Wall Interference Correction System of the NASA Ames 11-ft Transonic Wind Tunnel

by

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1. Introduction

A wall interference correction system was developed for the *NASA Ames 12-ft Pressure Wind Tunnel* (PWT) during the second half of the 1990s that used model load and test section boundary flow measurements as input for the assessment of wall interference corrections for wind tunnel test data (Ref. [1]). The system became known by its acronym *WICS* (*Wall Interference Correction System*). WICS was the starting point for the development of a similar wall interference correction system for the *NASA Ames 11-ft Transonic Wind Tunnel* (TWT) that was deployed in the early 2000s (Refs. [2] to [5]). This *system is known as TWICS (Transonic Wall Interference Correction System*). *WICS* is also the original source for the wall interference correction system that was implemented at *NASA Langley Research Center* in both the *National Transonic Facility* and the *14- by 22-ft Subsonic Wind Tunnel* (Refs. [6], [7]). As such, the basic methodology used by *WICS & TWICS* has become a "*de facto"* standard for wind tunnel wall correction assessment within *NASA*, with localized modifications to account for facility differences and testing requirements.

The wall interference correction system of the *Ames 11-ft TWT* is a compromise between predicting wall interference corrections close to "real-time" while, simultaneously, using boundary flow measurements for the accurate assessment of separation wake blockage effects. It is necessary to first review some basic ideas and challenges associated with the prediction of wall interference corrections before specific elements of *TWICS* may be discussed in more detail.

In general, wind tunnel wall boundary conditions influence interactions between flow field and test article during a wind tunnel test. These interactions introduce unwanted test section specific bias errors in test data whenever the wall boundary conditions do not exactly match conditions that the model would experience in free flight. These bias errors are traditionally described as "wind tunnel wall interference". They need to be removed from test data by applying "wall interference corrections" so that (i) tunnel-to-tunnel comparisons of test results can be done and/or (ii) wind tunnel test data can be extrapolated to flight conditions.

Different approaches have been developed since the beginning of the 20th century to estimate wall interference corrections. Experience showed that a reliable prediction of the corrections depends on (i) a sufficiently accurate mathematical description of the wall boundary conditions of the wind tunnel test section and (ii) the successful modeling of solid volume, separation wake, and lifting effects of the wind tunnel model. The "far field" assumption is an important concept in this context. It describes wall interference effects as "small perturbations" of the uniform flow field that the test article experiences in the wind tunnel. Then, the numerical calculation of wall interference corrections can significantly be simplified as long as extreme test conditions such as near-sonic flow and the use of very large models are avoided. Only characteristics of principle parts of the wind tunnel model have to be used as input for the numerical prediction of wall interference corrections. This conclusion also means that wall interference corrections obtained from, for example, the "Method of Images" or a panel method code can be as accurate as corrections obtained from a "state-of-the-art" CFD solver as long as solid volume, separation wake, and lifting effects of the wind tunnel model and the wall boundary conditions are described correctly.

The description of solid volume and lifting effects for the purpose of computing wall interference corrections is straight forward as (i) solid volume effects are directly related to the cross-sectional area distribution of the test article along the tunnel centerline and (ii) lifting effects are proportional to the lift force and pitching moment that act on the wind tunnel model. The description of the separation wake effect, on the other hand, is more difficult. This phenomenon primarily depends on the displacement of the flow that is observed downstream of the test article. Separation wake effects must be included in the wall interference assessment whenever (i) the model generates a large separation wake and (ii) accurate values of the blockage corrections, i.e., of the Mach number & dynamic pressure correction, are needed. Maskell-type corrections are traditionally used to assess separation wake effects for models tested in solid wall tunnels. A more accurate description of separation wake effects requires flow measurements on or in the vicinity of the wind tunnel boundaries. With this information, separation wake blockage corrections for different types of boundary conditions and test article geometries can be assessed with greater confidence.

2. Basic Approach

A variety of techniques were developed over the years that utilized boundary flow measurements as input for the prediction of blockage effects of a test article (see, e.g., the discussion in Ref. [8], Section 4). One such approach was developed by Hackett (Ref. [9]). Hackett's method needs a singularity description of the model in the test section but does not require a surface integration of the wall pressure measurements. The latter characteristic was seen as an advantage as it would make the wall interference correction assessment less dependent on the availability of wall pressure measurements at specific locations on the test section boundaries. Therefore, it was decided to develop a modified version of Hackett's "Wall Signature Method" for *TWICS* that would (i) use global regression analysis for the fit of the wall pressure signature and (ii) construct the singularity representation of the test article from point and line doublets (see Refs. [1], [2], [5]).

Hackett's original approach uses a potential flow model of the wind tunnel and wall interference flow field of the test article for the prediction of wall interference corrections. The wind tunnel flow field is needed for the correct interpretation of the boundary flow measurements. The wall interference flow field, on the other hand, is required for the calculation of the wall interference corrections themselves. The test article and its separation wake are represented by singularities. *TWICS* uses lifting line doublets to represent lifting effects on the model. Chains of point doublets are used to represent solid volume and separation wake effects (Ref. [10]). Point doublets are also used to model propulsion simulator blockage effects (Ref. [11]). The strengths of the singularities are derived from wall signature measurements on the tunnel walls, the lift force & pitching moment measurements on the model, and the propulsion simulator thrust (if applicable).

TWICS computes the mathematical representation of the wind tunnel and wall interference flow field of the model close to "real-time" by applying the principle of superposition. First, normalized solutions of flow fields of a set of evenly spaced singularities are read from a database file. Then, tri-linear interpolation is applied to the flow fields of the eight closest singularities to a given test article singularity so that its wind tunnel and wall interference flow field is obtained. This process is repeated for all singularities that represent the test article. Finally, the interpolated flow fields of all test article singularities are superimposed so that (i) the strength values of the singularities can be matched to the measured lift force, pitching moment, and wall signature and (ii) wall interference corrections can be computed at the test article's reference points.

In principle, the singularity model of a test article and its separation wake can consist of a large number of singularities as chains of point doublets may be used to represent the test article's solid volume and separation wake. Therefore, the number of unknown singularity strength values could be large. However, *TWICS* uses weighting factors to reduce the total number of unknown values to four. For example, elliptic lift distribution is used to reduce the number of unknown line doublet strength values of the wing to a single reference strength. Similarly, elliptic lift distribution is used to reduce the number of unknown line doublet strength values of the tail to a single reference strength. The cross-sectional area distribution of the test article in the streamwise direction is used to reduce singularity strengths associated with solid volume blockage to a single reference value. Finally, the strengths of singularities associated with the separation wake is reduced to one by assuming that the strength of each individual point doublet of the separation wake is constant.

The two reference strength values of the line doublets of the wing & tail are obtained from the lift force & pitching moment measurements on the model after applying the *Kutta-Joukowski* equation (Ref. [1], App. 5). The reference strength of the point doublet of a propulsion simulator is obtained from its thrust measurement (Ref. [1], App. 10). The two remaining reference strength values, i.e., values associated with solid volume and separation wake effects, are obtained from a least squares fit of the measured wall signature (see Ref. [2], pp. 7-11, or, Ref. [3]).

TWICS obtains the wall signature from a wall pressure measurement system that was implemented in the *Ames 11-ft TWT* in the early 2000s. Characteristics of this system are described in the next section (see also Ref. [4]). Afterwards, the application of a panel method code for the calculation of normalized solutions of the wind tunnel and wall interference flow field is discussed in some detail. Then, key elements of the wall interference correction algorithm and the data correction approach are summarized. Finally, operational experiences with preparation and use of *TWICS* during a wind tunnel test are described.

3. Wall Pressure Measurement System

Wall Pressure Row Layout

In general, the precise measurement of the wall pressure signature is a critical input for the determination of wall interference corrections if the wall signature method is used. Its analysis makes a calculation of blockage corrections possible that takes both solid volume & separation wake effects into account. Therefore, it is important to implement a wall pressure measurement system in a wind tunnel that is capable of detecting very small pressure changes. Those pressure changes quantify the displacement of the flow that is caused by the solid volume of the model and its separation wake.

Different options were considered for the *Ames 11-ft TWT* as far as the installation of pressure ports in the test section was concerned (see also discussion in Ref. [4]). It was decided to directly install pressure ports on the solid panels of the slotted test section because the use of removable pressure rails would have greatly increased the complexity of the wall pressure measurement system. The slotted portion of the test section has a length of approximately 22 [ft]. A total of 52 evenly spaced slots exist on the two side walls, the floor, and the ceiling of the test section. Two pressure port rows each were installed on the side walls, floor, and ceiling. The elevation view given in Fig. 1a below shows the location of the two pressure port rows that are installed on one of the test section's side walls.

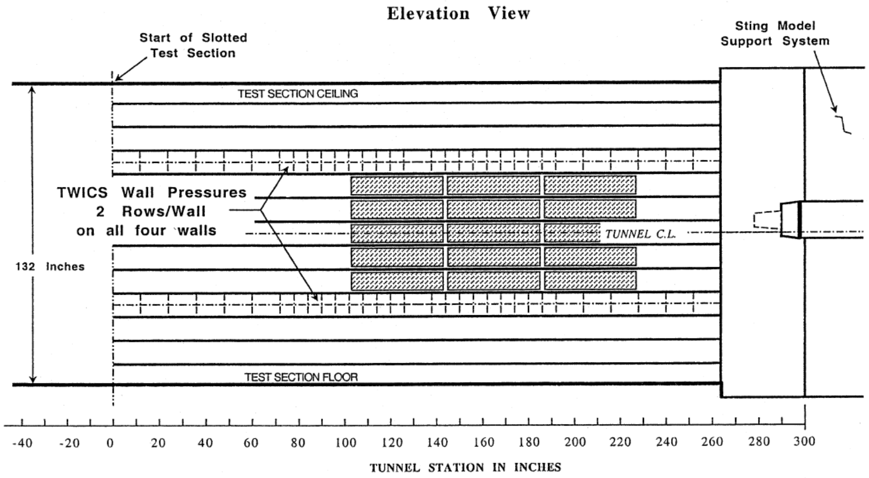

Fig.1a Elevation view of the test section of the *Ames 11-ft Transonic Wind Tunnel* (image courtesy of *NASA Ames Research Center*).

The total number of pressure ports is 240 as each one of the eight pressure port rows has 30 ports. The pressure ports were installed on the centerline of eight solid wall panels that are located between pairs of test section slots. Figure 1b below shows the location of the eight pressure port rows in a cross-sectional view of the test section.

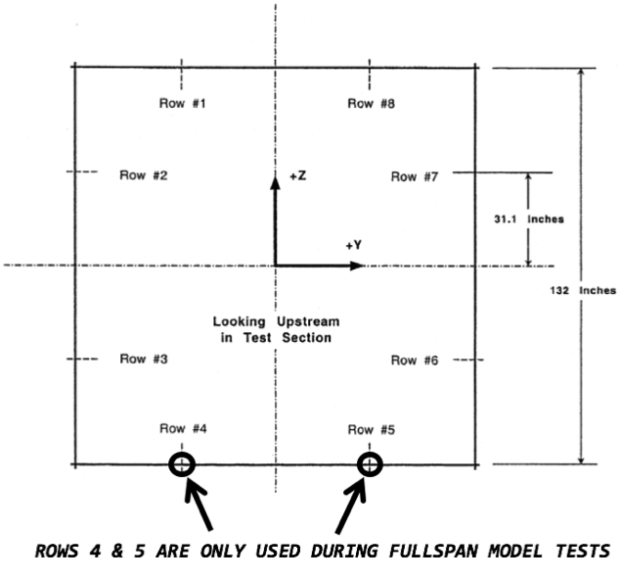

Fig.1b Cross-sectional view of the test section of the *Ames 11-ft Transonic Wind Tunnel* (image courtesy of *NASA Ames Research Center*).

The streamwise spacing of the ports is 1.0 [ft] near the start & end of the slotted part of the test section and 0.5 [ft] in the center of the test section. The latter choice makes it possible to detect maxima & minima of the wall signature at locations where a test article is typically tested in the tunnel. An empty tunnel calibration of the wall pressure signature was performed by using (i) the total pressure and (ii) the Mach number as independent calibration variables (see Ref. [4]). It provides reference wall signatures for both the removal of orifice installation errors and the monitoring of the pressure port status during a wind tunnel test. Figure 2 below shows the *Ames Check Standard Model* installed in the test section of the *Ames 11-ft TWT*. In this case, all 52 slots of the test section are in "open" configuration.

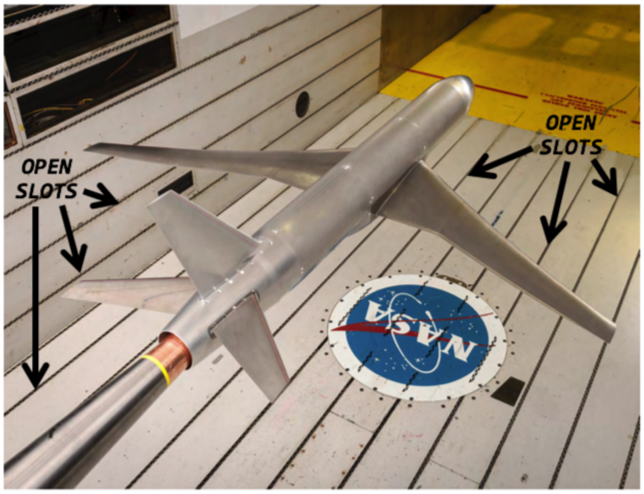

Fig. 2 The *Ames Check Standard Model* in the test section of the *Ames 11-ft Transonic Wind Tunnel* (image courtesy of *NASA Ames Research Center*).

Semi-span model tests are also performed in the *Ames 11-ft TWT*. In that case, the baffles in the floor slots are replaced with solid fillers and the model is mounted on a turntable that is located below the test section floor (see Fig. 3 below). Therefore, an empty tunnel calibration of the pressure ports was also done for this alternate test section configuration so that wall signature data during semi-span model tests can be processed correctly.

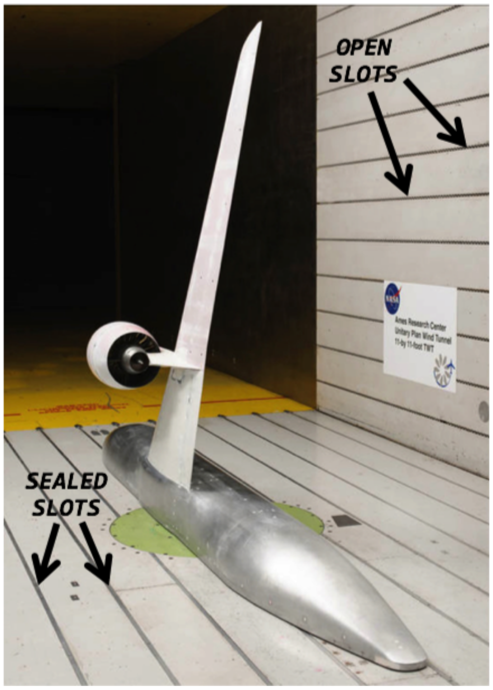

Fig. 3 The *UHB* semi-span model in the test section of the *Ames 11-ft Transonic Wind Tunnel* (image courtesy of *NASA Ames Research Center*).

It must be mentioned that the floor becomes a sealed "image plane" during semi-span model test. Consequently, pressure port rows 4 and 5 are no longer in the "far field" of the model and must be excluded during the processing of the wall signature (see also Fig. 1b).

Figure 4 below shows a close-up view of the test section slot geometry of the *Ames 11-ft TWT*. Baffles can be seen inside the test section slots. They force the axial velocity component inside the slots to be zero. This characteristic made it possible to describe the boundary conditions of the test section by (i) applying the "perforated wall boundary condition" at each one of the 52 slots and (ii) the solid wall boundary condition anywhere else.

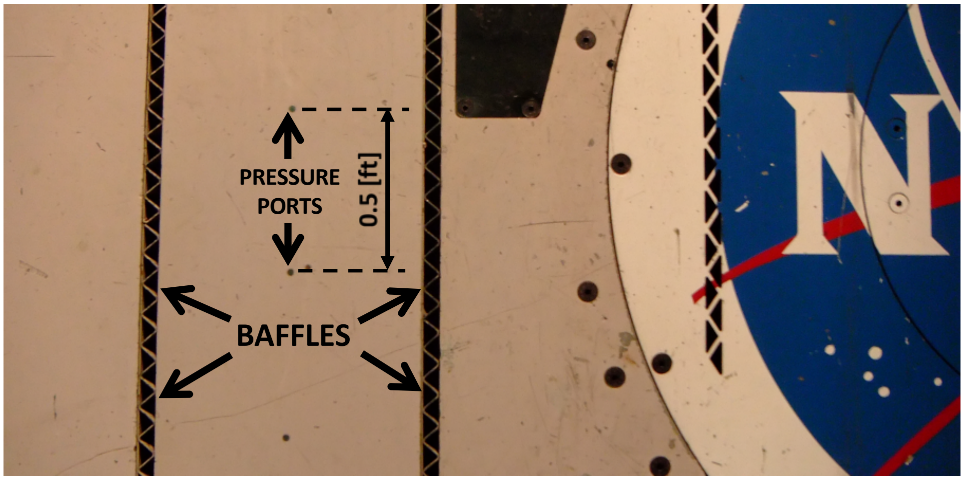

Fig. 4 Pressure port row 4 on the floor of the test section of the *Ames 11-ft Transonic Wind Tunnel* (image courtesy of *NASA Ames Research Center*).

The 240 pressure ports were directly installed on solid wall panels of the test section. In addition, the measured pressure coefficients on the test section boundary are small when compared to values that are typically measured on the surface of a wind tunnel model. Therefore, it was necessary to perform an empty tunnel calibration of the pressure ports in order (i) to remove orifice installation imperfections from the raw wall signature and (ii) to better detect small pressure changes that are exclusively caused by the wind tunnel model and its wake. Key elements of this calibration are described in the next section.

Empty Tunnel Calibration

An empty tunnel calibration of the wall pressure signature of the *Ames 11-ft TWT* was done to improve the quality of the wall signature that is used as input for wall interference calculations. The independent variables of the calibration are the total pressure and the Mach number (see also the related discussion in Ref. [4]). Different combinations of total pressure and Mach number were chosen for the calibration. Wall signatures were recorded for each combination and stored in a database file (empty tunnel calibration database). Bi-linear interpolation is used during the wind tunnel test of a model to obtain the empty tunnel signature for the combination of total pressure and Mach number that the model experiences. The interpolated empty tunnel signature is subtracted from the raw wall signature. This signature difference is ultimately used as input for the wall interference correction calculation.

The *Ames 11-ft TWT* is used for both full- and semi-span model tests. The slots on the floor of the test section are sealed during semi-span model tests as the model is mounted on a turntable that is below the floor of the test section. Consequently, a separate calibration of the wall pressure signature had to be done for this alternate test section configuration by using again the total pressure and the Mach number as independent calibration variables.

Pressure Port Status Monitoring

Status and health of the individual pressure ports of the wall pressure measurement system of the *Ames 11-ft TWT* are monitored on a regular basis. A table with wall port status flags is maintained that uses the value "1" to identify a "good" and the value "0" to identify an "unused" or "bad" port. The correction software reads this table before wall interference corrections are computed. In addition, empty tunnel runs are performed from time to time in order to compare the current wall signature with the baseline/reference signature that is stored in the empty tunnel calibration database. This process makes it possible to quickly identify ports that either need service or that must be omitted during the wall interference correction calculation.

4. Panel Code Calculations

The accuracy of wall interference corrections depends on a good assessment of both the wind tunnel and wall interference flow field of the test article if the wall signature method is applied. The wind tunnel flow field of the test article is needed so that (i) blockage effects can be extracted from the measured wall signature and (ii) the correct strength of all test article singularities can be determined. The wall interference flow field is needed so that blockage and angle of attack corrections can be determined from the singularity representation of the test article.

The boundary conditions of the test section of the *Ames 11-ft TWT* are complex. Therefore, it became necessary to use a 3D panel method code for the calculation of the wind tunnel and wall interference flow field of the test article. Panel method code *ANTARES* was selected for these flow field calculations because (1) it can use panels to describe the boundary conditions of the test section and (2) it accepts lifting line doublets & point doubles for the description of lifting & blockage effects of the test article (see Refs. [12], [13]). The use of singularities for the description of the test article is sufficiently accurate for the assessment of wall interference corrections because the test section boundaries and its influence on the test article are considered to be in the "far field".

A key requirement for the development of the wall interference correction system of the *Ames 11-ft TWT* was the ability to compute wall interference corrections close to "real-time". Therefore, the "Principle of Superposition" is used for the calculation of the wind tunnel and wall interference flow field of the test article. First, singularities of unit strength are distributed on a fixed singularity grid in the test section. Then, wind tunnel & wall interference flow field for those singularities are computed using the panel method code and stored in a perturbation velocity database file. This database file has to be computed only once for a given test section geometry as long as the test section's physical characteristics remain unchanged. Figure 5 below shows the panel model of the slotted part of the test section that was used for the panel code calculations.

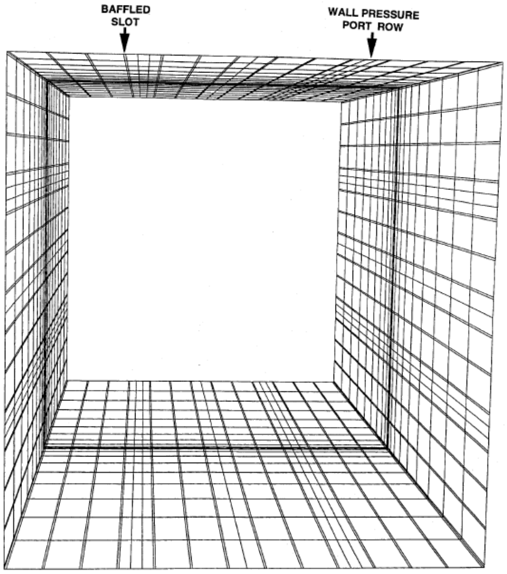

Fig. 5 Panel model of the slotted test section of the *Ames 11-ft Transonic Wind Tunnel* (image courtesy of *NASA Ames Research Center*).

The perturbation velocity database was computed for both the full-span and semi-span model configuration of the test section by placing singularities on a singularity grid and obtaining the flow field solutions for one singularity at a time. The orientation of the lift vector, i.e., of the lifting line doublet, was varied during the calculation of the perturbation velocity databases for the full-span configuration so that wall interference for a full-span model tested in upright, inverted, and other orientations can be computed. Therefore, eight separate perturbation velocity database files were prepared for the full-span configuration using lift vector orientations from 0 [deg] to 315 [deg]. A single perturbation velocity database was computed for the semi-span model configuration of the test section. In that case, the lift vector was kept parallel to the floor and perpendicular to the tunnel centerline while assuming that the left wing of a model would be tested.

The wall interference correction software reads all required perturbation velocity database files for a given test section configuration before data is first recorded. Then, for each data point, the wind tunnel & wall interference flow field of each test article singularity is obtained by (i) using tri-linear interpolation of the normalized flow field solutions that are contained in the perturbation velocity database and by (ii) multiplying the result with the computed singularity strengths that are either obtained from the lift force & pitching moment measurements on the model or the least squares fit of the measured wall signature. The algorithm for the calculation of wall interference corrections using the modified wall signature method is summarized in the next section.

5. Correction Calculation Algorithm and Correction Approach

Previous sections described (i) the empty tunnel calibration of the wall pressure ports and (ii) the calculation of the perturbation velocity database files in great detail. Results of these tasks are stored in database files that are read when the correction software is first started. The flow chart in Fig. 6 below summarizes the calculation of wall interference corrections assuming that the test article does not use a propulsion simulator.

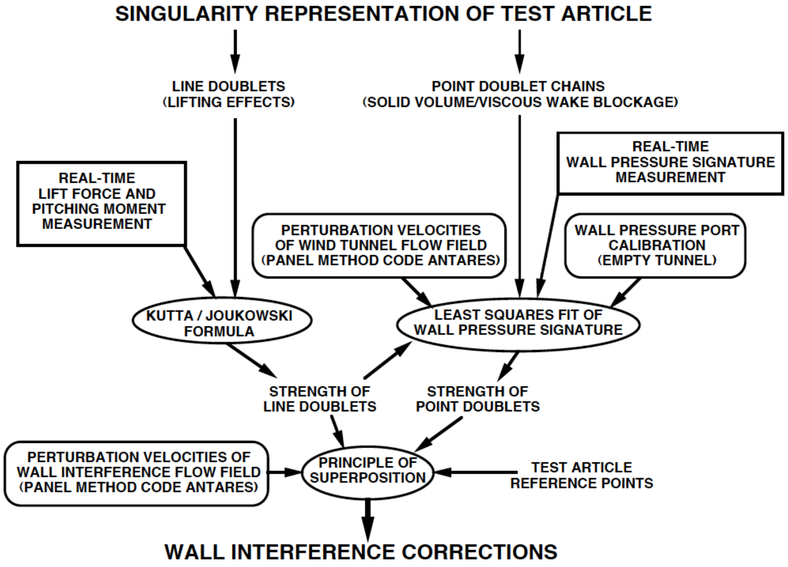

Fig. 6 Summary of wall interference correction calculation (taken from Ref. [2], p. 29, Fig. 4).

In principle, the modified wall signature method defines a singularity representation of the test article and its separation wake to compute wall interference corrections. Lifting line doublets are placed along the 1/4 chord line of the wing & tail to model lifting effects. Similarly, chains of point doublets are placed on the test article's centerline and where flow separation is expected. In addition, chains of point doublets are placed where a propulsion simulator is attached to the model. The location of the singularities is defined by the location of the test article in the test section. The strength of the singularities, on the other hand, is obtained from real-time measurements of lift force, pitching moment, thrust (if applicable), and the wall pressure signature.

First, strengths of the lifting line doublets are determined for the given data point. The lift force & pitching moment of the model is used as input for the *Kutta/Joukowski* formula to compute the reference line doublet strengths of the wing & tail if the model has two lifting surfaces. These reference strength values are used in combination with the chosen lift distribution assumption (elliptic distribution, or, distribution derived from lifting line theory) to determine the strength of the individual lifting line doublets.

It is assumed that the test article does not have a propulsion simulator. Then, it remains to calculate the strength of point doublet chains that represent solid volume and separation wake effects. The individual strength values are reduced to two reference values. The first reference value describes solid volume effects of the model. Related point doublet strength values are computed by using the first reference strength in combination with the cross-sectional area distribution of the model as input. The second reference value is related to point doublet chains that describe separation wake blockage effects. A least squares fit of the wall signature needs to be performed to determine the two reference strength values. Therefore, the wind tunnel flow field at the wall pressure ports resulting from the lifting line doublets is predicted by using the perturbation velocity database. Then, these values plus the interpolated empty tunnel signature are subtracted from the raw wall signature so that only the part of the wall signature is left that is caused by blockage effects. This remaining signature is fitted in the least squares sense so that the two unknown reference strength values are obtained. Afterwards, the strengths of all singularities associated with solid volume and separation wake blockage effects can be computed.

Now, the singularity representation of the test article, i.e., type, location, and strength of all singularities, is known. This representation can be used in combination with (i) perturbation velocities of the wall interference flow field, (ii) the principle of superposition, and (iii) tri-linear interpolation for the determination of interference velocities at the model's reference point set.

The reference point set for the calculation of first order corrections, i.e., for the calculation of the (i) Mach number correction, (ii) dynamic pressure correction, and (iii) angle of attack correction, needs to be chosen with care as the arithmetic mean of the corrections at the reference points is used to correct the test data. Reference points placed along the 3/4-chord line of the wing are often selected to compute mean correction if the test article is a traditional airplane with fuselage, wing, and tail. These points are a good choice for this type of test article because the angle of attack at the 3/4 chord line determines the lift whenever the angle of attack distribution in the chordwise direction is variable (see *Theorem of Pistolesi*, Ref. [14], p. 78/79, Eq. (2-113a)). Alternatively, reference points located on the test article's centerline are used if the test article is a body of revolution with no lifting surfaces.

The dynamic pressure, Mach number, and angle of attack corrections are applied to the uncorrected test data so that the corrected values can be used to better describe wind tunnel test results. The wall interference correction system of the *Ames 11-ft TWT* computes up to sixteen first and second order corrections for every data point. They can be summarized as follows:

1. First Order Corrections (mean values of corrections are computed at reference point set):

(1.1) Blockage factor;
(1.2) Mach number correction;
(1.3) Dynamic pressure correction;
(1.4) Angle of attack correction;

2. Higher Order Corrections (force/moment corrections are described in the stability axis system):

(2.1) Angle of attack correction along the wing's 1/4 chord line (if applicable);
(2.2) Tail incidence angle correction (see also (2.9));
(2.3) Drag force correction due to inclination of lift vector at 1/4 chord line;
(2.4) Lift force correction due to inclination of lift vector at 1/4 chord line;
(2.5) Buoyant drag force caused by wall induced axial pressure gradient;
(2.6) Total pitching moment correction (sum of 2.7, 2.8, 2.9);
(2.7) Pitching moment correction associated with span-wise angle of attack correction variation;
(2.8) Pitching moment correction associated with chord-wise angle of attack correction variation;
(2.9) Pitching moment due to induced tail incidence (not used if correction (2.2) is applied);
(2.10) Yawing moment correction due to inclination of lift vector at 1/4 chord line;
(2.11) Rolling moment correction due to inclination of lift vector at 1/4 chord line;
(2.12) Rolling moment correction due to asymmetric lift distribution.

Wall interference corrections are a function of the location of a reference point in the tunnel coordinate system. The correction magnitude can vary substantially depending on the physical location of a given reference point in the test section. Therefore, the wall interference correction system of the *Ames 11-ft TWT* computes coordinates of both the test article singularities and the reference points as a function of the model support system motion. These coordinates are used as input for the wall interference correction calculation in order to increase the accuracy of the correction estimates. - A discussion of an approximation of more complex wing planforms for the purpose of computing wall interference corrections can be found in Ref. [15]. In addition, the rolling moment correction due to asymmetric lift distribution in described in Ref. [16].

A significant amount of operational experience was gained with the correction system of the *Ames 11-ft TWT* since it became first operational. This experience is discussed in the next section.

6. Wind Tunnel Test Experience

The wall interference correction system of the *Ames 11-ft TWT* first became operational in 2003. It is being used on a regular basis to assess wall interference effects. Some comments regarding preparation and application of the wall interference correction system are provided in this section to better illustrate important system characteristics in a real-world context.

Test Preparation

The preparation of the wall interference correction system for a test is simple. Only basic information describing (i) model planform and (ii) support system geometry needs to be obtained so that singularity and reference point input files of the model can be defined. A standardized worksheet was developed for that purpose. It helps a test manager to collect all required inputs in order to specify the singularity model and the reference points in the model's "home" position. The system software has an algorithm that describes the motion of the model support system. This algorithm moves the singularities and reference points during the test from their "home" position to the model's actual location in the test section. The contents of the worksheet itself is entered into the system software in sequential order by using a text user interface so that the singularity and reference point input files can be generated in a format that the software understands.

The correction system software also needs database files as input. These files have (i) information about the empty tunnel calibration of the wall pressure ports and (ii) the normalized potential flow field solutions (perturbation velocities) of the wind tunnel & wall interference flow field. The flow field solutions were obtained by using panel method code *ANTARES* (see Refs. [12], [13]). They are used to construct the flow field of the test article at its actual location in the test section by using (i) the lift force & pitching moment measurements, and (ii) the wall pressure signature as input. All details related to input files, data correction options, and the most current wall pressure port status flags (1 = port is used, 0 = port is omitted) of the 240 ports are saved in a text file. This file is read when the software is first started so that the system software is ready to compute corrections as soon as data from the first data point arrives.

Operational Experience

TWICS was originally designed to generate corrections at a rate of 10 Hz. Then, tunnel conditions could be modified in "real-time" to perform angle of attack sweeps at a constant corrected Mach number. The implementation of this original goal would have required the development of an interface between *TWICS* and the *Facility Control System (FCS)* of the *Ames 11-ft TWT*. It was ultimately decided to keep the correction system software independent of *FCS* in order to limit software complexity. Consequently, the 10 Hz requirement was relaxed. Corrections are currently computed in "near-time" and become available for review after completion of a set of angle of attack sweeps.

The correction system software performs a variety of automated input data quality checks for each data point. Corrections are set to "zero" whenever "faulty" inputs are detected. Linear approximations of the wind tunnel and wall interference flow field in subsonic flow are used to predict wall interference corrections. Therefore, the accuracy of the predicted corrections decreases as the Mach number approaches one. Consequently, it was necessary to define an upper Mach number limit. The limit equals 0.92. It is the largest Mach number that was used for the panel code calculations of the normalized solutions of the wind tunnel & wall interference flow fields. No extrapolation of flow field solutions is performed beyond the Mach number limit.

Corrections are simply set to "zero" whenever the uncorrected Mach number of a data point exceeds the Mach number limit.

Consistency checks of the Mach number and angle of attack corrections are performed during a wind tunnel test to ensure that the system computes meaningful corrections. Simple empirical rules were developed over the years that help both tunnel operator and customer identify system faults. These rules look at the variation of the corrections as a function of the uncorrected Mach number. Figure 7a below shows how empirical "rules" may be used to assess the Mach number correction. First, a specific test article configuration is chosen. Then, a set of angle of attack sweeps, i.e., "runs", with varying Mach number is selected for this configuration. In the next step, the Mach number correction of each "run" is plotted versus the uncorrected angle of attack. It is expected that the resulting family of curves shows "trends" that are indicated in Fig. 7a above. The curves themselves should have the overall shape of an inverted parabola within the linear region of the lift curve. The maximum of the inverted parabolas, i.e., the point with the smallest correction magnitude, should be near the uncorrected angle of attack for "zero" lift. In that case, the model experiences mostly "solid volume" blockage as the separation wake is either near its smallest extend or non-existent. The corrections should be negative everywhere with increasing magnitude as the angle of attack increases. The curves should appear to be shifted by a constant value relative to each other. The magnitude of the shift depends on the magnitude of the uncorrected Mach number of each curve. The greater the Mach number difference between pairs of curves the larger the shift is expected to be. The most negative values should be observed for the curve that has the highest uncorrected Mach number.

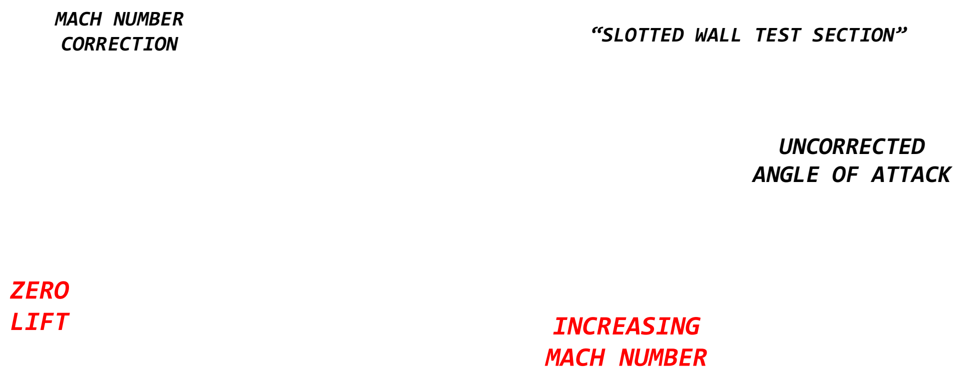

Fig. 7a Validation of the Mach number correction in a slotted wall test section.

Recently, the *Ames Check Standard Model* was tested in the *Ames 11-ft TWT* (Ref. [17]). Figure 7b below shows Mach number corrections for a family of Mach numbers that were computed during the test. The corrections show exactly the expected behavior that is described in the previous paragraph.

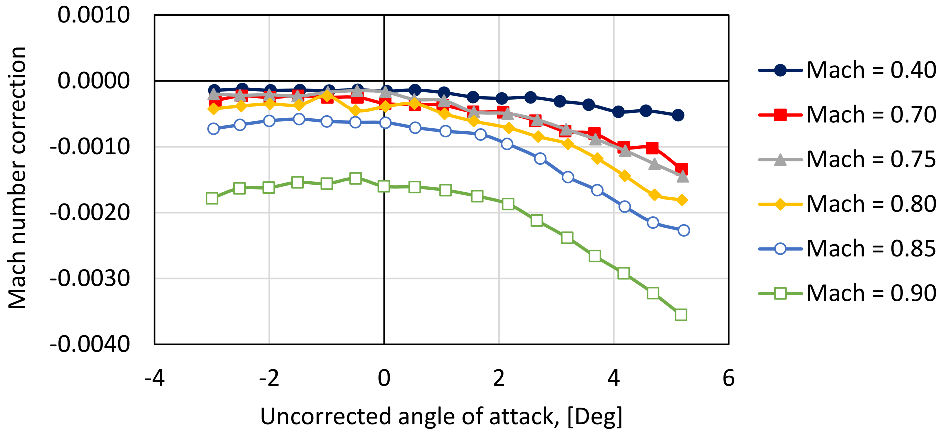

Fig. 7b Mach number correction versus uncorrected angle of attack for the *Ames Check Standard Model* (data plots courtesy of *NASA Ames Research Center*).

Figure 8a below shows how similar empirical "rules" may be used to assess the angle of attack corrections. Again, a specific test article configuration and a set of uncorrected Mach numbers are chosen. Then, the angle of attack correction of each "run" is plotted versus the uncorrected angle of attack. The resulting family of curves should show "trends" that are indicated in Fig. 8a below. This time, the curves are expected to be straight lines within the linear region of the lift curve as long as no significant flow separation is observed. All curves should have a negative slope and should intersect at the uncorrected angle of attack for zero lift. The angle of attack correction at that point is close to zero assuming the model was tested such that its center of lift is at or near the tunnel centerline. The greater the uncorrected Mach number of the angle of attack sweep is the more negative the slope of the related line of angle of attack corrections becomes.

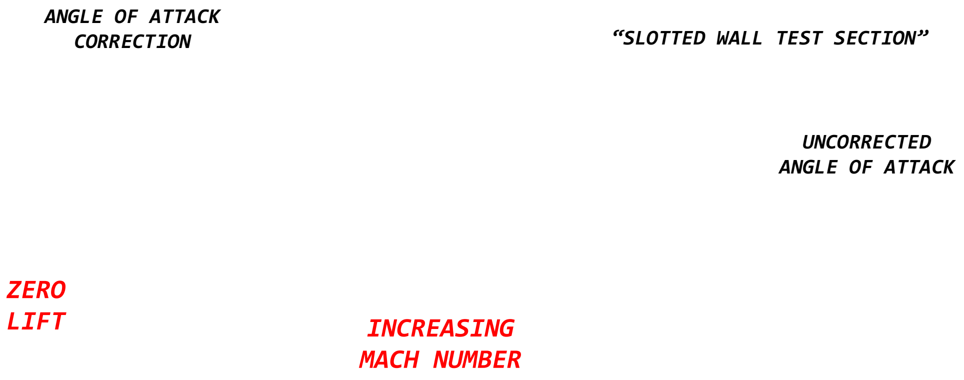

Fig. 8a Validation of the angle of attack correction in a slotted wall test section.

Figure 8b below shows the angle of attack corrections that were obtained during the test of the *Ames Check Standard Model*. Again, the computed corrections show the expected behavior that is discussed in this section.

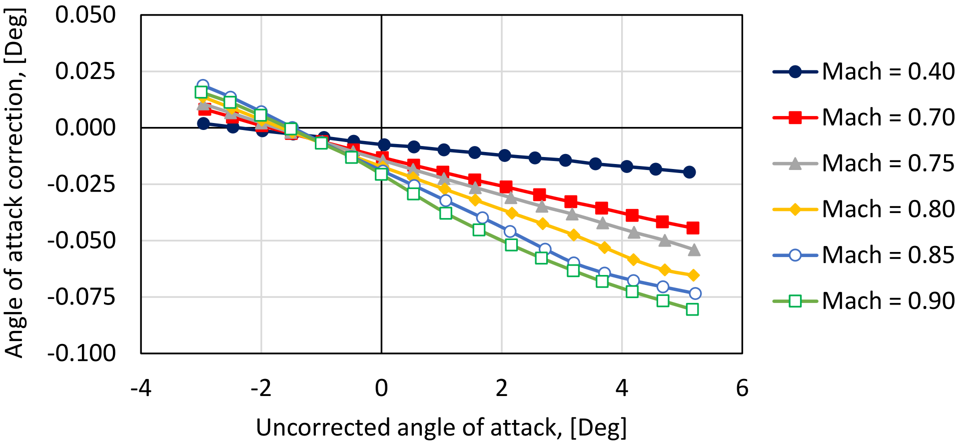

Fig. 8b Angle of attack correction versus uncorrected angle of attack for the *Ames Check Standard Model* (data plots courtesy of *NASA Ames Research Center*).

Tunnel staff and customers of the *Ames 11-ft TWT* often use the repeatability, i.e., the precision error, of a wind tunnel measurement for the assessment of overall data quality. This "test" can also be applied to wind tunnel wall interference corrections. In other words, both "run-to-run" and "test-to-test" repeatability of the wall interference corrections for a specific wind tunnel model are good indicators of the reliability and quality of the correction assessment.

7. Concluding Remarks

An important aspect of the implementation of a wall interference correction system in a wind tunnel is the selection of a suitable method to verify the magnitude of the corrections. Different approaches have historically been used for that purpose. One approach applies wall interference corrections to data from a family of geometrically similar test articles of different sizes (this approach, for example, was used by *Ulbrich and Cooper* in Ref. [18]). In this case, the validation is considered "successful" if the corrected aerodynamic coefficients of all test articles collapse. The validation approach, however, has the disadvantage that it is expensive to fabricate & test geometrically similar test articles in a wind tunnel. In addition, support system interference may negatively influence the comparison of the corrected aerodynamic coefficient sets.

Alternatively, assuming that a wall interference correction system is implemented in a test section with ventilated walls, it may be possible to generate uncorrected test data sets for the validation by changing the boundary conditions in the test section. Then, test article geometry, test article size, the support system, and the data reduction algorithm used for the calculation of the aerodynamic coefficients remain unchanged. This approach was chosen by *Ulbrich and Boone* in 2003 who used data from the test of a large semi-span model in a "slotted" and "closed" wall test section configuration for the validation of the wall interference correction system of the *Ames 11-ft TWT* (Refs. [2], [3]). A similar validation approach was used by *Walker* in 2005 when he validated blockage corrections in *NASA Langley's NTF* (Ref. [19]).

Several lessons were learned after *Ulbrich and Boone* completed their initial validation of the wall interference correction system of the *Ames 11-ft TWT* in 2003 (Ref. [2]). They concluded, for example, that a more accurate data interpolation algorithm should have been used for the comparison of the corrected data sets from the "slotted wall" configuration with the corrected data sets from the "closed wall" configuration. In addition, the Mach number calibration for the "closed wall" configuration of the *Ames 11-ft TWT* was not as accurate as the Mach number calibration of the "slotted wall" configuration (data recorded at the wall ports had to be used to reverse-engineer the missing Mach number calibration equations for the "closed wall" configuration). Finally, only data from the test of a semi-span model was used for the validation. Therefore, *Ulbrich, Amaya, and Flach* proposed in 2018 to use the *Ames Check Standard Model* for a future validation test of the wall interference correction system of the *Ames 11-ft TWT* (Ref. [20]). The new validation test would address some of the shortcomings that were identified in 2003.

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