Evaluation of the One Variable Measured Boundary Condition Method WIN3VE

Master of Science Thesis

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Summary

Introduction:

This thesis is an evaluation of a wall interference correction program called WIN3VE. This program was developed in the 1990s by the National Aerospace Laboratory of the Netherlands (NLR) but never validated. WIN3VE is written for the High Speed Tunnel (HST) in Amsterdam. This wind tunnel is now run by the German and Dutch Wind tunnels (DNW). In order to provide their customers with more accurate results the DNW decided to investigate if WIN3VE could be used regularly during testing. To this end they started a validation process. This thesis is a step in the validation process, the goal given by the two following research questions:

- What are the strengths and weaknesses of WIN3VE?
- Where do the weaknesses come from?

Background:

Wall interference has been known to affect experimental results since the beginning of wind tunnel testing. There are several different effects which fall under wall interference. The most prominent of these effects being solid blocking, wake blocking, streamline curvature and buoyancy. In order to correct wind tunnel measurements for these effects WIN3VE was devised.

WIN3VE uses what is known as a one variable measured boundary condition method. This method takes measurements on control surfaces, the tunnel walls in this case, and solves for wall interference effects at any point inside the tunnel. It does this by using the principle of superposition. It first calculates the total disturbances in the tunnel before subtracting the disturbance effects only due to the model. The result of this step are the disturbance effects only due to the tunnel walls. Once these are known along the wall, wall induced disturbance velocities at any point in the tunnel can be calculated using a panel representation. From the wall induced disturbance velocities at chosen points correction values for the Mach number and angle of attack are corrected. The aerodynamic forces and moments are also corrected to match the new conditions defined by the Mach number and angle of attack. The program has three control parameters which allow for calculation steps to be replaced by user input data. These bypasses were used in order to evaluate the method.

The evaluation process uses CFD simulations as input for the WIN3VE bypasses. In order to have all in the input required for the bypasses a total of three difference CFD simulations were run. The reason that CFD simulations were used is that they yield a large amount of information compared to experimental results. The CFD simulations in this case in fact replicate an actual experiment performed by the DNW in the HST in 2009. This experiment tested a half model for a range of different Mach numbers and angles of attack. The goal of the CFD simulations was to build a virtual wind tunnel replicating the geometry of the model and tunnel as well as the conditions present in the HST.
Approach/Results and Analysis:

The first step of any process is to become familiar with the different aspects involved in that process. As the comparison process had already been defined the next step was to understand why said process has been chosen and how it worked. The preparation of the data was then undertaken. Once the correct input was prepared all the different possible runs (variations in the use of the WIN3VE bypasses) were carried out. There are a total of eight runs, the number of possible combinations of the different control parameters.

As the code had sparsely been used over the past decade it was deemed necessary to test it. This was done by comparing results for the present model with past results. These showed good correlation. The next step was then to choose a baseline scenario. This scenario served as a base for all the different comparisons to come. This was chosen to the case with all input data proceeding from the CFD calculations.

It is possible to directly compare the different calculation steps of the WIN3VE baseline results to the CFD simulations. The wall induced disturbance velocities calculated from WIN3VE did not match those calculated using the CFD simulations. As the corrections to the aerodynamic forces and moment are calculated from these velocities, the corrections calculated by WIN3VE also did not match those calculated using the CFD simulations.

After the comparison of the baseline scenario, the individual calculation steps within WIN3VE were investigated. This was done by examining the differences between the eight possible cases. This showed that in its current set up, the normal velocities through the walls have nearly no effect. The major contributions to the corrections stem from the total disturbance effects and the model disturbance effects.

Conclusion/Recommendations:

From the analysis and results the following was concluded. The panel representation of the tunnel seems to be working properly for the estimation of wall interference velocities only in streamwise direction. It is however incapable of correctly predicting velocities in the other directions (transverse and normal). This is a major flaw as a number of corrections are based on velocities in the normal direction. Furthermore most of the calculation steps that WIN3VE uses return answers which differ from those in the CFD simulations.

Based on these observations it is recommended to consider a different approach for correcting for wall interference in the HST. A two variable measured boundary condition method may be more suited to address wall interference in the HST. Should more investigations into WIN3VE be carried out it is recommended to try a different CFD approach. The enhancement of the model representation as well as of the panel representation may also lead to better results.
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Nomenclature

Symbols

\( \rho \)  
Density  
[kg/m\(^3\)]

\( u \)  
Velocity in axial direction  
[m/s]

\( v \)  
Velocity in transverse direction  
[m/s]

\( w \)  
Velocity in normal direction  
[m/s]

\( A \)  
Cross section area  
[m\(^2\)]

\( \alpha \)  
Angle of attack  
[deg]

\( M \)  
Mach number  
[-]

\( C_L \)  
Lift coefficient  
[-]

\( C_D \)  
Drag coefficient  
[-]

\( C_M \)  
Pitching moment coefficient  
[-]

\( Re \)  
Reynolds number  
[-]

\( p_0 \)  
Total pressure  
[Pa]

\( p \)  
Static pressure  
[Pa]

\( Q \)  
Dynamic pressure  
[Pa]

\( \gamma \)  
Heat capacity ratio  
[-]

\( C_p \)  
Pressure coefficient  
[-]

Indices

\( t \)  
Total disturbance

\( m \)  
Model induced disturbance

\( w \)  
Wall induced disturbance

\( \text{exp} \)  
From experiment
**Abbreviations**

- *free* From free flow
- *ref* Reference conditions
- *CL* Centerline
- *PL* Plenum
- *int* Interpolated
- *old* Uncorrected
- *new* Corrected
- *WIN* WIN3VE

- CFD Computational Fluid Dynamics
- MPS Model Present Simulation
- ETS Empty Tunnel Simulation
- FFS Free Flow Simulation
- FFSwp Free Flow Simulation with Peniche
- RANS Reynolds-Averaged Navier-Stokes
- MRP Moment Reference Point
- HST High Speed Wind Tunnel
- PHST Pilot High Speed Wind Tunnel
- NLR National Aerospace Laboratory of the Netherlands
- DNW German-Dutch Wind Tunnels
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1 Introduction

This thesis describes the evaluation of a wall interference correction code. This chapter provides historical information about the code, starting from its conception to present day. The research goals of the thesis are then presented. Finally a brief discussion on the approach taken to answer the research questions is given.

1.1 History of WIN3VE

Correcting wall interference is as old as wind tunnels. It has been the subject of many correction attempts, which are still being developed to this day. In order to deliver more accurate results to its customers, German-Dutch Wind Tunnels (DNW) is also seeking a validated correction method. The method which DNW have decided to pursue is a Measured Boundary Condition method. This method is implemented using an in-house developed FORTRAN code known as WIN3VE. The code was written in the 1990’s by the Dutch Aerospace Research Laboratory (NLR) but was never validated.

WIN3VE was created for the High Speed Transonic Wind Tunnel (HST) in Amsterdam. This wind tunnel has slotted walls and operates in the transonic regime. The goal of WIN3VE was for it to become an online correction system. That is to say that the wall corrections would be applied to the data real time instead of as a post processing step. Several investigations have been carried out in the mid-1990s using full models and wind tunnels of different sizes [6]. These investigations were early attempts of validation.

The full model tests used two different facilities, the HST wind tunnel and the PHST. The PHST is a smaller version of the HST. The thought behind this investigation was that the HST is large enough compared to the size of the model that the model would not be affected by wall interference. The same model placed in the PHST however should be largely affected by wall interference due to its smaller test section size. Comparing the results of the tests in the two tunnels would then reveal the influences of the walls and could be compared to results from the code. This investigation was the first step towards validation.

The focus of the investigations for the validation of the program then switched to half-span models. The reason for this switch is the size of half-span models. In general these tend to be much larger than their full-span counterparts. The larger size of the models will lead to a higher influence of the walls. Half-span models are generally used to investigate the effect of different wings. This may be a different wing shape, or the effect of the addition of a part to the wing, such as an engine or pylon. These tests in general aim to look at the aerodynamic effect of these different components but not at forces or moments on the model.

In a bid to more accurately measure forces and moments on half models in the HST the DNW decided to continue the validation process of WIN3VE. The final goal being that the code be validated, functioning and online. To this end in 2009 a student was brought in to further the process. This student brought the
Introduction

1.2 Research Goals

Based on the work accomplished by the previous student, the goal of this thesis was to further along the validation process of WIN3VE. This was to be done by answering the following questions:

- What are the strengths and weaknesses of WIN3VE?
- Where do the weaknesses come from?

Essentially the questions are an evaluation of the theoretical method. This evaluation is a step in the overall validation process of WIN3VE. In order to evaluate the code, the methods and processes used to run the code also need to be analyzed. It is also necessary to distinguish between the strengths/weaknesses of the actual code versus strengths/weaknesses of the method utilized by the code. It should be noted that the goal of thesis is not to improve the code but simply localize the areas of weakness.

The criteria used to evaluate the strengths and weaknesses of WIN3VE will be quality. In this case quality refers to how well the code can match CFD data.

1.3 Research Approach

A brief description of the general approach to answering the research questions is given here. A more detailed look at how this process was carried out can be read in chapter 3.

1. In order for a comparison to take place another method to obtain wall interference corrections was required. It was decided by the DNW that this source of information would be CFD simulations. The CFD simulations are discussed in more detail in section 2.5. One of the reasons that CFD simulations were chosen was the fact that they deliver a large amount of information. It was therefore decided to order CFD simulations to replicate an experiment conducted in the HST. More details about the experiment can be seen in section 2.2. The experiment chosen to be the base for the simulations involved a half model. This was chosen as half models tend to be larger than full models, meaning that they will be more influenced by wall interference.

2. Once the decision was made to use CFD simulations a method for obtaining wall interference corrections from the simulations was devised. This method involves two different CFD simulations. One which replicates the conditions in the HST (MPS) and another replicating the model in free flow (FFS). The idea is then to subtract the free flow results from the virtual HST results in order to obtain the wall interference effects. The idea behind this is that the virtual HST will contain disturbances emanating from both the presence of the walls as well as the model. The free flow case will however only contain the disturbances caused by the model. Therefore subtracting the two should deliver disturbances caused solely by the presence of the model.
walls. This is graphically represented in Figure 1. A more detailed description of the CFD input process is given in section 3.2.

![Figure 1: Disturbance velocities and where they are defined](image)

3. Another reason why CFD simulations were chosen as comparison is due to options which WIN3VE offers. More detail about WIN3VE and its workings are given in section 2.4. WIN3VE is capable of accepting input in order to bypass certain of its own calculation steps. The data which can be input into WIN3VE can be obtained from the CFD simulations. This then allows for comparisons between the CFD data and WIN3VE results at different points in the code.

4. In order to compare the results from the CFD simulations and WIN3VE a point of comparison is required. This point of comparison is called the baseline scenario. This baseline scenario was chosen to be the best possible case. That is to say that all possible bypasses in WIN3VE are used. This means that all of its preliminary calculation steps are replaced by data obtained from the CFD simulations. Solely the final step which converts the input into wall interference corrections remains. This then allows for the wall interference corrections (see Appendix D) from WIN3VE and those obtained by the subtraction of the CFD simulations to be compared. For more details on this comparison process refer to section 3.2.

5. In order to further analyze WIN3VE the different calculation steps which were bypassed in the baseline scenario were investigated. This is done in order to see where the strengths and weaknesses of WIN3VE originate. This comparison can be carried out using the input data which was obtained from the CFD simulations.
2 Background

This chapter aims to provide the necessary background information required to follow the rest of this thesis. This background information will first cover the topic of wall interference. The experiment on which the project is based on will then be briefly discussed. From here a basic description of WIN3VE and its workings will be given. This will be followed by a more in detail description of the calculation steps of WIN3VE. Finally the CFD cases used for the evaluation of the WIN3VE will be presented.

2.1 Wall Interference

The presence of wind tunnel walls will lead to different conditions than those encountered in free flight. This is due to the fact that the walls will alter or change both the magnitude and direction of airflow around the model. Therefore the purpose of calculating and applying wall interference corrections is to eliminate the effect of wind tunnel walls and provide measurement data which are equivalent to those in free air. This is made particularly difficult by the fact that the wall interference varies in streamwise direction along the tunnel. Due to the fact that there are a number of effects causing wall interference it is convenient to break down the corrections into groups depending on which effect they deal with. Therefore wall interference corrections can be split up into two different categories [1]:

- **Primary corrections:** These corrections correspond to parameters which define the test conditions during wind tunnel experiments. Normally these are: total pressure, static pressure, angle of attack and sideslip angle. Classically from the corrected static pressure the corrected Mach number and dynamic pressure are calculated. These are then used to correct the force and moment coefficients.

- **Residual variations:** These are deviations which remain between the freestream flow and the experimental flow after the primary corrections have been applied. These are due to the walls altering the flow around the model and the subsequent wake created by the model.

It is important to note that data can be correctable or not. This is defined by whether the uncertainty for the corrections is less than the accuracy of the correction.

2.1.1 Effects

Some of the effects caused by the presence of walls are discussed here. This is by no means an exhaustive list but a brief discussion of some of the more prominent effects:

1. **Solid blocking**- The incorporation of the model in the test section will reduce the area that the air must flow through. This leads to an increase in velocity of the flow. This increase in velocity also means an increase in dynamic pressure which in turn increases forces and moments for a given angle of attack. The increase in velocity can be illustrated by starting at the continuity equation for quasi-one-dimensional flow (equation (2.1)). After a number of substitutions the relationship between the velocity and area is given by equation (2.2) [2].
2.1 Wall Interference

\[ \frac{d\rho}{\rho} + \frac{du}{u} + \frac{dA}{A} = 0 \]  \hspace{1cm} (2.1)

\[ \frac{dA}{A} = (M^2 - 1) \frac{du}{u} \]  \hspace{1cm} (2.2)

Equation (2.2) explains the behavior showcased in Figure 2. This shows the resulting increase in velocity \((U_1 < U_2)\) caused by the reduction in area \((A_1 > A_2)\).

---

Figure 2: Depiction of solid blocking

2. Wake blocking- The wake of the model will have a velocity which is slower than the freestream velocity. This is due to the fact that the flow around the body will be slowed down by the presence of the body. The continuity equation however states that constant volume of flow must pass through the test section. This therefore means that the flow outside the wake must travel at a higher velocity than the freestream velocity. This difference in velocity creates a difference in pressure which leads to a pressure gradient which is felt by the model [3]. This is shown graphically in Figure 3.
3. **Streamline Curvature** - A streamline contraction occurs as the streamlines cannot follow the path they would in an unbounded situation. This flattening of the streamlines leads to a decrease in apparent camber of the body [4].

This situation is shown in Figure 4 where the solid lines represent how the flow would behave in an unbounded case and the dashed lines represent how the flow acts in a wind tunnel. It should be noted that these streamlines do not accurately depict actual flow but are exaggerated for effect. Also the presence of a model tends to induce upwash interference, meaning that the walls alter the upwash of the model. This generally leads to a change in the angle of attack of the model. This change in effective direction of the freestream should therefore also be corrected.
4. Buoyancy- As the boundary layer on the walls thickens it is effectively reducing the jet area. This leads to a variation in static pressure along the walls. This variation tends to be negative, in a sense that there is lower pressure downstream than upstream, leading the model to be attracted downstream [3].

2.2 The HST
As mentioned in section 2.2, the base experiment was carried out in the HST wind tunnel. This section will provide general information about the geometry of this wind tunnel as well as some information about its capabilities.

2.2.1 General
The HST wind tunnel, Figure 5, is a closed circuit continuous transonic wind tunnel. It operates in a Mach range of $M = 0$ to $M = 1.3$. The pressure inside the tunnel can be controlled. This allows for the Reynolds number to be kept constant while varying Mach number. The tunnel can be pressurized to up to 390kPa. In all these cases flow disturbances in the tunnel are minimized. Thermally this is done via a large water cooler. This cooler ensures that the temperature variation across the length of the test section is at most 1K. The turbulence in the flow is kept to a minimum by using three anti-turbulence screens in the settling chamber. This is also aided by the larger contraction ratio (1:25) of the tunnel. A number of different model supports are available depending on the requirements of the client and model.

![HST wind tunnel](image)

**Figure 5: HST wind tunnel**

The speed inside the test section is regulated by a flexible nozzle in front of the test section. The desired speed can be attained by changing the nozzle area. The nozzle and the two jacks (one above and one below) which are used to change its size can be seen in front of the test section in Figure 6. Once the desired Mach number is reached it can be maintained using the blade pitch control system of the compressor. This system keeps the Mach number constant within a value of ±0.001 ([18], [19]).
2.2.2 Test section
There are two available configurations of the test section as the height is adjustable. The width is constant and measures two meters. The height can either be 1.6 or 1.8 meters. Generally the smaller height is chosen when maximum attainable Reynolds number is required. A side view of the test section is shown in Figure 6.

![Figure 6: Side view of the HST test section](image)

The top and bottom wall of the test section comprise slots. There are four complete and two half slot in each. This is represented in Figure 7.

![Figure 7: Test section slots](image)
The slots are used to reduce wall interference effects and prevent choking of the flow. In the HST the openness ratio of the wall is approximately 12 percent. The entirety of the test section is surrounded by the plenum chamber. Thus allowing flow to enter and exit the slots without further action being required ([18], [19]).

2.3 Experiment
As mentioned in section 1.3 the CFD simulations are based on an experiment conducted in the HST. This section details that experiment and the information which was taken from the experiment in order to set up the CFD simulations.

2.3.1 General
The experiment tested a half model in the DNW-HST wind tunnel in Amsterdam. The scale of the model used was 1:12. Figure 8 shows a photograph of a typical half model in the HST. The test was carried out in order to determine forces and moments as well as investigate several different wing shapes [17]. During this measurement process pressure measurements along the wall were also carried out.

As is common in half model testing a peniche was used. A peniche is a device which fills the gap between the model and the wall it is closest to. The purpose of the peniche is to ensure that the boundary layer along the wall does not impinge on the model.

2.3.2 Information used in CFD Simulations
This experiment serves as the basis of the CFD simulations used in order to evaluate WIN3VE. The reason this experiment was chosen is due to the fact that the model tested is a half-span model. These
models tend to be large which leads to a larger effect of wall interference on the results. The relevant information taken from the experiment is detailed here:

1. Tunnel and model geometry- The CFD simulations were based on the HST wind tunnel geometry and the model used in the experiment. The 1.8 meter high test section was used. The geometric data from both was used to set up the CFD simulations. It should be noted that the peniche is also used. In Appendix A the CAD drawings of the model can be seen. The location of the model with respect to the test section and particularly the slots in the upper and lower wall is shown in Figure 9. Note that the indication of the slots only indicate the x position of the slots. These are in fact in the wall with respect to z position.

![Figure 9: Picture depicting the approximate position of the model with respect to the slots in top and bottom walls](image)

2. Pressure measurements- As stated before pressure measurements were taken along the walls of the wind tunnel. This is done via pressure taps. The location of these pressure taps, labeled W6000, W7000, W8000, and W9000, is shown in Figure 10. These pressure taps run along the walls in streamwise location. Furthermore pressure measurements in the settling chamber and the plenum chamber around the test section were also performed.
3. Reference conditions- The total pressure and total temperature were also recorded. These are needed in order to set the reference conditions in the CFD simulations.

4. Similarity parameters- The Mach number and Reynolds number are also required for the CFD simulations.

5. Aerodynamic coefficients- The force and moment coefficients of the experiment were also used in the CFD simulations.

2.4 WIN3VE

This section will describe the wall interference correction method WIN3VE. Firstly a number of definitions will be given. Secondly the method that the code employs is briefly mentioned, this will be followed by an overview of how the program operates. Lastly the predominant calculation steps of the code are discussed.

2.4.1 Definitions

Before describing the program a few definitions will be given in order to clarify certain terms.

- Reference points- Coordinates of positions at which information, such as velocities, is known or calculated. These may be in the tunnel axis system or the model axis system.
- Model representation- This is how the flow due to the model is simulated in the program. The model is created using a simple mathematical flow description (singularities).
- Axial velocities- Velocities in the x-direction of the tunnel as defined in Figure 11.
- Transverse velocities- Velocities in the y-direction of the tunnel as defined in Figure 11.
- Normal velocities- Velocities in the z-direction of the tunnel as defined in Figure 11.
- Onset flow- Undisturbed flow entering the test section. $u_\infty$ in Figure 1.
- Disturbance velocity- A velocity caused by a disturbance to the onset flow.
- Total induced disturbance velocity- This is the sum of all the disturbance velocities present in the tunnel. This velocity is present in all three directions. When in axial direction it is referred to as $u_t$ (see Figure 1), in transverse it is $v_t$ and in normal it is $w_t$.
- Model induced disturbance velocity- This is the disturbance velocity solely caused by the presence of the model. This velocity is present in all three directions. When in axial direction it is referred to as $u_m$ (see Figure 1), in transverse it is $v_m$ and in normal it is $w_m$. 

![Figure 10: HST test section](image)
• Wall induced disturbance velocity - This is the disturbance velocity solely caused by the presence of the wind tunnel walls. This velocity is present in all three directions. When in axial direction it is referred to as $u_w$ (see Figure 1), in transverse it is $v_w$ and in normal it is $w_w$.

• Panel representation - Panels are used to replicate the wall induced velocities at the tunnel walls. This is done by using a constant strength doublet singularity in the center of the panels.

• Reference velocities - Velocities which are used to calculate the wall interference corrections to the aerodynamic coefficients in WIN3VE. These are present on the $1/4$ and $3/4$ chord position of the aircraft and around the fuselage. Their position is defined using a specific set of reference points.

![Figure 11: Axis description of the wind tunnel (Wind tunnel axis system)](image)

2.4.2 Method

WIN3VE is a one variable measured boundary condition method. This means that measurements along the boundary of the tunnel are used in order to determine the wall interference. As its name indicates measurements in only one direction, the streamwise, are used. In order to calculate the effect that the model will have on the onset flow this method uses a simple model representation. This is used in order to distinguish between wall induced disturbance velocities and model induced disturbance velocities.

The main assumption made when using one variable measured boundary condition methods is that the flow near the wind tunnel walls can be represented using linear potential equations. This assumption is made as it believed that near the wall the flow will be less prone to stagnation regions or supersonic flow than at regions close to the model. Excluding viscous effects, this should lead to a flow which is less disturbed and therefore make linearization of the flow near the wall applicable.

The information from the measurements along the boundaries is then used to estimate for the effect of the walls anywhere inside the tunnel. This can be achieved in several different ways. In the case of WIN3VE a panel representation is used to carry out the estimation. This estimation entails that the axial component of the wall interference potential satisfies the potential flow equations at every point in the interior of the tunnel. This also being true for positions inside the model volume. Therefore in order to calculate a wall induced disturbance velocity at any point in the tunnel all that is needed is for the axial wall induced disturbance velocity at the wall to be supplied. This value can be calculated by subtracting the model induced disturbance velocities from the total disturbance velocities. The total disturbance velocities can be derived from the measured static pressures along the walls while the model induced velocities are calculated using a model representation.
The reason that the panel method uses the axial component of the wall induced velocity and not another component is due to the fact that the axial velocity component is the simplest to derive from measurements in a wind tunnel. It will also be the component that can be most accurately measured, as accurately measuring normal velocities in a slotted test section remains complicated [5].

2.4.3 Main Elements of WIN3VE
The outcome of a WIN3VE calculation is corrected force and moment coefficients as well as corrected flow conditions, such as Mach number and angle of attack. The accuracy of these measurements is dependent on the accuracy of the balance measurements. It is therefore aimed for WIN3VE to deliver correction values with the following uncertainties:

- $\Delta \alpha < 0.02$
- $\Delta C_D < 0.0005$
- $\Delta C_M < 0.005$
- $\Delta M < 0.002$

It should be noted that these uncertainties do not apply to the corrections themselves but to the difference between the experimental values, adjusted using the correction values, and the free flow values. This is shown below for the angle of attack:

$$\left(\alpha_{\text{exp}} + \Delta \alpha\right) - \alpha_{\text{free}} < 0.02$$

Before getting to this output which can be seen on the right hand side of Figure 12 several steps need to be taken. Working back from the output, the corrections on the forces and moment need to be obtained. This is done using reference velocities which are derived from the doublets present at the panel centroids. The strength of these doublets is calculated using the axial wall induced disturbance velocities near the wall along the top, bottom and side wall centerlines. This axial wall induced disturbance velocity is the result of the subtraction of the axial model induced disturbance velocities from the axial total disturbance velocities along the walls. Before this point WIN3VE is split into two different paths, the calculation of the axial model induced disturbance velocities and the axial total disturbance velocities. The axial model induced disturbance velocities are solely derived from the model representation. On the other hand the axial total disturbance velocities are derived from a combination of the wall pressure measurements and the normal velocities through the wall. The normal velocities are determined from the model representation and the method of mirror images. The first step in WIN3VE is therefore the creation of this simple model presentation.
2.4.4 Model Representation

The model representation is used in order to calculate the model induced disturbance velocities at the tunnel centerlines. The model representation in WIN3VE can be constructed using a set of different singularities. These different singularities are used to model different parts of the aircraft. In general the model representation only represents first order effects of the models. Examples of these effects and the singularities used to model them is given in Table 1.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model shape and volume</td>
<td>Source doublet</td>
</tr>
<tr>
<td>Model lift</td>
<td>Line vortex</td>
</tr>
<tr>
<td>Model parasite drag</td>
<td>Point source</td>
</tr>
</tbody>
</table>

Assumptions are made when creating the model representation. The first one is that the loading (i.e. the forces) on the model will only change slightly when comparing the free air (perturbation free) and wind tunnel cases. The second is that the freestream conditions in the free flow and wind tunnel case are identical. These assumptions make it possible to use the strengths of the singularities used to create the model representation in the perturbation free case for the wind tunnel case. For a more detailed description of singularities see Appendix C. An example of a model representation used by WIN3VE is shown in Figure 13.
In Figure 13 the blue circles are a source distribution to model the fuselage of the aircraft. The black stars and line represent a vortex line. These are used to model the lift generated by the wings of the model. As can be seen WIN3VE converts the half model into a full model. This example is rather simple, but model representations can be more complex and utilize more singularities. This may be needed when certain other features of the model, such as a horizontal tail plane, are to be represented.

The effect of all the singularities can be summed at the desired location in order to calculate the model induced disturbance velocity. It is then assumed that these will remain the same when the model is in the wind tunnel. It should be noted that the model representation can be bypassed. In that case the axial model induced velocities can be directly entered into WIN3VE. This is done using the INPUM control parameter and an input file which is detailed in Appendix H.

2.4.5 Normal Velocities

The normal velocities through the walls of the wind tunnel are calculated in order to find their influence on the axial total disturbance velocities. These velocities in WIN3VE are calculated using the method of
images. The model induced disturbance velocities calculated using the model representation are mirrored using the side walls of the tunnel as the plane of symmetry (Figure 14).

![Figure 14: Illustration of the method of images](image)

Using this method, the velocities are canceled at the side walls while a value for the velocity through the top and bottom walls can be calculated. This is the desired situation as the side walls are solid while the top and bottom walls are slotted. The individual effect of the slots is not calculated as instead the normal velocity is calculated only along the top and bottom wall centerlines. This means that the slots are not modeled instead the entire wall is taken to be open as shown in Figure 15. Only the front and end parts of the test section which are solid are not open. This is corrected using a smoothing operation, for more detail on this procedure refer to [6].

As with the model representation it is possible to bypass this calculation step and directly enter the normal velocities through the slots. This can be done using the NORVEL control parameter and an input file which is discussed in more detail in Appendix G.
2.4.6 Total Disturbance Velocities
The total disturbance velocities are calculated using the measured pressure coefficient along the tunnel boundaries. This can be done by using equation (2.3). For the derivation of this equation see reference [6].

\[
u_T = \sqrt{\left(1 - 5\left(1 + 0.7 \cdot \frac{M_{ref}^2}{C_{PC}^2}\right)^2 - 1\right) - \frac{v_T^2}{w_T^2}} - 1 \quad (2.3)
\]

The total disturbance velocity in the normal direction is given by the estimated normal velocities through the slots. In the transverse direction the total disturbance velocity is hard coded to be zero in WIN3VE.

As with the model representation and normal velocities through the slots, this calculation step can be bypassed. This then requires that the axial total disturbance velocity at the centerline of top, bottom and sidewall be input from a file. This is controlled via the IVEL control parameter and the required input file is detailed in Appendix I.

2.4.7 Panel Representation
As stated previously there are several ways to estimate flow within the wind tunnel. WIN3VE accomplishes this by using a panel representation. The way WIN3VE constructs its panel representation is based on the pressure tap input it receives. These pressure tap locations are taken from the experiment as discussed in section 2.3.2. This is due to the fact that the panels are created using the
pressure tap positions. More specifically the panel centroids are placed in between two pressure tap positions. Both pressure tap and panel centroid positions are given in Appendix B. This method of setting up the panels is hard coded into the program and cannot be altered. This therefore limits the number of panels per wall to the same number of pressure taps, in this case 51.

![Figure 16: Front view of WIN3VE tunnel representation](image)

Figure 16 shows the wind tunnel which is recreated in WIN3VE by the panel representation. The four pressure lines which are used for input are given (W6000,W7000,W8000,W9000). The squares in Figure 16 indicate the wall centerlines. At these locations the axial wall induced disturbance velocities have been calculated from the previous steps in WIN3VE. Note that the side wall data is replicated along the axis of symmetry of the model and only needs to be entered once.

As can been in the dimensions given in Figure 16, the width of the tunnel is not exactly 2 meters. This difference is attributed to the lack of peniche. The peniche was in fact excluded as is explained in reference [6]. Since the peniche is excluded the origin of the tunnel was shifted by the size of the peniche (0.044 meters) to match with the plane of symmetry of the model.

Figure 17 depicts an example of the resulting panel representation. The triangles that can be seen in the figure represent the pressure tap positions. The black circles as indicated in the figure represent the center of the panels at which the panel doublet is defined. The center of the panels are placed in between two pressure tap locations. This therefore means that the panels are not equally distributed due to the fact that the pressure taps are not equally spread apart.

The panel method solves the so called double layer potential equation to establish the strength of the doublets using the axial wall induced disturbance velocity. The double layer potential equation solves the Laplace equation which the potential flow equation in the axial direction can be reduced to. The
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The purpose for using the double layer potential solution to Laplace’s equation is that it guarantees a single solution at any point within its bounding surface. It should be noted that during this procedure the effect of the front and back area of the test section are neglected. This is made as these planes are thought to be sufficiently removed from the model to have a significant effect [11]. Once the panel doublet strengths are known, using geometrical data and the position of the point of interest all three velocity components of the resulting velocity vector can be obtained.

![Diagram of WIN3VE panel representation](image)

**Figure 17:** Panel representation used in WIN3VE

### 2.4.8 Wall Interference to WIN3VE

In order to be able to compare results from WIN3VE and CFD simulations it is necessary to have a clear definition of wall interference. In other words it is needed to know which factors can be attributed to wall interference. This will be given in this section for WIN3VE.

During a wind tunnel experiment the model does not actually feel the reference freestream conditions. Here the reference freestream conditions refer to the reference Mach number and angle of attack of the model. The reason the model does not feel these conditions is due to the presence of the wind tunnel walls. WIN3VE attempts to correct this difference by correcting the Mach number and angle of attack to what the model would feel were the walls not present. It then corrects the aerodynamic force and moment coefficients according to the change in Mach number and angle of attack.

This is done by subtracting the influence of the model from the total disturbance velocity in the tunnel. The model influence is derived from a free flow case at the same Mach number and angle of attack as
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those present in the wind tunnel (not what the model actual feels). It is also assumed that the model loading will not change or that the difference between the two cases will be small.

The corrections calculated by WIN3VE should adjust the freestream conditions as well as the force and moment coefficients to what the model actual feels in the tunnel. Note that this will not correspond to the free flow case used for the model representation as the Mach number and angle of attack will be different. Instead it should correspond to the free flow case used in the model representation plus the corrections calculated by WIN3VE.

2.5 CFD Simulations

This section will discuss the CFD simulations that will be used in order to evaluate WIN3VE.

2.5.1 General

In order to evaluate how well WIN3VE performs data is required. This data is not only needed as comparison for output but also to compare and/or to be used as input. It was felt that the best way to have all of the required data was to use CFD simulations. The advantage of using CFD data versus experimental data is the fact that CFD offers much more data. The CFD simulations recreated the experimental data generated from the experiment described in section 2.2.

In order to obtain data in the tunnel a virtual wind tunnel was created using CFD. This virtual wind tunnel was created using geometric data about the HST as well as the model. The closed wall entry part, the entire test section, part of the diffuser, the full-span model fairing as well as the plenum chamber were all modeled according to specifications from the HST. Essentially the virtual wind tunnel is a replica of the HST.

A total of three different CFD simulations were run. These were needed in order to operate the virtual wind tunnel like the HST. These three simulations, model present, empty tunnel and free flow, will now be discussed in a bit more detail.

- **Model Present Simulation (MPS)** - This simulates operating the HST wind tunnel. The model is attached to the wall in the same way as it was during the experiment on which the simulation is based. That is to say that a peniche is present between the wall and the model. The domain used during this simulation contains 34 million grid cells and 4996 blocks [7]. A rendition of these cells is shown in Figure 18.

- **Empty Tunnel Simulation (ETS)** - This simulation is essentially the same as the MPS. The only difference being that the model was not present in the tunnel. This simulation was needed for a calibration procedure to obtain freestream conditions which will be discussed further on. 33.5 million grid cells and 4940 blocks were used [7]. The grid cells were reused from the MPS case in order to ensure that the virtual wind tunnel in this simulation is exactly the same as in the MPS case.

- **Free Flow Simulation (FFS)** - In this case the model is simply put into a flow with no tunnel present. The computational grid used in this simulation comprised 7.2 million points and 953
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blocks [7]. For two cases only (see Table 2) this simulation was run with peniche. The peniche present case will be referred to as FFSwP. For all other cases the FFS did not have the peniche present.

For all three simulations the flow is modeled by the full Reynolds-Averaged Navier-Stokes (RANS) equations. Additionally an Explicit Algebraic Reynolds Stress Model was used to model turbulence as well as other complex phenomena. More information about the CFD runs can be seen in [7].

![Figure 18: CFD tunnel representation [7]](image)

For the different simulations given above a number of cases were run. These cases were run at a total of six different Mach numbers. For each Mach number two different angles of attack were investigated. All cases were run at the same Reynolds number. A summary of all the cases run is shown in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Re (10^6)</th>
<th>M</th>
<th>(\alpha)</th>
<th>MPS</th>
<th>FFS</th>
<th>FFSwP</th>
<th>ETS</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>✓</td>
<td></td>
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<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td>0.6949</td>
<td>0.2322</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
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<td>0.7640</td>
<td>0.2163</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2 Background

2.5 CFD Simulations

|  |  |  |  |  |  |
|---|---|---|---|---|
| 6 | 7.95 | 0.7640 | 2.4561 | ✓ | ✓ |
| 7 | 7.97 | 0.7780 | 0.1565 | ✓ | ✓ |
| 8 | 7.97 | 0.7780 | 2.3938 | ✓ | ✓ |
| 9 | 8.00 | 0.7860 | 0.0000 | ✓ | ✓ | ✓ |
| 10 | 8.00 | 0.7860 | 2.4525 | ✓ | ✓ | ✓ |
| 11 | 8.00 | 0.8070 | 0.0825 | ✓ | ✓ | ✓ |
| 12 | 8.00 | 0.8060 | 2.4070 | ✓ | ✓ | ✓ |
| 13 | 8.03 | 0.4982 | - | - | ✓ |
| 14 | 7.94 | 0.6949 | - | - | ✓ |
| 15 | 7.95 | 0.7640 | - | - | ✓ |
| 16 | 7.97 | 0.7780 | - | - | ✓ |
| 17 | 8.00 | 0.7860 | - | - | ✓ |
| 18 | 8.00 | 0.8070 | - | - | ✓ |

In Table 2 can be seen the Case number, the Reynolds number, the Mach number, the angle of attack and for which simulation the cases were run. The first 12 cases are based on experimental runs. The last six cases (13-18) were run after the original 12. These cases were run for the ETS. It was decided these were necessary in order to properly set the reference conditions before inputting them in WIN3VE. This will be discussed in greater detail in section 4.1. Cases 13-18 are run at the same Reynolds and Mach number as cases 1-12.

For each of the cases and in each of the simulations it is possible to extract a total of eight variables. These variables can be extracted at the various grid points defined in the simulations. It is however impossible to extract data at locations where solid surfaces are represented, such as the model volume for example. The variables that can be extracted are, the three coordinates (x,y,z), the Mach number, the pressure coefficient, and the local velocities in all three directions (u,v,w).

2.5.2 Comparison with Experiment

The CFD simulations do a fair job at recreating the same conditions as the ones during the experiment. This can be seen by looking at the pressure distribution calculated along the walls in comparison to those measured experimentally. Differences still exist as can be seen in Figure 19. Some of these differences can be attributed to the scatter present in the experimental measurements. The reason brought forth for the rather large differences in the W8000 and W9000 pressure lines in reference [7] is the proximity of those pressure lines to the slots. The normal flow through the slots at these locations will have a large influence due to the proximity of the pressure lines to the model.

The aerodynamic coefficients of the MPS compared to the experiment are shown in Table 3. It can be seen that the coefficients coincide fairly well. This is particularly true for the lower the Mach numbers. The reason for the differences can be attributed in part to the differences seen in the pressure coefficients shown in Figure 19. The shape of the wing will also play a role as in the MPS the wings were kept rigid. Another reason which may cause differences is the peniche. The forces and moments in the MPS case are attained from numerical integration of the pressure and skin friction distributions on the
surface of the model. The peniche was not included in the integration but is believed to still have an effect on the coefficients according to reference [7].

![Figure 19: Pressure coefficient distribution along the walls for case 10 (M=0.786, \(\alpha=2.4525\)) [7]](image)

### Table 3: Aerodynamic coefficients of the experiment and MPS

<table>
<thead>
<tr>
<th>Case</th>
<th>Mach</th>
<th>Reynolds</th>
<th>alpha</th>
<th>(C_L) (exp)</th>
<th>(C_D) (exp)</th>
<th>(C_M) (exp)</th>
<th>(C_L) (MPS)</th>
<th>(C_D) (MPS)</th>
<th>(C_M) (MPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4982</td>
<td>8.03E+06</td>
<td>0.2154</td>
<td>0.1904</td>
<td>0.021</td>
<td>-0.0666</td>
<td>0.2171</td>
<td>0.0187</td>
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<td>2</td>
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<td>0.6949</td>
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<td>0.2163</td>
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<td>0.0241</td>
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<td>0.021</td>
<td>-0.1058</td>
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<tr>
<td>8</td>
<td>0.778</td>
<td>7.97E+06</td>
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<td>8.00E+06</td>
<td>2.407</td>
<td>0.4757</td>
<td>0.0321</td>
<td>-0.0881</td>
<td>0.5391</td>
<td>0.0322</td>
<td>-0.1123</td>
</tr>
</tbody>
</table>

The differences seen between the experiment and CFD led to the decision of using data solely from the virtual wind tunnel (CFD simulations). This was done in order to avoid discrepancies in input and output. The procedure which describes how the CFD data was calibrated and prepared for use in WIN3VE is given in section 3.3.
3 Approach
This chapter will detail the necessary steps in order to carry out the analysis required to answer the research questions. This will be done by describing the different phases taken during the project in order to reach conclusions.

3.1 Familiarization
The first step of the project was to become familiar with the different aspects of it. The most fundamental step was to read literature about wall interference. The goal of this literature survey was to start with a broad theme, wall interference in this case, and then progressively look more closely at relevant topics. Some of these topics for example include the causes of wall interference, the effects that it has on measurements and the corrective steps taken to improve measurements. This part of the familiarization process resulted in a literature review. This document is a summary of relevant theoretical information. This theoretical knowledge is the cornerstone on which observations and conclusion can be drawn. It also helped providing ideas for possible improvements.

Furthermore it was necessary to become familiar with work that had already been accomplished. This project is the continuation of the work started by another student. Therefore in order to further the process it was necessary to know what had already been done and how. The previous student documented the WIN3VE code and also laid out the foundations for possible comparison processes with CFD. He also ordered the CFD simulations. Reading and understanding the description of the source code was key in order to be able to modify it. This required the learning of the FORTRAN and PV-WAVE programming languages. As the program was run on a Linux system it was also essential to learn how to use such an operating system. This was particularly important as without these basics operating the code would not have been possible. It was also needed to change the source code in order to analyze certain parts of it.

3.2 Comparison Process
The evaluation process is based on a comparison between the CFD simulations and WIN3VE. This process is crucial as it is based on these comparisons that conclusions will be drawn. It was therefore of great importance to establish a clear plan detailing how and why points were to be compared.

The comparison process used is based on CFD datasets. These were discussed in section 2.5. The reason that CFD datasets are used is that they provide a complete flow solution. This means that at all points of interest all the required WIN3VE input data is known. This allows for the use of various control parameters in order to input CFD data in certain parts of WIN3VE. The advantage of these control parameters is that they allow some of the calculations steps of WIN3VE to be bypassed. It is this change of input which will lead to finding which parts of the code do a poor job at recreating actual conditions.

The validation process will be explained by using the numbered comparison points in Figure 20.
The numbering of this list corresponds with the comparison points.

1. In the first step the model induced velocity at the wall is compared. This step makes it possible to see how well the simple model representation simulates actual flow conditions. The $u_m$ variable is calculated in WIN3VE solely using the model representation. To get a $u_m$ value from the CFD data it is necessary to look at the FFS. From this run the $u_m$ can be determined as the model is the only element present in the flow and is therefore the sole cause of disturbance velocities. When comparing the CFD results and WIN3VE results it will be concluded that WIN3VE is accurate if the difference approaches zero. This is shown in equation (3.1).

$$u_{m_{FFS}} - u_{m_{WIN}} = \Delta u_m \approx 0$$  \hfill (3.1)

2. The second point of comparison will be the total disturbance velocity at the wall. The same process as that carried out for $u_m$ can now be carried out for $u_t$. The $u_t$ calculated in WIN3VE will be compared to the one obtained in the MPS. The differences between the two should then reveal where differences come from. If WIN3VE performs well the differences should approach zero as is shown in equation (3.2).

$$u_{t_{CFD}} - u_{t_{WIN}} = \Delta u_t \approx 0$$  \hfill (3.2)

As in WIN3VE $u_t$ is calculated from both $C_p$ and the normal velocities through the slots, the normal velocities will also be compared at this point.
3. The next possible comparison looked at how well the panel method used at the walls simulates
the flow inside the tunnel. Before this step both building blocks for $u_w$ have already been
compared, namely $u_m$ and $u_c$. How WIN3VE calculates $u_w$ is shown in (3.3).

$$u_c - u_m = u_w$$ (3.3)

This step will help see if the velocity values that are calculated before lead to an appropriate
panel representation.

4. The next step is to compare the reference velocities obtained from WIN3VE to the ones
calculated in CFD. This is done to check if the panel representation created by WIN3VE to
simulate the disturbances at the wall work properly. This will be done by looking at the
reference velocities that are calculated and interpolated in WIN3VE and comparing them to the
CFD values at the same points.

5. Finally the last link in the chain is the comparison of the actual corrections. This will be
compared by inserting the reference velocities obtained from the processed CFD simulations
(subtraction of the ETS and FFS from the MPS). This will then give an idea of whether the
corrections yield trustworthy results.

Once these five steps have been carried out, the final step will be to compare the free flow case to the
constraint flow case plus the increments to the Mach number and angle of attack with the ultimate goal
that these match. This is shown schematically in Figure 21.

![Figure 21: Final step of CFD comparison process](image-url)
Using the corrections from WIN3VE a new FFS/FFSwP case can be run. This is to be run at conditions defined by the original Mach number plus the addition of the correction calculated by WIN3VE. The same holds true for the angle of attack which should be set to the original angle plus the WIN3VE correction. The resulting force and moment coefficients from this new FFS/FFSwP case should be the same as those calculated by WIN3VE [8].

It should be noted that the last step of this process was not completed in this thesis. That is to say that the new FFS/FFSwP CFD simulation was not run. Therefore comparisons of the force and moment coefficients will take place between the original MPS and FFS. This therefore means that the comparison between the WIN3VE results and the CFD simulation process will not be at the same Mach number and angle of attack. The difference between the WIN3VE results and CFD simulations, (i.e. the corrections to the Mach number and angle of attack) should however be small meaning the comparison should still be indicative.

The comparison process detailed above is broken into two different sections. Steps 4 and 5 were compared to CFD data using the baseline case. A comparison of the baseline case can then be carried out with the other WIN3VE runs (see Table 5). This is steps 1 through 3 of the process described above. The comparison with CFD (Steps 4 and 5) was carried out first as these steps will be the same regardless of the input. A resume of the comparison process is given in Table 4.

<table>
<thead>
<tr>
<th>Step in comparison process</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline vs CFD simulations &amp; WIN3VE runs</td>
</tr>
<tr>
<td>2</td>
<td>Baseline vs CFD simulations &amp; WIN3VE runs</td>
</tr>
<tr>
<td>3</td>
<td>Baseline vs CFD simulations &amp; WIN3VE runs</td>
</tr>
<tr>
<td>4</td>
<td>Baseline vs CFD simulations</td>
</tr>
<tr>
<td>5</td>
<td>Baseline vs CFD simulations</td>
</tr>
</tbody>
</table>

### 3.3 Preparing CFD data

In order to input data from CFD into WIN3VE it needs to be compatible. This means that the input needs to be correctly presented. Correctly in this case means in the same way as it would be if it were from an experimental run. If the data is not properly input, distinguishing the source of weaknesses of the code would be difficult. There are different steps that need to be taken on different parts of the data. This is due to the fact that not all the data is entered in the same manner in WIN3VE. The three major adjustments steps will be discussed here.

#### 3.3.1 Setting the Reference Conditions

Having explained how the reference conditions are set in the CFD case in section 3.2, it is explained here how the reference conditions are normally set in the HST.

During experimental testing the model will experience a flow condition. The flow around the model is distorted due to the presence of the model and the tunnel walls. In order to be able to set a Mach
number a reference pressure is needed far from these distortions. This reference pressure is taken in the plenum. For the empty tunnel simulation the pressure in the plenum and along the tunnel center line are measured. The pressure distribution along the center line will contain scatter. In order to obtain smooth curves for the pressure from the measurements an interpolation is carried out in streamwise direction. At the Model Reference Point (MRP) the pressure from the interpolated curve will differ from the pressure in the plenum. This difference in pressure will cause a difference in the Mach number. Therefore a calibration of the test section is needed to establish a relationship between the plenum pressure and the pressure along the center line of the empty test section. From this test section calibration and the measurement of the plenum pressure, the free stream condition for the model present case can be determined.

In order to calibrate the virtual wind tunnel in the same manner as the HST the same calibration procedure was applied to the CFD simulations.

### 3.3.1.1 Calibration Step

A procedure based on the one for the HST has been devised for the CFD simulations to ensure consistency of the input data for WIN3VE. This process will be detailed here. The main assumption made during this process is that the flow conditions for both the ETS and the MPS were the same and are based on the experimental data. This therefore means that it is assumed that the Mach number and Reynolds number but also the total pressure, static pressure and dynamic pressure are the same. This is shown in equations (3.4) to (3.8).

\[
\begin{align*}
Re_{\text{MPS,ref}} &= Re_{\text{ETS,ref}} = Re_{\text{exp}} \quad (3.4) \\
M_{\text{MPS,ref}} &= M_{\text{ETS,ref}} = M_{\text{exp}} \quad (3.5) \\
P_{0,\text{MPS,ref}} &= P_{0,\text{ETS,ref}} = P_{0,\text{exp}} \quad (3.6) \\
P_{\text{MPS,ref}} &= P_{\text{ETS,ref}} \quad (3.7) \\
Q_{\text{MPS,ref}} &= Q_{\text{ETS,ref}} \quad (3.8)
\end{align*}
\]

The starting block of this calibration step are the total pressure and the Mach number. From these the reference static pressure of the tunnel in the ETS can be calculated. This is shown in equation (3.9).

\[
P_{\text{ETS,ref}} = P_{0,\text{MPS,ref}} \cdot \left(1 + \frac{\gamma - 1}{2} \cdot M_{\text{MPS,ref}}^2\right)^{-\frac{\gamma}{\gamma - 1}} \quad (3.9)
\]

\(P_{0,\text{MPS,ref}}\) and \(M_{\text{MPS,ref}}\) are taken from the experimental results used to run the MPS. This then makes it possible to calculate the reference dynamic pressure (equation (3.10)).
Approach

3.3 Preparing CFD data

\[ Q_{ETS,ref} = \frac{1}{2} \cdot Y \cdot p_{ETS,ref} \cdot M_{ETS,ref}^2 \quad (3.10) \]

The next step is to find the static pressure distribution along the center line for the ETS run. This distribution is input in the test section calibration procedure. This is done by solving the definition of the pressure coefficient for static pressure or in other words dimensionalizing the pressure coefficient. The static pressure is determined from the CFD pressure coefficient results as show in equation (3.11) and (3.12).

\[ C_{p,CL,ETS} = \frac{p_{CL,ETS} - p_{ETS,ref}}{Q_{ETS,ref}} \quad (3.11) \]

\[ p_{CL,ETS} = C_{p,CL,ETS} \cdot Q_{ETS,ref} + p_{ETS,ref} \quad (3.12) \]

Here \( C_{p,CL,ETS} \) are the pressure coefficients along the center line of the tunnel, extracted from the ETS CFD run. Figure 22 illustrates the position at which pressure measurements are taken inside the wind tunnel.

![Figure 22: Illustration of different measuring positions inside the wind tunnel](image)

Furthermore the corresponding static pressure in the plenum is needed, as this is the reference pressure in the experimental test section calibration procedure. The \( PL \) subscript here stands for plenum and the pressure is calculated in the same way as before, namely solving the definition of the pressure coefficient for the static pressure in the plenum (equation (3.13)).

\[ p_{ETS} = \text{avg}(C_{p,PL,ETS}) \cdot Q_{ETS,ref} + p_{ETS,ref} \quad (3.13) \]
$C_{p,PL,ETS}$ is extracted from the ETS run. The average of all the pressure coefficients from a line segment, which spans the entire length of the test section, at the approximate height where this pressure is measured experimentally is taken.

Combining the reference static pressure in the plenum with the known total pressure the corresponding Mach number can be calculated as shown in equation (3.14).

$$M_{ETS}^* = \frac{\left(\frac{p_{0,ETS,ref}}{p_{ETS}}\right)^{\frac{\gamma}{\gamma}}}{{\frac{\gamma - 1}{\gamma}} \cdot \left(\frac{p_{ETS}}{\gamma - 1}\right)} - 1 \quad (3.14)$$

This then leads to the calculation of the dynamic pressure given in equation (3.15).

$$Q_{ETS}^* = \frac{1}{2} \cdot \gamma \cdot p_{ETS}^* \cdot M_{ETS}^2 \quad (3.15)$$

All the necessary components required to define the pressure coefficient as it is defined in the experimental test section calibration procedure are now known. This therefore leads equation (3.16):

$$C_{p,ETS}^* = \frac{p_{CL,ETS} - p_{ETS}^*}{Q_{ETS}^*} \quad (3.16)$$

A surface is fitted through the test section centerline values, $C_{p,ETS}^*$ and the corresponding Mach number $M_{ETS,ref}^*$. This surface fit is the result of the calibration step. The coefficients from the surface fit will allow for pressure coefficient values to be calculated at all necessary $x$ positions along the tunnel center line and for any required Mach number.

### 3.3.1.2 Obtaining Freestream Conditions

With the test section calibration for the CFD simulations available it is possible to determine the freestream conditions in the MRP for the tunnel model simulation. This is done by using the plenum pressure from the MPS as input. The method is described in more detail below.

The MRP is situated at $x = 0.55$ m. At this point the pressure coefficient at the MRP is determined from the fitted surface. This interpolated pressure coefficient, $C_{p,int,MRP}^*$, is then dimensionalized with the plenum based dynamic and static pressure from the MPS.

$$p_{int,MRP} = C_{p,int,MRP}^* \cdot Q_{MPS}^* + p_{MPS}^* \quad (3.17)$$

$Q_{MPS}^*$ and $p_{MPS}^*$ are determined in the same way as for the ETS case described above in equations (3.13) and (3.15). Using the interpolated static pressure, $p_{int,MRP}$, and the total pressure it is possible to calculate the Mach number at the MRP as shown in equation (3.18).
3 Approach

3.3 Preparing CFD data

\[ M_{MPS,MRP} = \sqrt{\left( \frac{P_{0,MPS,ref}}{P_{int,MRP}} \right)^{\frac{\gamma-1}{\gamma}} - 1} \]  

\( (3.18) \)

Subsequently the dynamic pressure at the MRP position can be calculated using equation (3.19).

\[ Q_{MPS,MRP} = \frac{1}{2} \cdot \gamma \cdot P_{int,MRP} \cdot M_{MPS,MRP} \]  

\( (3.19) \)

This dynamic and static pressure are then used to correct the force coefficients as well as the wall pressure distributions of both the MPS and ETS as shown in equations (3.20) to (3.24).

\[ C_L = \frac{L}{Q_{MPS,ref} \cdot S} \cdot \frac{Q_{MPS,ref}}{Q_{MPS,MRP}} \]  

\( (3.20) \)

\[ C_D = \frac{D}{Q_{MPS,ref} \cdot S} \cdot \frac{Q_{MPS,ref}}{Q_{MPS,MRP}} \]  

\( (3.21) \)

\[ C_M = \frac{M}{Q_{MPS,ref} \cdot S} \cdot \frac{Q_{MPS,ref}}{Q_{MPS,MRP}} \]  

\( (3.22) \)

\[ C_{p,MPS,new} = \frac{C_{p,MPS,old} \cdot Q_{MPS,ref} + P_{MPS,ref} - P_{int,MRP}}{Q_{MPS,MRP}} \]  

\( (3.23) \)

\[ C_{p,ETS,new} = \frac{C_{p,ETS,old} \cdot Q_{ETS,ref} + P_{ETS,ref} - P_{int,MRP}}{Q_{ETS,MRP}} \]  

\( (3.24) \)

3.3.2 Boundary Layer Investigation

In order to input the correct data into WIN3VE it is necessary to extract it at the correct location from the CFD simulations. This means that the extracted CFD data needs to be correctly manipulated before. The first step was discussed in section 3.3.1. However more needs to be done to ensure that the data can be used. This section will discuss the procedure used to determine at which location the CFD data needed to be extracted.

Firstly the location at which the data extracted is important. This is particularly true for the disturbance velocities. If these velocities are extracted in the wrong place it could lead to ambiguous results. An example of this is if the velocities are extracted in the boundary layer of the tunnel. This would be a problem as the velocities in the boundary layer are not representative of disturbance velocities in the rest of the flow domain. Therefore in order to be able to use the data from the CFD it is required to determine the size of the boundary layer. The actual size of the boundary layer is not critical as it is simply needed to insure that the measurements used from the CFD simulation are outside of the boundary layer. This is necessary as otherwise the disturbance velocities used will not be representative of the flow inside the tunnel but rather inside the boundary layer.
An way of determining the height of the boundary layer on a wall is to look at the total pressures. In the boundary layer the total pressure will be lower than in the rest of the flow. This is due to viscous effects which lower the energy in the boundary layer leading to a subsequent total pressure drop. In order to find the limit of the boundary layer the ratio between the local total pressure and the total pressure in the settling chamber, or reference total pressure is investigated. From the CFD all the necessary data is present in order to carry out this calculation. The ratio between the local total pressure and the static pressure is given by equation (3.25).

\[
\frac{p_{0,\text{local}}}{p_{\text{local}}} = \left(1 + \frac{\gamma - 1}{2} \cdot M_{\text{local}}^2\right)^{\frac{\gamma}{\gamma-1}} 
\]

The local Mach number is extracted from the CFD. This Mach number was verified to be correct using the velocity coefficients and the reference conditions. The local static pressure required in (3.25) is calculated from the definition of the pressure coefficient shown in equation (3.26).

\[
C_p = \frac{p_{\text{local}} - p_{\text{ref}}}{Q_{\text{ref}}} 
\]

The reference conditions are known while the pressure coefficient is extracted from the CFD. This analysis should therefore ensure that the correct measurements are taken. In order to cope with the change in height at which the data is extracted the tunnel in WIN3VE is also adjusted. This is done in order to ensure that the dimensions of the wind tunnel in WIN3VE correspond to the locations at which the data is extracted in the CFD simulations.

### 3.3.3 Nondimensionalization

Furthermore the velocities in CFD have also been nondimensionalized. This nondimensionalization however is not the same as the one that is required by WIN3VE. This therefore means that the velocities need to first be dimensionalized after being extracted from the CFD. And subsequently nondimensionalized with the correct parameter before being entered in WIN3VE. An additional challenge is present due to the fact that the velocities from the ETS and MTS cases are not nondimensionalized in the same manner. This is due to the nature of the CFD simulations as the ETS were timed average solutions of the RANS equations while the MTS were not time averaged.

For the MTS the nondimensionalization occurs by dividing the velocities with the reference streamwise onset velocity. The original streamwise onset velocity is calculated from the original CFD flow conditions. The reference velocity used in order to nondimensionalize the velocities before they are input in WIN3VE is calculated during the setting of the reference conditions (section 3.3.1). For the ETS the approach is slightly different. The velocities are nondimensionalized using the ratio of the static pressure and density. Therefore these quantities are calculated from the reference conditions used for the ETS and the velocities are dimensionalized from that. The velocities are then nondimensionalized using the reference streamwise onset velocity calculated for WIN3VE.
3.4 Plausibility

As WIN3VE had not been utilized in a while it was decided to ensure that it was still running as it once did. This was decided as changes made to the program that have not been catalogued may change the workings and results of the code. It would then be impossible to distinguish between the weaknesses of the code and possible programming mistakes/changes.

In order to gain confidence in the fact the code was running as it once was it was compared to results obtained using WIN3VE in the past. In order to be sure that the results can be compared, the input of the cases will first be compared. Then the output of the WIN3VE runs will be compared.

3.5 Establishing a Baseline

Once the data from the CFD simulations has been prepared and confidence of the proper running of WIN3VE the next step is to establish a baseline solution. This baseline will serve as a comparison for all other cases (see Table 3). For this project it was chosen that the baseline be the best possible scenario. That is to say that the baseline is the case where all the input comes from CFD. Therefore the total disturbance velocities, the model induced disturbance velocities as well as the normal velocities will be input into WIN3VE. This was done in order to be able to compare how well the individual parts of WIN3VE work.

This means that counting the baseline run, a total of 8 runs were carried out in WIN3VE for every case (see Table 2). This stems from the fact that there are three control parameters which each have two possible values. These runs are tabulated in Table 5.

<table>
<thead>
<tr>
<th>Run</th>
<th>IVEL</th>
<th>INPUM</th>
<th>NORVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>UT,UM</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>UT</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>[-]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UM</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>UM,WT</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>WT</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>UT,WT</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

In Table 5 the name of the control parameter and what it is set to is give. This is explained below:

I. IVEL- This is the control parameter which allows the total disturbance velocities to be input. When this is set to 1 the velocities are read from a file bypassing the derivation of these velocities from the pressure measurements. This file is created from the CFD MPS.

II. INPUM- This is the control parameter which allows the model induced disturbance velocities to be input directly. In other words for the model representation to be ignored. When this is set to 1 the velocities are read from a file. This file is created from the CFD FFS/FFSwP.
III. NORVEL- This is the control parameter which allows the normal velocities through the slots to be input directly. This means that the code bypasses this calculation step and reads the velocities directly from a file. This file is created from the CFD MPS.

The runs in Table 5 are labeled according to which data is read in from files created from CFD data. Therefore the baseline run uses all CFD data, while the UM run for example utilizes the model induced disturbance velocities from the CFD FFS case and calculates the normal velocities and total disturbance velocities using the WIN3VE calculation steps.

Only 4 of the cases of the 12 cases given in Table 2 will be used for detailed analysis. This was chosen as it would be too time consuming to analyze all 12 cases in depth. The four cases that were chosen are case 1, 2, 9, 10. Cases 1 and 2 are chosen as they are at the lowest Mach number meaning the closest to incompressible flow. Cases 9 and 10 were chosen because they represent the design Mach number of the aircraft.
4 Results and Analysis

4.1 Analysis

This section analyses the one variable measured boundary condition method as well as the CFD subtraction process. The aim is to look at the assumptions made during both procedures.

4.1.1 One Variable Measured Boundary Condition Methods

This section will analyze the assumptions made when using a one variable measured boundary condition method. The first of these is that the disturbance level of the flow next to the walls is low (see section 2.4.2). This can be verified by looking at the CFD data near the walls and comparing it to data closer to the model.

![Case 1](image1.png) ![Case 10](image2.png)

Figure 23: Total axial disturbance velocities at centerline vs at the walls

Figure 23 shows the total disturbance velocities at the centerline of the wind tunnel as well as the centerline of the top and bottom walls. In both cases the large peak which can be seen in the centerline data is caused by the wing of the model. This peak can also be seen in the disturbance velocities along the bottom wall. In case 1 the disturbances after the wing do not readily appear on the top and bottom walls. However when examining case 10 the disturbance velocities behind the wing have the same magnitude along the tunnel centerline and top and bottom walls. This seems to indicated that this assumption is valid at lower Mach numbers, such as for case 1. But that this assumption might be too simplistic for higher Mach numbers, such as for case 10.

The next assumption is that the loading on the model in the tunnel will be similar to the one the model would feel at the same conditions in free flow. This assumption was needed in order to use the velocities calculated from the model representation (see section 2.4.4) in free flow for the model in the tunnel case. This can be checked by comparing the values of the model loading in the virtual tunnel (MPS) to the model in free flow (FFS). This is shown in Table 6.
4.1 Analysis

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$C_L$</th>
<th>$C_D$</th>
<th>$C_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPS</td>
<td>0.5222</td>
<td>0.0298</td>
<td>-0.1011</td>
</tr>
<tr>
<td>FFS</td>
<td>0.5771</td>
<td>0.0321</td>
<td>-0.1209</td>
</tr>
</tbody>
</table>

The results from Table 6 indicate that there are in fact differences between the two cases. This indicates that the aerodynamic loading in the FFS and MPS are not the same. To determine whether this difference is too large, its effects was investigated. This difference will directly affect the model representation created by WIN3VE. The resulting axial model induced disturbance velocity from the model representation of the original and modified $C_L$ are shown in Figure 24.

![Figure 24: Effect of different loading on model representation (case 10 M=0.7831, $\alpha=2.453$, top wall)](image)

From Figure 24 it can be seen that the difference in $C_L$ leads to a difference in the model induced disturbance velocities. This difference reaches a maximum absolute magnitude of 0.005. This is large as it is the same order of magnitude as the wall induced velocities. This is therefore a major flaw of the model representation and of the method.

The following assumption is that by entering the axial component of the wall induced disturbance, all three components of the velocity field can be approximated inside the tunnel by the panel representation (see section 2.4.7). This seems to be more problematic as the input for the strength of the panels is solely the magnitude of the axial component of the velocity. That therefore means that the transverse and normal velocity components inside the tunnel are only replicated using the strength of the doublets as well as the location at which the point is located. No actual information about those velocity components is used. Due to this the accuracy with which the wall induced disturbance velocities in transverse and normal velocities can be estimated will decrease.
It should also be noted that as this method uses linear potential theory it cannot predict many of the flows likely to be encountered within a wind tunnel. Viscous effects, such as the boundary layer, are for example not considered. These viscous effects will have an influence on the flow solution. Due to this the CFD data was extracted outside of these regions. Vortices also cannot be predicted. The same can be said for regions of supersonic flow. Both of these phenomena, vortices and supersonic flow, alter the flow solutions and therefore effect the disturbance velocities.

4.1.2 CFD Process

This section takes a critical look at the procedure used to obtain the disturbance velocities from the various CFD simulations. This will be done by showing an example of the process, of how the input files for WIN3VE are set up. The goal of evaluating this process is to establish whether the data obtained from the CFD simulations can be compared/used with WIN3VE.

The pressure coefficient will be the variable used to show the effect of the different subtractions between the CFD simulations. The goal of the CFD process is to be able to obtain the disturbance velocities from the different influences present in the tunnel. The subsequent subtractions of these influences to reach the wall induced disturbance velocities will also be discussed. This will be shown for all three walls where data is used as input, name the centerline of the top, bottom and side walls. The chosen case for the analysis is case 9 (α=0,M=0.7821).

1) The starting point for the process is to look at the MPS. From this simulation the total disturbance velocities are extracted. This is due to the fact that in the virtual wind tunnel the influence of the test section, model and tunnel walls will be present.
The high pressure coefficient seen in the closed part of the test section can be attributed to wall interference. It is believed that it stems from the effect the walls and the model will have on the plenum pressure. The reference Mach number in the MPS is set by matching the plenum pressure in the MPS to the plenum pressure from the ETS. In order for the same plenum pressure to be reached in the MPS the pressure upstream of the slotted test section will either need to be higher or lower than in the ETS case. Due to the model orientation (upside down) it can be seen that the Cp has a higher magnitude along the bottom wall. The shape of the distributions for all three cases clearly show the influence of the wing.

2) The following step is to remove the effects of the empty test section. This process is also carried out in WIN3VE. The goal of this step is to remove effects which are not due to the wall model interactions but to other small imperfections in the virtual tunnel as well as the full-span model fairing. The distribution along the centerlines of the walls of the ETS case are shown in Figure 26 (Note the model is shown in the figure but is not actually present in the ETS).
Results and Analysis

4.1 Analysis

Figure 26: Pressure coefficient distribution for the ETS case (M=0.7821)

The $C_p$ in the ETS steadily decreases until approximately $x = 0$, after which it rapidly increases. This increase is due to a stagnation region caused by the diffuser present after the test section. The sharp decrease which can be seen at the end of the curve is caused by the strut which reduces the cross section area of the tunnel and therefore speeds up the flow. A good indication that this simulation is properly representing the flow in the virtual tunnel is the fact that to top and bottom wall distributions are identical. This was of course to be expected as there is nothing in the tunnel to disturb the flow.

3) The first subtraction to take place is to eliminate ETS effects from the MPS. The result of the MPS-ETS subtraction is shown in Figure 27. The most notable change occurs towards the rear of the model where the value from the MPS is decreased. The closed section part of the tunnel still delivers relatively high values, with this effect still being contributed to the same reason explained for the MPS. The corresponding disturbance velocities from this $C_p$ distribution are used as input in WIN3VE. It should be mentioned that even though the ETS has been subtracted certain flow phenomena which occur only the MPS case will still be present. These include the model and wall effects as well as more complex phenomena such as vortices caused by the model in the MPS.
4.1 Analysis

The FFS take place at the same Mach number and angle of attack as in the MPS case. The Cp distribution at the location where the walls would be located is shown in Figure 28. The same characteristic peak at the level of the wings can also be seen. Furthermore it is also noted that the Cp upstream of the model is small but not exactly zero. This therefore means that the model influences the flow upstream.

Figure 27: Result of subtracting the ETS pressure distribution from the MPS

4) The FFS take place at the same Mach number and angle of attack as in the MPS case. The Cp distribution at the location where the walls would be located is shown in Figure 28. The same characteristic peak at the level of the wings can also be seen. Furthermore it is also noted that the Cp upstream of the model is small but not exactly zero. This therefore means that the model influences the flow upstream.
5) The final step is to remove the model influences in the MPS-ETS case. The assumption made by WIN3VE when carrying out this subtraction is that the force and moment coefficients of the model in the MPS and FFS will also be the nearly equal. As was shown in

6) Table 6 that is not the case. The subtraction process carried out here will remove the model effects but not the complex flow effect still present in the MPS-ETS but not in the FFS. An example of the complex flow that will remain is the horseshoe vortex which emanates from the nose of the model in the MPS. The result of the subtraction is shown in Figure 29.
4 Results and Analysis

4.1 Analysis

4.1.1 Analysis

Figure 29: Wall induced disturbance velocities

The most apparent effect of the subtraction of the FFS from the MPS-ETS is the smoothening of the peak over the wing (Figure 29). The overall result from the CFD process is a smoother curve which still includes effects of the walls but also of more complex flow phenomena (i.e. horseshoe vortex from the nose of the model).

4.1.2.1 Effect of the Peniche

A different result than that obtained in the previous section is achieved if the FFSwP case is used. The effect of the peniche on pressure distribution at the tunnel centerline of the top wall is shown in Figure 30. It can be seen that along all three walls the effect of the peniche is visible.
Figure 30: Effect of the peniche

This effect is also seen after it is subtracted from the MPS-ETS case as can be seen in Figure 31.
This small change in the pressure distribution will also lead to a change in the axial wall induced disturbance velocity field. It is felt that using the FFSwP instead of the FFS is more suitable. This is due to the fact that it has been shown the peniche has a noticeable effect. This effect will also be present in the MPS-ETS case as the peniche is also present in that case. The peniche effect is not a wall interference effect and therefore should be removed.

4.1.3 Discussion

The Cps shown in section 4.1.2 and the process which was used to obtain them will be discussed in this section. The aim is to evaluate the validity of the process and/or possible problems or differences that could arise when inputting/comparing the results to WIN3VE.

In WIN3VE it is assumed that the FFS, which is represented by the model representation, is at the same freestream conditions and model loading. For the CFD process, the freestream conditions were indeed the same for all cases. However the aerodynamic forces in the MPS and FFS/FFSwP were not the same. This difference in $C_L$, $C_D$ and $C_M$ between the two is the influence of the walls.

Certain phenomenon present in the CFD simulations also cannot be represented by WIN3VE. A full RANS model was used in CFD along with other enhancements to better render the flow. The different effects present in CFD will never be able to be rendered in WIN3VE. For example the presence of a horse-shoe vortex emanating from the junction of model and the wall. These phenomena will also not be present in
the FFS/FFSwP and will therefore persist even after the model induced Cps have been subtracted from the MPS-ETS. These effects are close to the model and should have little effect at the points of extraction, along the tunnel wall centerlines. These will however show up when comparing the disturbance velocities close to the model. It should be noted that the boundary layer effects along the tunnel walls have no influence on the disturbance velocities as these were extracted outside the boundary layer is explained in section 4.3.

4.2 Calibration step

This step was taken in order to set reference conditions for the WIN3VE runs. The main reason that was needed was due to the fact that the ETS did not match the empty test section calibration curves of the HST. This is shown in Figure 32.

From Figure 32 the differences between the CFD and HST tunnel can clearly be seen. The reason for this difference is simply that the two are not exactly the same tunnels. Therefore small geometry differences or the effect of the long static tube used for the HST measurements all contribute to this difference. It should be noted however that the CFD results show similar behavior to the HST results. In other words it can be deemed that the ETS results allow for the HST calibration to take place.

The results of this calibration procedure can be seen in Table 7, where the change in reference conditions is given for the four analyzed cases.
4 Results and Analysis

4.3 Boundary Layer investigation

Table 7: Overview of calibration results

<table>
<thead>
<tr>
<th>Case</th>
<th>$M_{ref}$ (original)</th>
<th>$M_{ref}$ (calibrated)</th>
<th>$C_L$ (original)</th>
<th>$C_L$ (calibrated)</th>
<th>$C_D$ (original)</th>
<th>$C_D$ (calibrated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4982</td>
<td>0.4964</td>
<td>0.2171</td>
<td>0.2184</td>
<td>0.0187</td>
<td>0.0188</td>
</tr>
<tr>
<td>2</td>
<td>0.4989</td>
<td>0.4973</td>
<td>0.4913</td>
<td>0.4943</td>
<td>0.0252</td>
<td>0.0254</td>
</tr>
<tr>
<td>9</td>
<td>0.7860</td>
<td>0.7821</td>
<td>0.2310</td>
<td>0.2324</td>
<td>0.0208</td>
<td>0.0209</td>
</tr>
<tr>
<td>10</td>
<td>0.7860</td>
<td>0.7831</td>
<td>0.5222</td>
<td>0.5254</td>
<td>0.0298</td>
<td>0.0300</td>
</tr>
</tbody>
</table>

As can be seen in Table 7 the changes are relatively small. Never the less this step is required to ensure that all the input use comes from the same source, namely the CFD. It should also be noted that though small these changes will have an effect on the final results as the corrections are also small. The calibrated values given in Table 7 serve as input for the WIN3VE runs.

4.3 Boundary Layer investigation

4.3.1 Height Determination
The results to the boundary investigation discussed in section 3.3.2 are given in this section. Firstly an explanation of how the values were obtained will be given for one wall followed by the results for all walls.

The points extracted from the CFD span down/ laterally along the top, bottom and side wall centerlines ($y=0$). A number of streamwise positions were used in order to see the evolution of the boundary layer. The results of the calculation for the bottom wall of case 1 are shown in Figure 33. In the figure a data point indicates the location at which the percentage between the local total pressure and the reference total pressure reaches 99%. In the figure the first point is at the beginning of the slots. The chosen range was taken to cover the range of the pressure taps as at these points data is extracted. Table 8 gives the overview of the distance from the wall at which the total pressure ratio reached 99 percent for the first point in x direction as well as the last.

Table 8: Bottom wall boundary layer heights

<table>
<thead>
<tr>
<th>Case</th>
<th>Distance from the wall First point [m]</th>
<th>Distance from the wall Last point [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.036</td>
<td>0.064</td>
</tr>
<tr>
<td>2</td>
<td>0.040</td>
<td>0.070</td>
</tr>
<tr>
<td>9</td>
<td>0.034</td>
<td>0.088</td>
</tr>
<tr>
<td>10</td>
<td>0.035</td>
<td>0.100</td>
</tr>
</tbody>
</table>
4.3.2 Locations for Data Extraction

This analysis was carried out in order to insure that the extract data used from the CFD simulation was not taken in the boundary layer. Table 9 gives the height at which the data will be extracted. The height positions are derived from the results given in section 4.3. On top of this an extra safety margin of 30 mm was applied. It should also be noted that the positions were also rounded up for convenience. Also in order to have symmetric conditions the limiting case from either the top or bottom wall was applied.

<table>
<thead>
<tr>
<th>Case</th>
<th>Position of extraction for bottom wall</th>
<th>Position of extraction for side wall</th>
<th>Position of extraction for top wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.810</td>
<td>-0.910</td>
<td>0.810</td>
</tr>
<tr>
<td>2</td>
<td>-0.800</td>
<td>-0.910</td>
<td>0.800</td>
</tr>
<tr>
<td>9</td>
<td>-0.780</td>
<td>-0.900</td>
<td>0.780</td>
</tr>
<tr>
<td>10</td>
<td>-0.770</td>
<td>-0.900</td>
<td>0.770</td>
</tr>
</tbody>
</table>

4.4 Plausibility

The first step to analyzing data generated by WIN3VE is to ensure that the program is functioning as it once was. To this end a comparison with previous results was carried out.
4.4 Plausibility

4.4.1 Comparison with previous results

In order to gain confidence in the results it is necessary to assess them. A way to do this is to compare them to older results. In this case this is possible as WIN3VE results from a previous test are available. The model is not exactly the same (Table 10), nor are the conditions (Figure 34), therefore the comparison cannot be exact. However the orders of magnitude can still be compared.

Table 10: Model comparison

<table>
<thead>
<tr>
<th>Part</th>
<th>OM</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Volume [m³]</td>
<td>0.06374</td>
<td>0.24165</td>
</tr>
<tr>
<td>Largest C.A. [m²]</td>
<td>0.05477</td>
<td>0.09376</td>
</tr>
<tr>
<td>Fuselage Length [m]</td>
<td>2.46605</td>
<td>3.215</td>
</tr>
<tr>
<td>Wing Area [m²]</td>
<td>0.32462</td>
<td>0.875</td>
</tr>
</tbody>
</table>

As shown in Table 10 the present model, the PM, is considerably larger than the previous model (OM). In order to be able to draw conclusions from the comparison first the input is shown in Figure 34, where the Cp distribution is given at the center of the top and bottom wall. Note that due to model orientation the top wall of the OM is compared to the bottom wall of the PM. As can be seen in the figure the models are not the same side up. Namely the OM model is upside up while the PM model is upside down. This means that when comparing the Cp input the top wall of the OM model needs to be compared with the bottom wall of the PM model.

When looking at the Cp distribution it can be seen that there are similarities between the two cases. The overall shapes of the distributions are fairly similar. It can easily be noted that the Cp values reached on the PM model are slightly larger than those on the OM model. This is particularly evident in the closed part of the tunnel. These differences can be attributed to the difference in size of the models and to the fact that the aerodynamic conditions are not exactly the same. For the purpose of comparison of results however they are deemed to be sufficiently similar to be compared.
Figure 34: Cp comparison for the two difference WIN3VE runs [16]

The final comparison point will be to look at the output of the program, namely the wall induced disturbance velocities. These are shown in Figure 35 along the span of the wing of the model. The lines from the PM model (color), fit the pattern from the ones calculated using the OM model. The difference in shape of the curves may be attributed to difference in model representation used for the two difference models. Though not exactly the same as those calculated previously the order of magnitude of the lines coincides well with previous findings. This final comparison gives even more assurance to the fact that WIN3VE is running as it was.
4.5 Baseline Results

This section will discuss the calculated baseline results. The baseline results are the results against which further results will be measured. The baseline results here are the results that were calculated using only input from CFD.

4.5.1 Corrections

The resulting corrections to the aerodynamic forces and moment and flow conditions calculated for the baseline case can be seen in Table 11.

<table>
<thead>
<tr>
<th>Case</th>
<th>$M$</th>
<th>$\Delta M$</th>
<th>$\alpha$</th>
<th>$\Delta \alpha$</th>
<th>$\Delta C_L$</th>
<th>$\Delta C_D$</th>
<th>$\Delta C_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4964</td>
<td>0.006954</td>
<td>0.215</td>
<td>-0.18804</td>
<td>-0.005</td>
<td>-0.00661</td>
<td>0.001012</td>
</tr>
<tr>
<td>2</td>
<td>0.4973</td>
<td>0.004193</td>
<td>3.214</td>
<td>-0.25872</td>
<td>-0.00686</td>
<td>-0.00693</td>
<td>0.00042</td>
</tr>
<tr>
<td>9</td>
<td>0.7821</td>
<td>-0.00168</td>
<td>0</td>
<td>-0.04506</td>
<td>0.000618</td>
<td>-0.00718</td>
<td>-0.00062</td>
</tr>
<tr>
<td>10</td>
<td>0.7831</td>
<td>-0.00211</td>
<td>2.453</td>
<td>-0.38338</td>
<td>0.001754</td>
<td>-0.00917</td>
<td>-0.00213</td>
</tr>
</tbody>
</table>

The following can be said about the baseline results:

- Mach number: The corrections to the Mach number are in the same order of magnitude as the maximum attainable constancy for the HST.
- Angle of attack: The alpha corrections are for all four cases negative. The reason for this could be the effect of the walls on the upwash of the model. The walls cause the upwash to be decreased...
therefore leading to a correction which increases upwash angle. Note that in this case an increase corresponds to a negative increment due to the fact that the model is upside down.

- **Lift coefficient:** In two out of the four cases the correction to the lift coefficient is positive indicating that the measured lift was originally too low. The $\Delta C_L$ is solely dependent on the dynamic pressure ratio as is the Mach number (see Appendix D). The behavior exhibited in the lift coefficient is due to the correction in dynamic pressure. The increment for case 2 is largest, this may be due to the fact that case 2 is the case at the highest angle of attack.

- **Drag coefficient:** All of the drag coefficient are negative indicating that initially too much drag is calculated. This seems logical as buoyancy drag will incorrectly increase the measured drag. As this pressure drag is related to the pressure gradient in the tunnel it is logical that the correction for cases 9 and 10 be higher. This is due to the fact that the pressure gradient is steeper for those cases than for cases 1 and 2.

- **Pitching moment coefficient:** The pitching moment is harder to predict as it reverses its behavior depending on the cases. For cases 1 and 2 it has a positive value whereas for cases 9 and 10 it is negative.

### 4.5.2 Effect of the Peniche

As previously mentioned for two runs the influence of the peniche is taken into account (FFSwP). The effect that the peniche has on the overall corrections can be seen in Table 12.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\Delta M$</th>
<th>$\Delta C_D$</th>
<th>$\Delta C_M$</th>
<th>$\Delta M$</th>
<th>$\Delta C_D$</th>
<th>$\Delta C_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 9</td>
<td>-0.00168</td>
<td>-0.00718</td>
<td>-0.00062</td>
<td>-0.003</td>
<td>-0.00715</td>
<td>-0.00079</td>
</tr>
<tr>
<td>Case 10</td>
<td>-0.00211</td>
<td>-0.00917</td>
<td>-0.00213</td>
<td>-0.00338</td>
<td>-0.00935</td>
<td>-0.00239</td>
</tr>
</tbody>
</table>

Table 12 demonstrates the effects of the model induced disturbance velocities on the correction values. The effect of the difference caused by the peniche has a definite influence on the corrections. This shows how sensitive the entire method is to changes.

### 4.5.3 Comparison with Empirical Corrections

During the experiment empirical wall interference corrections were applied to the force and moment. The correction applied to the force and moment coefficients is the so called “body-alone” correction [17]. This correction addresses the wall induced pressure gradient which has a buoyancy effect on the model. These body-alone corrections were carried out for all Mach numbers but only at angles of attack equal to zero. Therefore only the baseline corrections for cases with zero angle of attack (case 1 and case 9) will compared.
4.5 Baseline Results

Table 13: Empirical corrections versus Baseline corrections

<table>
<thead>
<tr>
<th>M</th>
<th>Baseline α</th>
<th>Baseline ΔC_D</th>
<th>Body-alone ΔC_D</th>
<th>Baseline ΔC_M</th>
<th>Body-alone ΔC_M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.4964</td>
<td>0.215</td>
<td>-0.005</td>
<td>0.005552</td>
<td>-0.00661</td>
</tr>
<tr>
<td>Case 9</td>
<td>0.7821</td>
<td>0</td>
<td>0.000618</td>
<td>0.003539</td>
<td>-0.00718</td>
</tr>
</tbody>
</table>

Table 13 shows few similarities when looking at the lift and pitching moment coefficient. The body alone correction is determined by subtracting a CFD free flow calculation (not the same as the FFS used for this thesis) from the experimental measurements. It can be seen that the lift and pitching moment values do not correspond well. This may be due to the fact that the wing is omitted in the body-alone correction. The drag coefficient values however are much more similar. This was to be expected as the buoyancy effect on the drag is calculated in WIN3VE.

Due to the nature of the different corrections it is hard to draw conclusive conclusions from the comparison. It does however seem that the buoyancy correction on the drag coefficient used in both cases yield similar results.

4.5.4 Comparison with MPS-FFS Values

Another possible point of comparison is to compare the corrections calculated by WIN3VE compared to those calculated for the difference in MPS and FFS. This comparison is also not conclusive due to the fact that the delta values are not for the same conditions. The delta coefficient values from WIN3VE represent the values to go from the MPS to the corrected FFS (FFS + (Δα, ΔM)). While for the CFD simulations the delta values account for the difference between the MPS and FFS case. Since the corrections in Mach number and angle of attack are however not very large, this comparison is still worthwhile, even if only in a qualitative sense.

Table 14: Delta values calculated from MPS-FFS compared to WIN3VE

<table>
<thead>
<tr>
<th>Case</th>
<th>Δα</th>
<th>ΔC_D</th>
<th>ΔC_M</th>
</tr>
</thead>
</table>
| MPS-FFS  
1      | -0.05942 | -0.0056 | -0.0016 | 0.0124          |
| 2      | -0.28011 | -0.0264 | -0.0031 | 0.0151          |
| 9      | -0.09771 | -0.0118 | -0.0005 | 0.0124          |
| 10     | -0.45462 | -0.0549 | -0.0023 | 0.0198          |
| Baseline  
1      | -0.18804 | -0.005 | -0.00661 | 0.001012        |
| 2      | -0.25872 | -0.00686 | -0.00693 | 0.00042        |
| 9      | -0.04506 | 0.000618 | -0.00718 | -0.00062       |
| 10     | -0.38338 | 0.001754 | -0.00917 | -0.00213       |
When comparing the values given in Table 14 to those in Table 11 a few remarks can be made. Firstly, the correlation for cases 1 and 2 is much better than for cases 9 and 10. This may be due to the fact that cases 1 and 2 are at lower Mach numbers. Compressibility effects which are disregarded by WIN3VE may cause the larger differences seen in cases 9 and 10.

These differences in corrections may stem from two different locations: the reference wall induced disturbance velocities calculated by the panel representation, or from the equations used to calculate the corrections. Both of these topics are discussed in section 4.6.

4.6 Comparison of Baseline with CFD

Two different parts of WIN3VE can be evaluated when comparing the Baseline scenario with CFD, namely the wall induced disturbance velocity fields and the corrections. This is because these are the only two calculation steps which are not bypassed using control parameters.

4.6.1 Wall Induced Disturbance Velocity Fields

The wall induced disturbance velocity fields are a direct result of the panel representation used by WIN3VE. Given an input on the boundary (4 in the case WIN3VE, 1 on the top wall, 1 on the bottom wall and 1 on the side wall which is mirrored) the panel representation constructs a velocity field inside the tunnel as explained in section 2.4.7.

Firstly to test that the panel representation was working properly two simple test were carried out. The first was to enter symmetrical input on all walls, which means that both the magnitude and direction are the same on the top and bottom wall. This is shown in Figure 36. The reason for using this input is that the correct output is known, in this case it is expected that the correction to the angle of attack calculated by WIN3VE be zero. This is expected because the doublet strengths in the panel representation will be the same for the top and bottom wall. This will result in the normal component of the wall induced velocity to be zero and therefore the angle of attack correction to be zero. This will therefore be tested for varying tunnel heights.

The corresponding output to the input shown in Figure 36 is given in Figure 37. As expected the correction to the angle of incidence is very small. It is however not exactly zero. This is due to the fact that the panels are not symmetric in streamwise direction with respect to the origin of tunnel coordinates. The correction in dynamic pressure which can also be seen in Figure 37 is not quantitatively
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4.6 Comparison of Baseline with CFD

representative but does give a qualitative impression. That is that as expected the correction drops with increasing tunnel height.

The second considered case was an asymmetric case (Figure 38). Here it can be seen that the input is of the same magnitude but acting in opposite directions on the top and bottom walls. The input on the side was set to zero. This case was again chosen as the expected output is known to have the correction in dynamic pressure, which is solely dependent on the axial component, to be zero.

This was indeed the case as can be seen in Figure 39. The fact that the value is not exactly zero can again be explained by the asymmetry of the panels in the streamwise direction. The same as was said about the dynamic pressure correction for the symmetric case can be said now for the angle of attack correction. The trend is correct in that it is expected for the value to decrease with an increasing tunnel height.
From these two simple cases it can be concluded that the panel representation behaves as expected and/or intended.

The following step is therefore to compare the velocity fields calculated inside the tunnel by WIN3VE to those with CFD. This will be shown for both case 9 and 10 to see the effect of the angle of attack. Two directions will be investigated as two directions are used for the corrections, these are the axial and the normal directions.

Case 9:

The wall induced velocity field in the axial direction for case 9 can be seen for both WIN3VE and CFD in Figure 40.

Figure 40 shows the spanwise and streamwise variation of the axial wall induced disturbance velocity. The spanwise direction is labeled as y, the streamwise as x, and the velocities are represented as colors, The position of the model (shown as the model representation) around y = 0 is also shown. The graphs
are for a z position situated under the wing of the model. This is shown for the WIN3VE baseline case (labeled WIN3VE) and for the CFD simulation procedure (MPS-ETS-FFS) (labeled CFD). Note that this description is valid for all graphs of the same nature shown in this section.

Comparing the colormaps it can be seen that WIN3VE catches the overall trend. That is the variation is going in the right direction. The correlation however stops there. As expected the variation in the WIN3VE velocity field is linear. Gradual changes occur along the length of the tunnel. When looking at the CFD case it can be seen that there are small areas of change particularly close to the model. These are effects which cannot be rendered by the WIN3VE panel presentation. The differences seen in the WIN3VE and CFD cases are the reason for the difference calculated in the corrections shown in Table 14.

When comparing the velocity fields in the normal direction more differences occur. This can be seen in Figure 41. The overall level of the WIN3VE velocity is not far off from the one calculated in the CFD method, however it can clearly be seen that WIN3VE does not capture the complex flow which occurs close to the model. This may seem problematic at first glance as the values used for the corrections are points close to the model. However as stated in section 4.1.3, the complex flow along the model in CFD is not subtracted out as it is not present in the FFS case and therefore cannot be reproduced using WIN3VE.

![Wall induced disturbance velocities in normal direction](image)

**Figure 41:** Wall induced disturbance velocities in normal direction (below the wing, $M = 0.7821$, $\alpha = 0$)

Case 10:

The model inclination in this case will lead to greater differences between WIN3VE and CFD particularly in the normal direction.
4.6 Comparison of Baseline with CFD

For the axial case this is particularly evident in the wake region behind the wing. This may be due to the fact that WIN3VE neglects the effect of the end plane of the test section (see section 2.4.7). Again the near model effects are missed and the linear behavior of the WIN3VE solution can clearly be perceived. This is again not a fault of the panel representation but of the assumption that the velocity field can be linearized.

When looking at the normal direction the conclusion that the panels cannot accurately represent velocities in directions other than axial is strengthened. This is clearly exhibited in Figure 43. As can clearly be see the magnitude of the WIN3VE compared to the CFD results is completely off. The amount of variation in the field also indicates that the trends which can be seen in the CFD field are not represented in the WIN3VE case. This confirms that the panel strengths do not accurately capture the velocity field in normal direction.
Another conclusion can be drawn when looking at both velocity components (Figure 42 & Figure 43). That is that WIN3VE does not correctly capture variation in spanwise direction. This was to be expected however due to the fact that at the top and bottom wall only one source is present. Representing gradients/variations from a single source in a spanwise direction is difficult. A more suitable approach would perhaps be to add another row of doublets. The same is true for variations in the normal direction. Gradients/variations in that direction will also be hard to replicate due to the single doublet representation.

A possibility for increasing spatial resolution was thought to be to increase the panels used in the panel representation. It was not possible to test this due to the rigidity of the program which requires as input for the panels the pressure tap locations. These locations are read in from the file which is produced from the experimental tests run by the DNW. Changing this file to include more or less pressure taps results in the code throwing an error due to the fact that the entire pre-processing is made solely to work with the file the way it is currently. Nevertheless it is possible to say that increasing the number of panels will most likely not be of much help. This can be derived from the fact that the Cp distribution is very well represented by the 51 points that are currently used. This is shown in Figure 44. In the figure the Cp distribution along the wall from MPS case 10 is shown. The original 51 point distribution is compared to a distribution which includes a total of 200 points. From the figure it can be concluded that increasing the number of panels will not increase the spatial resolution of the panel representation. The 51 points used currently fully capture the Cp distribution meaning an increase in points will not increase the accuracy of the method.

What is true is that the number of panels used in both transverse and normal directions should be increased. This can be seen when looking at the pressure distribution in those directions. It is clear from Figure 45 (for normal directions) and Figure 46 for transverse direction that these curves cannot be reproduced from a single doublet in normal or spanwise position. The obvious downside to this is of course that more pressure measurements are required. It should be noted that increasing the number of panels in those directions would solely increase the accuracy with which the axial component of the wall induced disturbance velocity is calculated. It would not better the resolution of the normal or transverse wall induced disturbance velocities.
4 Results and Analysis

4.6 Comparison of Baseline with CFD

Furthermore there is another clear flaw with this panel representation. This can be seen when considering the hypothetical case in which the only disturbance velocities present are in normal direction. This situation is shown in Figure 47. This hypothetical input would lead to the panel representation calculating zeroes everywhere within in the tunnel. This would of course be wrong. The panel representation is therefore overly dependent on the axial direction.

Figure 47 is an exaggeration however it can be seen from the CFD simulations that the transverse and normal directions should not be neglected. This can be seen when looking at the magnitude of the disturbance velocities in those directions. Examining Figure 48 reveals that the magnitude of the normal and transverse velocities is in fact just as large as the axial component. Therefore not properly accounting for them is a major weakness of this method.

Figure 45: Cp distribution along the side wall in normal direction

Figure 46: Spanwise Cp variation
4.6 Comparison of Baseline with CFD

4.6.1.1 Effect of the peniche

This difference in pressure distribution shown in Figure 31 also translates to a difference in the wall induced disturbance velocity field. This is shown in Figure 49 which compares two of these velocity fields.

Figure 47: Hypothetical situation in which all disturbance velocities occur in the normal direction

Figure 48: Magnitude of total disturbance velocities in all directions

Figure 49: Effect of the peniche of the Uw fields
4 Results and Analysis

4.6 Comparison of Baseline with CFD

From the figure clear differences in wall induced disturbance velocities can be seen next to the model. This indicates that these effects are solely due to the effect that the peniche has on the free flow as nothing else other than that is different. As the solution is smoother in FFSwP velocity field it can be concluded that this case better represents the wall induced disturbance velocity. This conclusion is drawn because the effects of the peniche should not appear in the wall induced disturbance velocity field as they are not wall effects.

4.6.2 Corrections

Using the CFD values as input it is possible to compare the correction values obtained by WIN3VE. The biggest problem however is to choose a point in the CFD disturbance velocity field which most appropriately matches the point used in WIN3VE. This problem arises due to the fact that in WIN3VE the disturbance velocities used are within the model volume. It is of course not possible to obtain a velocity at the exact same point in the CFD simulations as there the model is solid. The points used for the comparison were therefore extracted at positions close to the points which they were meant to represent. Thusly the quarter chord point was chosen above the actual quarter chord point of the model. The same was done for the three quarter chord point.

The problem that arises however is that there is a spanwise variation of the axial and normal values of the wall induced velocity. This therefore makes difficult it to choose the most appropriate value. This variation is showed at both the quarter chord and three quarter chord location for both axial and normal component of the velocity in Figure 50 for case 9. The third closest point to the fuselage was selected to use in the corrections (middle point in the curves). This point was chosen as it was felt it was sufficient removed from the model.

![Spanwise Uw distribution](image1.png) ![Spanwise Ww distribution](image2.png)

Figure 50: Spanwise distribution of wall induced velocity fields (M = 0.7821, α = 0)

The correction values calculated using the aforementioned CFD values are shown in Table 15, these are compared to the Baseline scenario in Table 16.
4.6 Comparison of Baseline with CFD

Table 15: Corrections using CFD values

<table>
<thead>
<tr>
<th>Case</th>
<th>$M$</th>
<th>$\Delta M$</th>
<th>$\alpha$</th>
<th>$\Delta \alpha$</th>
<th>$\Delta C_L$</th>
<th>$\Delta C_M$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4964</td>
<td>0.003745</td>
<td>0.215</td>
<td>0.15574</td>
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<td>3.214</td>
<td>3.02181</td>
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<td>0</td>
<td>-0.00508</td>
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<td>2.453</td>
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</table>

Table 16: Baseline corrections

<table>
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<th>$\alpha$</th>
<th>$\Delta \alpha$</th>
<th>$\Delta C_L$</th>
<th>$\Delta C_M$</th>
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To make the comparison simpler a graphical representation of the tables is given in Figure 51. In the figure it can be seen that the values which are dependent on the axial velocity component give more closely matched results ($\Delta M$, $\Delta C_L$). As expected from the velocity fields shown in section 4.6.1 the corrections based on the normal velocity component are far apart ($\Delta \alpha$, $\Delta C_M$).

It should again be noted that this comparison can only serve to show trends and not more. This due to the differences between the CFD and WIN3VE solutions as well as the fact that the points used for the corrections are not exactly the same. The only conclusion to be drawn from this is to again state that the panel representation in WIN3VE does a poor job at replicating velocity fields in the normal direction. The spanwise variation of the wall induced disturbance velocities seen in the CFD runs also show that more input may be needed in order to have WIN3VE reproduce those variations.
4.7 Comparison of Baseline with WIN3VE

This chapter will compare the baseline scenario to the WIN3VE results. There are a total of 8 possible combinations combining CFD input and WIN3VE calculations which were given in Table 5. Firstly the results from all the runs will be given. This will be followed by an analysis of the different calculation steps and their effect on the results.

4.7.1 Overall Results

Figure 52 sums up the correction values calculated for all the runs. In the figure the x axis indicates which input was used from CFD. WT are the normal velocities through the slots, UM are the model induced disturbance velocities and UT are the total disturbance velocities. The [-] columns represent the runs during which no bypasses were used. On the other end of the axis the Baseline columns indicate that all the input was from CFD.

When gaging how well WIN3VE does as a whole without CFD input the [-] columns should be compared to those from the Baseline. The corrections calculated for the [-] cases can be seen to differ quite largely from those calculated using the Baseline case. A close look reveals that the higher the Mach number and
4 Results and Analysis

4.7 Comparison of Baseline with WIN3VE

the higher the angle of attack, the worse the [-] case performs. This can be attributed to the fact that these cases comprise more complex/disturbed flow making it harder to linearize.

The different inputs (WT, UM, UT) will now be analyzed individually. This will be done in order to try to identify where their respective strengths and weaknesses stem from.

4.7.2 Normal Velocities (WT)
The values calculated from the [-] WIN3VE (labeled WIN3VE in the figure) case compared to those extracted from CFD (labeled CFD in the figure) are shown in Figure 53. It should be noted that a smoothing is applied to this velocity in order to have it zero when the slots are no longer present. From Figure 53 it can be seen that the assumptions used to calculate these velocities in WIN3VE are not necessarily accurate. As mentioned before this however has little influence on the overall corrections and will not be discussed in greater detail.

From Figure 52 it is evident that the normal velocities through the slots have very little to no influence in the calculations. This can be seen as their contribution does not influence the corrections. This is of course due to how the normal velocity is incorporated in the overall calculation of WIN3VE. Its magnitude is used only in the calculation of the total disturbance velocity. From these results it seems as though it could in fact be completely left out.
4. Results and Analysis

4.7 Comparison of Baseline with WIN3VE

4.7.3 Model Induced Velocities (UM)

Figure 52 shows the big influence that these velocities have on the corrections. It is in fact stated in reference [14] that WIN3VE “stands or falls” depending on model representation. It can also be seen that the model representation used by WIN3VE is rather poor. This is particularly evident when comparing the UT and UT, UM columns. This is essentially a comparison of the model representation compared to the CFD free flow case.

This means that the singularities used to represent the model in WIN3VE do not match those calculated in the CFD FFS. A comparison of the disturbance velocities at the centerline of the tunnel walls, which is used for input, can be seen in Figure 54. The overall trend seems to be captured by the model representation as the shape of the curves resemble those extracted from the CFD FFS case especially for the side and bottom wall. The magnitude is not well replicated along all three walls.

These differences may indicate the model representation is not properly set up. The tweaking of the model representation could lead to better results. As a simple test the number of singularities used to represent the fuselage of the aircraft was varied to see the effect that this would have on the velocities calculated. Two other configurations were considered, a 10 point model and a 30 point model for the fuselage. The results of these variations is shown in Figure 55. From the figure it can be seen that simply adding more sources to mimic the model fuselage does not necessarily lead to better results as the 30 point model is not closer to the CFD line. The conclusion which can be drawn from this is that simply adding more singularities to the fuselage will not make for a better model representation. Perhaps a better approach would be to use different singularities or adjust their strengths to better represent the model in the far field.
4 Results and Analysis

4.7 Comparison of Baseline with WIN3VE

Figure 54: Model induced velocities along the walls (Case 2, $M = 0.4973$, $\alpha = 3.214$)
4.7 Comparison of Baseline with WIN3VE

4.7.4 Total Disturbance Velocities

Like with the model induced disturbance velocities the total disturbance velocities are seen to have a big effect in Figure 52. This indicates that WIN3VE is not carrying out this calculation very well. In order to understand the reason for this the calculation step (equation (4.1)) used to calculate this velocity in WIN3VE is studied.

\[
    u_T = \sqrt{\frac{1 - 5 \left(1 + 0.7 \cdot \frac{M^2_{ref} \cdot C_{PC}^2}{M^2_{ref}}\right)^2 - 1}{M^2_{ref}}} - 1 \quad (4.1)
\]

The way that this equation is tested is by supplying it with \(C_p\) values from a CFD case as well as transverse and normal velocities (labeled WIN3VE in Figure 56). The result is then compared to the known axial component also from the CFD (labeled CFD in Figure 56).
4.7 Comparison of Baseline with WIN3VE

The result of the substitution can be seen in Figure 56. From the figure it can be seen that the formula used to derive UT from Cp is not accurate as it differs from the CFD values. These differences may seem small, approximately 0.005, but that is approximately the order of magnitude of the wall induced velocities. This means that a small error in UT may potentially lead to a big error in the corrections. This is confirmed by the behavior that is observed in Figure 52.

One of the reasons for this difference was thought to be the fact that WIN3VE sets the transverse component of the velocity to zero and uses the estimated normal velocities through the wall for the normal component. From the CFD simulations it is known that both of those estimations are incorrect. That is why in Figure 56 the actual velocities from the CFD simulations were used. Even using these the axial total disturbance velocity was not correctly replicated.

Another possible reason for the difference seen in Figure 56 could be related to the size of the paneled test section. It is mentioned in reference [13] that measure boundary condition methods will only work if the paneled test section is of sufficient size. If this is not the case the influence of the front and back plane of the paneled may be too large to neglect. It may be the influence of these planes that is seen in the figure.
5 Conclusions

The conclusions drawn from the analysis will be evaluated using the research questions as reference. It is also important to distinguish between strengths and weaknesses of the method and the tool. Conclusions will also be drawn regarding the CFD procedure used to obtain input for WIN3VE.

5.1 Strengths and Weaknesses

What are the strengths and weaknesses of WIN3VE?

Before addressing the strengths and weaknesses of the actual code, these will be discussed for the method that it employs, the one-variable measure boundary method. This is done as these set the limits for what the code can achieve. This then aims to avoid attributing weaknesses to the code which are in fact inherent to the method it employs. The strengths and weaknesses of WIN3VE will be evaluated using quality as the main criteria. The quality criteria is based on how well WIN3VE reproduces the results calculated using the CFD procedure. Further remarks will then be made which do not directly fall under the quality criteria.

One-Variable Measured Boundary Method:

Strengths:

- Simplicity- One of the reasons that this method is used is that it is simple. The assumptions made, such that all three components of the wall induced velocity can be calculated using only the axial component as input, considerably simplify the problem at hand.

- Measurements- This method requires a relatively low amount of measurements. The measurements should accurately describe the behavior of the pressure distribution along the walls. Since in general flow close to the wall is less disturbed this tends to lead to a small number of pressure measurements being required. This was shown to be true for low Mach numbers. The validity of this for higher Mach numbers is not as clear.

Weaknesses:

- Superposition- This method uses the principle of superposition to subtract disturbance effects from the total disturbance in order to calculate wall induced effects. The problem with this is that there are phenomena present in the flow which cannot be linearized and therefore are not accurately depicted when using the superposition principle. An example of this would be vortices emanating from the tip of the wing. Depending on the size of the model these vortices may be close enough to the wall to where their influence should be taken into account.

- Model Representation- The use of a model representation is not ideal. This system leads to uncertainties which stem from the determining the strength of the singularities used to represent the model [5].
5 Conclusions

5.2 Cause for Weaknesses

- Incorporation of transverse and normal velocities- This weakness is twofold. Firstly these velocities are ignored when calculating the doublet strengths. The equation used for calculating the input for the panel strengths (equation (4.1)) is not influenced by these values. Secondly the panel representation does a poor job at calculating disturbance velocities in these directions. This is of course linked to the fact that they are not taken into account as input and that no more than one doublet per wall is present in those directions. This weakness was already identified, as in reference [14] it is stated that this process does not allow for spanwise variations to be accurately modeled.

WIN3VE:

Strengths:

- Panel representation- This part of the code works well in that it accomplishes what it is meant to do. This has been tested by using simplified and actual data and it has been shown that the panel representation delivers what is expected of it. It uses input, which it has received on the tunnel boundary, to calculate corresponding velocities inside the tunnel. It is believed that this done to the best of its ability given the number and character of the inputs. It has also been shown that increasing the number of panels in streamwise direction would not make it better.

Weaknesses:

- Calculation of axial disturbance velocity from Cp- It has been shown that this process in WIN3VE is not sufficiently accurate. When applying the formula to the MPS case the same velocities as those present in the CFD simulation were not calculated. This is a crucial weakness as it was showed that the error in the formulation is of the same magnitude as the wall induced disturbance velocities which in the end the code is made to replicate.

As a concluding remark it can be stated that the panel representation used by WIN3VE performs fairly well within the limits that are set by the method which it uses. This is however not the case for the model representation. The size of the corrections calculated by the program however indicate that this method may be too simplistic or that the accumulation of mistakes made in all the different calculation steps leads to a significant difference in the end. It should also be kept in mind that the magnitude of the disturbance velocities which are desired is small. This means that the accuracy of the various calculation steps as well as the input needs to be high.

5.2 Cause for Weaknesses

Where do the weaknesses come from?

- Axial total disturbance velocities- The difference between the calculated and actual total disturbance velocities may be due to the fact that the front/ rear planes of the wind tunnel are neglected. Their contribution may be the difference seen in Figure 56. This weakness was
discussed in both references [6] and [11]. This may be particularly true in this case as the length of the paneled section is relatively short.

- Transverse and normal velocity determination- In order to better calculate these in any position inside the tunnel a different panel representation would have to be used. Instead of solely using one panel in in transverse and normal direction more panels would have to be used. Reference [10] states that accuracy when determining wall interference effects with a panel code is dependent on the number of panels used. It is clear that only using one doublet in transverse and normal direction will not be sufficient to predict wall induced velocities in those directions.

5.3 CFD Input

In conclusion the following can be said about using the CFD as input/ comparison. The complex flow present in the CFD calculation will be in the regions close to the model. At the position where the data is extracted for use in WIN3VE these effects should not have a great influence. It is therefore deemed that the CFD simulations serve as suitable input and comparison as long as the points of comparison/input are far enough removed from the model. With regards to the peniche it is believed that this component will have an effect on the overall outcome of the calculations. As in WIN3VE the peniche was omitted it is important for this effect to also be removed from the CFD simulations. Therefore for a more accurate results the FFSwP should be used instead of the FFS.

5.4 Further Remarks

A few more conclusion about the code can be drawn which are not directly related to the quality of the code.

- Length of the paneled test section- It may be that the axial wall induced disturbance velocity from the front and back planes of the wind tunnel is significant and cannot be neglected as it is currently done in WIN3VE. This was indicated as a possible problem in reference [11]. As a reference the ANTARES code by NASA, which is a similar panel method, uses a paneled wind tunnel length for fullspan models equal to eight times the width [10]. Since a half model is larger it can be estimated that an even larger paneled tunnel length would be required.

- Ease of use- The program is fairly easy to use. Given the necessary input little knowledge of programming is required to obtain results from the code. The validity of these results are of course subject to the input.

- Rigidity- This is one of the major drawbacks of the code in its current state. It is only meant to work for a certain input.

- Structure- The structure of the program is also complex. This is due to the fact that pre and post processing operations are not built directly into the program but are carried out from
elsewhere. The fact the that code is run in one environment but using two separate programming languages (FORTRAN, PV-WAVE) can also be confusing.

- Time- The end goal is for this process to take place online in order to have the wall corrections directly applied. The way in which the code is set up currently it takes approximately 30 seconds to obtain corrections for a single point. This is too slow considering that the rate at which an alpha sweep is carried out in the HST is approximately 0.2 degrees per second.
6 Recommendations

The recommendations stem from difficulties encountered during the process of reaching the results presented in this report.

6.1 Continuation

The flaws of one variable measured boundary condition methods and of WIN3VE currently outweigh the strengths. Improvements could certainly be carried out on WIN3VE but the limitations of the method will persist. The incapability of the method to calculate normal wall induced disturbance velocities is a major drawback. Further research into wall interference should certainly be carried out in order to produce more accurate measurements in the HST. However these should focus on other methods, such as two variable measured boundary condition methods (see reference [5]).

6.2 Process/Input

- CFD input- CFD simulations are great in that they provide a lot of data. However many steps need to be taken in order to be sure that this data can be properly used by WIN3VE. Before starting to use the program it is important to understand in what format and how the data needs to be input. Furthermore when making a change in the CFD input it is of great importance to ensure that all the corresponding changes are made in WIN3VE. Book keeping and organization are therefore key.

- FFS vs FFSwP- As the peniche is included in the MPS model it is recommended to use the FFSwP case for the model induced disturbance velocities. This was not done here as the data was not available for all cases analyzed. However the results with the peniche show smoother axial disturbance velocity fields (see 4.1.2.1). This would therefore indicate that using the FFSwP leads to the cancellation of the peniche effects.

- Second CFD procedure- In order to compare results and the validity of the CFD input method employed here the second method given in reference [8] could be tried. This could help shed light on where if any errors arise when utilizing the CFD input process used here. The second approach which was not chosen, was based on an iterative process aimed at altering the FFS until the same lift as in the MPS case was achieved. This iterative process is most likely why the process was not chosen, as CFD calculations can be both time consuming as well as costly.

6.3 WIN3VE

- Results- To better the results a greater number of panels would have to be used in transverse and normal direction. At the moment as only one is used in those directions the results are far to inaccurate. The downside of this is that since a pressure distribution needs to be given for each of the panels, in order to calculate the corresponding panel strength, extra measurements would be required. Determining how many extra panels would be necessary can be established by looking at the pressure distribution variation in both directions. The number of panels
6 Recommendations

6.3 WIN3VE

requires is then equal to the number of pressure taps it would take to accurately define the pressure distribution. It was also suggested in reference [16] that the influence of the top and bottom walls is very large compared to that of the side wall due to the fact that the width of the tunnel is doubled but not the height. The effect of this may be an interesting investigation.

- Model representation- The model representation was not given as a weak point of WIN3VE as it is inherent to one variable measured boundary condition methods. However it can be said that a more detailed representation could be implemented. For the transonic region a “transonic” doublet such as the one described in reference [15] may be considered. This doublet has yielded satisfactory results for two dimensional flows and could perhaps be used in this case.

- Operation of the program- Changes to the source code or pre/post processing can be made. However the consequences of these changes can important due to the nature of the magnitudes involved. Keeping a unchanged copy of the code is therefore recommended.
7 References

[18] - (-). High speed wind tunnel (HST) user guide. NLR
[19] - (-). Description of the capabilities of the DNW high speed wind tunnel. DNW-HST
Appendix A  Model Details

All figures in this section are from reference [6].

Figure 57: Side view of model
Figure 58: Top view of model
Figure 59: Front view of model
### Appendix B

**Pressure Tap and Panel Centroid Locations**

#### Table 17: Streamwise position of the pressure taps and panel centroids

<table>
<thead>
<tr>
<th>Pressure Tap [m]</th>
<th>Panel Centroids [m]</th>
<th>Pressure Tap (Continued) [m]</th>
<th>Panel Centroids (Continued) [m]</th>
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<td>-0.2</td>
<td>-0.15</td>
<td>2.3</td>
<td>2.35</td>
</tr>
<tr>
<td>-0.1</td>
<td>-0.05</td>
<td>2.4</td>
<td>2.43</td>
</tr>
<tr>
<td>0</td>
<td>0.05</td>
<td>2.46</td>
<td>2.47</td>
</tr>
<tr>
<td>0.1</td>
<td>0.15</td>
<td>2.49</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.53</td>
<td>2.55</td>
</tr>
</tbody>
</table>
Appendix C  Singularities

C.1 Source/sink flow
Source flow is characterized by flow which emanates from an origin with velocity inversely varying with distance. The opposite, where streamlines are all heading towards one point is sink flow. In both cases the streamlines are straight. This is illustrated in Figure 60.

![Source and sink flow](image)

**Figure 60: Source and sink flow**

For two dimensional, incompressible flow the divergence of the velocity is zero at all points of the flow except for at the origin where it is infinity. Source flow is also irrotational throughout. The radial velocity and tangential velocities which stem from a source are:

\[ V_r = \frac{\Lambda}{2\pi r}, \quad V_\theta = 0 \]

where \( \Lambda \) is the source strength and \( r \) the radial distance from the origin. If \( \Lambda \) is positive then a source is present, while if it is negative a sink is present. The streamlines for the flow can then be calculated by using:

\[ \frac{1}{r} \frac{\partial \psi}{\partial \theta} = V_r, \quad -\frac{\partial \psi}{\partial r} = V_\theta \]

This then leads to:

\[ \psi = \frac{\Lambda}{2\pi} \theta \]

where \( \theta \) is the angle of rotation. It should be noted that both equations above are given in polar coordinates.
In WIN3VE these sources can be input in order to model a particular feature. This can be done by specifying both the coordinates of the desired source as well as its strength. This can however only be introduced along a line in the plane of symmetry.

**C.2 Source distribution**

This flow is a collection of point sources which have been discussed previously. This is used in WIN3VE to model the fuselage of the model. It is to be defined along the tunnel axis and the corresponding cross sectional area of the model must also be supplied. From the desired cross section area the code will assign the correct required strength.

**C.3 Source Dipole/Doublet flow**

This type of flow arises from the coupling of a source and a sink. The flow which emanates from a discrete doublet is shown in Figure 61.

![Figure 61: Source dipole](image)

This type of singularity is used to simulate model volume in the tunnel. In WIN3VE either the desired volume or the required strength can be entered in order to represent said volume in the tunnel. The radial and tangential velocities for a doublet flow are equal to:

\[ V_r = -\frac{\kappa \cos\theta}{2\pi r^2} \quad V_\theta = -\frac{\kappa \sin\theta}{2\pi r^2} \]

The streamlines for such a flow, using the same equation as that given for the point source:

\[ \psi = -\frac{\kappa \sin\theta}{2\pi r} \]

where \( \kappa \) is the strength of the doublet and is defined as \( \kappa \equiv lA \), in which \( l \) is the distance between the source and the sink.
C.4 Vortex flow
This flow is characterized by streamlines of concentric circles around an origin. Along this circular streamline the velocity is constant. However the velocity does vary from circle to circle inversely to the distance from the concentric origin. A vortex flow is depicted in Figure 62.

![Figure 62: Vortex flow](image)

For this flow the divergence of the velocity is zero at all points. The flow is irrotational at all points except the for at the origin. The radial and tangential velocities in a vortex flow are:

\[ V_r = 0 \quad V_\theta = -\frac{\Gamma}{2\pi r} \]

From these velocities the streamlines can be calculated to be:

\[ \psi = \frac{\Gamma}{2\pi} \ln r \]

In WIN3VE the coordinates of the vortex need to be entered. The strength of the vortex is then based on the input lift coefficient.

C.5 Dipole Vortex flow
This sort of flow is similar to vortex flow. The difference is however that the vortex dipole comprises of only two lines which are symmetric about the plane of symmetry of the tunnel. The strength of this singularity is based on not only the lift coefficient but on the pitching moment coefficient as well.

The superposition of a combination of these singularity elements allows for the shape of the aircraft to be created mathematically. The shape of the body is defined by a boundary where the streamlines are equal to zero.

\[ \psi = 0 \]
Figure 63 shows the reconstruction of the model representation for the considered case. The fuselage is made using a source distribution, which appears in blue in the figure. The wings and their assorted lift are modeled via the use of vortex lines and are represented by black lines in the Figure 63.

Figure 63: Dipole vortex in the case of WIN3VE
Appendix D  Corrections

The parameters here are the building blocks of the corrections carried out in WIN3VE. This means that they are used in order to approximate the corrections to force and moment coefficients and corrections to flow conditions.

**Blockage Factor $\varepsilon$**

In WIN3VE the blockage factor is approximated using the axial wall induced velocity at the quarter chord position.

$$\varepsilon = \frac{u_{\frac{w}{4}}}{u}$$

**Angle of Attack $\alpha$**

The correction applied to the angle of attack is based on the normal wall induced velocity at the $\frac{3}{4}$ chord position.

$$\Delta \alpha = \frac{180}{\pi} \cdot w_{\frac{3}{4}}$$

With the corrected angle of attack therefore being calculated using:

$$\alpha_c = \alpha_f + \Delta \alpha$$

**Mach Number $M$**

The corrected Mach number is calculated using the reference Mach number and the blockage factor.

$$Ma_c = Ma_{REF} \cdot \left[1 + (1 + 0.2 \cdot Ma_{REF}^2) \cdot \varepsilon \right]$$

**Dynamic Pressure $Q$**

The corrected dynamic pressure is a function of the measured dynamic pressure, the reference Mach number and the blockage factor.

$$Q_c = Q_f \cdot \left[1 + (2 - Ma_{REF}^2) \cdot \varepsilon \right]$$

The ratio of the dynamic pressures $\frac{Q_c}{Q_f}$ is used as a correction factor in the force and moment coefficient calculations.
Reynolds Number Re

The corrected Reynolds number is a function of the uncorrected Reynolds number, the reference Mach number and the blockage factor.

\[ \text{Re}_c = \text{Re}_T \cdot [1 + (1 - 0.7 \cdot \text{Ma}^2_{\text{REF}}) \cdot \varepsilon] \]

Lift Coefficient \( C_L \)

The corrected lift coefficient in WIN3VE is defined by the following equation:

\[ C_{L,c} = (C_{L,T} + \Delta C_L) \cdot \frac{Q_T}{Q_c} \]

Where for this particular case \( \Delta C_L \) is equal to zero because there is no horizontal tail on the model.

\[ \Delta C_L = (\Delta \alpha - \Delta \alpha_H) \cdot 0.1 \cdot \frac{A_H}{A_H + 2} \cdot \frac{CH \cdot SH}{C_{\text{MEAN}} \cdot SW} \]

Where \( A_H \) is the aspect ratio, \( CH \) is the mean aerodynamic chord and \( SH \) is the half span, all of the horizontal stabilizer. \( \Delta \alpha_H \) is the correction applied to the angle of attack due to the horizontal stabilizer and is therefore also zero. This means that the sole correction carried out on the measure lift coefficient is only dependent on the dynamic pressure ratio.

Drag Coefficient \( C_D \)

The corrected drag coefficient in WIN3VE is calculated as follows:

\[ C_{D,c} = (C_{D,T} + \Delta C_{D,I} + \Delta C_{D,B}) \cdot \frac{Q_T}{Q_c} \]

Where \( \Delta C_{D,I} \) is the induced drag correction,

\[ \Delta C_{D,I} = C_{L,T} \cdot \frac{w_{\text{wall}}}{A_c} \]

and \( \Delta C_{D,B} \) is the buoyancy drag correction.

\[ \Delta C_{D,B} = -\sum_{i=1}^{N-1} [(S'_F)_i + (S'_F)_{i+1}] \cdot [(u_F)_{i+1} - (u_F)_i] \]

\( u_F \) is the wall induced disturbance velocity along the centerline of the fuselage and \( S'_F \) is the cross sectional area of the fuselage.
Pitching Moment Coefficient $C_M$

The corrected pitching moment is calculated as follows in WIN3VE.

$$C_{M,c} = \left( C_{M,T} + \Delta C_{M,C} + \Delta C_{M,H} \right) \frac{Q_T}{Q_c}$$

$\Delta C_{M,C}$ is the correction applied based on the following:

$$\Delta C_{M,c} = (w_{3/4c} - w_{1/4c}) \cdot \frac{0.25 \cdot \pi}{\beta}$$

Where $\Delta C_{M,H}$ is the correction due to the horizontal tail plane and is therefore zero.
Appendix E: Using the code

There are two different ways to use the code. This can be done remotely using a MATLAB platform, or the code can be used directly on a Linux system. Instructions on how to use the latter option are given reference [6] and therefore will not be repeated here. Instead this chapter will focus on using the code from MATLAB.

Firstly the different programs required and their location will be explained. This will be followed by the different files required for input as well as how to construct these files. Finally the different m-files used and the output from the code will be documented. Please note that this process will only work if the same set up is used. That is to say that WIN3VE is run from a remote computer.

E.1 Programs
The required program list:

On Linux machine:

- PV-Wave- Used to run WIN3VE. Also certain pre/post processing steps are carried out by files in this language.

On Windows machine:

- MATLAB- This is the environment in which all is run. The version used was R2010b.
- Plink- Allows the automatic transfer between the Windows and Linux machines. Free software which can readily be found on the internet.

E.2 Set Up
A certain structure is required in order for the process to function properly. This will be discussed here.

The following folders are required:

- Batch- Contains the batch files which command the file transfer operations. It should also contain the Plink.exe file. Without this file present the transfer processes will not work.
- Filestobesused- This folder should contain folders for all the cases which are to be run in WIN3VE, as well as the TOUT file (standard experimental output of DNW wind tunnels, for more information see reference [12]) composed of the data from all cases. It should also contain an excel file from which the certain parameters need to be read.
- Mfiles- All of the various MATLAB files used during the running of WIN3VE are in this folder. In this folder the excel file with CFD coefficient data should also be present.
- Results- This is the folder in which the results are put after they are retrieved from the Linux machine. These will be organized by date.
- Case#- These folders encompass all the CFD cases that are to be run by WIN3VE. These folders contain the results of the CFD simulations and the data files that have been extracted from them. For cases 1-12 both an MPS and FFS file should be present. The corresponding ETS files are in cases 13-18.
Appendix E

Using the code

The set up on the Linux machine is like the one described in reference [6]. The main difference is that different folders are required for the different points used. As different input information is required on a point basis, the code was modified not to use input for an entire polar but for a point. Therefore one run is carried out for only one point. It is possible to run the program for a polar but only if no CFD input is used. A screen shot of the different set up folders is shown in Figure 64.

![Screenshot of Work folder on Linux machine](image)

Figure 64: Screenshot of Work folder on Linux machine

This set up is needed as the file transfer process uses the Base# folders. The Base# folders contain the information pertaining to that specific case. This means that if the dimensions of the tunnel need to be changed for case 5, this change should be applied in the Base5 folder. The Run<date> folders are the results obtained on the day given by the folder name. They are created by the code automatically. The taring folder contains the files which tare the TOUT file of the MPS case with the data from the ETS case. The Results file contains the results from the Run<date> files which are to be transferred back to the Windows machine.

A flow diagram of the entire process, starting from the experiment all the way to WIN3VE results is given in Figure 65.
E.3 Input/mfiles

Once all necessary folders and programs are in place, all the code needs to run is input. This input needs to be provided in the right format in order to have the code properly run. This section will detail the different functions used to run WIN3VE from MATLAB as well as the input they require.
1. Creation

Description:

The entire process is run from the Creation mfile. A screenshot of this file is shown in Figure 66. This file calls all the other functions needed to get an output from the Linux machine.

Input:

The input required in this mfile control the WIN3VE run.

- **file_transfer** - This Boolean value regulates whether the newly written input data for WIN3VE should be transferred to the Linux machine. A true value does send the data while false does not. Running the program once will create the necessary data files for all cases. All of these files will also be transferred to the Linux machine. So in order to run all 12 cases the files only need to be transferred the first time.

- **ivel** - This is the ivel control parameter. It can be given the value of either 0 or 1:
  
  0: Total disturbance velocities are calculated by WIN3VE.

  1: Total disturbance velocities are input from the file WALLVEL. This file is created in the WALLVELCreation2 function and is detailed in Appendix I.

- **inpum** - This is the inpum control parameter. It can be given the value of either 0 or 1:

  0: Model induced disturbance velocities are calculated by WIN3VE.

  1: Model induced disturbance velocities are input from the file UM_WIN3D. This file is created in the UM_WIN3DCreation function and is detailed in Appendix H.

- **norvel** - This is the norvel control parameter. It can be given the value of either 0 or 1:
Appendix E

Using the code

0: Normal velocities through the slots are calculated by WIN3VE.

1: Normal velocities through the slots are input from the file NORM_VEL. This file is created in the NORMVELCreation function and is detailed in Appendix G.

- ip- This refers to which polar is to be used. This should always be given a value even if point values are used.
- use_point- Boolean value which controls whether a point value or entire polar is to be corrected by WIN3VE. A true value uses a point value, while a false value will use the polar specified by the ip variable.
- point- This is the value of the point to be investigated. It is important to note that since the numbering in PV-Wave starts at 0, this value does not directly relate to a case. As the case indexing starts at 1 the difference between point and case will be 1. For example, point 0 is case 1 and would therefore use the Base1 folder shown in Figure 64.

Process:

As this is the main script it runs through all the necessary functions in order to complete the entire WIN3VE process. This includes the taring of the TOUT files which is carried out as a pre-processing step in PV-WAVE.

2. Taring

This is the first function called by the Creation script is the taring function. This should not be confused with the TOUT file taring. This taring refers to the setting of the reference conditions in the virtual wind tunnel. This function does not require any direct input. Instead it reads files from the Cases folders.

Input:

- Pressure data- Static pressure data from the four pressure taps as well as the pressure from the plenum chamber is read in. This data is extracted from both the MPS and ETS cases. This is done as two different TOUT files are created, one from each case. This data is obtained from .DAT files as well as an excel file. Furthermore the total pressure corresponding to each case is also read in from this excel file. The presence of these files is required for the program to run.
- Force and moment coefficients- The coefficients are read in from an excel file. This file is crucial and without it the code will not run.
- Mach number- The reference Mach number from the experiment is also read in at by this function. It is read in from the same excel file as the total pressure and static pressure in the plenum.

Process:
Like its name indicates this function tares the data. It follows the taring/calibration procedure discussed in section 3.3.1. Several plots can be made during the taring process, these are not normally displayed and have been commented in the code.

Output:

From this function all calibrated values are output such that that can be used in the functions which are called after it. These values are:

- Corrected force and moment coefficients
- Corrected pressure coefficient data (both MPS and ETS)
- Corrected Mach number and dynamic pressure (both MPS and ETS)

3. TOUT Creation

As its name indicates this function will create the necessary TOUT files.

Input:

- Corrected force and moment coefficients
- Corrected pressure coefficient data (both MPS and ETS)
- Corrected Mach number and dynamic pressure (both MPS and ETS)

Process:

This function handles the creation of two TOUT files, one for the MPS and ETS. The ETS TOUT file is use only for taring purposes. The tared MPS TOUT file is used in WIN3VE for multiple reason. Firstly the pressure tap locations are read in from the TOUT file. The pressure distribution along the pressure taps are also read in from the TOUT file. The way in which the TOUT files are created is given in detail in Appendix F.

Output:

The result of this step are the two TOUT files, which are placed in the TOUT folder of the Filestoreused folder. The MPS TOUT file is labeled TOUT036 while the ETS TOUT file is labeled TOUT054.

- TOUT036
- TOUT054

4. NORMVEL Creation

This function creates the NORM_VEL file used for directly inputting the normal velocities through the slots.

Input:
Appendix E

- Mach numbers (Uncalibrated, calibrated)
- Velocities- These velocities are extracted from the MPS. This is done from the Case# folder for the corresponding case.

**Process:**

In order to correctly input the velocities they are nondimensionalized as mentioned in section 3.3.3. Once they have been made ready to be used they are written to the NORM_VEL file. For a more complete description of the NORM_VEL file refer to Appendix G. This file is placed in the appropriate Case# folder in the Filestobeused folder.

**Output:**

- NORM_VEL file (one for each cases)

5. **UM_WIN3DCreation**

This function is responsible for creating the file which is to be used to bypass the model representation in WIN3VE.

**Input:**

- Velocities- These velocities are extracted from the FFS. This is done from the Case# folder for the corresponding case.

**Process:**

In order to create the UM_WIN3D file the model induced velocities are read in from the extracted FFS values. The velocities are manipulated in order to ensure that they are presented to WIN3VE in the correct fashion. For more details on the UM_WIN3D file refer to Appendix H. This file is placed in the appropriate Case# folder in the Filestobeused folder.

**Output:**

- UM_WIN3D file (one for each cases)

6. **WALLVELCreation2**

This is the last function which creates an input file. The input file it creates contains the total disturbance velocities. Note that there are two WALLVELCreation files and that the one discussed here is the second, hence the 2 at the end of the function name.

**Input:**
Appendix E

Using the code

- Velocities - The total disturbance velocities are read in from the Case# folders. They are extracted from the MPS.
- File_transfer - This value is needed in order to know whether the transfer batch file should be run or not.

**Process:**

Like for the other files used to input velocities into WIN3VE the velocities that are read in from extracted CFD data. In this case as the total disturbance velocities are needed these are extracted from the MPS. Once the velocities have been properly calibrated and prepared they are written into the WALLVEL file. This file is then saved in the appropriate Case# folder in the Filestobeused folder. For a more detailed discussion of the WALLVEL file refer to Appendix I. This function as it is the last to be called which constructs an input file also gives the transfer command (depending on the value of file_transfer).

**Output:**

- WALLVEL file (one for each case)

7. **Remote commands**

Once the necessary input files have created and sent to the Linux computer it is this function which actually gives the commands to run WIN3VE.

**Input:**

- ip- Value set in Creation script.
- ivel- Value set in Creation script.
- inpum- Value set in Creation script.
- norvel- Value set in Creation script.
- point- Value set in Creation script.
- use_point- Value set in Creation script.

**Process:**

This function is tasked with setting up all the files required for the WIN3VE run. It does this via a number of batch files which use Plink.exe to give commands to the Linux machine. The first task is to transfer all the files to their correct locations. This is done as described in reference [6]. Once the files are in place the taring procedure is called. The result on this procedure is a tared TOUT file which is transferred to the folder it needs to be in. Once all of the files required are in the right place the command to run WIN3VE is given.

**Output:**

None
Appendix E

8. Finalize

This is the last function called by the Creation script. This function is responsible for retrieving the WIN3VE results. It also closes the command windows which otherwise stay open.

Input:

- point- Value set in the Creation script.
- ivel- Value set in the Creation script.
- inpum- Value set in the Creation script.
- Norvel- Value set in the Creation script.

Process:

This file first creates the necessary folder on the Windows machine. For this is uses the input values specified in the Creation script. It then synchronizes the results folder on the Linux machine with the results folder on the Windows machine.

Output:

- Result files from WIN3VE
Appendix F Creating a TOUT file

In order to input data into WIN3VE with as little change to the source code as possible, it was decided to create TOUT files from the CFD results. This chapter will therefore describe how this was done.

F.1 General information

To begin with the header information is taken from existing TOUT files. This is discussed more in detail below. The same is true for the pressure tap information which is also copied from existing TOUT files. This is also discussed in more detail below. The data required for the creation of the TOUT file was obtained from different sources:

- Pressure measurements- These are extracted from the obtained flow solution in Tecplot via a macro. The data is extracted at the same location as that given in the experimental TOUT files. The macro then creates a text file for all four rows of pressure taps. This text file is then read into MATLAB.
- Run information- This is entered directly in MATLAB. The number of the test is the same as for the experimental TOUT files, therefore NTEST is 9009. The number for polars, NPOL, is started at 3641 and runs until 3645. This means that there are a total of six polars, which represents the point pairs. The point number starts at 3601 and runs until 3612, as there are a total of 12 points.
- Flow conditions- This is read in from the corresponding TOUT files
- Forces and moments- These are read in by MATLAB from an excel sheet. This excel sheet contains the results from all the CFD cases.

Once this data has been input into MATLAB it needs to be pieced together in the correct order. This order is as follows:

1. The run information
2. The flow conditions
3. Forces and moments

The complete set of variables is described in more detail in section F.4.

The arranging of the data is carried out in MATLAB. This is then output in a text file format. The complete TOUT file is then pieced together in gedit. This is done in the following order, first the header information is entered, then the pressure tap information and finally the data set.

F.2 Header information

This information is common to the two TOUT files (tout041.066, tout079.066) that were considered for the experimental simulations. The information is nearly the same for both runs. The only differences between the two are the time, at which the measurement series was started and the run number. Bare these two things all the other information that is provided is the same. Therefore the created TOUT file (tout036.066) uses the same header with the only change being the run number which is changed to 3600.
Appendix F

Creating a TOUT file

F.3 Pressure tap information
This information is the same for all three TOUT files as the tap positions are the same for all three simulations. Therefore for the created TOUT file this was simply copied from one of the experimental TOUT files.

F.4 Data information
The data is split up in rows of ten columns. First comes the a block of 31 variables as can be seen in Table 18.

Table 18: TOUT file header

<table>
<thead>
<tr>
<th>NTEST</th>
<th>NPOL</th>
<th>NDP</th>
<th>MACH</th>
<th>q</th>
<th>P0</th>
<th>P*</th>
<th>P</th>
<th>RE</th>
<th>T0</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA</td>
<td>BETA</td>
<td>CL1</td>
<td>CL3</td>
<td>CD1</td>
<td>CD2</td>
<td>CD3</td>
<td>Cm12</td>
<td>Cm3</td>
<td>Cy12</td>
</tr>
<tr>
<td>Cy3</td>
<td>Cn1</td>
<td>Cn3</td>
<td>CL1</td>
<td>CL2</td>
<td>CL3</td>
<td>CPB</td>
<td>CDB</td>
<td>DCD</td>
<td>ALFC</td>
</tr>
<tr>
<td>MAST</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Not that the values is red are not used by WIN3VE. Only the values that are used by WIN3VE will be discussed here, a description of the other values can be found in [11].

- NTEST- Number of the test. Used for constructing WIN3VE output files.
- NPOL- Number attributed to the different polars present in the TOUT file. Used for constructing WIN3VE output files.
- NDP- Point in the TOUT file. Used for constructing WIN3VE output files.
- MACH- The Mach number for the data point. Used in calculations.
- q- The dynamic pressure for the data point. Used in calculations.
- RE- The Reynolds number for the data point. Used in calculations.
- ALPHA- The angle of attack. Used in calculations.
- CL1- Normal force in model axis system. Used in calculations.
- CL3- Lift in wind axis system. Used in calculations.
- CD1- Tangential force in model axis system. Used in calculations.
- CD3- Drag in wind axis system. Used in calculations.
- Cm3- Pitching moment in wind axis system. Used in calculations.

Other than the values mentioned above, all other values are set to zero as they have no influence on the outcome of the simulation.

This data is then followed by the pressure data for that data point. This is done in the following order: W6000 (62 values), W7000 (62 values), W8000 (53 values) and W9000 (51 values). This therefore means that a total block of data for one data point contains 27 rows, with 40 values comment the first block and 228 values for pressures. The last two values in the last row are padded with zeros in order to ensure that all rows of 10 columns.
Appendix G  Creating Norvel control parameter and NORM_VEL input file

The Norvel control parameter was added in order to add an extra step in the verification process. It is believed that the normal velocity through the slots is a crucial part of the correction process. It was therefore decided that the original source code be amended to include a way to bypass the calculation step of the normal velocities. This bypass then enables CFD data to be input directly. This can be seen in Figure 67. This section will discuss the actual implementation of the control parameter and also how the input file is to be constructed.

![Figure 67: NORVEL schematic](image_url)
Appendix G

Creating Norvel control parameter and NORM_VEL input file

G.1 The control parameter
In order to implement the new control parameter it was necessary not only to include it in the source code but to update the pre and post processing as well. This was done in the same manner as that of the other control parameters already present in the source code. This means that the value of the control parameter can be set in the wall_corrections file. It can be set to two different values:

- 0 – The normal procedure for calculating the normal velocities through the walls is used.
- 1 – The normal velocities are read in from the NORM_VEL file which is to be entered in the same directory as the wall_corrections file.

A more in detail description of the actual changes to the source code and pre and post processing can be found in the XChangesX section.

G.2 The NORM_VEL file
These are the files which contain the CFD normal velocity data. They contain data for only one point which means that it is not appropriate to use them for an entire polar. The program will however run for the entire polar, it will however use the same normal velocity data for all points which is clearly incorrect. The actual construction of the file takes place in MATLAB. The code assembles data from Tecplot files containing the CFD model present data. The output of this assembly can be used directly as input for WIN3VE. The file contains four columns of data all of which have 51 rows. These 51 rows correspond to the 51 pressure tap positions of the tunnel. The format of the file can be seen in Table 19. Please note that these number are not representative of actual data and that two rows of the file are shown.

<table>
<thead>
<tr>
<th>0.0008</th>
<th>0.000</th>
<th>0.0007</th>
<th>0.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0007</td>
<td>0.000</td>
<td>0.0006</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The four different columns have the following data:

- **Column #1-** The first column contains data for the normal velocity through the upper wall of the tunnel.
- **Column #2-** The second contains the data for flow through the right side wall. In the case of the HST these walls are not ventilated leading this entire column to be filled with zeros.
- **Column #3-** The third column is the normal velocity through the bottom wall of the tunnel.
- **Column #4-** The last column should contain the normal velocity through the left wall. Again as the HST has no side ventilation this column is again filled with zeros.
Appendix H  Creating the UM_WIN3VE file

This chapter explains how the UM_WIN3VE file is created before it is used in WIN3VE.

The INPUM parameter is the control parameter for this bypassing step. When activated the calculation of the axial model induced disturbance velocities are no longer calculated in WIN3VE but are entered from the free air CFD run. This is shown in Figure 68.

![INPUM schematic](image)

Figure 68: INPUM schematic
Creating the UM_WIN3VE file

The created UM_WIN3VE file has the format which is shown in Table 20. It should be noted that the data in the table does not consist of actual data and that therefore the table is only representative of the format of the file.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-2.705</td>
<td>0.001</td>
<td>0.005</td>
<td>0.001</td>
</tr>
</tbody>
</table>

This is how the format works:

- **Row 1**: In the first column the number of tap positions that are used should be given. It therefore also indicates how many rows of information will follow. The other columns are padded with zeros in order to make the creation process simpler.
- **Row 2**: This row is the first of a total that is indicated on row 1. Here is a definition of the columns:
  - **Column #1**: This contains the x position of the point along the wall center.
  - **Column #2**: This is the axial model induced disturbance velocity along the top wall centerline. This information is extracted via Tecplot from the free air CFD run.
  - **Column #3**: This is the axial model induced disturbance velocity along the side wall centerline. This information is extracted via Tecplot from the free air CFD run.
  - **Column #4**: This is the axial model induced disturbance velocity along the bottom wall centerline. This information is extracted via Tecplot from the free air CFD run.

The complete file therefore consists of an indicated number of rows. Once the file has been assembled in MATLAB it can be directly entered into WIN3VE.
Appendix I Creating the WALLVEL file

This chapter discusses how the WALLVEL file is assembled before it is entered into WIN3VE.

The IVEL control parameter allows the user to directly input total disturbance velocities into WIN3VE. This bypasses the entire method of mirror images and wall pressure measurements phase of the code. This is illustrated in Figure 69.
Creating the WALLVEL file

The WALLVEL file to be input into the code has the format shown in Table 21. It should be noted that the numbers present in the table are not indicative of the actual data used. They are simply meant to demonstrate the format of the file.

Table 21: WALLVEL format

<table>
<thead>
<tr>
<th>51</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2705</td>
<td>0</td>
<td>895</td>
<td>0.946</td>
<td>-0.00006</td>
<td>0.0008</td>
</tr>
<tr>
<td>2</td>
<td>-2705</td>
<td>-995</td>
<td>0</td>
<td>0.943</td>
<td>0.003</td>
<td>-0.00006</td>
</tr>
<tr>
<td>3</td>
<td>-2705</td>
<td>0</td>
<td>-895</td>
<td>0.987</td>
<td>-0.00007</td>
<td>-0.0008</td>
</tr>
<tr>
<td>-1.76e-05</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Row 1: This row is only entered one time at the beginning of the file. It serves to tell the code how many tap positions are present. This value is entered in the first column, while the other six columns are padded with zeros. These zeros serve no purpose other than simplifying the process of creating the file. They have no influence on the actual running of the code.
- Rows 2 through 4: These rows contain the coordinates of the pressure tap and the corresponding total disturbance velocities. Row two represents the top wall. Row three the side wall and row four the bottom wall. Here is what is in the respective columns of the row:
  - Column #1: This is simply a number sequence which has no bearing on the calculation. Therefore it was chosen to simply label the rows from one to three.
  - Column #2: This is the x-coordinate of the position at which the data needs to be entered. This corresponds to the pressure tap positions from the wind tunnel.
  - Column #3: This is the y-coordinate of the position at which the data needs to be entered. This corresponds to the pressure tap positions from the wind tunnel. In order to ensure that this data is taken from outside the boundary layer present on the wall an offset of 50 mm was taken.
  - Column #4: This is the z-coordinate of the position at which the data needs to be entered. This corresponds to the pressure tap positions from the wind tunnel. In order to ensure that this data is taken from outside the boundary layer present on the wall an offset of 50 mm was taken.
  - Column #5: This is the where the total disturbance velocity along the wall center line in the x direction is entered, \( U_T \), at the specified coordinate location. This data is extracted via Tecplot from the CFD model present run.
  - Column #6: This is the where the total disturbance velocity along the wall center line in the y direction is entered, \( V_T \), at the specified coordinate location. This data is extracted via Tecplot from the CFD model present run.
  - Column #7: This is the where the total disturbance velocity along the wall center line in the z direction is entered, \( W_T \), at the specified coordinate location. This data is extracted via Tecplot from the CFD model present run.
Appendix I

Creating the WALLVEL file

- Row 5: This row contains the derivative of the axial disturbance velocity on the side wall center line. In the code this is calculated as follows:

\[ DUZ = -0.5 \frac{CPM_{W7000} - CPM_{W6000}}{DZ} \]

where \( CPM_{W7000} \) and \( CPM_{W6000} \) are the pressure coefficients from rail W7000 and rail W6000 respectively. \( DZ \) is the distance between the two pressure rails, which is equal to 0.30 m. The pressure coefficients are also extracted from the CFD model present run via Tecplot.

In total the file therefore contains 51 iterations of rows 2 through 5 as explained above. The assembly of the file is carried out in MATLAB script. This script also creates a text file for all 12 cases which are to be considered. These text files can then be used directly as input for WIN3VE.