ON STATUS OF WIND TUNNEL WALL CORRECTION

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Abstract

The problem of wall interference has been of lasting concern to experiments and theoreticians while wind tunnel design, model shapes and experimental techniques have been developing through the years. The status, experiences and some results of this research for two-dimensional wind tunnel wall interference effects, in this paper are presented.

1 Introduction

The development of highly subsonic airplanes has necessitated high accuracy of the wind tunnel data so as to enable aerodynamic design. Such airplanes have been examined in transonic wind tunnels in working sections with ventilated walls. Throughout history, perforated walls have been developed so that they could minimize the effect of blocking that occurs while testing model airplanes in wind tunnels, at high subsonic Mach numbers.

Naturally, even in the best transonic wind tunnels it is not possible to have the flow past the model resemble the flow in free air completely. Therefore, experts in aerodynamics have always had to tackle the task of defining and then eliminating wall interference in wind tunnels during experiments and theoretical research, either when designing new wind tunnels or when exploiting them [1].

Interference effects that occur during wind tunnel tests can be caused by a boundary layer of the wind tunnel, by disturbances brought about by the measuring equipment and the suspenders that support the model in the airflow, or by irregularities in the airflow itself, caused by its non-uniformity, non-stationary, or inadequate turbulence. The nature of the flow, bounded by the wind tunnel walls, can be understood from physical principles that govern the movement of streamlines. These can be obtained by theoretical analysis, where the differential equations of the flow are the same regardless of whether the flow occurred in the wind tunnel or in free air, but with different boundary conditions. Calculating the disturbance flow adjacent to the model by linear theory requires, firstly, a solution to the velocity in the presence of the wind tunnel boundaries, followed by a solution to the velocity field near the model with all the boundaries removed, including the boundary of the model. The velocity potential at the surface of the model is maintained by the former solution.

The effects of wall interference in wind tunnels can be divided into and then observed from two directions: first, through the correction of flow direction and streamline curve, known as lift interference and related to defining the circulation and vortex around the model; second, through the changes in longitudinal velocity, known as blockage interference, caused by the volume of the model and its wake. Although the main difficulty lies in determining the interfering flow field, it is necessary to present it in the form of corrections to almost all measured aerodynamic properties [2].

The doctrine of how to calculate wind tunnel corrections has undergone several changes and it has developed in a number of phases. In the beginning, there was Prandtl's concept of analyzing disturbance singularities of boundary layer and lifting line. It was followed by the concept of presenting the field far from the airfoil by concentrated singularities and linear homogeneous boundary conditions at the walls, and, finally, correcting the wall interference from boundary values yielded by measurements taken either at the walls or from a certain distance. The application of the measured static pressures and (or) flow angles as boundary values ensures that accurate physical behaviour of the ventilated wind tunnel is considered when calculating corrections [3].

2 Status of wind tunnel wall corrections

As far back as 1975 it was held that computer analysis, together with other fields of computational aerodynamics, was to surpass the results of wind tunnel tests as regards cost efficiency and accuracy in the simulation of flight aerodynamics [1, 4]. It was considered that wind tunnels would become inferior to computers. Still, a routine computer solution to the entire problem of viscous flow is hindered by lack of necessary memory space, low work speed and inadequate turbulent flow models. However, the participation of computer analysis in airplane design shows relative growth, since the cost of computer simulation is steadily falling, in proportion to the advance of numerical computation methods and progress of computer technology. Beyond 2000, the share of computer analysis in overall costs should be in the region of *50 %* (see Figure 1). On the other hand, the efficiency of the wind tunnel can be enhanced by its integration to the computer, as has been shown in the concept of adaptable walls. Although it was first believed that wind tunnels would become obsolete as far as airplane design was concerned, this prediction will not be fulfilled due to the aforementioned computer limitations and the absence of an adequate mathematical model of turbulent flow. This view is confirmed by the fact that wind tunnels are still being built worldwide, especially the gigantic and costly ones, such as NASA's cryogenic wind tunnel at Langley - NTF, USA or the European cryogenic transonic wind tunnel - ETW, with the costs exceeding half a billion dollars (Since 1995, after commissioning and calibration, ETW has been in full operation and has, in numerous test campaigns, proved to meet the design specifications.) [5-9]. The original motivation to build these facilities for flight Reynolds number tests on aircraft models was based on significant differences between wind tunnel tests and real flight, often leading to costly design changes after the first flights of a new aircraft.

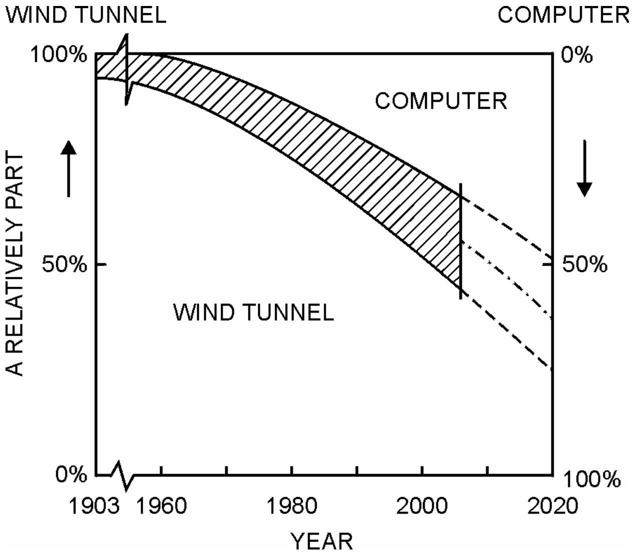

Fig. 1: The participation of wind tunnel tests in design, research and development of new airplanes.

The importance of wind tunnel simulation can be perceived from a comparative analysis of the time spent on aerodynamic tests carried out on particular airplanes in the development phase, the results of which are shown in Figure 2 [1, 4, 10-13]. According to this analysis, the development of the famous DC-3 in the 30s took only 100 hours of aerodynamic testing; in the 70s it took Lockheed over 25000 hours to develop the wide-bodied Tristar L-1011; at the beginning of the 90s, the development of the Airbus-340 passenger carrier exceeded 50000 hours, which is the equivalent to over five years of wind tunnel testing. A grand total of 43889 wind tunnel test hours have been accumulated on the YF -22 and F- 22 configurations at the mid of the 90s. So far, most time has been spent on wind tunnel tests on Space Shuttle - a total of

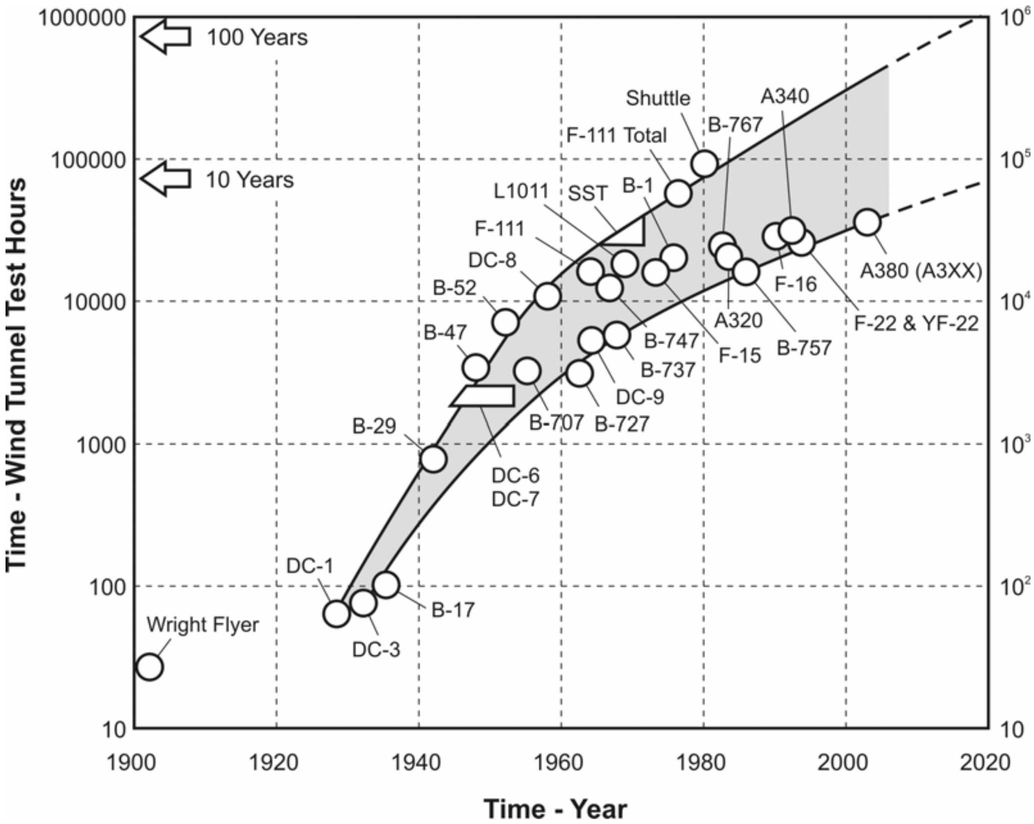

Fig. 2: Wind tunnel testing time of new aircraft in the development phase as a function of aircraft type and year. Source: [10-13] (1978-1996); updated by author (2006).

10 years. It has been estimated that at the beginning of the new millennium the development of new aircraft will consume as much as incredible 10^6 hours of wind tunnel time, which is the equivalent to 100 years.

The fields containing problems that contribute to inaccuracy in defining wind tunnel corrections can be arranged into four groups: (1) Nonlinearity of the referent equation in the condition of supercritical flow, (2) Nonlinearity of the boundary conditions of crossflow through ventilated walls and difficulties in predicting or measuring them, (3) Geometric characteristics of the wind tunnel (finite length of the ventilated walls), the entrance to the diffuser and the presence of the testing wake rake and its support, and (4) Boundary layer at the sides of wind tunnel walls, which produces flow deviations as regards the conditions of two-dimensional flow.

The contemporary concept of calculating the wind tunnel effects was established at the convention of experts: Fluid Dynamics Panel Specialists' Meeting, with the objective: *Wall Interference in Wind Tunnels,* held in London, 19-20 May 1982. The participants discussed wall interference in wind tunnels, with the conclusion that there was a great advance in understanding and treating the effects of wind tunnels. There was a general agreement on the fact that the measurements of flow conditions at the wall boundary of the working section are vital to calculate wall interference. The same measurements taken at the wall can also improve the analysis that uses traditional methods by the model of boundary conditions in ventilated walls [14, 15].

The wall interference effects and Reynolds number effects were described as two primary sources of unreliability of the results from wind tunnel tests (see Figure 3). By then, the two effects were considered as unrelated to each other. On the same occasion it was concluded that the definition (estimate) of wall interference and adaptable walls technology were, as far as two-dimensional flow was concerned, well-exploited topics of experimental aerodynamics [5, 6, 14 and 15].

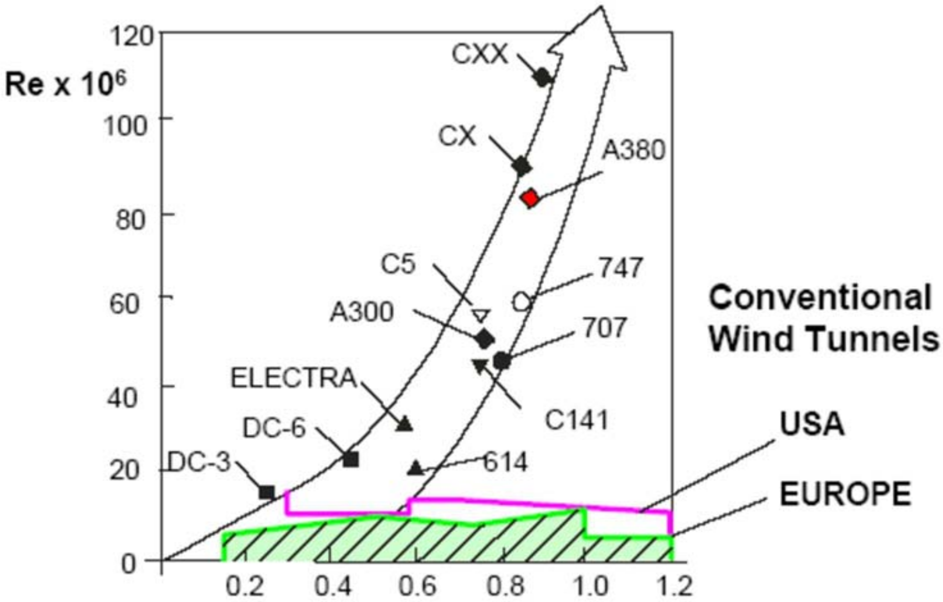

Fig. 3: The representative flight Reynolds numbers for several vehicles in the function of the Mach numbers, as compared to some European and US wind tunnels. Source: W. Burgsmüller [5], (2001) and D. Schimanski [7], (2004).

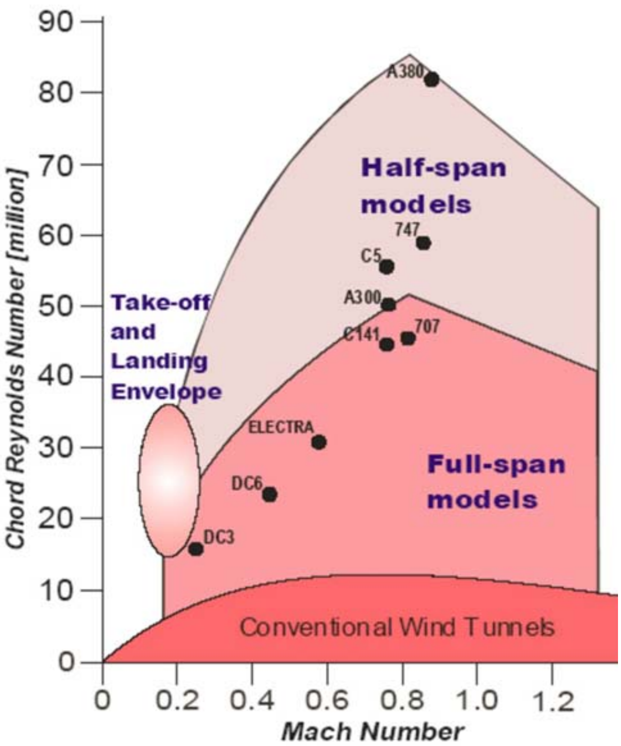

Fig. 4: Flight Reynolds Number Test Capability. Source: Schimanski [7], (2004); updated [8] (2005).

It was the difficulties in measuring the flow through ventilated wind tunnel walls and those in mathematical flow modeling with complex boundary conditions that brought upon the advance of a multitude of methods which estimate wall interference effects on test models, integrating the pressure measured at the wall [1, 3, 16-27].

Since serious airplane development in wind tunnels started, aerodynamicists struggled with the Reynolds number problem, so called “Reynolds number gap”. The wind tunnels became bigger and bigger but also the airplanes became bigger and bigger and faster. So at all times of wind tunnel utilization the Reynolds number achieved in wind tunnel was far below the full scale Reynolds number.

This was not so serious in the old days of piston engine passenger airplanes but in more modern times the highly loaded high speed wing operates with a transonic flow field and phenomena like shock-boundary layer interaction, which has a big influence on lift, lift-curve slope, drag and pitching moment and is highly sensitive to Reynolds number. So, the extrapolation of the wind tunnel data to flight Reynolds number become more and more critical.

In figures 3 and 4 the maximum Reynolds number envelope achieved in all existing conventional European wind tunnels is plotted

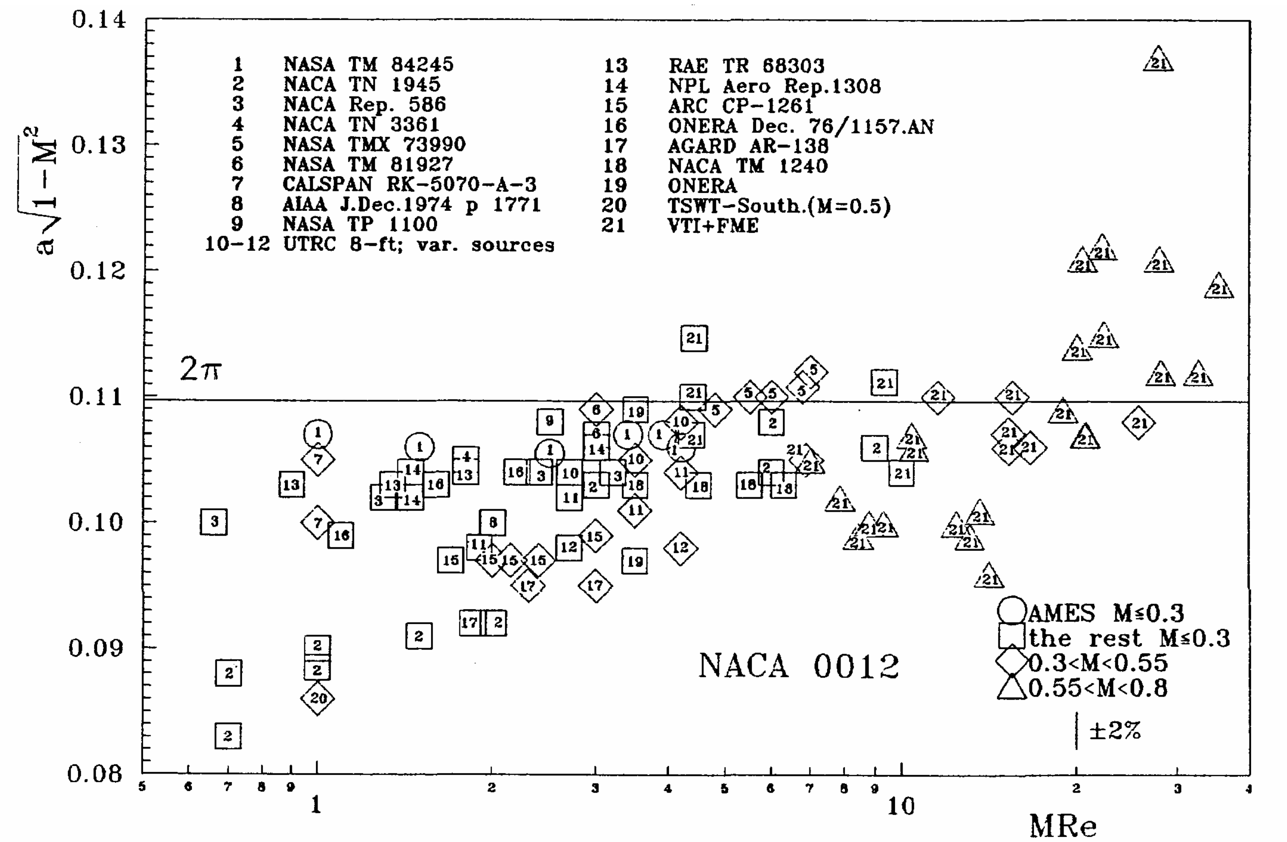

Fig. 5: Illustration of the collected results of the tests of lift-curve slope in the function of the Reynolds number.

against Mach number. The cruise and take-off and lending Reynolds number regions of transport airplanes are far outside of all wind capabilities. Figure 4 shows Reynolds and Mach number range of the European Transonic Wind Tunnel (ETW) for complete models and for half models [5 and 7-9].

The ETW facility is a transonic wind tunnel using nitrogen as test gas. High Reynolds numbers are achieved under the combined effects of low temperatures and moderately high pressures. The test section size and the pressure and temperature ranges represent the best combination of parameters to meet the requirement from the aerospace industry to achieve a Reynolds number of 50 million at cruise conditions for large transport aircraft. This takes into account the limitations on minimum temperature (condensation effects) and maximum pressure (model loads). The operating range expressed as Reynolds number versus Mach number is presented in Figure 4 [5, 7-9 and 28].

Real nature, controversy and complexity of the problem we are faced with are evident in Figure 5. There are so many solutions for one at the first sight simple question of lift-curve slope for the simplest NACA 0012 airfoil. One of the first attempts to clarify and explain in detail this problem was made at the gathering of experts called "Wall Interference in Wind Tunnels" held in London in 1982 [14]. On that occasion the attention as drawn for the first time to an interesting problem of mutual interdependence of the Reynolds number effects on the test model and the Reynolds number effects on the facility, i.e. wind tunnel. The present dilemma about this interdependence can be also illustrated by posing the similar question. What is actually the lift-curve slope $a=dC_l/d\alpha$ of the conventional symmetrical NACA 0012 airfoil in the function of the Reynolds number? 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

Fig. 6: Aerial view of the T-38 wind tunnel complex at Zarkovo - Belgrade. The T-38 trisonic wind tunnel has been in operation since 1986. It is a blowdown, intermittent type wind tunnel with rectangular test sections.

Fig. 7: T-38 hall. T-38 is a blowdown-type wind tunnel with 1.5 x 1.5 m and 0.38 x 1.5 m test sections and trisonic Mach number range (0.2 to 4). It is driven by air stored in 2600 m^3 tanks charged to 20 bars pressure by a 4 MW compressor.

literature about such a subtle premature as lift-curve slope of airfoil [1, 14 and 15-33].

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 analyzed 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 analyzed.

The results of this analysis are presented in Figure 5 for NACA 0012 airfoil. 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 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 (see Figures 6, 7 and 8) [1, 16-20 and 30-33].

The VTI-Aeronautical Institute trisonic blowdown wind tunnel T-38 has a transonic test section with two- and three-dimensional inserts. 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. Each of the four parallel walls of two-dimensional insert are 4.6 m long: side-walls are 1.5 m wide and the upper and lower wall are 0.38 m. Upper and lower wall consists of a pair of perforated plates with holes inclined 60^o to the vertical. Variable porosity is achieved

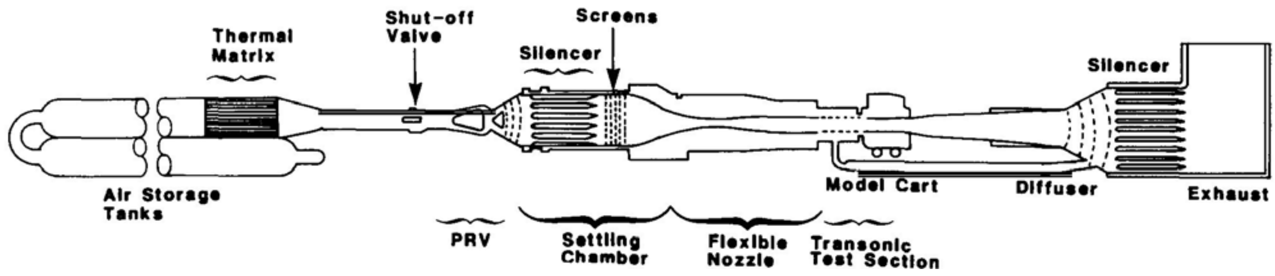

Fig. 8: Schematic of the T-38 wind tunnel *(PRV - Pressure Regulating Valve).*

by sliding the backplate to throttle the hole opening, the range being 1.5-8 %.

PERFORMANCE ENVELOPE: Mach number range: 0.2 to 4, Reynolds number range: up to 140 million/m, Run time: 6 to 60 seconds, Stagnation pressure: 1.8 to 14 bar, Run frequency: average 1 run/hour, Blowing pressure regulation: +/-0.3%, Mach number regulation: +/-0.5% and Flow uniformity: LEHRT requirements.

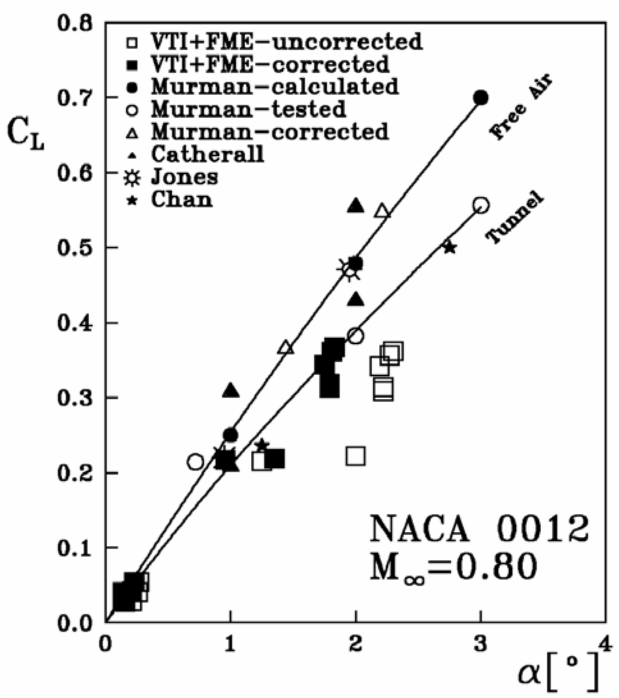

Fig. 9: Results of the test of lift coefficient in the function of the angle of attack.

MODEL SUPPORTS: Straight and bent-sting pitch/roll 3D model support, Half-model sidewall support and Wing-section (2D) sidewalls model support.

TEST SECTIONS: Subsonic/supersonic solid-walls 3D test section 1.5 x 1.5 m; Transonic perforated-walls 3D/half-model test section 1.5 x 1.5 m with controlled blow-off; Subsonic/transonic 2D (wing section) test section 0.38 x 1.5 m with controlled blow off and sidewall boundary layer removal.

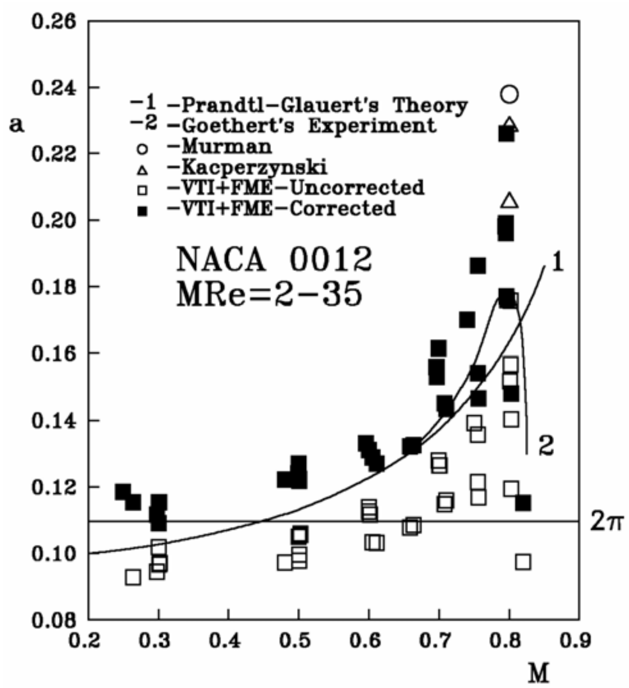

Fig. 10: Results of the test of the dependence of the lift-curve slope from Mach number.

In the case of the simulation of transonic flow, the situation becomes even more complex when defining the aerodynamic flow parameters. The effects of solid and flow blockage are even more evident, the side-wall boundary layer becomes thicker, the areas of separated flow and shock waves are created, which cannot be eliminated even by the full presence of the ventilated transonic walls. All this makes it even more difficult to define the exact aerodynamic parameters measured in wind tunnels. All controversy and uncertainty of the achieved results can be seen in Figures 5, 9, 10 and 11.

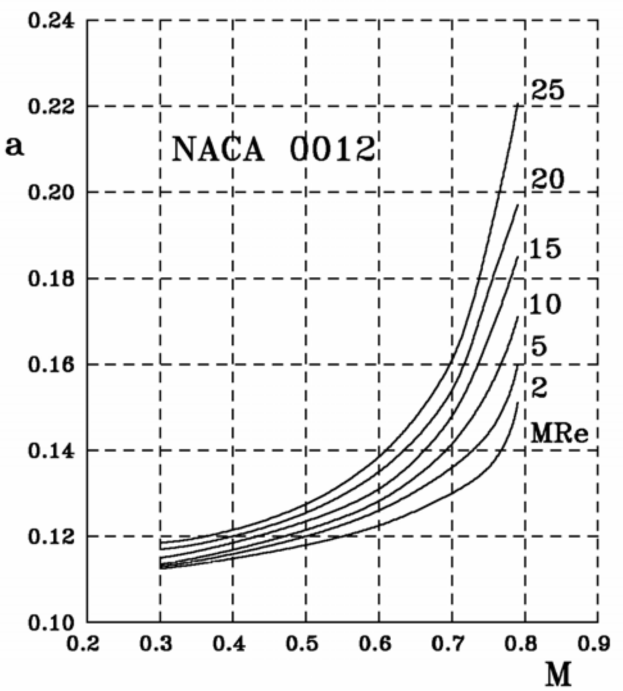

Fig. 11: Dependence of the lift-curve slope from Mach number for NACA 0012 airfoil.

The Prandtl-Glauert theory which in the early stage of the development of aviation could satisfy for many years the needs of the experts in aerodynamics, in the last few decades could not remain the mainstay for the modern researches carried out all around the world. This dependency which does not contain in itself the Reynolds number effects either to the model or to the facility, can serve today only as a standard measure for classic thinking and assessments in this field of the experimental and mathematical aerodynamics. Such conclusion is applied on the classic experiments made in the first stage of the development of wind tunnels, like the classic experiment made by Göthert (Figure 10) [34].

The experiments and theoretical studies carried out recently by Murman [35], Kacperzynski [36], Chan [37, 38] and Catherall [39] and the latest tests made in NASA, Canada, by the VTI and the Faculty of Mechanical Engineering [1,30-33] illustrate an exceptionally great interdependence 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 Figure 5, as well as in the corresponding results achieved in the world and presented in Figures 10 and 11 [1, 30-33].

3 Review of bibliography

The foundations of research in wall interference effects in wind tunnels were laid by L. Prandtl while he was carrying out his theory of lifting surfaces (the theory of lifting line). The theory required a substantial amount of experimental research in order to be verified. It was published for the first time in *Tragflügeltheorie*, part II, Nachrichten der K. Gesellschaft der Wissenschaften zu Göttingen in 1919 [40]. Besides, the basic principles of the theory of lifting line are essential for understanding simplified calculations of wall interference effects on lift surfaces. Prandtl's analysis took into consideration both open and enclosed wind tunnels in two-dimensional tests.

Theoretical and empirical studies that ensued in the following ten years of research into the elements of wall interference became firmly set into practical frames for design and wind tunnel exploitation. An extended report on this early stage of the development of wind tunnel corrections was submitted by H. Glauert in his classic monograph, *Wind Interference of Wing, Bodies and Airscrews*, ARC R&M 1566, in 1933 [41].

Soon after Glauert's treatise, works were published by T. Teodorsen in 1931 [42], T. von Karman in 1935 [43], and A. Toussaint in 1935 [44] that contributed enormously to developing the theory of wall interference in wind tunnels. General solutions were given for two- and three-dimensional flow for lift surfaces in open and enclosed circular and rectangular wind tunnels.

T. von Karman analyzed the lift interference, and Toussaint gave a much more comprehensive analysis of blockage interference than it was done in Glauert's monograph.

Two invaluable treatises on the exploitation of wind tunnels were published as separate chapters by Pankhurst and Holder in *Wind-Tunnel Technique* [45] and by A. Pope in *Wind-Tunnel Testing* [46]. Both these works give a complete calculation of wall interference correction. Pankhurst and Holder paid special attention to octagonal wind tunnels, suggesting alternative methods for applying two-dimensional lift interference corrections. Particular emphasis was laid on the conditions of stalling flight conditions. A. Pope gave the procedure of calculating the corrections to wake downwash of lift surfaces, including in his calculations certain numerical analyses of the flow line curve. A. Pope also gave a detailed graphic representation of empirical examples of calculating wall interference corrections.

Unfortunately, neither of the treatises included ventilated wind tunnels as all information on them was confidential at the time. The confidentiality threshold has since moved towards much more serious limitations, with intensive development and wider use of ventilated wind tunnels in transonic tests.

At the beginning of the sixties, B. Göthert in AGARDograph 49 [34] gave an exceptional overview of physical properties of the working section of a wind tunnel. The contribution to ventilated walls at subsonic, transonic and supersonic velocities.

A considerable contribution to generalizing the problem of wall interference in wind tunnels was given by M. Garner, W. Acum, E. Rogers and E. Maskell in their treatise *Subsonic Wind Tunnel Wall Corrections* (AGARDograph 109) in 1966 [2]. They encompassed all previously published material and systematized it, with their personal contribution to satisfying the need to define wall interference effects for the ensuing ten years, i.e., until the computer became substantially applied in design and wind tunnel exploitation.

Basic principles of forming wall boundary conditions, which are today considered as classic, were set by B. Baldwin, J. Turner and E. Knechtel [47]. Interestingly, this work was published as far back as 1954 but it is still relevant. It requires a sole inclusion of the nonlinear concept of wall characteristics, conceived by J. Kacperzynski [36], and of the non-homogeneous wall conditions in transonic wind tunnels by Sayadian and Fonarev [48].

The year of 1978 saw the publication of the method by C. Capelier, J. Chevalier and F. Bouniol [21], which was at the time the most advanced research work in the field of wall interference in the ventilated wind tunnel walls. This work came as a logical result of the growing concept of self-correcting wind tunnels. This method yielded a novel approach to dealing with the effects of wind tunnel walls, i.e., that it was no longer necessary to know the conditions of crossflow through perforated walls. A serious drawback of this concept of calculation lies in the fact that the problem was set for an "infinite" segment of the working section in the wind tunnel.

In Canada in 1980 M. Mokry and L. Ohman [3,24] worked within the NAE (National Aeronautical Establishment) and the NRC (National Research Council Canada) to further develop this concept. They experimentally defined the boundary conditions to solve two-dimensional problems of effects of transonic wind tunnel walls. They invested considerable effort to pass on the results of two-dimensional wind tunnel testing and correlate them among the world's leading research centers, thus enabling mature status to the field of two-dimensional wall interference in transonic wind tunnels [3, 24].

Apart from the work by Canadian authors, there should be special notice of Lo's [22, 23] concept of experimentally defined conditions at the wind tunnel wall boundary. He measured two components of flow at a particular distance from the boundary: the static pressure and the angularity of flow. There is also my doctor's thesis [16], showing how the static pressure was taken directly at the wind tunnel walls, creating the basis for the definition first of boundary conditions for ventilated walls, and then of the two-dimensional interference occurring in a trisonic wind tunnel T-38 at Aeronautical Institute VTI Zarkovo (see Figures 6-8) [1 and 16-20].

Technically, Lo's concept had considerable weaknesses regarding the great complexity of measuring angularity adjacent to wind tunnel walls along the working section [8, 9]. On the other hand, my concept of forming boundary conditions from the measurements taken at the walls of the working section had a drawback of a great "disturbance" that permeated the results of measuring static pressure along the wind tunnel walls. However, it was proved to be of the same level as the "disturbance" generated by the equipment that measures static pressure, say tube-like, which is placed at a particular distance from the walls, as was the case in the experiments conducted at Canadian NAE research center [3]. These conclusions were confirmed by the integration performed as well as the results of the tests. It was shown that the Fourier's calculation method applied was rather insensitive to local inaccuracies in measuring static pressure at wind tunnel walls and thus formed boundary conditions [1 and 16-20].

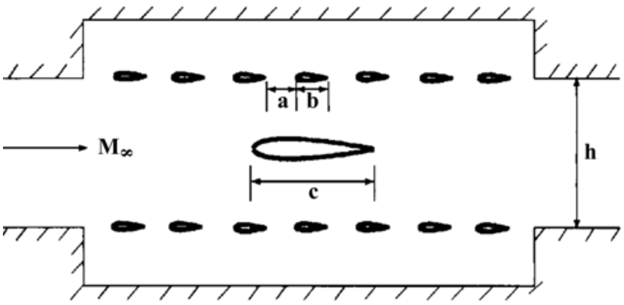

Fig. 12: Working section of the Low-Correction Wind Tunnel (Tolerant Wind Tunnel), The University of British Columbia, Vancouver, Canada [51].

Besides the afore mentioned concept of self-correcting wind tunnels, developed by Prof. W. Sears of Cornell University within CALSPAN institute [49] and also, developed by DLR in Göttingen Kryo-Rohrwindkanal (DNW-KRG) [50], there is a noteworthy concept by L. Kong, which evolved throughout his master's and doctor's theses at the University of British Columbia in Vancouver, Canada. This wind tunnel, named *Low-Correction Wind Tunnel* (*Tolerant Wind Tunnel*), had the walls made in the form of perpendicular wing segments of high aspect ratio, where each individual segment adjusts to the shape of the streamline at the boundary of the working station so as to least disturb the flow (see Figure 12) [51].

Moreover, there is an interesting and influential overview of both classic and contemporary solutions and methods of calculating the wind tunnel effects in two- and three-dimensional test conditions in AGARDograph 336 (by Editors B.F.R. Ewald) [52].

4 Conclusion

Viewed quantitatively, the empirical results from two-dimensional wind tunnel tests worldwide cannot on any account be considered final. This specially refers to subtle aerodynamic values, such as lift-curve slope, pitching-moment, or aerodynamic drag. Wall interference of the walls of any type: solid, perforated, or completely open, brings about such disturbance into the wind tunnel flow during two-dimensional tests that the results cannot be taken as valid even in engineering application, let alone in serious, fundamental research. This conclusion arises from all the works cited, along with the other research treating two-dimensional wind tunnel interference.

This treatise comprises the results of aerodynamic research that clearly show a great difference between the results of wind tunnel tests and those that correspond to free-flow conditions. The difference is usually ascribed to two-dimensional wind tunnel interference, without a precise definition of which or its inclusion in the results it is impossible to obtain an accurate quantitative result in two-dimensional wind tunnel tests.

So, final conclusion is that for aerodynamic development of modern airplanes only the combined use of the tools of numerical aerodynamic as well as of wind tunnel measurements leads to success.

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