GARTEUR AG18

ADAPTIVE WALL WIND TUNNELS

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CONTENTS

NOTATIONS .............................................................................................................................. 6

PREFACE .................................................................................................................................. 7

CHAPTER 1 ............................................................................................................................... 9

1. INTRODUCTION.................................................................................................................. 9

Objectives ................................................................................................................................. 9
Scope of work .......................................................................................................................... 10
Participating wind tunnels and models ................................................................. 10

CHAPTER 2 .......................................................................................................................... 11

2. WALL INTERFERENCE ASSESSMENT AND WALL ADAPTATION PRINCIPLES ................................................................................................. 11

2.1. Fundamentals.................................................................................................................. 11

2.1.1. General concepts ...................................................................................................... 11

2.1.2. Principles for linear flows ...................................................................................... 12

2.1.2.1. Two-component methods ............................................................................. 12

2.1.2.2. One-component methods ........................................................................... 13

2.2. Wall interference assessment ....................................................................................... 14

2.2.1. Wall constraints ..................................................................................................... 14

2.2.2. Survey of existing methods ................................................................................... 15

2.2.3. Passive methods for wall interference reduction ............................................. 18

2.2.4. Inhomogeneity of wall interference ..................................................................... 20

2.2.5. Wall pressure methods ....................................................................................... 21

2.2.6. Adaptive test sections ......................................................................................... 22

2.2.7. Discussion of existing methods ........................................................................... 22

2.2.8. WIA strategies used at the wind tunnels involved in the AG18 project .......... 23

2.3. Wall Interference Correctability with inferences on wall adaptation .................... 25

2.4. Two-dimensional wall adaptation for three-dimensional measurements .............. 26

2.4.1. Existing applications ............................................................................................ 26

2.4.2. HPS Strategy ....................................................................................................... 28

CHAPTER 3 .......................................................................................................................... 31

3. TEST CASES FOR WALL INTERFERENCE ASSESSMENT .................................... 31

3.1. Arrow-head model test case ....................................................................................... 33

3.1.1. The test section ................................................................................................... 33

3.1.2. The model .......................................................................................................... 33

3.1.3. The streamlining technique ............................................................................... 34

3.1.4. Results with the Arrowhead test case ............................................................... 35
CHAPTER 4

4. COMPARISON OF TWIG TEST RESULTS

4.1. Interference-free reference data

4.1.1. Introduction

4.1.2. The wind tunnel investigation

4.1.3. Reference data for GARTEUR

4.2. TWIG/NL300

4.2.1. T2 (FWTS)

4.2.2. S3Ch (FWTS)

4.2.3. S3Ch (PWTS)

4.2.4. PHST (SWTS)

4.3. TWIG/D750

4.3.1. DLR TWG (FWTS)

4.3.2. DLR TWG (VWTS)

4.3.3. BAe Warton 4ft (VWTS)

4.4. Results of High Productivity Strategies

4.4.1. T2

4.4.2. S3Ch

CHAPTER 5

5. OPERATIONAL ASPECTS OF FWTS VS VWTS
NOTATIONS

SYMBOLS

Ma, infinite Mach number
\( \alpha \), angle of attack
\( C_L \) lift coefficient
\( C_D \) drag coefficient
\( C_M \) pitching moment

ABBREVIATIONS

CWTS Closed (solid) Wall Test Section
FWTS Flexible Wall Test Section
PWTS Perforated Wall Test Section
SWTS Slotted Wall Test Section
VWTS Ventilated Wall Test Section
HPS High Productivity Strategy
WIA Wall Interference Assessment
WIAC Wall Interference Assessment and Correction
PREFACE

This report presents the results of a study by an action group as proposed by the Aerodynamics Responsables of the Group for Aeronautical Research and Technology in Europe: GARTEUR AD (AG-18). The study focussed on "relative merits" of flexible wall test sections versus conventional ventilated wall test sections, for a Mach number range that is of particular interest to modern transport aircraft development (0.70<Ma<0.85).

The ever increasing demands for higher accuracy and lower development cost are the measuring sticks, against which the respective merits of the different types of test section should be held. The group's primary objectives concerned data accuracy and reliability, productivity and operating cost, and systems reliability. Secondary objectives concerned the accessibility of the test section (for personnel, tools and instrument mounting) and its consequences in terms of versatility.

The report is the joint product of all action group members. For practical reasons only, some action group members have been made "editor" for a specific chapter or "co-author" for a specific section of the report. The work covered in a particular chapter or section, however, is most often the sum of contributions of the individual members. For that reason, no other references to individual persons have been made. Also, the final report has been endorsed by all action group members.

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January  1994  Amsterdam, The Netherlands
June  1994  Toulouse, France
October  1994  Warton, United Kingdom
March  1995  Meudon, France
September  1995  Göttingen, Germany
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Chapter 1

1. INTRODUCTION

Objectives

In spite of the existence of successful demonstrators, application of flexible wall test sections for production wind tunnels is still looked upon with scepticism, even to the extent that some degree of prejudice might be suspected. Therefore, a GARTEUR Aerodynamics Action Group (GARTEUR AD AG-18: "Adaptive Wall Test Sections") has been assigned the task to investigate, and wherever possible quantify, the relative merits of flexible wall test sections versus conventional ventilated test sections.

A comprehensive survey of adaptive wall wind tunnel technology and applications has been established by the AGARD FDP Working Group 12 in 1990. Their report (Ref. 1) covers, among other things, the history of adaptive wall development and surveys of test sections and techniques, including a prospective high-productivity strategy. The ICAW91 conference in Xian, China (Ref. 2) basically confirmed the AGARD FDP WG12 recommendations.

For easy reference, the recommended research areas (as formulated in Ref.1) are quoted here:

a. Systematic inter-tunnel experiments of the same model, including tests in conventional tunnels in order to test quantitatively the advantage provided by wall adaptation and the well-defined boundary conditions. It is recommended that two- and three-dimensional flows be tested.


c. Further experimental development of adaptive-wall and residual-correction methods for Group 2 flows. [i.e. subsonic free-stream, supersonic pockets reach the walls]

d. Further experimental development of adaptive-wall and residual-correction methods for Group 3 flows. [i.e. near-sonic or supersonic free stream]

e. Application of the recommended technique for unsteady flows in two-dimensional adaptive-wall tunnels for three-dimensional flows.

f. Continued development of methods for computing or experimentally reducing the effects of the side-wall boundary layer especially for two-dimensional and half-model testing, equally important for conventional and adaptive-wall wind tunnels.

The primary objectives of the present study concern recommendations a and b and "productivity" in a broader sense, also including maintenance and systems reliability aspects. The latter, however, require some extrapolation from the smaller test sections considered to the scale of production wind tunnels in the proper sense.

Recommendations c and d are treated as secondary objectives because of the limited possibilities available. In addition, attention is paid to the issue of accessibility (for personnel, tools,
lighting and auxiliary instrumentation) and its consequences in terms of operational versatility. The remaining issues (e and f) are beyond the scope of this action group.

**Scope of work**

The scope of work has been laid down in the proposal for the action group on "Adaptive Wall Wind Tunnels" (Ref. 3) and can be summarized as follows:

- Investigate the reliability of wall interference assessment (WIA) methods, since WIA eventually determines the accuracy of the test data, both for conventional and flexible wall test sections (to be elaborated upon in Chapter II).
- Investigate the effects of (possibly residual) wall induced velocity gradients on the model characteristics in order to quantify the "correctability" of the model data when that model is subjected to such gradients. Adaptive wall test sections are unique in creating the possibility of isolating "buoyancy" and "streamline curvature" (as a spin-off of their capability to virtually eliminate these interference components).
- Reconsider the definitions of wall interference corrections and their ranges of applicability.
- Develop and demonstrate a high-productivity strategy that, if the necessary hardware were available, would allow continuous sweep (as opposed to step/pause) testing in flexible wall test sections.
- Perform and compare inter-tunnel experiments of the same three-dimensional model, including conventional ventilated and flexible wall test sections.
- Make comparisons of ventilated and flexible wall test sections in terms of productivity and versatility.
- Explore the possibilities of flexible test sections to test up to and beyond $Ma=1$ because ventilated transonic test sections generally cover a Mach number range from subsonic up to low-supersonic.

**Participating wind tunnels and models**

The main body of test results acquired by the group is on the Transonic Wall Interference Generator (TWIG) geometry (Fig. 1.1 and 1.2). Two similar models were built to suit the different test section sizes, supported by two similar sting:

- TWIG/NL300: 300 mm span, built by NLR,
- TWIG/D750: 750 mm span, built by DLR.

The TWIG geometry has been designed (by NLR) to generate large interferences in order to enable comparisons with a "magnifying glass", so to speak. This led to the generic fighter geometry with strakes. At the same time, the model is reasonably simple to manufacture. A drawback is that the model pressure distributions are bound to be complicated and hardly accessible for linearized analyses.

TWIG/NL300 was tested in NLR HST (nominally interference-free), NLR PHST (slotted), ONERA T2 (flexible) and ONERA S3Ch (perforated and flexible, successively). TWIG/D750 was tested in BAe Warton 1.2m (perforated) and DLR TWG (perforated and flexible, successively). More detailed information is given in Table 1.1 and Figures 1.3 and 1.4.

Southampton University performed all two-dimensional testing (aerofoil NPL 9510 in TSWT) and the analyses of the effects of isolated gradients on that model. In addition, Southampton University provided the data on their "Arrow-Head" semi-span model for the purpose of validating the various wall interference assessment methods.
Chapter 2

2. Wall interference assessment and wall adaptation principles

2.1. Fundamentals

2.1.1. General concepts

Wall Interference in the broader sense is the aerodynamic interaction between the test article and the test section walls. In a narrower sense, it is the disturbance of the aerodynamic characteristics of the model due to the presence of confined, rather than unbounded, flow.

Originally, the test article was considered to be the model. Presently, the "test article" is often considered to comprise all hardware that happens to be present inside the test section (i.e. the model, its support system and possible auxiliary instrumentation). This definition allows a mathematical generalisation of the internal flow and a fictitious external (or outer) flow. In addition, disturbances due to the model support etc. are thus separated from wall interference effects and reduced to their unbounded flow behaviour.

Nowadays, it is recognized that the wall interference problem consists of three distinctive parts:
- Wall Interference Assessment (WIA)
- Wall Interference Reduction (WIR) or even Elimination
- Wall Interference Correction (WIC)

Throughout this report, all procedures applied start with and, for that matter, rely strongly on WIA. Consequently, the quality of the particular WIA method is determining the quality of the final product to a major extent.

In a way, the test data presented in this report benefit from WIR also, either passively (by means of "optimized wall ventilation") or actively (through wall adaptation). Essentially, the claim that an "optimized" ventilated test section has negligible wall interference in a wide variety of test conditions, implies that nature is presumed to effectively take care of wall adaptation for that test section.

In the end, WIA is necessary to establish the effectiveness of the WIR applied and to decide whether or not a further attempt at WIR shall be required or that the WI level is sufficiently low to allow (possibly "residual" or even "zero") corrections with enough confidence.

WIC is based on two fundamental assumptions:
- The flow around the model is "sufficiently close" to a corresponding unbounded flow condition,
- The differences can be "translated" into correction terms.

The confined flow can only be exactly identical to a corresponding unbounded flow if the interference velocities in the neighbourhood of the model are uniform. In that case, the corrections would be limited to mere shifts in the magnitude and/or the direction of the "free-stream" vector (\(\alpha\) and/or Ma). In general, the interferences will not be uniform.

Non-uniformities have been handled by either correcting the measured pressure distribution (typically for two-dimensional models and by applying CFD codes) or, more commonly, by correcting the measured forces according to "classical" similarity rules. In view of modern accuracy requirements, non-uniform wall interferences are a major issue. Obviously, buoyancy and variations in wall-induced upwash along the model deteriorate the accuracy with which the "effective" free-stream Mach number and angle-of-attack can be identified. In addition, such variations might have a significant effect on boundary layer development and/or shock location. For that reason, interference velocity gradients have been given special attention.

### 2.1.2. Principles for linear flows

For linear subsonic flows, WIA and WIR are faces of the same coin. Although different mathematical techniques (with possibly different efficiencies) are being used by different people, they all are based on the same principle. In this section, the principle shall be illustrated by means of Green's Third Theorem. For illustration purposes, mathematical rigour has been neglected, and a conceptual, rather than exact, approach will be followed. (A detailed description is, for instance, given in Ref. 64).

#### 2.1.2.1. Two-component methods

The basic principle is the following: Let a closed surface \(S\) divide space into two domains: \(D_i\) inside \(S\) and \(D_o\) outside \(S\). Let a function \(\phi\) be harmonic (i.e. satisfy the Laplace Equation) in domain \(D_i\) and let \(r\) be the distance from a given point \(P\) to any point of \(S\). Then, Green's Third Theorem states the surface integral:

\[
I = \oint_S \left[\phi \frac{\partial}{\partial n} \left(\frac{1}{r}\right) - \frac{1}{r} \frac{\partial \phi}{\partial n}\right] dS = \begin{cases} 
4\pi \phi(P) & \text{if } P \in D_i \\
2\pi \phi(P) & \text{if } P \in S \\
0 & \text{if } P \in D_o 
\end{cases}
\]

Note that if \(\phi\) is harmonic in \(D_i\), it must have one or more singularities in \(D_o\) and vice versa (unless \(\phi\) is a constant). Also, the original theorem may be reworked in order to obtain an expression in possibly more convenient quantities, such as perturbation velocity components, instead of \(\phi\) and \(\partial \phi/\partial n\). Therefore, methods that can be traced back to these properties have been called: "two-component methods".

From an engineering point of view, these properties of the integral may be re-phrased and exploited in the following manner:
For a point $P_i$ in domain $D_i$:
- The integral yields $\phi(P_i)$ if $\phi$ is harmonic in $D_i$,
- The integral yields ZERO if $\phi$ has singularities in $D_i$,
- If $\phi$ is a linear combination ($\phi_l$) of functions $\phi_i$ that are harmonic in $D_i$ and functions $\phi_o$ that have singularities in $D_i$, then the integral yields only the sum $\phi_l(P_i)$ and effectively eliminates all $\phi_o$ contributions.

In this formulation, the subscripts "i" and "o" may, of course, be interchanged without violating the statements.

For wall interference applications, the inner domain $D_i$ may be associated with the flow in the test section containing all mathematical singularities associated with the "test article" perturbation flow potential ($\phi_m$). The outer domain $D_o$ then represents a fictitious flow outside the test section, containing all singularities associated with wall interference ($\phi_w$). Consequently, $\phi_m$ is harmonic in $D_o$ and $\phi_w$ is harmonic in $D_i$. The two domains are separated by a closed surface $S$ which is generally chosen to closely follow the inside of the test section walls and which may extend to up- and downstream infinity or be closed by vertical planes.

Then, if the distributions of two "components" of the composite function $\phi_t$ are known on $S$, $\phi_w$ can be determined throughout $D_i$ whereas $\phi_m$ can be determined for any point in the outer flow domain $D_o$. The determination of $\phi_w$ is one way to perform wall interference assessment.

In addition, $\phi_m$ may (in principle) be applied to define unbounded flow streamlines to which the walls might be adapted to attain interference-free flow about the test article. Also, $\phi_m$ can be used to check possible "model representations" as applied in "one-component methods" (to be discussed below).

Complications:
- In case of a vertical closure downstream of the model, singularities belonging to $\phi_m$ may protrude into $D_o$ and, thus, be wrongfully attributed to wall interference unless appropriate corrective action is taken.
- A three-dimensional model support system must be attached to, or through, the test section walls and, thus, corrupts the definition of the surface $S$.
- Mimicking unbounded flow streamlines by means of mechanical wall adaptation is hardly practicable, particularly in three dimensions. It might, however, be applied theoretically and thus provide a means to improve the efficiency of CFD computations.

2.1.2.2. One-component methods

Interpreting the integral $I$ to represent source and doublet distributions on the bounding surface $S$, $I$ can be rewritten to contain only terms with either $\partial \phi / \partial n$ or $\phi$ (therefore called: "one-component methods"). In that case $\phi$ must be harmonic in the domain considered. Moreover, this alternative approach is NOT valid for a composite function $\phi_t$ as introduced in the previous section.

Quantities measured inside the test section generally correspond with the total perturbation flow ($\phi_t$). Consequently, $\phi_w$ must be isolated by subtracting $\phi_m$ from the measured quantity:
\[ \phi_W = \phi_t - \phi_m \]

Usually, \( \phi_m \) is estimated by singularity distributions that represent the "far field" perturbations attributed to the model (in corresponding unbounded flow). The distributions are chosen carefully and the strengths are usually derived from known model properties such as: model volume and measured model forces and moments, perhaps supported by additional data coming from the walls. The estimated \( \phi_m \) is called: "model representation".

One-component methods are used to assess wall interference in circumstances where it is impossible and/or impractical to measure two components on the entire control surface (in particular: ventilated wall test sections). An inherent drawback of the approach is that errors in \( \phi_m \) are directly transferred into spurious wall interference.

A one-component method, however, can be applied, without the aforementioned drawback, to control and/or determine the effects of wall adaptation. The flow inside an "empty" flexible wall test section, e.g., may be assumed to be harmonic. Wall adaptation may be considered to consist of controlling the normal velocity distribution on the adaptive walls. The corresponding perturbation flow velocities may thus be determined by means of a one-component approach. Inversely, the necessary adaptation can be calculated from a specified (i.e. desired) perturbation velocity distribution along an arbitrary line inside the test section. Such a line is called "target line" when this procedure is applied with the purpose of cancelling the wall interference along that line. (The interference may have been assessed by means of a "two-component method").

2.2. Wall interference assessment

2.2.1. Wall constraints

The flow about a model in a wind tunnel is different from free flight. This is due to the presence of the test section boundaries (e.g. solid walls, free jet), these differences are called wall interferences. Confined flow in an empty test section is only slightly different from an infinite flow, and these differences - they are also called wall interferences - are only due to the influence of boundary layer displacement thickness (in case of solid walls). Mostly these wall interferences can be neglected, or compensated by the appropriate divergence of the walls, at least they can be corrected for.

A three-dimensional flow about a model can be generated by superimposing an infinite translational flow and the velocities induced by the model. Additional model dependent velocities are generated by the presence of the tunnel boundaries and prevent the desired duplication of free flight conditions. Superimposing all these velocity fields, the wind tunnel flow, more precisely the flow in the test section of the wind tunnel, can be regarded as a disturbed and inhomogeneous flow, because the disturbances are not constant throughout the test section.

To correct wind tunnel data of a model to free flight conditions, classical potential theory is often applied - even today. Mathematical models are used to simulate blockage and lift influences separately and the results are then superimposed (Ref.4).

There are two main difficulties when proceeding this way:
The accuracy of the corrections determined by potential theory depends on the experience of the wind tunnel engineer, who uses this method. The mathematical model to be constructed, has to represent the flow in the test section of the wind tunnel - blockage and lift influences – in a realistic way. This is particularly difficult when dealing with separated flow.

The additional velocities induced by the test section walls are not constant throughout the test section. When superimposing these interference velocities with the homogeneous translational flow of the empty test section, we find the model being subject to an inhomogeneous flow field. Therefore the test results are only correctable to a limited extent. The constraints of the test section boundaries cause for example an undesired vertical velocity, which leads to a variation of the effective angle of attack along the centreline of the model, cf. Fig. 2.1, and the quarter chord line of the model, cf. Fig. 2.2. The variation of the vertical interference velocity in the longitudinal direction leads to an undesired streamline curvature of the flow in the tunnel, not present in free flight. So we have to deal with induced camber and effective twist of the wing, and the model in the tunnel is subject to different conditions than is the case in unlimited flow.

The former difficulty can be avoided when determining the necessary corrections using measured wall pressures. A model in a wind tunnel causes a wall pressure distribution representing the influence of the model. Evaluating the wall pressure distribution enables us to separate the model induced additional velocities, which are also present in free flight, and the wall induced additional velocities, the wall interferences. A model representation is not needed when proceeding this way. However, the variation of the interference velocities remains.

To avoid or at least to minimize the wall interferences of the flow in the wind tunnel, adaptive test sections have first been proposed as early as 1936 (Ref.5) and then in the seventies by Ferri and Baronti (Ref.6), Sears (Ref.7), and Goodyer (Ref.8). Wall adaptation may be achieved by shaping impervious walls of a test section to form a stream tube - emerging from the nozzle of the wind tunnel - corresponding to free flight conditions.

Another possibility to approach free flight conditions is the application of segmented suction and variable porosity in test sections equipped with porous walls. Also here, it is desired to approximate an effective wall contour, which corresponds to a stream tube of free flight. Porous walls are able to eliminate Mach waves originating from a model in supersonic flow. They can not be reflected and thereby affect model data. It should be mentioned that waves can be eliminated in two-dimensional testing in impervious-walled adaptive test sections, cf. Taylor (Ref.9).

Other possibilities to alleviate the wall interference problems (reduction of wall interference and its variation throughout the model region) are test sections with adjustable longitudinal slots (Ref.10) and two-dimensional adaptive test sections for three-dimensional measurements (Ref.8, 11, 12, 39).

### 2.2.2. Survey of existing methods

To correct wind tunnel results to free flight conditions, it is necessary to know the additional velocities caused by the presence of the walls. Only the additional velocities in $x$ and $z$ directions are taken into account. This results in a correction of the flow velocity or the Mach number, and a correction of the angle of attack, respectively. This is shown in Fig.2.3, also the co-ordinate system used is indicated in the figure. In general, the $y$-component of wall interference is small, even for models at an angle of yaw, because not only the yaw angle but also the area of the rudder-assembly
is small. Therefore it is legitimate to neglect the y-component of wall interference. This is not valid for fighter aircraft, because the above mentioned prerequisites do not apply here.

The relation of the angle of attack correction $\Delta \alpha$ and the wall induced additional velocity component in the $z$-direction is given by the following equation (Ref.13 and 4), and the lift interference factor $\delta_0$ is hereby defined:

$$\Delta \alpha = \frac{w_j}{U_\infty} = \delta_0 \frac{A_m}{A_{ts}} C_L$$

The interference factor is determined at the location of the model, this means the reference point of the model. In the equation above, $w_j$ is the interference velocity in direction of the $z$-axis, superimposed on the velocity $U_\infty$ of the undisturbed flow. $\Delta \alpha$ is the angle of attack correction, $A_m$ the reference area of the model - e.g. the area of a wing - $A_{ts}$ the cross-sectional area of the test section, and $C_L$ the lift coefficient of the model. The interference factor $\delta_0$ is a function of $(x,y,z)$, as it is not constant throughout the test section. At the location of the model this lift interference factor depends on the sweep-back angle $\phi$, the relative span $b/B$ (Ref.14), the cross-sectional shape and the type of the walls which could be solid, perforated or slotted. For example: the lift interference factor for solid walls is known to be positive, for free jets it is negative. For test sections being equipped with partially open walls, slotted or perforated, also known as ventilated test sections, there are cases where $\delta_0$ is zero.

The relationship between the blockage correction $\varepsilon$ and the additional $x$-component of the velocity induced by the presence of the walls is given below (Ref.4) This is also the equation defining the interference factor $\tau$:

$$\tau = \frac{u_i}{U_\infty} = \tau \left[ \frac{A_m}{A_{ts}} \right]^\frac{1}{2} \frac{\lambda_3}{\beta^3}$$

$\tau$ is the blockage interference factor or tunnel shape parameter for incompressible flow conditions, $u_i$ the additional velocity in $x$-direction, $\lambda_3$ the body shape parameter, $A_m$ is here the area of the model projected on a plane $x = \text{const}$ and $\beta$ the Prandtl-Glauert-factor accounting for compressibility effects. The blockage interference factor $\tau$ is also known as the tunnel shape parameter, because for incompressible flow conditions it depends only on the cross-sectional shape of the test section (at the position of the model). The model is here effectively represented by a sphere - mathematically by superimposing translational flow and doublet flow. The diameter of the sphere is given by $\sqrt{4A_m \lambda_3}$. The body shape parameter $\lambda_3$ relates the actual model geometry to the blockage interference factor. An alternative approach for slender bodies is the factor $T$, which is related to $\tau$ by $T = \tau \sqrt{\pi} / 2$ according to Ref.4:

$$\varepsilon = \frac{u_i}{U_\infty} = T \frac{V_m}{\left[A_{ts}\right]^3} \frac{1}{\beta^3}$$

where $V_m$ represents the volume of the model.

Both these interference factors characterize the interference velocities $u_i$ caused by the presence of the test section boundaries. These interference velocities $u_i$ do not exist in free flight.
Determination of wall interference using a model representation

The methods for wall interference determination making use of classical theory all need a mathematical representation of the model. Lift is represented by horseshoe vortices, blockage by doublets, sources and sinks. Determination of wall interference depends on the experience of the wind tunnel engineer, who has to build up the mathematical model close to reality. For cases with large regions of separated flow, this is a particularly difficult task. Also, in many cases data needed for the determination of the wall interference parameters do not exist and have to be estimated. In the case of pressure distribution measurements on an airplane model, the lift coefficient would be needed for correcting the angle of attack. If no force measurements were carried out simultaneously, the lift coefficient is not known and has to be estimated. Similar difficulties arise e.g. for the determination of the Mach number correction when there is flow separation over the model in the tunnel.

Wall interference velocities are not constant throughout the test section. It is unpractical to correct the data at various points of the model. Therefore the interference parameters are taken to be constant at the location of the model, or suitable average values are taken for correction. Only a global correction can be carried out.

Constant interference factors

In Figure 2.3 a test section of rectangular cross section and the co-ordinate system is shown. The section \( x = x_M \) contains the model, i.e. the reference point of the model. Blockage and angle of attack corrections are indicated. At the location of the model, the influence of lift only causes additional velocities in the direction of the \( z \)-axis. For test sections with solid walls they are directed upward, for free jets they are directed downward. These velocities change the effective angle of attack in comparison to the geometrical angle of attack. There is no additional velocity in direction of the \( x \)-axis in the case of lift, because the reference point of the model is on the test section centerline.

Model blockage causes only a change of the longitudinal velocity component. A correction of the flow velocity and the Mach number has to be made.

The computation of the interference factors is performed using the method of images (Ref. 4, 13, 15), when dealing with test sections of rectangular cross-sections, whether they have solid walls or they are free jets. Glauert gives a description of the method of images, which is given below:

"The conception of images, as used in aerodynamical problems, can be appreciated by considering a few simple examples. If two aeroplanes are flying horizontally side by side there will be no flow across the vertical plane of symmetry midway between the aeroplanes, and this plane could be replaced by a rigid wall without altering the flow in any way. Thus the problem of an aeroplane flying parallel to a vertical wall can be solved by introducing the image aeroplane on the other side of the wall and by considering the new problem of two aeroplanes flying side by side. Similarly the interference experienced by an aeroplane flying close to the ground can be solved by introducing the inverted image aeroplane below the ground. This method of introducing the appropriate image or set of images to represent the constraint of the boundary of the stream is capable of a very wide application, and is the method used for analysing most problems of wind tunnel interference."

(from Glauert (Ref.13), page 5)
The boundaries of test sections having rectangular cross sections can be represented by a doubly infinite set of images. The boundary condition for solid walls is \( v_n = 0 \) (the velocity normal to the boundary is zero), for free jets it is \( \Delta p = 0 \) across the boundary, approximated by \( u = 0 \). These boundary conditions can be fulfilled by adequate signs of the singularities representing the images of the model. The velocities induced by the images have to be summed up from \(-\infty\) to \(+\infty\), the contribution of the original model has to be excluded. The sum of all the velocities induced by the images is called wall interference. These velocities describe the corruption of the test conditions caused by the presence of the test section boundaries.

### 2.2.3. Passive methods for wall interference reduction

In the following, we assume an unchanged test section geometry. We will only investigate how the characteristics of the test section boundaries should be chosen to minimize the influence of wall interference on the test results.

It is well known that the interference factors are of positive sign for test sections with solid walls, and that they are of negative sign for free jets. It is therefore obvious, to suggest the use of test sections with walls that are partially open (free jet) and partially closed (solid walls). It could be shown that test section walls with appropriate longitudinal slots or appropriate wall perforation give zero wall interference, e.g. at the position of the model (Ref.16). A homogeneous boundary condition taking account of the partially open and partially closed test section boundaries, is fulfilled at a set of control points.

The wall interference parameters for test sections of arbitrary cross sections and arbitrary wall configurations can be determined applying the so called vortex lattice method - which makes use of the above mentioned homogeneous boundary condition (Ref.16, 17). This method is also qualified for solid walls and free jets of rectangular cross sections, thus allowing for these cases a comparison with the results of the method of images.

Presently there are doubts about the validity of the homogeneous boundary condition - see also Firmin and Cook (Ref.18) - but at least the results (vortex lattice method with homogeneous boundary condition) are qualitatively useful and show some trends. When using the vortex lattice method for wind tunnel wall interference determination (Ref.19, 20) the test section boundaries have to be subdivided into a large number of panels. The centrepoint of each panel is the control point, on which the appropriate boundary condition is fulfilled. A mathematical model, causing lift or blockage, violates the boundary condition. The vortex strengths of the vortex lattice, which represents the test section boundary, are determined so that the sum of the velocities induced by the model and the vortex lattice just fulfils the homogeneous boundary condition required. The influence of the vortex lattice alone then represents the wind tunnel wall interference.

### Slotted test sections

For the solid parts of the walls, the slats, the boundary condition is \( v_n = \frac{\partial \Phi}{\partial n} = 0 \) (zero normal velocity), while for a free jet the boundary condition is \( u = \frac{\partial \Phi}{\partial x} = 0 \) (constant pressure through the boundary). For walls with longitudinal slots - the boundaries are partially open and partially closed - an approximate boundary condition was derived by Baldwin et al. (Ref.17):
The constant $K$ is the slot geometry factor. The limiting case $K = 0$ gives (as expected) the boundary condition for a free jet, while $K \to \infty$ yields the boundary condition for solid walls. An approximate relationship for the slot geometry factor and the factor $P$ derived from $K$ is given by the following equations (Ref.16):

$$K = -\frac{1}{\pi} \ln \left( \sin \left( \frac{\pi a}{2l} \right) \right)$$

$$F = \frac{2K}{H}$$

$$P = \frac{1}{1 + \frac{2K}{H}} = \frac{1}{1 + F}$$

$H$ is the tunnel height, $l$ is the slot separation, $a$ is the slot width, and $a/l$ is the open area ratio.

Fig. 2.4 shows the lift interference factor $\delta_0$ as a function of the slot geometry factor $K$ or $P$ respectively for a test section of rectangular cross section. The lifting system is a wing of rectangular planform having a relative span of $b/B=0.7$ ($b$ is the wing span and $B$ is the tunnel width). It can be seen that $\delta_0$ is zero for $P = 0.5$ and that the value of $\delta_0$ for the limiting cases of solid walls and a free jet are reproduced properly by the vortex lattice method. These are the two cases which allow a comparison with the method of images at least for test sections of rectangular cross sections.

**Porous test section walls**

For a test section with porous walls $\delta_0 = 0$ can also be achieved. According to Goodman (Ref.21) the approximate homogeneous boundary condition is as follows:

$$\frac{\partial \Phi}{\partial x} + \frac{\beta}{R} \frac{\partial \Phi}{\partial n} = u + \frac{\beta}{R} v_n = 0$$

$\Phi$ is the velocity potential, $vn$ is the velocity component normal to the wall and $R$ is the wall porosity parameter. The factor $\beta$ takes account of the influence of compressibility according to the Prandtl-Glauert approximation.

The assumption is that the flow through the perforated wall is proportional to the pressure drop across the wall. This boundary condition is a linearized approximation of a viscous flow through a porous medium. The second assumption is that the pressure of the plenum surrounding the perforated test section is equal to the static pressure $p_\infty$ of the flow.

The porosity factors $Q$ and $R$ are given by the following equations:

$$\frac{\partial \Phi}{\partial n} = v_n = \frac{R}{\rho_\infty u_\infty} \Delta p$$
\[ Q = \frac{1}{1 + \frac{\beta}{R}} \]

\( \Delta p \) is the pressure drop through the perforated wall, \( \rho_w \) the density and \( U_\infty \) is the velocity of the undisturbed flow. The boundary condition is composed of the condition for solid walls \((v_n = 0)\) and the condition for a free jet \((\Delta p = 0 \text{ or } u = 0)\). (Because of the influence of the model, the local static pressure \( p \) at the test section boundary is different from \( p_\infty \), the static pressure of the undisturbed flow.) The porosity parameter \( R \) depends on the wall geometry and the Mach number and has to be determined experimentally for every specific wall configuration.

Fig. 2.5 shows the dependence of the lift interference factor \( \delta_0 \) on the porosity factor. The two cases of a rectangular wing and a swept wing are presented here. It can be seen that in case of a rectangular wing, the lift interference factor \( \delta_0 \) is zero for \( Q = 0.45 \). The lift interference factor has been computed "at the location of the model", i.e. at \( x = x_m, y = z = 0 \).

The method and the computer program presented in (Ref.20) have been extended in (Ref.14) to the case of model blockage (without lift). As shown in Fig. 2.6, in case of model blockage, the blockage interference parameter \( \tau \) is zero for \( P = 0.59 \). This is another slot geometry factor as in the case of lift. Also for porous walls - see Fig. 2.7 - lift interference factor and blockage interference parameter are not zero for the same porosity factor. It is not possible to achieve zero lift and blockage interference simultaneously by test sections with slotted walls or by test sections with perforated walls. So, when selecting a wall configuration for minimum wall interference, a compromise has to be found in view of the specific interests of the measurements to be carried out.

The lift interference factor \( \delta_0 \) depends on the cross-sectional shape of the test section. For solid walls and for free jets the results of the vortex lattice method and the method of images can be compared, and show good agreement. For small ratios of \( H/B \) the lift interference factors \( \delta_0 \) for solid walls are smaller than for large ratios of \( H/B \). Even smaller lift interference \( \delta_0 \) can be achieved by introducing perforated walls, but still there is a dependence on the cross-sectional shape of the test section.

2.2.4. Inhomogeneity of wall interference

Hitherto it had been assumed that the wall interference parameters were constant for the model in the tunnel and only depended on the cross-sectional shape of the tunnel (therefore the name tunnel shape parameter for \( \tau \)) and the wall configuration (solid walls, free jet, slotted or perforated). Only the interference parameters at the position of the model were of interest and they resulted e.g. in a correction of the angle of attack for the model as a whole.

In reality the wall interferences depend on the position of the point under consideration inside the test section, and an elevator unit downstream of the main wing of a wind tunnel model experiences a different angle of attack correction than does the wing itself. This results in a pitching moment correction. Also along the span of the wing \( \delta_0 \) is not constant. In the case of a square solid walled test section the effective angle of attack increases towards the wing tip, caused by the presence of the walls. (For other values of the ratio of tunnel width \( B \) to tunnel height \( H \) it can also decrease towards the wing tip.) This fact corresponds to an effective twist of the wing experienced in the wind tunnel, because the angle of attack is not constant along the span. Also the \( \delta_1 \), which is
the gradient $\partial \delta_0 / \partial (x/H)$, represents the additional effective camber of the wing induced by the tunnel walls. A lifting wing in a wind tunnel is exposed to a curved flow field due to wall interference, and this is aerodynamically equivalent to an additional camber of the wing profile (Ref.20).

There are cross-sectional shapes - in combination with model sweep – for which the $\delta_0$ distribution is approximately constant along the wing span for finite sized models. In this case the problem associated with additional effective twist does not exist. The necessary pitching moment correction and the correction because of the additional camber still remains. It has already been mentioned that wall interferences due to lift and wall interferences due to blockage behave differently.

The increase of the angle of attack correction, also the spanwise increase of the angle of attack correction and of course the resulting inhomogeneity of the flow about the model can be considerable. Especially at the wing tips $\delta_0$ as well as $\delta_1$ have large values. It is then no longer justified to regard the interference factors as being constant at the position of the model.

2.2.5. Wall pressure methods

By using wall pressure methods, the wall interferences can be determined by simply evaluating the wall pressure distribution. There exist methods with and without model representation.

The "influence function method" proposed by G. Schulz for test section with solid walls does still need a model representation (Ref.22). Based on the method of images, the method of G. Schulz makes use of the fact that there are locations at the wall where the wall pressures are independent of specific model features, e.g. the model span. Therefore a standardized model representation can be chosen, and only very few wall pressures have to be measured. It seems questionable whether the optimal positions for the wall pressure measurements do really cover all possible cases for both lift and blockage influences, with one set of tables required for each. Blockage and lift interferences have to be computed separately.

The method reported by Hackett und Wilsden (Ref.23), also needs a model representation. Only very few wall pressures have to be measured. Again the method of images is employed to compute the wall interferences on the basis of measured wall pressures. The wind tunnel model is mathematically represented very simply by just a few singularities. At the beginning, the position and the strength of these singularities is unknown. A system of equations is set up, which links the measured wall pressures with the unknown positions and strengths of these singularities. The more wall pressures available, the more accurately the model representation can be realized. The corrections needed can be determined with the aid of the method of images.

A wall pressure method for perforated walls is given by Mokry (Ref.24), but this method also needs a model representation and the knowledge of the force coefficients.

Finally Ashill and Weeks (Ref.25) suggest the application of Green's theorem to the problem of wind tunnel wall interference, using quantities measured at the wind tunnel boundaries like $u$ and $v_n$. This method does not need any model representation. In Ref.26 the same authors describe the application of Green's theorem to the determination of wind tunnel wall interferences inside the test
section, now extending the method to the determination of wall adaptation. This had already been proposed in Ref.27. A detailed theory and test results can be found in Ref.28.

2.2.6. Adaptive test sections

The requirement to perform interference-free measurements in the transonic regime led to the development of adaptive test sections (Ref.30). In adaptive test sections, the walls are deformed in a way to build up a stream tube of free flight originating from the nozzle of the wind tunnel. To determine the wall displacements needed (i.e. the wall shape), the longitudinal component $u$ and the normal velocity component $v_n$ have to be determined at the position of the walls. The computation of the interference-free wall shape can be performed iteratively or in a single step. When the wall is initially contoured, the normal velocities at the wall $v_n$ are not zero, but correspond to the inclination of the wall. The computation of a new wall shape can be performed starting from any given wall shape.

A test section permitting a three-dimensional wall adaptation has been described in (Ref.29). This flexible adaptable test section (known as DAM) is a rubber tube of circular cross section. The wall adaptation procedure needs only one single step for the computation of the interference-free wall shape, it is not an iterative procedure. The flow field inside the test section is given by the potential $\Phi_0$ which is normally not known. On the other hand, the velocity components $u_0$ and $v_0$ are known by measuring the wall pressures and the wall displacements. An additional wall displacement generates an additional perturbation of the flow inside the test section, corresponding to an additional perturbation potential. In the first instance this additional potential is mathematically represented by a Fourier series for the flow field inside the test section and the fictitious outer flow field. In a single computational step the new wall shape can be determined by matching the inner with the outer flow field.

The procedure developed for the rubber tube test section does not allow the determination of residual interference - i.e. the check that the wall adaptation is correct. Also it is only designed for circular test sections. Nevertheless the force and pressure coefficients of models tested in this wind tunnel prove that this test section generates nominally an interference-free flow. The model then does not "feel" the presence of the wind tunnel boundaries.

Interference-free flows can also be achieved by using perforated walls, when segmented suction is used. The control surface, where the velocities $u$ and $v_n$ are measured, is then at a certain distance from the wall. A wall contour can approximately be realized by segmented suction, which corresponds effectively to a stream tube of free flight (Ref.31).

2.2.7. Discussion of existing methods

When using slotted or perforated test sections, wall interferences cannot fully be eliminated by using the above mentioned passive methods. It is possible to find the theoretical optimum conditions using the vortex lattice method together with homogeneous boundary conditions (Ref.20, 32), but the results have to be viewed in the light of the simplifying assumptions of the slot geometry factors and the porosity parameters. It is an additional difficulty that the interference factors for lift and for blockage respectively give different zero interference conditions, and that a model representation is always required. In addition, the “theoretically optimum conditions” must still be realised in hardware, for an existing test section. Moreover the wall characteristics may change by adding instrumentation.
So far as the method of images is concerned, it can only handle test sections of rectangular cross sections, it is only valid for free jets or solid walls and it needs a model representation. Also it depends on the experience of the user.

The wall pressure method of G. Schulz (Ref.22) is an attempt to overcome the difficulties of a detailed model representation by introducing a standardized model representation. It seems questionable whether the "influence functions" given by G. Schulz cover all cases of models in wind tunnels, e.g. cases of separated flow.

The method of Hackett and Wilsden (Ref.23) again is based on the method of images and is therefore only valid for test section of the solid wall type. It uses a standardized model representation with only a very few singularities, thus not allowing a detailed representation of the model. The method given by Hackett and Wilsden has been modified by different authors.

The method reported by Ashill and Weeks (Ref.25, 26), see also Ref.33, can be used for the determination of wall interferences in test sections with straight solid walls and adapted walls (Ref.35). It only needs measured wall pressures and wall shape for the computation and does not need any model representation. It is not suited for slotted or perforated test sections (the flow direction is not measurable near the walls). Ashill and Weeks do not include the evaluation of wall interferences at the position of the walls, which would mean the determination of wall adaptation.

The wall adaptation procedure for the rubber tube test section DAM is only valid for the determination of wall adaptation in test sections of circular cross sections having solid flexible walls. The wall adaptation computation is performed in one single step with the aid of measured wall pressures and measured wall displacements. A model representation is not required. This method is not suited for test sections of rectangular cross sections and this method does not permit the determination of wall interference in test sections with aerodynamically straight walls or of residual interference in test sections with already adapted walls.

The technical realization of a fully three-dimensional wall adaptation as it can be achieved in the rubber tube test section (DAM) is impractical. The minimization of wall interference is more practical. One approach to minimize wall interference is to equip test sections of rectangular cross sections with adjustable longitudinal slots. The so-called two-step-method (Ref.28) is able to determine the residual wall interferences in such a test section.

Another approach to minimize wall interference is given by the two dimensional wall adaptation for three-dimensional models. Upper and lower walls are adapted in a plane manner, in order to nominally eliminate the test wall interferences at a chosen target line. The wall adaptation of the upper and the lower walls respectively can be determined using the so called Wedemeyer/Lamarche procedure which is also known as the VKI-procedure (Ref.11). This method is very fast and needs only about 0.1 seconds on a modern work station (Ref.36). It does not allow the determination of residual wall interference all over the test section. Therefore a check, whether the wall interference on the test section centreline is really zero after wall adaptation, is not possible with this method. This can be performed by a wall pressure method also described in Ref.28 and 35.

2.2.8. WIA strategies used at the wind tunnels involved in the AG18 project

TWG
The WIA method for straight and adapted walls is based on the application of Green's theorem (Ref.25). This method allows the computation of wall interferences or residuals everywhere in the test section, including the test section walls. For the case of determining the residuals at the position of the model, only about 20 values have to be determined. This would need about a tenth of a second.

For the application of this method, the wall pressure distribution on all four test section walls has to be known, but it does not need a model representation.

**T2**

The WIA method used at T2 (Ref.39) is due to Y. Le Sant (S3Ch) and is briefly described in the paragraph below.

**S3Ch**

The WIA method used at S3Ch is due to Y. Le Sant (S3Ch) and is more detailed in Ref.38. The main features of the method are:

- The effect of lateral walls are separated from the effect of the top/bottom walls
- Use of a model representation
- Lateral wall interference computed with the image method
- Top/bottom wall interference computed with a 3D integral method
- The model representation is identified by using top/bottom wall pressure measurements
- The WIA method is able to compute the wall effect in all test section space
- A target line can be defined

The WIA method needs a model representation (space positions of sources, doublets, vortices) and the pressure measurements at the top/bottom walls.

**Southampton University**

The method used for wall interference assessment at the University of Southampton is based on that developed by Ashill and Weeks (Ref.22) for solid straight walled test sections, modified to account for curvature in the top and the bottom walls (Ref.35). Measurements invoked include wall pressure distributions and the coordinates of the curved walls assessed at each jack. In two-dimensional testing the wall pressures are those provided along the centrelines of the flexible walls at the jack locations. Half-models are normally used in three dimensional testing and in these cases the measured wall pressures are extended to include five rows of tappings on each flexible wall and similarly on the sidewall opposite to the model as described in chapter III.1. During 3D model-in testing the code uses the measured pressure coefficients referenced to those values existing in the empty aerodynamically straight test section. In 2D model testing the wall pressure signature is not referenced for practical reasons including the existence of a rather large pressure footprint. The output is distributions of wall-induced blockage and upwash, along the lateral centreline of the test section at any z for 2D tests, and anywhere in the test section for 3D tests.

**NLR**

The method used at NLR for the determination of residual wall interferences is based on Green's theorem. This method was derived to compute wall induced velocities on the tunnel centreline from a sparse set of wall pressure distributions (Ref.33). To achieve this, it heavily uses all available arguments about symmetry etc. This limits the applicability, however, for positions outside the centreline.
2.3. Wall Interference Correctability with inferences on wall adaptation.

Corrections for the effects of wall interference may be divided into primary and secondary. Primary corrections are applied to account for the wall-induced perturbations in streamwise velocity and flow angularity existing at a point in the model. Secondary corrections may be made for the gradients existing in the wall-induced perturbations.

The comments in this section are all based on the assumption that the WIA is reliable, and that it is used subsequently to determine corrections. In these circumstances primary corrections may be applied immediately, leaving the question of the application of secondary corrections. An ideal situation with respect to secondary corrections would be one where there was confidence in the knowledge of the effects of wall-induced gradients on all of the aerodynamic coefficients of concern. These might include, as a minimum, the lift, drag and pitching moment coefficients. In such circumstances it might seem that test sections designed to reduce interference, having ventilated or adaptive walls (there are others), would not be required on the argument that both WIA and C are reliable.

This is unlikely. Transonic test section designs will be required for testing through Mach 1 in order to avoid applying very large corrections. For example a closed test section will choke at a reference Mach number below 1. Progressively larger corrections would be required, quickly becoming inconceivable, with increase of the desired reference Mach number above this choking value.

Even with the blockage relieved in a transonic test, such that the user is comfortable with the primary correction, it is unlikely that the same can be said at the present time about secondary corrections because of the incomplete state of knowledge of secondary interference effects. A similar situation probably exists in some low speed tests at high lift, that is a need to apply uncomfortably large secondary corrections in circumstances where there is uncertainty of the effects of wall-induced gradients. Therefore correction procedures will be required, although the nature of secondary corrections in not fully understood. References 4 and 64 contain some sources of information on the subject but the state of current knowledge is such that the coverage is incomplete.

It happens that the adaptive wall test section can be used to provide information on secondary interference effects. They have the ability, possibly uniquely among test section types, of permitting the introduction of a controlled wall-induced gradient in a chosen velocity component. This has been exploited in two-dimensional flow (Ref.65 to 68) and has led to a better understanding of the effects of gradients in wall-induced upwash on some of the aerodynamic coefficients of interest, and to the demonstration of some effects of blockage gradients. The work is very incomplete in several respects. The range of variables explored so far, such as aerofoil section, Mach number and incidence, is rather restricted and is confined to two-dimensional flow. However the work continues and may be expected to add gradually to the breadth of knowledge of the subject of secondary interference effects. Eventually, when extended to three-dimensional shapes and an adequate range of variables, the product of this type of investigation will be of general use in aerodynamic testing in improving the accuracy of wind tunnel data.

From the point of view of the advancement of adaptive wall technology it would be very useful to understand secondary effects in order to define and broaden tolerances on the required quality of wall adaptation with a view to applying this knowledge in due course to improving productivity. One avenue which might be explored in the meantime to improve tunnel productivity is that of exploiting
any tolerances on aerodynamic coefficients which are acceptable without correction, such as established for example in reference 69. In summary, two actions are required: to learn how, in adaptive wall testing to best exploit existing permissible tolerances in aerodynamic coefficients, and to extend the understanding of the effects of components of wall-induced velocity gradient in order to broaden the tolerance bands by means of the application of secondary corrections.

2.4. Two-dimensional wall adaptation for three-dimensional measurements

In principle, two-dimensional wall adaptation can eliminate wall interference on a prescribed target line for three-dimensional models. Mostly the test section centreline is selected as target line. Very fast wall adaptation computation schemes are available for determining the adapted wall shapes (Ref. 11, 34, 38) in a single iterative step, because in most cases the changes of model potential due to the changes in wall shape can be neglected. The two-dimensional wall adaptation can be achieved by different technical realizations as can be seen in the list of the tunnels hereafter.

2.4.1. Existing applications

A list of existing adaptive test sections can be found in Ref. 37 and out of it the list of the relevant two-dimensional adaptive test sections is repeated here in a tabular form, some updates have been made.

**List of the facilities:**

<table>
<thead>
<tr>
<th>Country</th>
<th>Organisation</th>
<th>Wind tunnel name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Belgium</td>
<td>VKI, Brussels</td>
<td>TWT S1</td>
</tr>
<tr>
<td>2. France</td>
<td>ONERA, Chalais-Meudon</td>
<td>S4 L Ch</td>
</tr>
<tr>
<td>3. France</td>
<td>ONERA, Chalais-Meudon</td>
<td>S5 L Ch</td>
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<tr>
<td>4. France</td>
<td>ONERA, Chalais-Meudon</td>
<td>S3 L Ch</td>
</tr>
<tr>
<td>5. France</td>
<td>ONERA-CERT, Toulouse</td>
<td>T2</td>
</tr>
<tr>
<td>6. Germany</td>
<td>DLR Göttingen</td>
<td>HKG</td>
</tr>
<tr>
<td>7. Germany</td>
<td>DLR Göttingen</td>
<td>TWG</td>
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<tr>
<td>8. Germany</td>
<td>DLR Göttingen</td>
<td>KRG</td>
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<tr>
<td>9. Germany</td>
<td>ILR Berlin</td>
<td>TUB (2D)</td>
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<tr>
<td>10. Italy</td>
<td>Istituto di Aerodinamica</td>
<td>AWWT</td>
</tr>
<tr>
<td>11. Peoples Republic of China</td>
<td>Northwestern Polytechnical University</td>
<td>NPU AWWT</td>
</tr>
<tr>
<td>12. United Kingdom</td>
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<tr>
<td>13. United Kingdom</td>
<td>National Physics Laboratory NPL</td>
<td>20 x 8 inch</td>
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<td>SSWT</td>
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<tr>
<td>15. United Kingdom</td>
<td>University of Southampton</td>
<td>TSWT</td>
</tr>
<tr>
<td>16. United States</td>
<td>AFWAL/FDL</td>
<td>9 in. Pilot</td>
</tr>
<tr>
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</tr>
<tr>
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<td>25 x 13 cm</td>
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<tr>
<td>19. United States</td>
<td>NASA/ARC</td>
<td>2 x 2 ft</td>
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<tr>
<td>20. United States</td>
<td>NASA/LaRC</td>
<td>0.3 m TCT</td>
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</tbody>
</table>
All these adaptive test sections are not detailed in this sub-chapter. Only the adaptive test sections involved in the AG18 project are briefly described below and in table 2.1.

**Facility Designation:** TWG

**Organization:** DLR-Göttingen

**Country:** Germany

**Description:**

The TWG is a continuously working wind tunnel with three exchangeable test sections for subsonic, transonic and supersonic speed ranges. The 4 (subsonic) and 8 (supersonic) stage axial compressor has an electric power supply of 12 MW. An auxiliary suction plant with radial compressors for the transonic test section (perforated walls) is also available. For flexible handling of the different components all test sections, the model support and the nozzles have an air-cushion transport system and the plenum chamber can be opened by a 10 m wide sliding door. All of the three test sections are 1 m x 1 m and are 4.5 m long. The two-dimensional adaptive test section has flexible top and bottom walls, the sidewalls are parallel. The shaping of these walls is performed by 21 jacks on the top wall, and by 20 jacks on the bottom wall. For 2D models and 3D models, very fast adaptation procedures are available. For measurements on wing profiles, there is an adaptation procedure based on the Cauchy integral formula (Ref.37). For the three-dimensional case, the Wedemeyer/Lamarche or VKI procedure is used [11], the residual wall interferences are computed by a method based on Green's theorem [28]. The Mach number range is from 0.3 to 0.93. To date a variety of 2D and 3D models has been tested in this facility.

http://www.wk.go.dlr.de/Facilities/TWG/index.html

**Facility Designation:** T2

**Organization:** ONERA

**Country:** France

**Description:**

The ONERA T2 adaptive wall wind tunnel (Ref.39) is one of the most active facilities in the development of test techniques in use at this time. The tunnel is an injector driven closed circuit transonic cryogenic facility (run of 2 minutes). The adaptive wall test section is 39.0 cm wide, 37.0 cm high, and 1.4 m in length. All four walls are solid with the top and bottom walls being flexible. These flexible walls were placed in operation in 1978 and first operated at cryogenic conditions in 1981 (Reynolds number of 25 millions based on a model chord of 0.15 m). For 2D models, an ONERA adaptation procedure is used; it is based on the split of the flow velocity near the flexible walls in four terms representing pure effects of blockage, wake, lift, camber (Ref.39). For 3D models, the Wedemeyer/Lamarche procedure is used (Ref.11). For both 2D and 3D models, the complete adaptation is performed in a few seconds.

The T2 facility has been extensively used to produce both two- and three-dimensional aerodynamic data. Four airfoil shapes as well as semi-span and sting mounted models are included in the test programs. Both basic research and industrial support programs are supported in this facility.
**Facility Designation:** S3 Ch

**Organization:** ONERA

**Country:** France

**Description:**

The ONERA S 3 Ch Wind Tunnel is a two-dimensional adaptive wind tunnel. It is a continuous flow closed return wind tunnel. The tunnel is driven by a two-stage compressor with variable pitch blades, compression ratio is 1.2, the Mach number ranges from 0.3 to 1.3. The contraction ratio is 28, the test section is square 0.8 m x 0.8 m and is 2.2 m long. There are exchangeable doors in the sidewalls, facilitating easy model access. The sidewalls are solid and they are parallel, top and bottom walls are flexible. The wall shapes can be adjusted by 15 jacks on top and bottom walls, respectively. Top and bottom walls are equipped with four lines of pressure orifices each (Ref.38).

**Facility Designation:** Transonic Self-Streamlining Tunnel

**Organization:** University of Southampton

**Country:** United Kingdom

**Description:**

The University of Southampton Transonic Self-Streamlining Tunnel (TSWT) is an intermittent, closed return, induced flow tunnel which operates at atmospheric stagnation conditions. The test section is 15.24 cm square and the controlled walls are 111.8 cm long. There are 20 positioning jacks on each wall but only 19 are used in the adaptation process. The flexible walls as well as the sidewalls are solid. Control of the flexible walls is completely automated and under computer control. The maximum Mach number capability of this facility is quoted to be about 1.8. This facility has been extensively used for both 2D and 3D tests. Models tested include three 2D airfoils, two sidewall mounted wings, and a sting mounted wing-body model. Most of the models were also tested in other facilities to provide data for comparison. This tunnel is still operational and is being used primarily to develop three-dimensional testing algorithms and techniques for two-dimensional testing through Mach 1.

### 2.4.2. HPS Strategy

Chapter 5 of the Ref.1 (author: J. Smith, from NLR) details the constraints of a production wind tunnel and the different problems set by the introduction of adaptive test sections to ensure efficiency and versatility. So these aspects will not be mentioned in this report.

Nowadays, production wind tunnels are working in continuous testing mode, i.e. measurements are performed while test conditions (usually angle of attack) are gradually changing with time. The aim of the HPS action within the AG18 project is to demonstrate the feasibility of wall adaptation in continuous testing mode (angle of attack evolution with time only).

Because no adaptive wind tunnel of the AG18 group was able to perform continuous testing mode, the HPS action consists to simulate a continuous change of incidence by a series of independent tests, the incidence being incremented from one test to the following ($\alpha_{N+1}=\alpha_N + \Delta\alpha$; $\alpha_0=0^\circ$ and $\Delta\alpha=1^\circ$ or $2^\circ$).
A major constraint in a production wind tunnel is time. Even if wall adaptation computation could be performed in a very short time (some tenths of a second), it is not feasible to calculate the optimum wall shape for the data point taken at a specific moment. On the contrary, at that moment, the adaptation strategy could be predictive for the next data point, the next angle of attack being known and enough time being available for the next wall shape computation. Reasonably, the prediction must be based on a one-step adaptation method and a more or less complex extrapolation procedure. The effect of the imperfection of the wall adaptation is assumed to be sufficiently small to be correctable by a residual interference correction method.

In consequence, the HPS action of the AG18 group consists of tests to evaluate different prediction procedures. The two wind tunnels concerned by this action are S3Ch and T2 facilities. The common process adopted for the HPS simulation at constant Mach number $Ma$ is the following for the data acquisition point number $N$ corresponding to the angle of attack $\alpha_N$:

1. the predicted wall shape for $\alpha_N$ is positioned while the model incidence is reaching $\alpha_N$.
2. the data measurement (aerofoil characteristics, wall shapes and pressure distributions) is performed.
3. the "adapted" wall shape at $\alpha_N$ is computed by the one-step method using the previous wall data measurement.
4. the predicted wall shape for $\alpha_{N+1}$ is determined by the extrapolation procedure, using "adapted" wall shapes at $\alpha_N$ and $\alpha_{N-1}$, and is positioned while the model incidence is reaching $\alpha_{N+1}$ (return to sequence 2).

The $\alpha$-sweep begins by two special points at $\alpha_0$ and $\alpha_1=\alpha_0 + \Delta \alpha$. For each of these two angles of attack, a complete wall adaptation (optimum wall shape obtained after several computation iterations) is carried out before data measurement.

The wall adaptation would reduce wall interference significantly and thereby increase the data quality and reliability. Nevertheless the application of the described prediction procedure assumes that the difference between predicted and complete adapted wall shapes does not induce significant changes of the model flow, like emergence or suppression of a separation flow. But the risk of such a drawback seems to be small, due to the gradually changing, always partly adapted for, test conditions during the $\alpha$-sweep. This behaviour assumes that the angle of attack increment is not too large.
Chapter 3

3. Test cases for Wall Interference Assessment

The correct assessment of wall interference, in terms of the magnitudes of wall-induced velocity perturbations, is central to the operation of adaptive wall test sections and is an important component of the correction procedures employed in many other wind tunnels. The users of adaptive wall test sections have each developed WIA procedures based on the use of inputs derived from test data, and this chapter is confined to consideration of this particular approach to the assessment of wall interference. The purpose of the two exercises covered by this Chapter was to compare the outputs of several WIA methods, using common inputs. It was felt that the comparison might suggest the reliability, or otherwise, of this area of AW activity. Strictly the codes are only applicable to FWTS's but they are very similar to the codes for conventional solid wall test sections which employ test data, including wall data, in their assessments.

Similarities and differences in the rôles of WIA in test sections designed for use up to transonic speeds are briefly highlighted, before moving to the exercises. This is in order to emphasise that a WIA procedure is central to the clearance of raw model data for corrections from most wind tunnel testing and types of test sections, the exceptions being, perhaps, supersonic and hypersonic tunnels. The model data correction procedure comprises WIA followed by data correction when necessary; these are two separate operations.

In conventional test sections the wall interference varies in severity dependent on features of the model such as its geometry and lift, on the test Mach number and on the nature of the walls:

- in some adverse circumstances the interference in CWTS's can be quite large which places elevated demands on accuracy in the assessment of its magnitude. However the source of information for this type of assessment of interference (that is the correction algorithm and the data from the wind tunnel test which is employed in WIA), could be judged collectively to be more reliable, because of circumstances, than the sources available in their ventilated counterparts,

- in the case of VWTS's the interference is expected to be appreciably lower than in the case of solid walls but the assessed magnitude of the interference is rendered less certain because of less well defined test section boundary conditions.

In normal tests in the FWTS the act of adaptation can lead to nominally zero interference from the flexible walls throughout the test section in two-dimensional testing and to nominally zero interference at certain targeted points along the test section in three-dimensional testing. Different approaches and algorithms are available for WIA:
in 2D tests an imbalance method may be used, that is the determination of an imbalance between the flow in the test section and imaginary flows outside. The imbalance is determined at the interfaces, top and bottom. This leads, by iteration of the shapes of the flexible walls, to nominally zero imbalance at the measuring points along the flexible walls, that is to zero aerodynamic loading at these points, from which it is inferred that their interference is zero. WIA is not necessary.

in 3D tests, and sometimes in 2D tests, the target point method is used in which the walls are driven to shapes which lead to low interference velocity components at a finite set of user-selected target points lying generally in the region of the model. The locus of the set of target points becomes a target line. One element of the procedure is a WIA algorithm. As the walls are impervious, the algorithm is as certain as that for the CWTS but with the difference that, following adaptation, wall interference is low. In this respect the FWTS combines the best features of each type of conventional test section. However the actual, as opposed to the indicated, achievement of low or zero interference is dependent on the WIA being correct. Therefore it is important to have confidence in the WIA method. Adaptive walls will drive each of the indicated wall interference components \( u \) and \( w \) nominally to zero, if so desired by the operator.\(^1\)

In each case, that is the CWTS, the VWTS and the FWTS, the output of useful model data relies on the confirmation, from WIA, of the achievement of wall interference which is sufficiently low for corrections not to be necessary, or that the interference which is present is of a character suitable for correction. But the rôles of WIA in the operation of the test sections are seen to differ somewhat because of the passive or active nature of the walls. In summary:

Rôles of WIA in:

(a) conventional test sections, CWTS and VWTS: WIA is a test for correctability. This is followed by estimates of the magnitudes of the corrections which should be applied to the airspeed and the flow direction and to the measured aerodynamic coefficients, where satisfactory correction is judged to be possible,

(b) adaptive wall test sections: WIA is a test for the adequacy of wall adaptation. This test is followed, if necessary, by iterations of wall shapes making use of WIA until interference at the target line is low, or possibly until the model data is judged correctable. The corrections are based on WIA.

Therefore the correct assessment of wall interference seems to be equally important for both conventional and adaptive-wall test sections.

\(^1\) This concept is reliable in principle. However, while in practice the imbalances might be very small at the measuring points they are not identically zero. Also there is the question of the magnitudes of imbalances, arising for a variety of reasons, in the spaces between measuring points: they may be small but they are unknown. Immediately the question arises of whether the imperfection implied by the residual imbalances is causing the walls to interfere significantly with the model. The imbalances existing at the measuring points have been used to assess wall interference along the centreline in low speed two-dimensional tests (Ref.43, 44)\(^1\)
The sources of test case input which were chosen include data from tests on an Arrow-head half-wing model during which the forces on the model were not measured, and data from sting-mounted full TWIG model tests where the forces were measured. The significance of mentioning the forces is that some WIA algorithms make use of measured forces for a model representation.

Guidance on the precision with which the components of wall-induced velocity should be known has been laid down (Ref.45) in terms of $\Delta M$ and $\Delta \alpha$, 0.0002 and 0.01° respectively. The incidence tolerance translates to $w=\pm 0.000175$ and at Mach 0.7 the delta $M$ translates to $u=\pm 0.00026$. If the spread of opinion on the magnitude of a component of interference is wider than the tolerance band, then presumably it must be concluded that the interference is not known with sufficient certainty. Conversely, if they do lie inside the tolerance it cannot be claimed that the interference is known well enough: they might all be incorrect.

3.1. Arrow-head model test case

3.1.1. The test section

This was the adaptive wall test section of the Transonic Self-streamlining Wind Tunnel TSWT at the University of Southampton (UoS). The tunnel is induced-flow, intermittent and driven by dried compressed air. The test section is nominally 0.1524m (6") square and has flexible top and bottom walls, 1.118m (44") long, the shapes of which are each controlled by 20 motorised jacks. The walls are anchored upstream while the downstream ends are free to move, within limits, under the control of jacks n° 20. The sidewalls are parallel and rigid. The instrumentation relevant to this work are sets of flexible wall position transducers, one at each jack, wall static pressure tappings and the usual pressures giving the reference test Mach number. The tunnel lines are given on figure 3.1.

3.1.2. The model

This, an arrowhead planform, was a starboard swept half-wing of uncambered section, mounted directly onto the port sidewall of the test section nominally at mid height. The model had no instrumentation. Its outline and principal dimensions are given on figure 3.2. The station shown on this figure, and those on the data plots associated with paragraph 3.1, is the distance in mm downstream from the anchor points of the flexible walls. Some model statistics are: nominal blockage 1.7%, span/test section width 0.67 and test section width/height 2 (both duplex), nominal alpha 4 degrees, test reference Mach number 0.7, thickness/chord ratio 0.06, aerofoil section RAE 102, wing aspect ratio 2.67. The centre of rotation of the mounting turntable was at station 547.6mm (21.56"). The lines are shown on this figure along which wall interference was assessed by the various methods:

- streamwise lines at the root and at 85% semi-span; the quarter-chord line,
- all projected onto the mid-height ($z=0$) horizontal plane.
3.1.3. The streamlining technique

The target line, the locus of the set of target points, was the horizontal centreline of the mounting sidewall. The test series began with a determination of aerodynamically straight wall contours for the intended test Mach number (also the nominal unit Reynolds number in this atmospheric tunnel) with the test section empty. These were the contours which gave nominally zero wall-induced blockage and upwash along the target line, as indicated by the WIA algorithm with the model absent. Convergence onto required wall contours was by the use of WIA, in conjunction with an influence-coefficient method which relates, approximately, wall movements to wall-induced velocity perturbations in the test section at mid height.

The WIA algorithm was based on the method of Ashill & Weeks (Ref.25), developed for straight solid-walled test sections (Ref.35) but modified to account for wall curvature (Ref.41), and was used both with the empty test section and with the model present. It uses wall data, that is wall pressure distributions and the shapes of the flexible walls. Lateral symmetry was assumed and therefore only the pressure distributions were used from the top and bottom walls and the starboard sidewall. The code provides the non-dimensionalised wall-induced velocity components u and w.

The adaptive walls provide independent control over the streamwise u-component of wall-induced velocity perturbation and the vertically upwards component w. This is by means of differential and collective wall movement respectively. The perturbations may be controlled separately or simultaneously. Tests with the model present were divided into three sets: walls aerodynamically straight, walls set to remove just wall-induced blockage, and walls set to remove just wall-induced upwash.

The elimination (according to the WIA algorithm) of indicated wall-induced blockage at the target points is possible, within experimental limits, along a substantial portion of the test section which was the procedure followed for blockage case. As only blockage was removed in this particular case a substantial wall-induced upwash distribution remained.

When a wing is lifting upwards, the elimination of the wall-induced upwash along the root line requires the downstream ends of the adaptive flexible walls to move significantly down from their straight positions, introducing a vertical misalignment between the flexible walls and first diffuser. Even with relatively modest lift the wall movement limitations in TSWT prevent the setting of such contours. For these reasons the wall contours are rotated so that there is a smooth connection between the downstream end of the test section and the rigid diffuser. When viewed to starboard an anticlockwise rotation is required for a model lifting upwards. The pivot point of rotation was located at a streamwise position corresponding to jacks n° 2. This location was chosen in order to allow the pressure signature in the vicinity of the pivot point to be captured by the wall tappings. The downstream end of the tunnel was aligned with the diffuser at jacks n° 18 for the same reason.

Application of the wall rotation technique causes the effective incidence of the model to change. The geometric incidence remained unchanged during these tests. Wall adaptation is considered complete once it has become apparent that the upwash component of interference has converged to a constant value along the important portion of the target line, i.e. the portion adjacent to the model. This is the angle of rotation of the test section. In such circumstances the upwash at this location is treated as an angle of incidence correction, a primary correction. The effective incidence is the sum of the geometric incidence of the
model and the incidence due to the constant level of wall-induced upwash. Therefore in this experiment not the upwash but the gradient of upwash was removed, eliminating the need for any secondary correction, while substantial blockage interference remained.

In summary, with the model present, the flexible walls were adapted for the following: the elimination of the wall-induced perturbation u, and separately the elimination of the wall-induced upwash gradient. Data was taken with these walls, for brevity called blockage and upwash walls respectively, and with aerodynamically straight walls. Ref.42 is the data source report.

3.1.4. Results with the Arrowhead test case

Figure set 3.3-3.5 shows dimensionless wall-induced perturbations assessed by several methods with the walls set aerodynamically straight. Set 3.6-3.8 applies to blockage walls and set 3.9-3.11 to upwash walls. The contributing institutions are identified by acronyms. The figures in each set are showing wall-induced interference along the root line, quarter-chord line and 85% semi-span line respectively.

The streamwise location of the root chord is indicated. The missing component of perturbation velocity, v, is identically zero along the root line from symmetry. The algorithms used by the University of Southampton and ONERA did not provide data on component v.

Following are comments2 on the figures in turn.

Figure 3.3, root line, straight walls. The tolerance bands quoted in this figure are shown under the symbols (w) and (u) on the right. There is good agreement on u throughout, the curves lying within this tolerance everywhere with the differences between opinions being particularly small over the wing. In the case of w there is no strong disagreement between estimates but the curves show a spread of perhaps ±0.02°, outside the recommendation.

Figure 3.4, quarter chord line, straight walls. The spread in u is acceptable out to about 2/3 semi-span, beyond which it rises a small amount to about twice the tolerance at the tip. v is small as expected, but the opinions on w diverge from root to tip by an unacceptable amount approaching a maximum difference of about 1/4° at the tip2. Therefore the opinions vary widely on the wall-induced twist existing along this line induced by the straight walls, from 0.32° (DLR method) to 0.54° (NLR method).

Figure 3.5, 85% semi-span, straight walls. Events along this line reflect the disagreements seen in the tip region of figure 3.4. The spread between the w-curves again shows the variations of estimated twist. The variations along each curve indicate the wall-induced camber at this spanwise station, a fairly uniform camber of 0.12°.

2 The WIA algorithm in use at the University of Southampton has been subject to a limited range of checks for its accuracy in regions away from the root line (Ref.35). The input data was derived from a Rankine Ovoid array for checks on the prediction of wall-induced blockage, and separately a simple horseshoe vortex array for checks on upwash. These were used in a numerical simulation of a straight walled test section and therefore were not a general check of the method with adapted walls. The agreement between the nominally exact solutions and the WIA code were generally very encouraging.
Figure 3.6, root line, blockage walls. By the nature of the experiments, as noted before, the UoS results show convergence to low indicated values of the u-component of interference. These data points are emphasised with filled symbols and the spread in these values of u lie inside the tolerance. In the model region all opinions on u lie within tolerance but show minor divergencies elsewhere. Estimates of w seem to be in two camps separated by about 0.04°, two lines suggesting that the upwash has remained unchanged by the blockage adaptation, two suggesting a reduction of upwash of 0.04°.

Figure 3.7, quarter chord line, blockage walls. All methods agree, just within tolerance, on a low level of u existing along the quarter chord line. Again however the estimates of w diverge increasingly with span to a spread of opinion on wall-induced upwash of 0.35° at the tip, all showing significant but differing changes in upwash remaining following root-line blockage adaptation.

Figure 3.8, 85% semi-span, blockage walls. Following the pattern established on fig. 3.7 the estimates for w are widely spread while those for u are low and in agreement within the tolerance.

Figure 3.9, root line, upwash walls. The UoS w data again have filled symbols to emphasise that these data points are from the adapted test section using this particular target line and, following the adopted policy, have been driven to a nominally constant indicated value within tolerance. The mean level of upwash is seen to be w=0.006, about 0.34°, the primary correction to incidence. The spread of opinions on w is not wide, about twice the tolerance. The values of u over the root are similar to these estimated for straight walls but elsewhere the u-curves diverge somewhat.

Figure 3.10, quarter chord line, upwash walls. In summary, the results exhibit the same divergencies of opinion towards the tip as already seen, most markedly in w. The estimates of twist, root to tip, vary from very near zero (NLR method) to -0.16° (ONERA method).

Figure 3.11, 85% semi-span, upwash walls. Again there is a substantial spread, 0.15°, in estimates of the mean levels of upwash, with an increased spread in u compared with the straight-walls case.

3.1.5. Summary.

Two broad claims might be made to summarise the outcome of the Arrowhead WIA test cases. Generally there is close agreement between opinions on the u and w components of interference existing along the root line, for all these conditions of wall adaptation. As noted earlier this does not guarantee that results are correct but the agreement does serve to raise confidence. In contrast the opinions on wall-induced perturbation components become progressively less well aligned with each other on moving outboard. In particular the estimates of w for the outer regions of the wing panel differ too much. The uncertainty suggests that a separate effort should be implemented in order to validate WIA procedures with particular emphasis on the estimation of wall-induced upwash off the tunnel centreline.
3.2. TWIG/D750 selected data points

3.2.1. The transonic wind tunnel of DLR Göttingen

The transonic wind tunnel TWG is a closed circuit (Göttingen Type) continuous wind tunnel (Ref.46, 47). The maximum power is 12 MW, the test sections are surrounded by a plenum and auxiliary suction of 4 MW can be applied - this of course only for the perforated test section, see below.

Recently the transonic facility has been modernized (Ref.48) and been equipped also with an adaptive test section.

3.2.1.1. Available test sections.

There are three test sections available, which are exchangeable within a short time with the aid of an air cushion transport system. The plenum chamber can for this purpose be opened by a sliding door.

3.2.1.2. Adaptive test section.

The test section is 1m wide, 1 m high and 4.51 m in length, Mach number range from 0.3 to 0.93, pressure range 30,000 Pa to 150,000 Pa, temperature range 283 K to 315 K, Reynolds number based on 0.1 m is 1.8 million.

Sidewalls are parallel, top and bottom walls are flexible. The top wall is equipped with 22 jacks for wall adjustment, bottom wall is equipped with 21 jacks. The adaptation scheme for three-dimensional models is based on the Wedemeyer/Lamarche procedure (Ref.11, 49) in a very fast version reported by Holst (Ref.36) in 1994. For the determination of wall shapes for which the wall interferences on a given target line are eliminated, only 25 top and 23 bottom wall centreline pressures are necessary. The wall shape computation takes about 0.15 seconds on a modern workstation, and this includes the control of the bending stress of the flexible walls. The starting point for the adaptation of the walls is that the top and bottom walls are set divergent for the compensation of boundary layer displacement thickness growth.

A code for the determination of residual wall interferences is available (Ref.50). For this purpose all four walls are equipped with three lines of pressure orifices, in total there are 207 pressure orifices.

The adaptation scheme for two-dimensional models is based on Cauchy's integral formula (Ref.37), which also gives the residual wall interferences.

3.2.1.3. Perforated test section.

The test section is 1m wide, 1 m high and 4.51 m in length. Mach number range from 0.3 to 1.2, pressure range 0.3 bar Pa to 1.5 bar, temperature range 283 K to 315 K, Reynolds number based on 0.1 m is 1.8 million.
The open area ratio is 6% and the perforation consists of 60 degree slanted holes. Auxiliary suction can be applied. The test section is equipped with three lines of pressure orifices on each wall, in total about 120.

3.2.1.4. Flexible Laval nozzle (supersonic test section).

The test section is 1m wide and 1 m high, Mach number range from 1.3 to 2.2, pressure range 30,000 Pa to 150,000 Pa, temperature range 283 K to 315 K, Reynolds number based on 0.1 m is 1.8 million.

3.2.2. Adaptation scheme.

The wall adaptation scheme is already described above, see also (Ref.11, 36). The control system of the TWG (Ref.51) is able to adjust the wall shapes so that all jacks reach their final positions at the same time.

It should be mentioned that for the two-dimensional adaptive test section of the TWG the number of iterations can be pre-selected, as well as the divergence of the top and bottom flexible walls to compensate for boundary layer displacement thickness growth.

3.2.3. The model TWIG/D750.

The model TWIG/D750 is geometrically identical with the model TWIG/NL300 described earlier in this report. The designation of the models read Transonic Wall Interference Generator, and then NL for the Netherlands and D for Germany. The last digits mean the spanwidth of the models: 300 mm and 750 mm respectively.

Measurements have been performed on the model TWIG/D750 in the adaptive and the perforated test sections of the TWG of DLR Göttingen. The model TWIG/D750 is equipped with pressure orifices on the wing and along the fuselage. Two types of mounting in the test section have been performed (mentioned in the figures 3.12 to 3.20):

\textit{With dummy} means that a special body has been added around the sting. In this case, sting geometries in TWG and HST wind tunnels are similar.

\textit{Without dummy} means that the sting geometries in TWG and HST wind tunnel are not similar.

3.2.4. Results with the TWIG D750 Test Case

Three organisations were involved in the computation and the comparison of the wall interference assessment: DLR, BAe, ONERA.

Three aerodynamic conditions have been selected for the comparison, using the adaptive wall test section:

* Ma=0.70, straight walls
* Ma=0.70, adapted walls
Ma=0.80, adapted walls

For each of these conditions, several angles of attack are considered.

The set of figures 3.12 3.20 present the results of the wall interference assessments computed by the concerned partners. Each of these figures consists in two diagrams, at the top and the bottom, showing respectively the longitudinal component (velocity $u_i/U$) and the vertical component (velocity $w_i/U$) of the interference term.

1st case: Mach number 0.70, TWIG model between straight top and bottom walls:

Along the model axis (figure 3.12), the distributions of the longitudinal interference component predicted by DLR and ONERA (above) are in fairly good agreement, for all angles of attack, over the TWIG model. Behind the model, the DLR prediction is higher than the ONERA one. This interference component is not varying very much with the angle of attack. The distributions of the vertical interference component (figure 3.12, below) are very close. This component is increasing significantly with the angle of attack due to the increasing effect of the confined flow with straight walls, and with the X position. The BAe results are significantly different; no explanation to the difference has been found.

Along the quarter chord line (figure 3.13), the comparison of the longitudinal component (above) is less good in level and shape. It seems that the DLR results are increasing linearly while the ONERA results are increasing exponentially near the wing tip. The evolutions of the vertical interference component (below) from DLR and ONERA are similar.

Along the 85% semi-span line (figure 3.14), DLR computations predict nearly constant longitudinal component (above) while ONERA ones present a strong parabolic variation like along the model axis (figure 3.12, above). The vertical component distributions are in fairly good agreement.

2nd case: Mach number 0.70, TWIG model between adapted top and bottom walls:

Along the model axis (figure 3.15), the distributions of the longitudinal interference component (above) are close together, except the DLR result for –1° of incidence. We can remark the strong reduction of the interference level (divided by 8 or 10 compare to the case with straight walls) which points out the efficiency of the wall adaptation. Nevertheless the level is not sufficiently low to reach the planned accuracy about the Mach number ($\Delta M = \pm 0.0001$). The vertical component of the interference has also been reduced, mainly on the upstream part of the model ($x < 0$) which is a lifting part.

Along the quarter chord line (figure 3.16), the longitudinal component distributions (above) computed by DLR appear to be more spread than the ONERA ones, but this impression is mainly given by the DLR curve relative to the incidence –1°. The DLR prediction of the vertical component of the interference (below) is significantly greater than the ONERA ones (ration of 2).

Along the 85% semi-span line (figure 3.17), we find again the difference of curve shape (above) between DLR and ONERA results. So the wall adaptation does not affect the evolutions of the longitudinal component of the interference, even if the level is significantly reduced. The comparison DLR-ONERA of the vertical component was fairly good for the case with straight walls; with adapted walls, the prediction from DLR is two times greater than the ONERA one and the global level remains rather high.

3rd case: Mach number 0.80, TWIG model between adapted top and bottom walls:
Along the model axis (figure 3.18), there is a certain scattering of partner results for the longitudinal interference component. DLR and ONERA predict similar evolutions and levels of the vertical component of the interference.

Along the quarter chord line (figure 3.19), the longitudinal component distributions exhibit the same tendency as seen along the model axis. The agreement between DLR and ONERA distributions of the vertical component is particularly good.

Along the 85% semi-span line, there are no change of curve shapes and levels compare to the interference components at Ma=0.70 on the same line, except that longitudinal interference component computed by ONERA have grown slightly.

3.2.5. Summary

From a general point of view, the agreement between the different WIA methods is not very good.

The two cases computed by BAe give results significantly different from the DLR and ONERA results.

The DLR and ONERA results are in better agreement, in terms of evolution and level, depending on the line where the wall interferences are computed. Along the model axis, the agreement is fairly good, mainly for the vertical component of the interference. Along the quarter chord line, the spread in longitudinal component is relatively important for the extreme angle of attack while the agreement on the vertical component is good, mainly for adapted cases. Along the 85% semi-span line, an important difference of the longitudinal component evolution curve exists and produces a significant difference of magnitude at the wing position, while the vertical component evolutions are in fairly good agreement.

Nevertheless, all the results show clearly the reduction of the wall interference due to the wall adaptation.
Chapter 4

4. Comparison of TWIG test results

4.1. Interference-free reference data

4.1.1. Introduction

For reference purposes nominally wall interference free data are required. It was adopted that the data obtained with the TWIG/NL300 model in the HST wind tunnel of the NLR should serve this purpose. The "model span/test section width" ratio is 0.15 and the HST test section walls (upper and lower) are conventionally ventilated (slotted; with an open ratio of 12.57% for each horizontal wall). The tests were carried out in the 1.60m high test section of the HST at a total pressure $P_o$ of 180 kPa (series T1360md of test #4003). The reference data are indicated as : HSTr.

The HST investigation is reported in (Ref.52) ; a discussion on the data is presented in reference (Ref.53).

4.1.2. The wind tunnel investigation

With TWIG/NL300 two tests were carried out in the HST.

The first test (test number 1011, Ref.54) was to assess that the TWIG data from HST investigations are essentially wall-interference free. The relevant discussion is presented in Ref.55 (see also Ref.53).

The second test (test number 4003, Ref.52) was to establish "the reference data" (HSTr) for GARTEUR AD AG-18 (see Ref.53 and Ref.55), as presented in the following section (4.1.3).

Both tests are not further discussed (in detail) in the present report. But, where appropriate, results of these tests are merely presented/included.

The accuracy estimates (table 4.1) are presented as nominal values (thus the estimate is + and/or-). They are based on experience related to the Full Scale Output (FS) of the measurement device.

Note that for alpha, measured with the resolver, the accuracy was conservatively estimated to be less than 0.05 degrees, as a result of problems related to the insufficient space for the original resolver housing. However, for the present HST test with a modified resolver housing the accuracy should be better, and ultimately approximate 0.01 degree as this value is claimed for the accuracy of the resolver itself (if properly calibrated).

The accuracy of model forces and moments is related to only the concerning test data. So no further estimates have been derived for the comparisons (either of the test data or of differences of test data) from measurements with different balances, at different total pressure $P_o$, from different wind tunnels, and so on. Thus for each comparison, specific accuracies should possibly be derived from a "combination" of the accuracy for each data set.
4.1.3. Reference data for GARTEUR

The measurements in the HST to establish the reference data for GARTEUR are carried out with TASK balance #615 (1.25" ER) at a total pressure \( P_o \) of 180 kPa. These data for \( Ma=0.70, 0.80 \) and \( 0.85 \) are presented in figures 4.1 (\( C_N \) vs \( C_T \)), 4.2 (\( C_L \) vs \( \alpha \)), 4.3 (\( C_L \) vs \( C_D \)) and 4.4 (\( C_L \) vs \( C_M \)).

It has been shown in (Ref.56) that for the NLR TWIG measurements Reynolds number effects (100 Kpa < \( P_o \) < 180 Kpa) are negligible with the exception of \( C_M \). It amounts to a decrease of about 0.01 for the applied \( P_o \) increase.

4.2. TWIG/NL300

4.2.1. T2 (FWTS)

The figures 4.5 to 4.10 present the comparison of the T2 data (uncorrected and corrected) with the GARTEUR reference data HSTr. Some full square symbols, larger than the reference one visible in the legend area, appeared on the plots. They are the result of the superposition of several test points corresponding to repeatability tests.

The corrected T2 data are the result of a two step process from measurements in the wind tunnel. The first step is the typical angle of attack and Mach number WIA, performed with the method explained in the paragraph 2.8.8. The second step consists to interpolate the result of the first step to get the aerodynamic coefficients at the nominal angle of attack and then at the nominal Mach number. This second step is realised very accurately. The interpolation relative to the Mach number has been possible due to test results corresponding to a specified Mach number M0 and to M0 ± 0.001 during the same run.

Globally speaking, the agreement between T2 results and HSTr ones is not satisfactory into the whole range of conditions.

Generally, the comparison is fairly good at low angle of attack, below the lift coefficient discontinuity (\( \alpha \approx 10^\circ \)). In this part, differences between the two sets of data (T2 and HSTr) are not especially increasing with the Mach number.

- For the three Mach numbers, the lift coefficient measured in the T2 wind tunnel is comparable to the HSTr one for moderate angle of attack (figures 4.5, 4.7 and 4.9) and slightly higher with the increase of the incidence. At the lift coefficient discontinuity (\( \alpha \approx 10^\circ \)), the lift value from T2 data is significantly higher than the HSTr one. This discontinuity corresponds to a sudden change in the flow configuration on the middle and outer parts of the TWIG wing. So a possible reason to the difference between T2 and reference data is a difference in the emergence of flow configuration change, in terms of critical angle of attack and maybe of intensity, due to sidewall vicinity into the T2 wind tunnel.
- For the drag coefficient (figures 4.5, 4.7 and 4.9), the agreement is not perfect but the correction displaces the points close to the HSTr curves.
- The pitching moment (figures 4.6, 4.8 and 4.10) is underestimated at low angle of attack at \( Ma=0.70 \) (figure 4.6), and at high angle of attack at \( Ma=0.80 \) and particularly at \( Ma=0.85 \).
- Two differences are affecting the polar curve comparison (figures 4.6, 4.8 and 4.10). The first difference occurs at low angle of attack and is due to the overestimation of the drag coefficient.
in the T2 data. The second difference is observed for high angle of attack ($\alpha > 10^\circ$) and is due to the overestimation of the lift coefficient in the T2 data.

4.2.2. S3Ch (FWTS)

Figures 4.11 to 4.16 present the results obtained in the S3Ch test section, between adapted walls. Results corresponding to $M=0.70$ are missing (unavailable). The freestream Mach number was adjusted during the test to the nominal value while the angle of attack has been corrected.

It seems that the agreement between HSTr and S3Ch results is fairly good, whatever the Mach number is.

On the other hand, the agreement is satisfactory all along the angle of attack range, with the same accuracy. Especially, the discontinuity of the lift coefficient, occurring around $10^\circ$, is fairly well reproduced.

4.2.3. S3Ch (PWTS)

Tests have been performed in the S3Ch test section equipped with the classical perforated walls (24% of perforated surface). These tests cover the total test program: $Ma = 0.70, 0.80$ and $0.85 ; -5^\circ \leq \alpha \leq -20^\circ$. Unfortunately no results are available in terms of final plots. After the tests, computations indicate very low values of Mach number and angle of attack residual corrections. This fact is due to the large size of the test section compared to the TWIG/NL300 size. In conclusion, the comparison between test results obtained with perforated and solid adapted walls in the S3Ch configuration of low wall interference does not allow to highlight the respective merits of the two types of flow boundary.

4.2.4. PHST (SWTS)

The comparison of PHST data (corrected for calculated wall interference) with the GARTEUR reference data (HSTr) shows that satisfactory agreement is not obtained. However, it should be emphasized that:

* for the PHST the corrected MACH number along a polar is less than the nominal MACH number, and the difference increases with $\alpha(C_L)$.

* the MACH number effects as measured in the HST are not at all sufficient to cover (and/or explain) the differences in PHST and HST data (Ref.57).

Also the difference in MACH number should certainly already result in "non-correctable" differences, especially for the high $C_L$-range as it concerns changes in separation behaviour.

The presented comparison indicate differences in:

$C_T$ (fig. 4.17), $C_D$ (fig. 4.21). The PHST data are about 0.002 to 0.004 low (fig. 4.18 and 4.22). The origin of this difference could not be established (Ref.56), and can not reasonably be attributed to wall interference.

the "stall development" ($C_L$-max),fig. 4.19 and 4.20, related to the above mentioned MACH number differences.

$C_M$ (fig. 4.23). The PHST data being about 0.010 higher (fig. 4.24) find its origin in the lower test Reynolds number, through effects on natural boundary-layer transition position and "redistribution" of wing lift (Ref.56).
4.3. **TWIG/D750**

4.3.1. **DLR TWG (FWTS)**

No data is presented from the FWTS at Mach 0.85 due to problems with the wall pressure Data Acquisition System (DAS).

The figures 4.25 to 4.28 present the comparison of the TWG (FWTS) data with the GARTEUR reference data HSTr. The wall adaptation is performed in one step.

Following are comments on the figures.

The lift coefficient is accurate for low angles of attack (figures 4.25 and 4.27). When the angle of attack increases, the discrepancy between the TWG values and the reference ones increase, for the two Mach numbers 0.70 and 0.80.

The drag coefficient presents the same tendency.

The agreement of the pitching moment is good (figures 4.26 and 4.28).

The agreement of the polar is fairly good at Ma=0.70, while a discrepancy appears at Ma=0.80 when the lift value becomes significant.

4.3.2. **DLR TWG (VWTS)**

No data corrected for wall interference are available from the ventilated wall test section. This is due to problems with the wall pressure DAS. No wall pressure data was acquired during this series of tests.

However, it can be seen that in some cases the uncorrected VWTS data is closer to the 'free-air' NLR reference data than that acquired from the adapted FWTS. This is true for the lift and the drag coefficients (figures 4.25 and 4.27).

We can also remark that the slope of the lift, the drag and the pitching moment distributions are slightly different from the reference ones.

A slight discrepancy exists on the polar comparison, but it does not grow with the Mach number.

4.3.3. **BAe Warton 4ft (VWTS)**

The comparison of BAe 4ft data corrected for wall interference with the NLR reference data shows that satisfactory agreement is not obtained.

Similar to the TWIG/NL300 PHST situation at NLR, the corrected Mach number is less than the nominal Mach number, and the difference increases with model incidence. If this Mach number difference were corrected out, the difference between the BAe and NLR HST reference data would decrease in most cases but satisfactory agreement would still not be obtained. The difference in CL at higher incidences would however be increased.

At higher incidences, the corrections to incidence at Mach 0.80 and 0.85 are much smaller than the corrections at the lower incidences. This may be due to the fact that non-linear transonic flow effects start to dominate the flow, and the method fails there.

The correction method used is that due to Mokry, see Ref.58. This would make the application of a linear flow based method such as Mokry's inappropriate.
The Mokry method utilises a crude model representation i.e. one horseshoe vortex for the lift effect, one doublet for the model volume and one source for the sting volume. This model may be inappropriate for a low aspect ratio, delta winged model such as the TWIG model which also has highly swept forebody strakes.

The presented comparisons indicate the following differences:

a) the stall development, Figures 4.31, 4.33 & 4.35. The Mach number difference explains this discrepancy only partially. The remaining difference may be explained by unsteadiness in the flow within the ventilated working section.

b) CD data. Figures 4.31, 4.33 & 4.35 show the BAe data roughly 0.002 to 0.008 too high. The reason(s) for these differences have not been determined.

c) CM is 0.003 to 0.006 too low for all three Mach numbers, see Figures 4.32, 4.34 & 4.36. From the work done at NLR on Reynolds number effects (Ref.56), it would appear that this difference is due to the higher test Reynolds number, through the effects of the natural boundary layer transition position and wing lift distribution.

4.4. Results of High Productivity Strategies

As developed in the paragraph 2.3.2, the requirement of a HPS strategy is a predicted wall shape to be applied at the next angle of attack during a continuous $\alpha$-sweep. This predicted wall shape is the result of an extrapolation procedure using information available at the two last angles of attack which have been achieved.

4.4.1. T2

The HPS simulation at the T2 wind tunnel is being performed by splitting the continuous $\alpha$-sweep into discrete distribution of angles of attack ($\Delta\alpha=2^\circ$), each of them corresponding to one wind tunnel run. So there is no continuity of the $\alpha$ variation and the predicted wall shape is computed between two consecutive runs.

At the T2 wind tunnel, four slightly different strategies of extrapolation have been performed. They are noted strategy 1 to 4, and they are explained in the figures 4.37 & 4.38.

- The strategy 1 (figure 4.37, above) consists to compute the increment of adapted wall shape (virtual shape; result of one iteration of wall adaptation computation) between the two last stages and to apply this increment to the last adapted wall shape (virtual shape).
- The strategy 2 (figure 4.37, below) consists to apply the increment previously defined to the real wall shape.
- The strategy 3 (figure 4.38, above) consists to compute the increment of relaxed wall shape (virtual shape; result of the relaxation between the real and the adapted shape) between the two last stages and to apply this increment to the last relaxation wall shape (virtual shape).
- The strategy 4 (figure 4.38, below) consists to apply the increment defined in the strategy 3 to the real wall shape.

These four strategies have been applied from 4° to 14° by step of 2°, at the Mach number
0.70. At the beginning of the procedure, the extrapolation relative to 4° is based on complete adapted wall shapes at 0° and 2°.

The wall shape prediction took about 1 second. This step can easily be reduced to some tenths of a second using a modern computer and some improvements in the adaptation procedure.

Figures 4.39 to 4.41 show the result of the four strategies for successive angles of attack. The different wall shapes are directly compared to the wall shape computed by the Wedemeyer-Lamarche method, result of a real adaptation (several iterations) realized during an additional run.

Some differences exist between the real adapted and the extrapolated wall shapes, mainly at 12° and 14° of incidence. It is not surprising if we consider the discontinuity of the lift evolution occurring around 10°, which is “seen” by the extrapolation procedure only just at 12°.

The strategy 1 prediction is more or less different from the three other ones which are closer together. The same strategy 1 presents often a saw-tooth shape.

For 12° and 14°, the opening of the rear test section part, behind the model, seems to be underestimated by the prediction. This drawback is probably due to the rapid increase of the drag with the incidence, which is not taken into account by the extrapolation process.

The figure 4.42 shows the evolutions of the lift and drag coefficients and of the pitching moment versus incidence, for the HPS simulation and for the complete adaptation. The agreement seems to be rather good for moderate angles of attack. The discrepancy rises at the lift discontinuity point, around 10°, and remains approximately constant for higher incidences. A smaller α step should give a better agreement.

We can imagine that the large step Δα of 2° between two consecutive tests is a part of the cause of the observations mentioned above. This is particularly true at the point of the lift discontinuity. Nevertheless the results obtained with the large α-step used for the experiments are very encouraging. A smaller α-step will improve significantly the accuracy of the procedure. This α-step could be variable, as a function of one/several parameter evolution.

4.4.2. S3Ch

The strategy used at S3Ch to predict the wall shape is a simple extrapolation of adapted wall shapes relative to the last two incidences which have been tested. Let $S_n$ be the real wall shape for the angle of attack $\alpha_n$ and $S_{an}$ the adapted wall shape computed at the same angle of attack. The wall shape relative to the angle of attack $\alpha_{n+1}$ is predicted by the following expression:

$$S_{n+1} = S_{an} + (S_{n} - S_{an}) \frac{\alpha_{n+1} - \alpha_n}{\alpha_n - \alpha_{n-1}}$$

Tests have been performed at Mach number 0.85, using a step of $\alpha_n - \alpha_{n-1}$ of 1° and 2°.

Generally speaking, the predicted wall shape is very similar to the adapted one, as shown in the figure 4.43. However, for angle of attack greater than 7°, the wall shapes oscillate, like indicated by the figure 4.44. This perturbation is confirmed by the change of sign of the incidence correction (Figure 4.45, below). Nevertheless the correction values of the Mach number and the incidence are rather low (Figure 4.45, above).

The figure 4.46 shows the lift and drag and the pitching moment evolutions versus the angle of attack, relative to the HPS tests and the HSTr reference tests. We can observe a fairly good agreement, except locally around the lift discontinuity.
CHAPTER 5

5. Operational aspects of FWTS vs VWTS

5.1. Productivity

The productivity aspect has already been developed in detail by J. SMITH from NLR in the AGARD-AR-269 (Ref.1, chapter 5) in 1990. In the present sub-chapter we make reference to this publication for the details and we remind the main features of this subject, adding information from the AG18’s experience.

Firstly, an additional investment is required by the realisation of a fully automated adaptive wall system. This additional investment can be estimated to 10-20 % of the “turn-key” cost of a transonic wind tunnel. The maintenance cost should also slightly increase.

For 3D testing, the power requirement is not affected by the type of test section walls used. Nevertheless adaptive walls (solid walls) induce significantly smaller energy losses than ventilated ones. So an interesting reduction of power requirement can be obtained by applying adaptive solid walls instead of ventilated ones.

During the testing, the duration of one data point depends on the development of several work steps : tunnel control, data acquisition, data processing, test procedures. The wall adaptation process increases the execution time of these actions, because it needs additional measurements like the flexible wall shape and the pressure field on/near these walls ; it needs also computation, setting and control of the next adapted wall shape. But these new actions to be taken into account do not constitute a major problem for the productivity for at least two reasons : on the one hand, modern technologies allow to perform a lot of measurements and to compute new shape very fast (the wall shape computation needs some tenths of a second on a personal computer) ; on the other hand, wall interferences being minimized by the wall adaptation, the required amount of data points should be considerably reduced, for a final and better knowledge of the aerodynamic behaviour of the model.

Adaptive wall wind tunnels will have to be able to operate in a continuous testing mode in order to be competitive. That means, like for classical industrial wind tunnels, that the angle of incidence is gradually changing with time. In these conditions, we can imagine that model data acquisition is performed for a number of discrete data points and that there is enough time between two data points to estimate and to set the adapted wall shape for the next data point. From the High Productivity Strategy investigations performed in S3Ch and T2 wind tunnels, it seems that the performance mentioned above is possible with a good accuracy, under certain conditions:

- The wall adaptation must be complete for the two first steps (two first angles of attack) in order to have accurate starting conditions.
- For the next points, the adapted wall shape will be estimated by a kind of extrapolation, using the two previous wall conditions (the two previous angles of attack) ; this prediction process must maintain the same level of accuracy, relative to the adapted
conditions, all along the testing progress. That means that the increasing inaccuracy due to successive extrapolations has to be avoided and that any sudden change of the model behaviour has to be taken into account immediately. The objective is reached if the extrapolation process is based not on real wall shapes but on one-step adapted wall shape, that corrects the prediction as the angle of attack change proceeds.

We can be more optimistic, thinking that the optimisation of all the steps mentioned above allows to carry out a complete wall adaptation process at each test point.

5.2. Reliability

5.2.1. Introduction

Wall adaptation needs the use of a special Active System (wall shape prediction software, mechanical set-up, control system) which introduces sources of inherent errors into the wind tunnel operation.

For several reasons, it is necessary to know the different aspects of these specific errors, in terms of qualification, seriousness, repairs, consequences about the productivity of the concerned facility.

The first and general reason is that the knowledge of the possible and well characterised drawbacks is useful for the appreciation of the real advantage of the wall adaptation in an objective manner. On the other hand, it is useful to know about the inherent errors, for an optimised design of a wall adaptation system. Finally the error logging list is indispensable to the supervision of the wind tunnel operation.

Unfortunately none of the considered facilities through the action group activity AG18 has capability to set the walls synchronously with the continuous model movement, in order to apply the wall adaptation concept to the industrial operating mode. Consequently “live wall control” aspects could not be taken into account. However the experience acquired through the use of adaptive walls in these facilities, during the GARTEUR study and a long time before, allows to list the possible errors and to qualify them.

5.2.2. Seriousness of an error

The judgement of the seriousness of an error depends on different aspects, like the type of the error, the tolerable inaccuracy, the correction action, the cost of the possible failures.

The type of the error

Three groups of error types can be defined.

The obvious errors : Majority of them can be easily detected because they lead to the breakdown of the system. Examples of obvious errors are the failure of a drive. Other obvious errors do not stop the wall adaptation procedure. They must be detected before a major damage. A mechanical problem of one jack is an example of that kind of error.
The hidden error: They are more incidious. They do not stop the adaptation procedure but they affect more or less the quality of the wall adaptation. The drift of the different instruments is the more common example of hidden errors. It increases continuously with time, degrading the result inaccuracy and so the repeatability of the tests. In this case, it is important to specify the criterion that distinguishes between “acceptable” and “erroneous”. The determination of the acceptable level must taken into account the consequence of the error frequency, often increasing with the decreasing of the tolerance. This source of error can affect theoretically the comparators measuring the wall shape. In fact, the experience from the different installations shows that this phenomenon does not occur very often.

External errors: These errors would normally not affect the wind tunnel operation as such, but result indirectly from auxiliary systems. A typical example is the failure of the error monitoring and/or safety system which may interrupt the operation although the actual tunnel systems themselves perform correctly.

The correction action taken
In situ repair or immediate replacement by a spare with subsequent repair “in the background” are two arguments which reduce the problem seriousness, reducing the duration of the breakdown. A majority of the errors could be treated like this. The immediate replacement by a spare can concern a jack, the mechanical system transmitting the displacement from the jack to the wall, the wall shape measuring device, the electronic cards. In order to benefit of the advantage of this kind of repair, it is necessary to make a modular design of the system (standard modules) with an easy replacement of the modules.

The time lost because of the necessary corrective action
This time should be first expressed in real time in order to estimate immediately the consequences of the stop on the timetable of the wind tunnel occupation. The time lost should also be expressed in the loss of productivity, in terms of polars for example if the polar is considered as a production unit.

5.2.3. Error detection
Error detection is a very important action of the procedure. Obviously, it is necessary from a safety point of view. In addition, a complete and clear network of error detection provides a gain of time when an error occurs. Error detections appear in several forms.

Checking: This type of error detection is dedicated to the hidden errors. Regular checks indicate the degree of accuracy of some basic parameter acquisition values. The first basic parameter is the reference shape of the walls. Usually, this shape corresponds to a plane wall setting, providing plane wall in the freestream flow direction. The real position of the wall depends directly on the accuracy of the jack displacement while the measured value of the shape depends on the accuracy of the shape measuring device, which is usually very fine. A good criterion of tolerance could be the smallest height of a local bump of the wall which changes the measurement of the pressure at this location. Because the drift of the wall shape measuring device is very small, the check can be carried out every month or more. The plane wall setting check requires a special equipment determining the reference plane (for example the horizontal plane) and including an instrument devoted to the measurement of the real wall shape compare to the reference plane. The reference plane equipment must be easy to install into or near the test section of the wind tunnel and the measuring instrument must be precise and simple to use. The second basic parameter requiring a
regular supervision is the pressure measurement system. The criterion corresponding to the tolerable drift could be directly deduced from the final accuracy of the absolute pressure or on the Mach number, taking into account the transducer full scale range and its sensitivity. The check can be carried out regularly, the frequency depending on the material used and the experience of the operator. It can be noted that this check is not particular to the wall adaptation procedure, but that the quality of the wall adaptation result depends on it.

Incidental errors: These errors are detected by safety/error monitoring system. It checks in time, all along the progress of the wall adaptation procedure, the different obvious error sources and safety criteria, informs the operator and stops the process if necessary. This checking system has to be complete (instrumentation, hardware, software, wall shape calculation and putting into position), to check and to respond in time.

Incidental errors detected by the operator: Source errors can be detected by the operator, without system warning. If the safety/error monitoring system is efficient, these type of errors should be very improbable.

Human errors: Because of the intervening of one or several operators, human errors can not be completely eliminated. But sources of human errors are rather few in the wall adaptation application itself.

History monitoring: The monitoring of the facility operation through a long/short term should allow to improve that operation. The checking system can be improved to take also new errors into account. Tolerance levels used by the checking system can be adjusted with acquired experience to better control the wind tunnel operation. The state of the different hardware devices could be estimated through their monitoring versus time, in order to anticipate some changes or more detailed controls.

5.2.4. Error logging list

This subchapter presents a list of the errors relative to the adaptation system, which is probably not exhaustive.

- Human errors
- Instrumentation errors
  * Potentiometers measuring the wall position
  * PSI pressure transducer measuring the pressures along the walls
- Controls hardware errors:
  * Drives used by the adaptation system (especially for the gradual deformation of the flexible wall
  * Controllers (pneumatic, hydraulic, electric) which pilot the jack movement
  * Jacks
  * Pieces of the flexible wall system: seals, stiffeners, link rods, hinged joint
- Control software errors
  * Bugs
  * Tracking/time-out errors
- Wall shape calculation
  * Computer hardware errors
  * Software errors (algorithm deficiencies)
  * Unacceptable wall shape: inconsistent with the mechanical displacement limits, with the acceptable curvature radius, with the acceptable strength into the wall
5.2.5. Maintenance

Two aspects of the maintenance have to be considered:

* A regular maintenance, aimed to anticipate problems. The question is what are the frequency and the extent of this kind of maintenance? Answers depend on the conception of the adaptation system (more or less robust), on the workload of the facility (combination of the number of performed data points and the time without maintenance), on the age of the system. Of course, this maintenance is necessary to minimize the risk of breakdown (accident or simple stop) of the adaptation system which is more complex than a classical test section.

* A special maintenance after a system repair or a part replacement. Firstly, this kind of maintenance must confirm that all the system works well before to start again with an automatic operation mode. Secondly, it is necessary to control the reference wall shape (usually straight walls) used for the wall displacement. Thirdly, it will be appreciable to perform a complete wall adaptation in a well known configuration and to compare all the results (pressure and shape of the wall, model pressure, lift and drag coefficients). This step is time consuming but the quality of the future tests depends on it.

5.3. Versatility

5.3.1. Interference and Correctability

For the following discussion on versatility it is assumed that the adaptive wall test section is impervious and comprises two flexible walls and two parallel rigid sidewalls.

Such a test section has well defined and better understood boundaries than has a ventilated test section. The clearly defined geometrical boundaries of the test section coupled with easily measured distributions of pressure and Mach number should lead to high quality WIA. Some relative merits are listed below:

- **CWTS:** Large, uncontrollable but well known interferences. (This presumes the necessary wall pressure taps installed and the use of Ashill & Weeks, two variable type assessment method (Ref.25) or Holst method (Ref.28)).
- **VWTS:** Smaller interferences but uncontrollable and not as well understood as with the CWTS.
- **FWTS:** Small indicated interferences at a predefined target line, interference is controlled and well known. Overall interference is subject to certain model size criteria i.e. $b/B \leq 60\%$. 


5.3.2. **Flexibility**

In general the flexible wall wind tunnel can be utilised in two ways. Firstly, with minimised interference, it can be used as a high quality design tool in the design and definition of new airframes. Secondly, the test section can be used with contrived measures of non-zero wall interference in order to investigate various areas of interest.

Some possible uses and advantages of FWTSs are discussed below.

**2D Testing**

Study of WIC. Methods of WIC have been developed where the corrections have been assessed by comparing the correction values yielded by a particular method to known levels of interference imposed by the flexible wall test section.

Wing camber and thickness optimisation. Gradients of Mach number could be induced over the wing chord, effectively thinning or thickening the wing section. This would decrease / increase the local Mach number without altering the freestream Mach number. Upwash gradients have been used in a similar fashion in order to assess camber changes, see Section 3.2.4 of this report. This work could be part of the design procedure or as a check on CFD calculations.

Boundary layer studies. Known Mach number gradients on either the walls or model could be induced and their effects studied, including the effects on free transition.

**3D Testing (Full Models)**

Ability to focus on sensitive flow regions for close control of flow speed and upwash i.e. intakes, engine pod support struts, areas of supercritical flow and the wing tip region.

Reduction of the wall induced twist of swept wings. In the case of the variable-pressure ambient temperature wind tunnel fitted with a FWTS, the control over wall induced wing twist might be exploited to correct for the variations of twist with load. In addition, if desired, the spanwise variations of effective twist may be matched to the wing twist expected over the flight envelope of the full-scale aircraft. One of the major operational, and at the present time unique, advantages of the pressurised cryogenic wind tunnel is the ability to independently control Mach number, Reynolds number and dynamic pressure. This advantage would be conferred on the pressurised, ambient temperature tunnel by the addition of a FWTS. The FWTS would confer the independent control of dynamic pressure. Variation in the twist of a model’s wing is the most important effect of variation of dynamic pressure.

Elimination of wall induced camber along any chosen chord line.

Control of upwash along the model length to remove tailplane trim error.

Reduced wall interference along pre-set target lines. Blockage effects can be well controlled over a substantial region of the test section. Wall-induced upwash can be well controlled at and near the target line.

5.3.3. **Flow Quality**
An FWTS has better acoustic qualities than a VWTS. Much noise is generated by the perforations or slots of a ventilated wall. Studies have shown that the presence of edgetone noise has a measurable effect on model measurements under supercritical flow conditions, (Ref.59, 60). This noise can be reduced but not eliminated in perforated walls by splitter plates placed within the perforations. However evidence is available to show that slotted wall test sections can be designed with noise levels similar to those of closed wall test sections (Ref.61).

A VWTS is surrounded by a plenum chamber. Due to various reasons i.e. access, structural constraints etc. these plenum chambers are rarely symmetrical about the test section. This causes differences in the static pressure levels between different areas of the plenum chamber and consequently affects the flow conditions at the ventilated walls. This of course is not a problem for solid flexible walls.

An AWTS has the added advantage of reduced drive power requirements for a given set of tunnel conditions relative to a VWTS. This is due to the fact that mixing losses along an open boundary are greater than the friction losses along a similar closed boundary. It has been reported that FWTS losses can be 30-40% lower than those of a VWTS, see Reference (Ref.62).

5.3.4. Mach Number Range

Testing in the low supersonic region is now extremely important to the design process of modern military aircraft. When the next generation supersonic transport aircraft project becomes a reality, testing through Mach 1 and up to around Mach 2.2 will be equally important.

VWTSs have been operating over the full transonic Mach number range (0.9-1.3) for many years. Some facilities, those whose plenums are driven solely by a second throat, have a small, low supersonic Mach number range that is unattainable. However, a plenum configuration that is ‘sucked down’ by auxiliary equipment can operate over the entire transonic Mach number range. However many facilities do not test at Mach numbers around unity even though the facility is capable of it. This is due to the very sensitive nature of the flow at these conditions to any stimulus.

At present two-dimensional testing has been accomplished in a FWTS over a limited supersonic Mach number range (Ref.9). Limited experience exists at present however with the testing of three-dimensional models through Mach 1 and into the low supersonic flow regime.

5.3.5. Sideslip Traverses

Some conventional facilities using sting mounting systems roll the model through 90° and then carry out a sideslip traverse in the same vertical plane as the pitch traverse. A FWTS facility would require flexible sidewalls (in addition to the top and bottom walls) if this approach to sideslip testing were to be adopted. These flexible sidewalls would also be adapted in a plane manner.

A second method would be to incorporate a yawing joint into the sting support system. This would enable the model to remain horizontal but would likely mean the model moving laterally in the tunnel, toward the planar sidewalls, as sideslip is increased. This may mean that the natural flow over the outboard portion of the wing may not develop due to the wall interference.

The 4.0m LSWT at BAe Warton has the sting support system mounted on roof and floor turntables above and below the model. This arrangement keeps the model on the tunnel centre-line
while performing sideslip traverses. Similar turntables would be used for blade mounted models. Turntables would, however, be very difficult to engineer into flexible top and bottom walls.

5.3.6. Optical Measurements and Observation

Pressure Sensitive Paint (PSP) is a non-intrusive, surface pressure measurement technique that is becoming increasingly important to the aircraft design process. It is likely to be used to generate data for inclusion into design datasets.

Currently the most advanced ‘production’ data PSP tests use the method to:

1. provide wing surface diagnostic data
2. provide component loads e.g. wing root bending moments and flap loads
3. qualify main balance loads by integration of the surface pressures. This is being done to a limited extent at the moment with the McDonnell Douglas system in the USA. Drag forces cannot be computed however, due to the lack of skin friction data.

A test in April 1996 at the Aircraft Research Association, Bedford acquired 3000 images from 7 cameras to provide such data. Forty camera apertures were provided in the test section’s walls in order to provide uniform illumination. This type of testing is expensive and so the productivity aspect is important.

Prior to testing the camera and lighting positions must be optimised for performance over the entire aircraft attitude range and to minimise shadow areas. In the case of a combat aircraft, the attitude range can be quite extensive. By far the most important views are the upper and lower surfaces of the wings. In a VWTS, the cameras and the lighting can be installed in the plenum behind windows (perforated if desired). Because the plenum configuration is altered, the flow conditions at the walls will consequently be altered from baseline conditions albeit by a small amount.

The use of a FWTS however, would require considerable optical access through the upper and lower flexible walls. Present FWTS facilities have limited optical viewing access. The T2 facility at ONERA-CERT for example has two viewing apertures of 1.5cm diameter. Models may be viewed in real time using very small cameras. The space between the wall jacks is usually very limited, hence the size of the cameras (or any hardware) is limited, as is the ability to position and adjust them accurately. In addition, when the flexible walls move, the windows move too! This implies that the cameras would either need to be mounted outside the walls or readjusted after each wall shape has been determined.

The present PSP systems use fiber optics and cameras. Optical access for fiber optics can be arranged without difficulty while cameras require apertures of the order of 50 mm in diameter. The ONERA-CERT T2 tunnel has 15mm windows as mentioned above but this is a relatively small research facility. A scaled up ‘production’ T2 could probably incorporate windows of this size. AWTS facilities could, in the future, be designed with flat glass lattices between each jack station to allow easy optical access to all sorts of viewing systems. This is just an idea at the present moment and yet to be tried.

These are the major requirements. Extra cameras may be required for higher resolution and to observe specific areas of interest.
Other Optical Techniques

Other non-intrusive flow measurement techniques such as Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) will become more important. PIV is a ‘whole flowfield’ technique and may be of use in determining boundary conditions for use in CFD WIAC methods. LDA is a single point technique and therefore uneconomical for routine wind tunnel testing as yet. PSP will, however, be the most widely utilised in routine production testing and thus sets the requirements for optical measurement and observation requirements for FWTS facilities.

5.3.7. Configuration Optimisation

FWTS facilities may be of use in optimising various aspects of new airframe designs or configurational modifications to existing designs.

For example, the efficiency of transport aircraft engine intakes is critically dependent on the direction of the flow entering the intake. The target line(s) could be set to run past the intakes to ensure that the local flow has negligible wall induced velocity perturbations.

The effective thickness of airfoils might be altered by introducing a Mach number gradient along the model chord. The Mach number at the leading and trailing edges would be left unaltered with just the local Mach number being modified.

A similar exercise could be carried out by introducing upwash gradients over the aerofoil, effectively increasing or decreasing its camber. The combination of modifying aerofoil thickness and camber might be a useful tool in assisting the development and verification of morphing aerofoils or active aeroelastic wings.

These capabilities might possibly be used in three dimensional testing by imposing the gradients along selected target lines to optimise new design configurations or as a check on the optimisation resulting from CFD calculations.

5.3.8. Support Interference Alleviation

It is thought that AWTS technology could be of use in alleviating the far-field effects of the model support hardware. The sting effects can be thought of as two separate effects, namely near field and far field.

Near field effects (NFE) are produced by the interaction of the sting and the model. The shape of the sting and its associated support hardware determines these effects.

Far field effects (FFE) are produced by the influence of the sting on the flow itself. They may therefore be understood as blockage and upwash effects. The sting and support hardware may be modelled as part of the wind tunnel model if a WIA method is used that utilises a model representation. The strength of the singularities could be deduced from the shape of the sting.

The FFE would then be computed as velocities induced by the support representation as per the usual image method. The difference being that the velocities inside the test section due to the
support representation singularities are also included and not ignored as is normal. Work done in this area at the ONERA T2 facility is reported in Ref. 63.
CHAPTER 6

6. Conclusions

The GARTEUR AG18 involved six partners: BAe Warton, DLR Göttingen, NLR Amsterdam, ONERA Chalais-Meudon, ONERA Toulouse and University of Southampton.

The two main objectives of the AG18 activity were

- to compare the relative merits of adaptive wall and ventilated wall test sections in terms of flow quality around a 3D model,
- to develop and demonstrate predictive strategies for use in production type wind tunnel.

A geometrically simple but aerodynamically sensitive aircraft has been designed, called TWIG, standing for Transonic Wall Interference Generator.

The first objective did concern all partners. Two activities have been carried out in parallel: the comparison of the WIA methods and the experimental investigation of the TWIG model.

The comparison of the WIA methods has been based on two sets of input. On the one hand, an experimental data base has been established at the University of Southampton. Tests have been performed in the transonic self-streamlining wind tunnel with the Arrow-head model (swept tapered wing, half model). Three wall conditions have been used: straight walls, blockage adaptation, wall-induced upwash gradient adaptation.

From the test data (wall pressure distributions and wall contours), WIA have been computed by the partners along three different target lines in the model plane: root line, quarter chord line, 85% semi-span line. Along the root line, the results of the different codes were in fairly good agreement, whatever the wall conditions were. On the outer part of the wing, a certain discrepancy of the results is growing from the root to the tip for the longitudinal component. This spread of the WIA curves is even larger for the vertical component of the wall-induced interference and is not acceptable.

On the other hand, the same exercise has been performed, using TWIG/DL750 model results from TWG Göttingen (FWTS) as input. The comparison of the results of the three methods concerned (BAe, DLR, ONERA) points out the tendencies previously observed: relative good agreement along the model axis and degradation towards the wing tip.

The experimental investigation of the TWIG model was the central point of the study. Two models of different scales have been used: TWIG/NL300 (span=300 mm) and TWIG/DL750 (span=750 mm).

Reference (interference free) tests have been carried out in the large HST wind tunnel (NLR, [SWTS]), using the TWIG/NL300 model. The lift and drag coefficients and the pitching moment
have been measured continuously during a large \( \alpha \)-sweep run for three Mach numbers 0.70, 0.80 and 0.85.

Then tests have been performed in the wind tunnels of the organisations involved in the AG18 activity, using one of the TWIG models and varied boundary conditions (slotted, perforated, adapted walls). Based on the accuracy of the results, two groups can be defined.

The results of the first group (PHST–NLR [SWTS] and S3Ch–ONERA [FWTS and PWTS]) are the more accurate, all along the test range, for the three Mach numbers. The discontinuity of \( C_L \), around 11° of incidence, is well determined. A small shift of \( C_M \) for the NLR’s experiments is the greatest discrepancy compared to the reference data.

The results of the second group (Warton 4 ft-BAe [PWTS], TWG-DLR [FWTS and PWTS], T2-ONERA [FWTS]) are more inaccurate. Usually some differences, compared to the reference case, are visible on \( C_L \) or/and \( C_D \) evolutions versus angle of attack. A discrepancy subsists on the polar, locally for high angle of attack or all along the \( \alpha \)-range. Another cause of difference is the crossing of the \( C_L \) discontinuity (\( \alpha \approx 11^\circ \)) which is not perfectly reproduced in the BAe and ONERA T2 wind tunnels (no result from DLR beyond 10°).

It should be mentioned that the relative span of 0.75 (TWIG/D750 in TWG wind tunnel or TWIG/NL300 in T2 wind tunnel) is obviously too large even for the adaptive test sections. The inhomogeneities of the wall interferences is very large. The corrections with spanwise averages of the interferences is therefore questionable. The size of the model should not exceed 60% of the tunnel width. New results for the TWIG/NL300 in TWG are reported in Ref. 70.

Considering all the results, it is not easy to separate clearly FWTS and VWTS in terms of flow condition quality. Good results have been obtained with SWTS (NLR), PWTS (ONERA S3Ch) and adapted FWTS (ONERA S3Ch). Less good results have been obtained with PWTS (BAe and DLR) and adapted FWTS (ONERA T2). The type of wall condition is not the only one active parameter constituting the difference between the wind tunnels.

We can think that the blockage ratio of the model is well taken into account by the different wall types. On the contrary, the ratio span/TS width (b/B) is probably playing a more important and complex role, due to the induced non-linear sidewall effects, (local perturbation of the flow, difficult to be taken into account by 2D flexible wall or by a global correction when it is very severe, at high lift). An upper limit of this ratio of about 0.6 seems to be more reasonable than the value 0.77 relative to TWG and T2 wind tunnels.

Concerning the second objective, simulations of High Productivity Strategies performed at ONERA (S3Ch and T2 wind tunnels) have demonstrated the feasibility of the use of adaptive wall test section for industrial tests realised by a continuous variation of the angle of attack. Simulations have shown that wall shape could be predicted by simple extrapolation, using a one-step wall adaptation at each step to correct this procedure and to keep the same degree of accuracy all along the \( \alpha \)-sweep.

Considering the technological progress, we can imagine a more natural procedure, based on a complete wall adaptation at each step. This procedure is probably today.
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8. LIST OF TABLES AND FIGURES

table 1 Main characteristics of the wind tunnels concerned by the TWIG tests

table 2 TWIG test conditions

table 3 Accuracy estimates for TWIG reference data (HSTr)

figure 1.1 Characteristics of the TWIG/NL300 model

figure 1.2 TWIG/NL300 in the T2 test section

figure 1.3 Test section sizes compared to the model size

figure 1.4 Test section sizes compared to the dimensionless model

figure 2.1 Variation of lift interference factors $\delta_0$ and $\delta_1$ along the centreline of a solid walled test section of square cross section for different sweep back angles, $b/B = 0.7$

figure 2.2 Variation of lift interference factors $\delta_0$ and $\delta_1$ along the model span in a solid walled test section of square cross section for different sweep back angles, $b/B = 0.7$

figure 2.3 Sketch of a test section of square cross-section, definition of coordinate system.

figure 2.4 Lift interference factor $\delta_0$ as a function of slot factor $P$ in a test section of square cross section, $b/B = 0.7$, wing of rectangular planform

figure 2.5 Lift interference factor $\delta_0$ as a function of slot factor $Q$ in a test section of square cross section, $b/B = 0.7$

figure 2.6 Body shape parameter $\tau$ as a function of slot factor $P$ in a test section of square cross section. A single doublet represents model blockage

figure 2.7 Body shape parameter $\tau$ as a function of porosity factor $Q$ in a test section of square cross section. A single doublet represents model blockage

figure 3.1 Sketch of the TSWT at the University of Southampton

figure 3.2 Arrowhead model in the TSWT at the University of Southampton

figure 3.3 Wall interference assessment along the root line of the arrowhead model with straight walls

figure 3.4 Wall interference assessment along the quarter chord line of the arrowhead model with straight walls

figure 3.5 Wall interference assessment along the 85% semi-span line of the arrowhead model with straight walls

figure 3.6 Wall interference assessment along the root line of the arrowhead model with blockage walls

figure 3.7 Wall interference assessment along the quarter chord line of the arrowhead model with blockage walls

figure 3.8 Wall interference assessment along the 85% semi-span line of the arrowhead model with blockage walls
figure 3.9 Wall interference assessment along the root line of the arrowhead model with upwash walls
figure 3.10 Wall interference assessment along the quarter chord line of the arrowhead model with upwash walls
figure 3.11 Wall interference assessment along the 85% semi-span line of the arrowhead model with upwash walls
figure 3.12 TWIG/DLR750 model - Wall interference assessment along the model axis, with straight walls, at Ma=0.70
figure 3.13 TWIG/DLR750 model - Wall interference assessment along the quarter chord line, with straight walls, at Ma=0.70
figure 3.14 TWIG/DLR750 model - Wall interference assessment along the 85% semi-span line, with straight walls, at Ma=0.70
figure 3.15 TWIG/DLR750 model - Wall interference assessment along the model axis, with adapted walls, at Ma=0.70
figure 3.16 TWIG/DLR750 model - Wall interference assessment along the quarter chord line, with adapted walls, at Ma=0.70
figure 3.17 TWIG/DLR750 model - Wall interference assessment along the 85% semi-span line, with adapted walls, at Ma=0.70
figure 3.18 TWIG/DLR750 model - Wall interference assessment along the model axis, with adapted walls, at Ma=0.80
figure 3.19 TWIG/DLR750 model - Wall interference assessment along the quarter chord line, with adapted walls, at Ma=0.80
figure 3.20 TWIG/DLR750 model - Wall interference assessment along the 85% semi-span line, with adapted walls, at Ma=0.80
figure 4.1 TWIG reference data (HSTr) - Evolution of the normal force \( C_n \) versus the tangential force \( C_t \)
figure 4.2 TWIG reference data (HSTr) - Evolution of the lift coefficient \( C_L \) versus the angle of attack \( \alpha \)
figure 4.3 TWIG reference data (HSTr) - Evolution of the lift coefficient \( C_L \) versus the drag coefficient \( C_D \)
figure 4.4 TWIG reference data (HSTr) - Evolution of the lift coefficient \( C_L \) versus the pitching moment \( C_M \)
figure 4.5 Comparison of TWIG T2 data and HSTr data - Lift coefficient \( C_L \) and drag coefficient \( C_D \) versus angle of attack \( \alpha \) at Mach number 0.70
figure 4.6 Comparison of TWIG T2 data and HSTr data - Pitching moment \( C_M \) versus angle of attack \( \alpha \) and polar at Mach number 0.70
figure 4.7 Comparison of TWIG T2 data and HSTr data - Lift coefficient \( C_L \) and drag coefficient \( C_D \) versus angle of attack \( \alpha \) at Mach number 0.80
figure 4.8 Comparison of TWIG T2 data and HSTr data - Pitching moment \( C_M \) versus angle of attack \( \alpha \) and polar at Mach number 0.80
figure 4.9  Comparison of TWIG T2 data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Mach number 0.85

figure 4.10  Comparison of TWIG T2 data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Mach number 0.85

figure 4.11  Comparison of TWIG S3Ch (FWTS) data and HSTr data - Lift coefficient versus angle of attack $\alpha$ at Mach number 0.80

figure 4.12  Comparison of TWIG S3Ch (FWTS) data and HSTr data - Drag coefficient versus angle of attack $\alpha$ at Mach number 0.80

figure 4.13  Comparison of TWIG S3Ch (FWTS) data and HSTr data - Polar angle at Mach number 0.80

figure 4.14  Comparison of TWIG S3Ch (FWTS) data and HSTr data - Lift coefficient versus angle of attack $\alpha$ at Mach number 0.85

figure 4.15  Comparison of TWIG S3Ch (FWTS) data and HSTr data - Drag coefficient versus angle of attack $\alpha$ at Mach number 0.80

figure 4.16  Comparison of TWIG S3Ch (FWTS) data and HSTr data - Polar angle at Mach number 0.85

figure 4.17  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the normal force $C_n$ versus the tangential force $C_t$

figure 4.18  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the difference $\Delta C_t$ versus the normal force $C_n$

figure 4.19  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the lift coefficient $C_L$ versus the angle of attack $\alpha$

figure 4.20  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the difference $\Delta C_L$ versus the angle of attack $\alpha$

figure 4.21  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the lift coefficient $C_L$ versus the drag coefficient $C_D$

figure 4.22  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the difference $\Delta C_D$ versus the lift coefficient $C_L$

figure 4.23  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the lift coefficient $C_L$ versus the pitching moment $C_M$

figure 4.24  Comparison of TWIG PHST data (cor.) and HSTr data - Evolution of the difference $\Delta C_M$ versus the lift coefficient $C_L$

figure 4.25  Comparison of TWIG TWG data (DLR) and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.85

figure 4.26  Comparison of TWIG TWG (DLR) data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Ma 0.70

figure 4.27  Comparison of TWIG TWG (DLR) data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.80

figure 4.28  Comparison of TWIG TWG (DLR) data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Ma 0.80
figure 4.29  Comparison of TWIG TWG data (DLR) and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.85

figure 4.30  Comparison of TWIG TWG (DLR) data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Ma 0.85

figure 4.31  Comparison of TWIG BAe data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.70

figure 4.32  Comparison of TWIG BAe data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Ma 0.70

figure 4.33  Comparison of TWIG BAe data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.80

figure 4.34  Comparison of TWIG BAe data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Ma 0.80

figure 4.35  Comparison of TWIG BAe data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.85

figure 4.36  Comparison of TWIG BAe data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Ma 0.85

figure 4.37  High Productivity Strategy - T2 wind tunnel data – Strategies 1 (above) and 2 (below)

figure 4.38  High Productivity Strategy - T2 wind tunnel data – Strategies 3 (above) and 4 (below)

figure 4.39  High Productivity Strategy – T2 wind tunnel data – Comparison of the adapted wall shape with those estimated by the HPS strategies, at 6° and 8° of angle of attack

figure 4.40  High Productivity Strategy – T2 wind tunnel data – Comparison of the adapted wall shape with those estimated by the HPS strategies, at 10° and 12° of angle of attack

figure 4.41  High Productivity Strategy – T2 wind tunnel data – Comparison of the adapted wall shape with those estimated by the HPS strategies, at 14° of angle of attack

figure 4.42  High Productivity Strategy- T2 wind tunnel data - Lift, Drag and Pitching moment evolutions versus the angle of attack

figure 4.43  High Productivity Strategy – S3Ch wind tunnel data – Comparison of the adapted wall shape with this estimated by the HPS strategy, at 5° and 10° of angle of attack

figure 4.44  High Productivity Strategy – S3Ch wind tunnel data – Wall shape estimated by the HPS strategy, at 10°, 11°, 12° and 13° of angle of attack

figure 4.45  High Productivity Strategy – S3Ch wind tunnel data – Mach number and angle of attack residual corrections at 10°, 11°, 12° and 13° of angle of attack

figure 4.46  High Productivity Strategy – S3Ch wind tunnel data – Lift, Drag and Pitching moment evolutions versus the angle of attack
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<tr>
<th>NAME of the WIND TUNNEL</th>
<th>TEST SECTION SIZE BxH</th>
<th>WALLS (top/bottom)</th>
<th>MODEL</th>
<th>SPAN/WIDTH</th>
<th>BLOCKAGE RATIO (%)</th>
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Table 1 : Main characteristics of the wind tunnels concerned by the TWIG tests
## Corrections to measured data

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<th>Derived quantities</th>
<th>Model and wall quantities</th>
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<tr>
<td><strong>Institution</strong></td>
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<td><strong>Tunnel</strong></td>
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<td><strong>TWG</strong></td>
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<td><strong>T2</strong></td>
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<tr>
<td><strong>Bae Warton Transonic tunnel</strong></td>
<td><strong>TWIG/D750</strong></td>
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**Table 2 : TWIG test conditions**
| Measurement          | Instrumentation               | Calibration range | $P_o$ kPa | | ACCURACY |
|----------------------|-------------------------------|-------------------|----------|----------|
|                      |                               |                   | S*       | Ma=0.70  | Ma=0.80  | Ma=0.85  |
| ALPHA ($\alpha$)    | TWIG resolver                 | -10°/30°          |          | 0.05     | (0.01 for resolver only) |
| BASE $C_p$ (PRES.)  | STATHAM diff.pr.transd.       | 5 psi             |          | 0.2%     | $\Delta(C_D)_{B} = 0.0001$ |
| MACH NUMBER         | MENSOR                        | 180               |          | 0.0003   | 0.0004   | 0.0004   |
| MODEL FORCES & MOMENTS | BALANCE 1.25"ER TASK #615     | 450ON (normal force) | 0.3%     | $\Delta C_L = 0.0121$ | 0.0103 | 0.0090 |
|                      |                               | 440N (axial force) |          | $\Delta C_D = 0.0012$ | 0.0010 | 0.0009 |
|                      |                               | 150Nm (pitching moment) |          | $\Delta C_M = 0.0044$ | 0.0037 | 0.0033 |

* denotes "Full Scale Output"

Table 3: Accuracy estimates for TWIG reference data (HSTr)
Figure 1.1: Characteristics of the TWIG/NL300 model

- Strake Contour: $Y_s = 25.85^*[(3^*(X/235) - (X/235)^*3)]$ [mm]
- Fuselage Contour: $R = 22$ [mm] for $X > 100$ mm
  
  $R = 11^*[(3^*(X/100) - (X/100)^*3)]$ mm for $0 < X < 100$ mm

- Wing Ref. Area (S): 0.025 m$^2$
- Cross-sectional area: 0.0028 m$^2$
- Wing bevel angle: 15 deg
- Strake area ratio ($S_s/S$): 0.15
- MRP is Moment Reference Point

TWIG is a Low-Wing Configuration
Figure 1.2: TWIG/NL300 in the T2 test section
Figure 1.3: Test section sizes compared to the model size
Figure 1.4: Test section sizes compared to the dimensionless model
Figure 2.1: Variation of lift interference factors $\delta_0$ and $\delta_1$ along the centreline of a solid walled test section of square cross section for different sweep back angles, $b/B = 0.7$. 

<table>
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<th>Description</th>
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<td>$\delta_1$, sweep back angle $\Phi=0^\circ$</td>
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<td>$\delta_1$, sweep back angle $\Phi=26.4^\circ$</td>
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<tr>
<td>$O$</td>
<td>$\delta_1$, sweep back angle $\Phi=52.8^\circ$</td>
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Figure 2.2: Variation of lift interference factors $\delta_0$ and $\delta_1$ along the model spanwise (quarter chord line) in a solid walled test section of square cross section for different sweep back angles, $b/B = 0.7$. 

<table>
<thead>
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<td>$\Delta$</td>
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<td>$\times$</td>
<td>$\delta_1$, sweep back angle $\Phi=0^\circ$</td>
</tr>
<tr>
<td>$\circ$</td>
<td>$\delta_1$, sweep back angle $\Phi=26.4^\circ$</td>
</tr>
<tr>
<td>$O$</td>
<td>$\delta_1$, sweep back angle $\Phi=52.8^\circ$</td>
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Figure 2.3: Sketch of a test section of square cross-section, definition of coordinate system
Figure 2.4: Lift interference factor $\delta_0$ as a function of slot factor $P$ in a test section of square cross section, $b/B = 0.7$, wing of rectangular planform.
Figure 2.5: Lift interference factor $\delta_0$ as a function of slot factor $Q$ in a test section of square cross section, $b/B = 0.7$. 

- o: wing of rectangular planform
- O: sweep back angle $\Phi=30^\circ$
- Δ: classical values from AGARDograph 109
Figure 2.6: Body shape parameter $\tau$ as a function of slot factor $P$ in a test section of square cross section. A single doublet represents model blockage.
Vortex lattice, homogeneous boundary condition classical values from AGARDograph 109

Figure 2.7: Body shape parameter \( \tau \) as a function of porosity factor \( Q \) in a test section of square cross section. A single doublet represents model blockage.
Figure 3.1: Sketch of the TSWT at the University of Southampton

Figure 3.2: Arrowhead model in the TSWT at the University of Southampton
Figure 3.3: Wall interference assessment along the root line of the arrowhead model with straight walls

Figure 3.4: Wall interference assessment along the quarter chord line of the arrowhead model with straight walls
Figure 3.5: Wall interference assessment along the 85% semi-span line of the arrowhead model with straight walls.

Figure 3.6: Wall interference assessment along the root line of the arrowhead model with blockage walls.
Figure 3.7: Wall interference assessment along the quarter chord line of the arrowhead model with blockage walls

Figure 3.8: Wall interference assessment along the 85% semi-span line of the arrowhead model with blockage walls
Figure 3.9: Wall interference assessment along the root line of the arrowhead model with upwash walls.

Figure 3.10: Wall interference assessment along the quarter chord line of the arrowhead model with upwash walls.
Figure 3.11: Wall interference assessment along the 85% semi-span line of the arrowhead model with upwash walls.
Figure 3.12 : TWIG/DLR750 model - Wall interference assessment along the model axis, with straight walls, at Ma=0.70
Figure 3.13: TWIG/DLR750 model - Wall interference assessment along the quarter chord line, with straight walls, at Ma=0.70
WIA along the 85% semi-span line - TWIG/D750 test case
Ma=0.70 - Straight Walls, With Dummy

Figure 3.14: TWIG/DLR750 model - Wall interference assessment along the 85% semi-span line, with straight walls, at Ma=0.70
Figure 3.15 : TWIG/DLR750 model - Wall interference assessment along the model axis, with adapted walls, at Ma=0.70
WIA along the quarter chord line - TWIG/D750 test case
Ma=0.70 - Adapted Walls, With Dummy

Figure 3.16: TWIG/DLR750 model - Wall interference assessment along the quarter chord line, with adapted walls, at Ma=0.70
Figure 3.17: TWIG/DLR750 model - Wall interference assessment along the 85% semi-span line, with adapted walls, at Ma=0.70
Figure 3.18: TWIG/DLR750 model - Wall interference assessment along the model axis, with adapted walls, at $Ma=0.80$
WIA along the quarter chord line - TWIG/D750 test case
Ma=0.80 - Adapted Walls, Without Dummy

Figure 3.19: TWIG/DLR750 model - Wall interference assessment along the quarter chord line, with adapted walls, at Ma=0.80
Figure 3.20: TWIG/DLR750 model - Wall interference assessment along the 85% semi-span line, with adapted walls, at Ma=0.80
Figure 4.1 : TWIG reference data (HStr)
Evolution of the normal force $C_n$ versus the tangential force $C_t$

Figure 4.2 : TWIG reference data (HStr)
Evolution of the lift coefficient $C_L$ versus the angle of attack $\alpha$
Figure 4.3: TWIG reference data (HSTr)
Evolution of the lift coefficient $C_L$ versus the drag coefficient $C_D$.

Figure 4.4: TWIG reference data (HSTr)
Evolution of the lift coefficient $C_L$ versus the pitching moment $C_M$. 
Figure 4.5 : Comparison of TWIG T2 data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Mach number 0.70
Figure 4.6 : Comparison of TWIG T2 data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Mach number 0.70
Figure 4.7: Comparison of TWIG T2 data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Mach number 0.80
Figure 4.8: Comparison of TWIG T2 data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Mach number 0.80
Figure 4.9: Comparison of TWIG T2 data and HSTr data - Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Mach number 0.85.
Figure 4.10: Comparison of TWIG T2 data and HSTr data - Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at Mach number 0.85
Figure 4.11: Comparison of TWIG S3Ch (FWTS) data and HSTr data - Lift coefficient versus angle of attack $\alpha$ at Mach number 0.80

Figure 4.12: Comparison of TWIG S3Ch (FWTS) data and HSTr data - Drag coefficient versus angle of attack $\alpha$ at Mach number 0.80
Figure 4.13: Comparison of TWIG S3Ch (FWTS) data and HSTr data - Polar at Mach number 0.80

Figure 4.14: Comparison of TWIG S3Ch (FWTS) data and HSTr data - Lift coefficient versus angle of attack $\alpha$ at Mach number 0.85
Figure 4.15: Comparison of TWIG S3Ch (FWTS) data and HSTr data - Drag coefficient versus angle of attack $\alpha$ at Mach number 0.80

Figure 4.16: Comparison of TWIG S3Ch (FWTS) data and HSTr data - Polar at Mach number 0.85
Figure 4.17: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the normal force $C_n$ versus the tangential force $C_t$
Figure 4.18: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the difference $\Delta C_t$ versus the normal force $C_n$
Figure 4.19: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the lift coefficient $C_L$ versus the angle of attack $\alpha$
Figure 4.20: Comparison of TWIG PHST data (cor.) and HSTR data
Evolution of the difference $\Delta C_L$ versus the angle of attack $\alpha$
Figure 4.21: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the lift coefficient $C_L$ versus the drag coefficient $C_D$
Figure 4.22: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the difference $\Delta C_D$ versus the lift coefficient $C_L$
Figure 4.23: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the lift coefficient $C_L$ versus the pitching moment $C_M$
Figure 4.24: Comparison of TWIG PHST data (cor.) and HSTr data
Evolution of the difference $\Delta C_M$ versus the lift coefficient $C_L$
Figure 4.25: Comparison of TWIG TWG data (DLR) and HSTr data. Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at $Ma=0.85$.
Figure 4.26: Comparison of TWIG TWG (DLR) data and HSTr data. Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at $Ma = 0.70$
Figure 4.27: Comparison of TWIG TWG data (DLR) and HSTr data. Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at $Ma = 0.80$.
Figure 4.28: Comparison of TWIG TWG (DLR) data and HSTr data. Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at $Ma=0.80$
Figure 4.29: Comparison of TWIG TWG data (DLR) and HSTr data. Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at $Ma=0.85$
Figure 4.30: Comparison of TWIG TWG (DLR) data and HSTr data. Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at $Ma = 0.85$
Figure 4.31: Comparison of TWIG BAe data and HSTr data. Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at Ma 0.70.
Figure 4.32: Comparison of TWIG BAe data and HSTr data. Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at $Ma$ 0.70
Figure 4.33: Comparison of TWIG BAe data and HSTr data. Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at $Ma=0.80$. 
Figure 4.34: Comparison of TWIG BAe data and HSTr data. Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at $Ma = 0.80$.
Figure 4.35: Comparison of TWIG BAe data and HSTr data.
Lift coefficient $C_L$ and drag coefficient $C_D$ versus angle of attack $\alpha$ at $Ma = 0.85$
Figure 4.36: Comparison of TWIG BAe data and HSTr data. Pitching moment $C_M$ versus angle of attack $\alpha$ and polar at $Ma = 0.85$
Figure 4.37: High Productivity Strategy - T2 wind tunnel data – Strategies 1 (above) and 2 (below)
Figure 4.38: High Productivity Strategy - T2 wind tunnel data – Strategies 3 (above) and 4 (below)
Figure 4.39: High Productivity Strategy – T2 wind tunnel data (Ma=0.70) – Comparison of the adapted wall shape with those estimated by the HPS strategies, at 6° and 8° of angle of attack.
Figure 4.40: High Productivity Strategy – T2 wind tunnel data (Ma=0.70) – Comparison of the adapted wall shape with those estimated by the HPS strategies, at 10° and 12° of angle of attack
Figure 4.41: High Productivity Strategy – T2 wind tunnel data (Ma=0.70) – Comparison of the adapted wall shape with those estimated by the HPS strategies, at 14° of angle of attack
Figure 4.42: High Productivity Strategy- T2 wind tunnel data (Ma=0.70) - Lift, Drag and Pitching moment evolutions versus the angle of attack
Figure 4.43: High Productivity Strategy – S3Ch wind tunnel data (Ma=0.85) – Comparison of the adapted wall shape with this estimated by the HPS strategy, at 5° and 10° of angle of attack.
Figure 4.44 : High Productivity Strategy – S3Ch wind tunnel data (Ma=0.85) – Wall shape estimated by the HPS strategy, at 10°, 11°, 12° and 13° of angle of attack
Figure 4.45: High Productivity Strategy – S3Ch wind tunnel data (Ma=0.85) – Mach number and angle of attack residual corrections at 10°, 11°, 12° and 13° of angle of attack.
Figure 4.46: High Productivity Strategy – S3Ch wind tunnel data (Ma=0.85) – Lift, Drag and Pitching moment evolutions versus the angle of attack