained from the VTI-Institute Zarkovo, are presented. The results were obtained from tests and integrations of surface static-pressure data over a model of the NACA 0012 aerofoil section. The data were obtained for a free-stream Mach number range of 0·25-0·8 and a chord Reynolds number range of 2-25*MRe*. The essential results of these measurements along with the results from other authors are presented and evaluated. The principal factors which influence the accuracy of two-dimensional wind-tunnel test results are analysed. The influences of Reynolds number, Mach number and wall interference with reference to solid and flow blockage as well as the influence of side-wall boundary-layer control are analysed. Interesting results brought to light the Reynolds number effects of the test model versus Reynolds number effects of the facility in subsonic and transonic flow as well as the effects of the side-wall boundary-layer control and wall interference.

NOMENCLATURE

a	$dC_L/d\alpha$ - the lift-curve slope
c	wing section chord
h	working section height
C_L	lift coefficient
M	Mach number
M_∞	free stream Mach number
MRe	mega-Re (10^6 Re), Reynolds number in millions
Re	Reynolds number
α	angle of attack

1.0 INTRODUCTION

The purpose of this note is to point out the principal factors which contribute to the greatest extent to the inaccuracy and diversity of results of measuring aerodynamic values expressed through lift-curve slope ($a = dC_L/d\alpha$) of the NACA 0012 aerofoil. On the basis of the results of this study, an attempt has been made to give an

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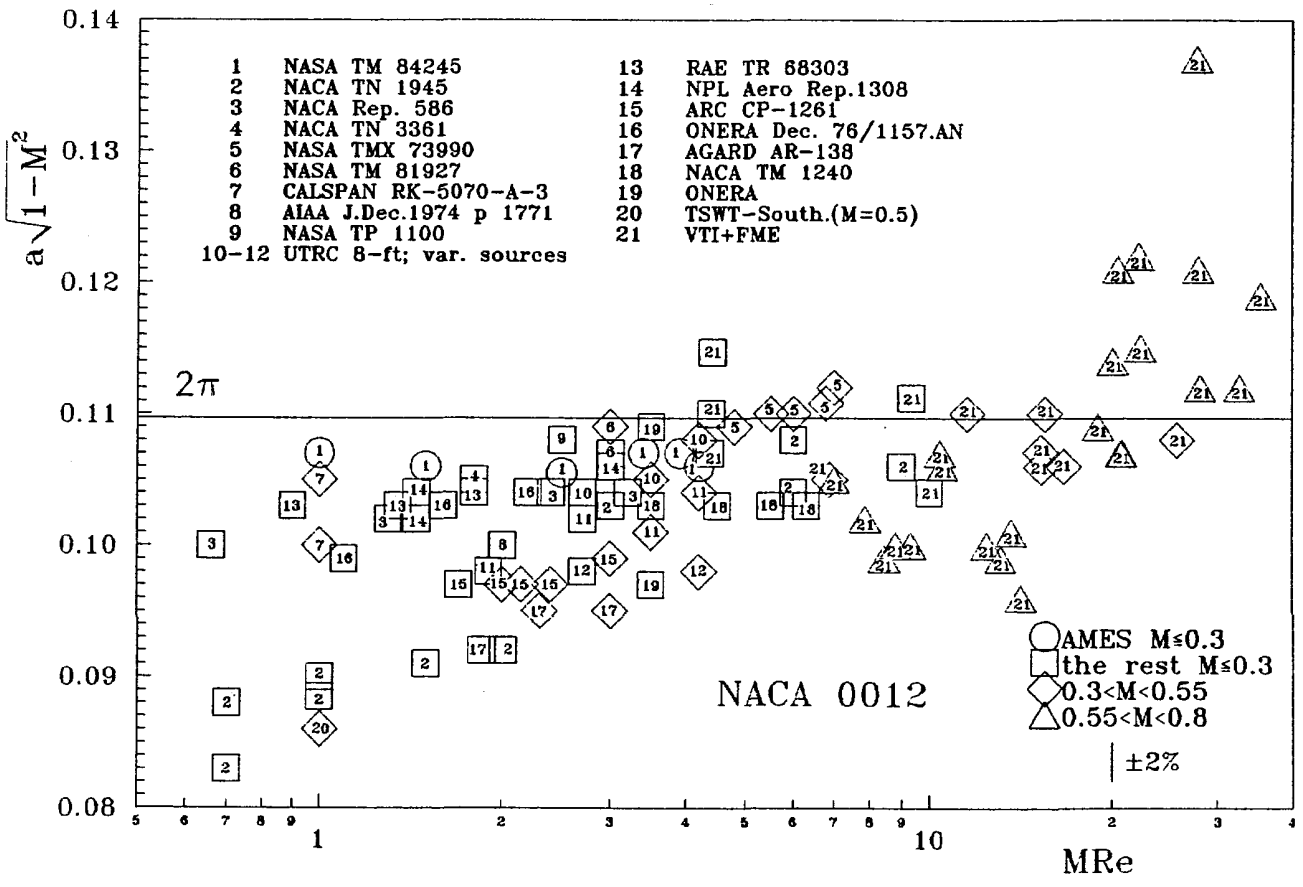


Figure 1. Illustration of the collected results of the tests of lift-curve slope in the function of the Reynolds number.

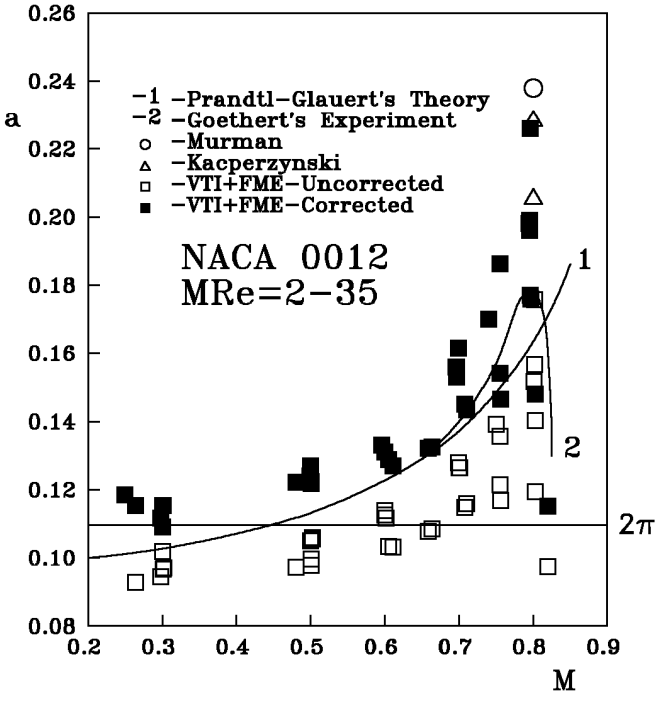


Figure 2. Results of the test of the dependence of the lift-curve slope from Mach number.

answer to the question: What is the actual lift-curve slope of the conventional symmetrical NACA 0012 aerofoil according to the Mach and Reynolds flow numbers?

In order to give an answer to this question an analysis should be made of the available results of wind-tunnel tests which are published in international literature about such a subtle premature as lift-curve slope of aerofoil[1,2].

First, in order to exclude from the analysis the effect of the Mach number, the range of subsonic flow (up to March number 0.55) has been analysed at small angles-of-attack only, because of which the possibility of creating and separating the flows and shock waves have been eliminated. Then the Mach number effects have been included in the analysis. In both cases the effect of the Reynolds numbers to the models and wind tunnels has been also analysed.

The results of this analysis are presented in Fig. 1 for NACA 0012 aerofoil. They are grouped according to 21 sources of quotation. Many of these results have been achieved by the outstanding and widely known international aerodynamic institutions. For example, an analysis has been made of some old wind-tunnel low speed tests made by NACA Institute (symbols 2-4), contemporary results of the NASA (1,5 and 6), the results achieved in the very good industrial facilities (10-12), detailed studies of the NPL and RAE (13-15), the results achieved by AGARD working group 04 DATA BASE (17), the results of ONERA (16-19), of the VTI and the Faculty of Mechanical Engineering (21), etc.

According to this illustration there is a great diversity in the achieved results, as a consequence of the strong influence of the Reynolds numbers effects on the test models and wind tunnels, of

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Figure 3. The T-38 trisonic wind tunnel has been in operation since 1986. It is a blowdown, intermittent type wind tunnel with 1·5m × 1·5m rectangular test sections.

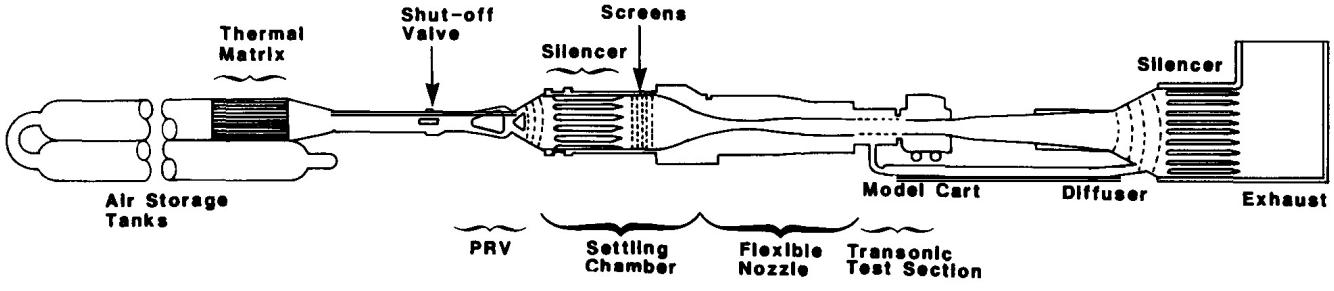


Figure 4. Schematic of wind tunnel. (*PRV – Pressure Regulating Valve*).

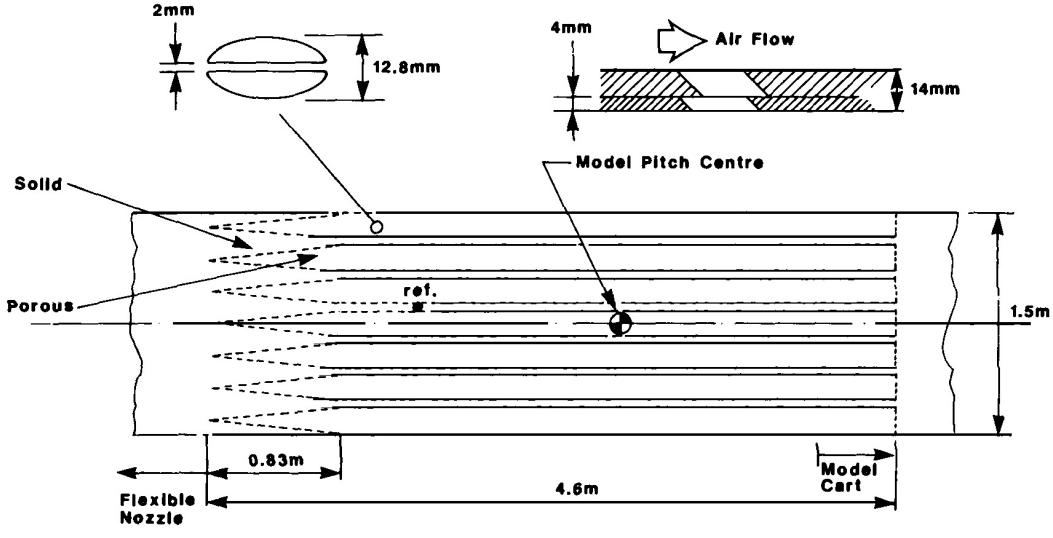


Figure 5. Schematic of test-section walls.

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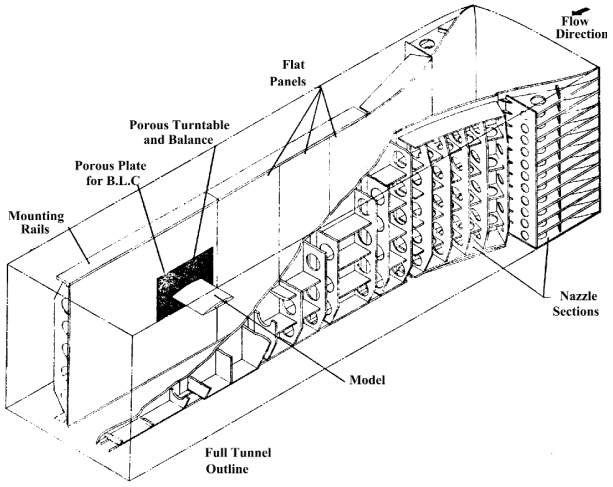


Figure 6. 0·38 × 1·5m two-dimensional insert.



Figure 7. The NACA 0012 model has a chord of 0·254m.

inadequate conditions of two-dimensional flows in the test section and the wall interference in the test section of wind tunnel. Wishing to complete this study, the analysis has been extended to the transonic speed range and it has incorporated new tests made by the VTI as well as the calculation of wall corrections made at the Faculty of Mechanical Engineering (Figs 1, 2 and 10)[2,3].

2.0 FACILITY DESCRIPTION AND EXPERIMENTAL RESULTS

The VTI-Institute blowdown wind tunnel has a transonic test section with two- and three-dimensional inserts (Figs 3-6). The inserts have 60° inclined-hole porous walls with variable porosity adjustment capability. Mach number is nominally set using either the second throat or flexible nozzle contour, depending on whether the flow is to be subsonic or supersonic. Final Mach number trimming is done using a blowoff system (with ejector assist if required) in which air reenters the circuit in the wide-angle diffuser just before the exhaust stack. Fig. 4 shows a schematic of the circuit airline[2].

Experimental tests have been made with transonic two-dimensional working section of dimensions 0·38 × 1·5m with changeable perforation of walls from 1·5-8 % (Figs 3-6). Aerodynamic coefficients have been calculated by measuring the distribution of the static pressure in 80 equally distributed tested points along the upper and lower side of the model with a chord of 0·254m (Fig. 7). For this measuring, the complete most modern equipment for aerodynamic measuring has been used (Fig. 8).

Figure 9 presents the selected results of the measurement of the distribution of the static pressure along the upper side and lower side of the aerofoil at angle-of-attack of 2·0° at Mach number of 0·8.

This additional experimental study has included the Mach test number from 0·25-0·8 and the Reynolds model numbers from 2-35 MRe. It has corroborated the conclusions made at the beginning about the influences of the Reynolds number in the subsonic speed range and at the same time it has expanded them to the transonic range, i.e. to the Mach number effects to the results of the wind-tunnel tests[1,2].

The experiments and theoretical studies carried out recently by Murman, Kacperzynski, Chan, Jones and Catherall, and the latest

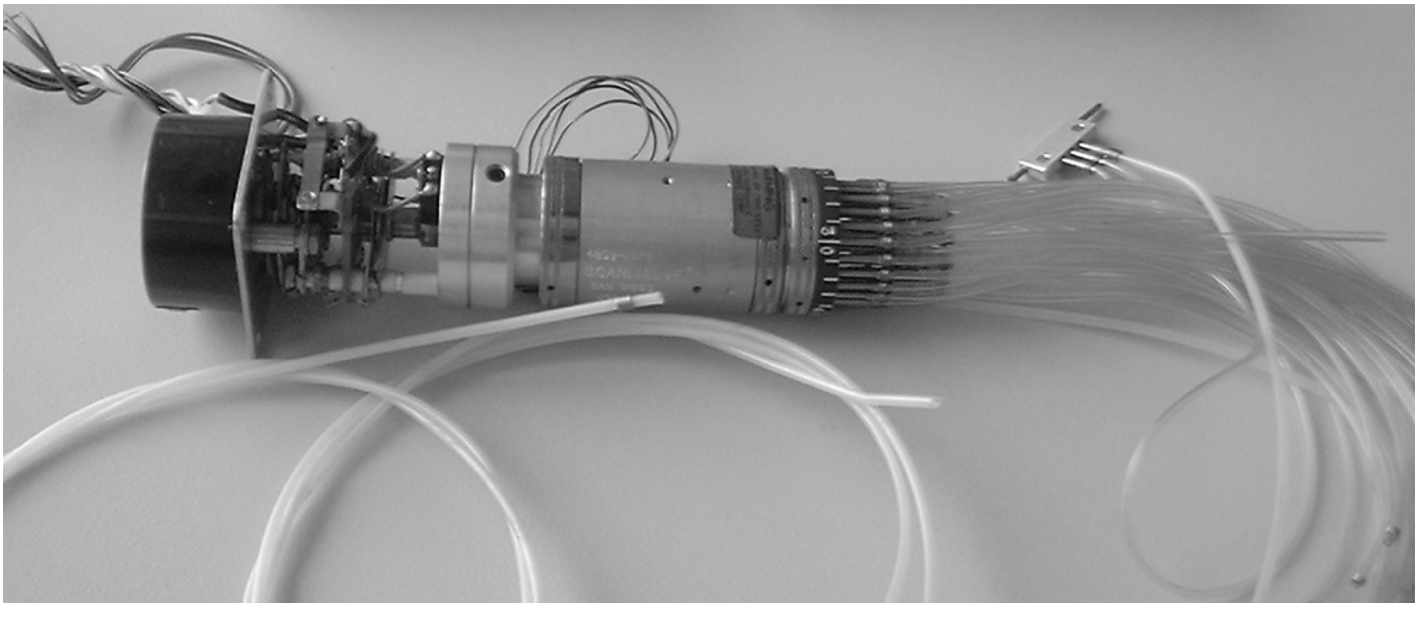


Figure 8. Pressure scanning system: five S3 or D9 Scanivalves (230 pressure taps), expandable.

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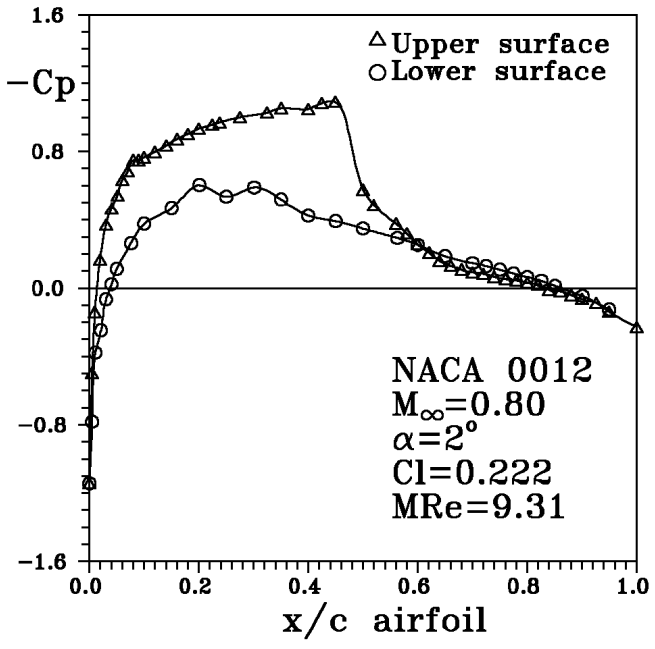


Figure 9. Results of measurement of the distribution of the static pressure along the upper and lower side of NACA 0012 aerofoil at angle-of-attack of 2° at Mach number of 0·8.

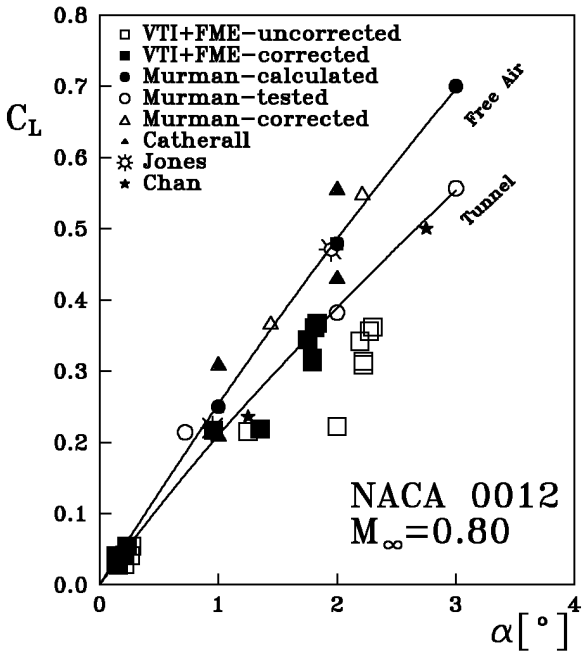


Figure 10. Results of the test of lift coefficient in the function of the angle-of-attack.

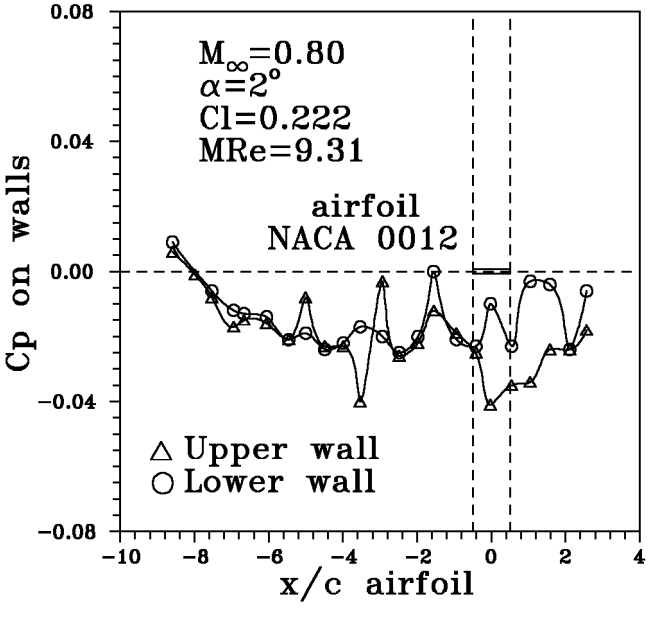


Figure 11. Results of measurement of the distribution of the pressure coefficient along the upper and lower wall of the working section of wind tunnel at angle-of-attack 2° at Mach number of 0.8.

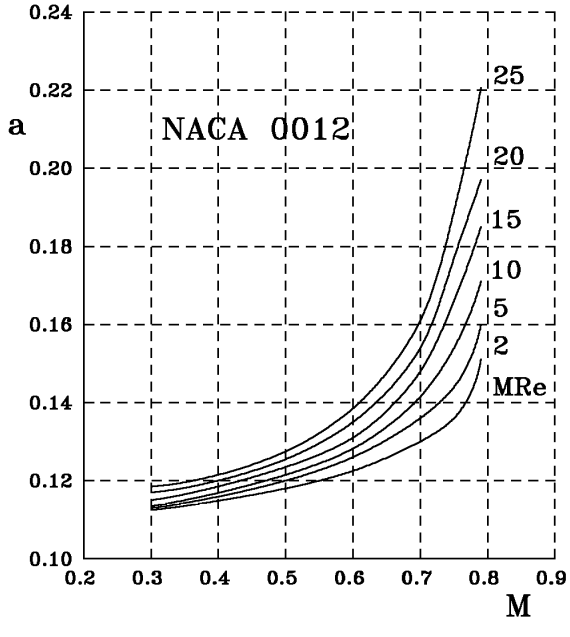


Figure 12. Results of the test of the dependence of the lift-curve slope from Mach number for NACA 0012 airfoil.

tests made in NASA, Canada, by the VTI and the Faculty of Mechanical Engineering[2-5] illustrate an exceptionally great inter-dependence of the Mach and Reynolds number effects, side-wall suction and the influence of the wind-tunnel walls on test results in transonic wind tunnels. These conclusions are completely evident in the results of the lift-curve slopes tests made by the VTI which are presented in Fig. 10, as well as in the corresponding results achieved in the world and presented in Figs 3 and 10[2-6].

In all analyses of tests results achieved in wind tunnels, the question of wall tunnel interference has been always raised. It has been manifested that, irrespective of the increased dimensions of the test section, i.e. of the Reynolds number effects on the wind tunnel, the effects of solid and flow blockage, i.e. the wind-tunnel wall interference cannot be eliminated. If we look at the results of the tests made by the VTI, with high Reynolds numbers and different Mach numbers which are presented in Figs 3 and 10, we can establish that these results, if not corrected, are completely useless from the point of view of an engineer. Only when the wall tunnel influence is calculated, these test results could be accepted as real results which are achieved in the world today and which could be expected in the conditions of free air flow. During all tests made by the VTI, the calculation of the perforated wall

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interference of T-38 wind tunnel has been made by the Fourier's method used to solve the Dirihlet's problem in the rectangle of the wind-tunnel test section[2,3].

During this calculation, in order to preserve in the computer analysis the reality of flows at the test section boundaries of transonic wind tunnel, the boundary conditions which are necessary to know for the solution of this type of boundary problems, have been experimentally defined by measuring the distribution of static pressure along the upper and lower wall of the test section in 46 equally distributed tested points. Figure 11 illustrates the distribution of measured pressure coefficients along the upper and lower wall of working section at angle-of-attack of 2·0° at Mach number of 0.8.

The problem of boundary value has been analysed, while the solution has been adapted for the application of the Fourier transformation and the Fourier coefficients have been calculated by the application of the fast Fourier transformation[2,3].

In order to create correct two dimensional flow conditions and uniform spanwise loading of the aerofoil model, it is necessary to apply side-wall suction, i.e. the control over the boundary-layer along the side walls of the wind tunnel. In the case that the control of boundary-layer along the side walls is not ensured, this will certainly result in a loss of lift (and difference in drag) caused by the two basic effects of the complex flow. First, the loss of lift is caused by the decreased speed near the wall (by the decreased circulation). This effect can be significantly diminished if the side-wall boundary-layer is reduced to the value which is very small in comparison with the spanwise of the model. Second, the influence of the aerofoil pressure range will cause nonuniform increase of boundary-layer along the side walls which will result in the creation of some three-dimensional effects in the flow around the aerofoil. The separation along the side walls is also quite normal. For example, it usually occurs near a rounded leading edge (in the vicinity stagnation point), approaching the trailing edge and during the subcritical and supercritical flow, as well as in the zone of the maximum local value of pressure.

It is desirable that the quantity of the removed volume of the air through porous side walls of the wind tunnel is minimal as required for creating satisfactory conditions for two-dimensional flow. If the too much quantity of air is removed from the working section this will cause an extensive axial gradient of pressure in the wind tunnel, which will result in (buoyancy) defect in drag and in the Mach number.

The importance of the correct definition of the quantity of the removed air is evident from the ONERA tests presented in Fig. 3 for its results given under point 19. The lower point is the case with inadequate suction and the upper point with right quantity of the removed air. Most frequently the removed quantity of air is expressed through the ratio of normal component of flow velocity through the wall, to the velocity of undisturbed flow (far upstream from the model) V_n/V_∞. In all tests made by the VTI which are presented in Figs 3,4,9-12, the velocity ratio has been within the limits: $V_n/V_\infty = 0{\cdot}0050-0{\cdot}0054$.

3.0 CONCLUSION

This rather pessimistic picture which one could get on the basis of the presented results can be partially balanced by the new development of corrections of walls and calculation methods which are published and used in the world today, and which, when applied in practice, should increase the confidence in the results of wind-tunel tests. In this context, it is more precise to take the definition of the correction of walls as 'adaptation of walls' which shall incorporate all mentioned factors which have an impact on the quality and accuracy of the flow area of the wind-tunnel test section and thereby contribute to the increased accuracy of the measured aerodynamic values. The results achieved in this way (Fig. 12) could satisfy the users of 'accurate' results of two-dimensional aerodynamic tests during the design and fundamental research or the testing of validity of the numerical methods of calculation.

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