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AERODYNAMIC DEVELOPMENT OF SAAB FCAS UNMANNED SUPERSONIC COMBAT AIRCRAFT

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Abstract

Within the Saab Future Combat Air System (FCAS) program, the aerodynamic development in early stages of design of a supersonic configuration is performed. With the goal of speeding up the design process, various levels of Computational Fluid Dynamics tools and wind tunnel testing with extensive additive manufacturing techniques, is used. Benchmarking between methodologies is done, showing coherence between computational and experimental results, with a fraction of the cost of typical production wind tunnel testing.

Keywords: Aerodynamics, additive manufacturing, UCAV

1. Introduction

Within the Saab Future Combat Air System (FCAS) program, there is a continuous study of new concepts, and evaluation of their operational effectiveness in different scenarios. For a variety of reasons, some concepts are matured a lot further than others are. One of the concept studies that have reached a higher level of maturity is an unmanned supersonic combat aircraft or “loyal wingman”. This paper is presenting the early stages of the aerodynamic development of this configuration, and the application of computational and experimental tools.

2. The Aerodynamic Design Loop

A typical development project for a new flying platform is shown in Figure 1. The figure shows two parts of the development process, the project initiation phase and the project execution phase. The two parts are divided by a decision point which aims at deciding if the project is going to be executed or not. The aim of the project initiation phase is to collect sufficient information for the project board to make a correct decision. The project execution also means that additional funding has been allocated to the project, while the initiation phase is normally made on a much smaller budget.

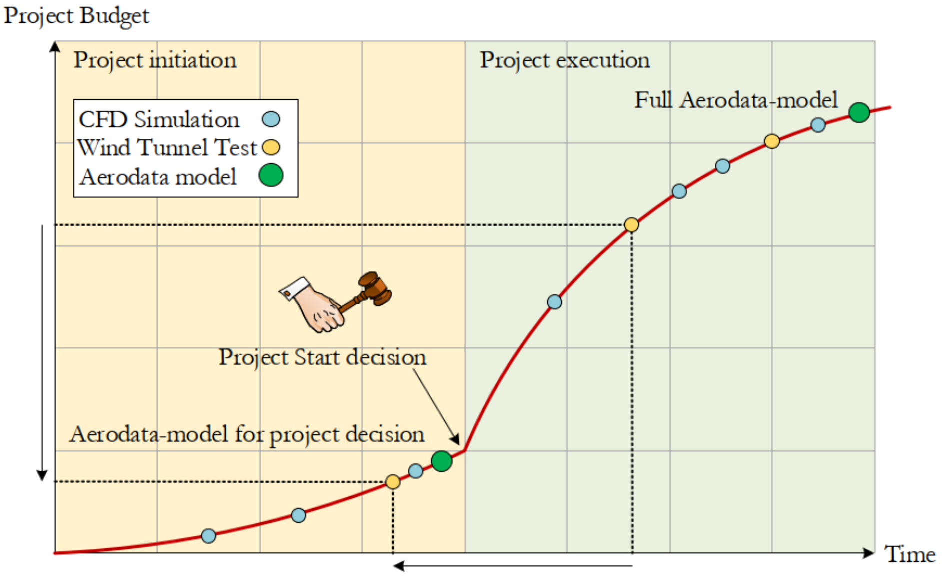

Figure 1: Generic time plan showing the opportunity to feed initial Aerodata-models with "early" WT test data.

An aerodata model is the term used at Saab for the summarized collection of tables describing the impact on the aerodynamic forces and moments for various alterations to the outer shape of the platform. Typical alterations can be e.g. control surface deflections, extended landing gears or carried external stores. There are also tables that describe the interrelations between different simultaneous alterations which will lead to so called “interference effects”.

Figure 1 also visualizes the main project activities undertaken by the aerodynamic department. The main work consist of CFD simulations (blue points), wind tunnel tests (yellow points) and aerodata modeling (green points), where the first two are used to create input to the work with the models. The aerodata models are used for flight mechanical simulations, in either “manned simulators” or desktop simulators, and for flight performance analysis. This is a part of a “large design loop” including design feed-back from these simulations, but in-between aerodata model updates, aerodynamic data will feed a “small design loop” based on static stability and controllability analysis. The smallest time frames for the small loop is “daily”, and is therefore not included in the generic Figure 1.

Historically, wind tunnel testing has been the only technology used as model input, but modern CFD-simulations has grown into an invaluable tool, especially in the project initiation phase, where its lower cost is beneficial. Wind tunnel testing on the other hand has grown gradually more expensive as many wind tunnels have been closed down and the maintenance of the hardware is increasing as tunnels are coming to age. It has come to be that CFD-simulations are used a lot in the project initiation phase, while wind tunnel testing, as shown in Figure 1, has been pushed into the execution phase because of its higher cost.

This paper elaborates on the possibility to use new technology such as additive manufacturing to increase the amount of data available for aerodynamic modeling in the project initiation phase. By decreasing cost and lead-time, wind tunnel testing might be pushed back into the project initiation phase, increasing the quality of aerodynamic models available for project decisions.

3. Tools for Aerodynamic Shaping

Early stages in conceptual design and development are characterized by quick evaluation and feedback to the multi-disciplinary design loop. Another aspect is the large parametric variations that have an expected large effect on the aerodynamics. This will affect the balance between speed and accuracy of the tools used during the design process. Historically the tools have been dominated by extensive wind tunnel testing. Today computing power for CFD and additive manufacturing in wind tunnel model design is affecting this mix of tools, and the strength and weaknesses of the individual technologies has to be benchmarked accordingly.

3.1 CFD – Computational Fluid Dynamics

For CFD the natural evolution of computing power over the years is increasing computational efforts to the left side in Figure 1. Different levels of modelled physics is also applied depending of type of flow case and required accuracy. The level of physical representation and accuracy from different aspects has to be validated in some way. The industrial application of CFD today typically ranges between Euler, RANS (Reynolds Averaged Navier Stokes), URANS (Unsteady Reynolds Averaged Navier Stokes) and different types of turbulence resolving LES (Large Eddy Simulation)[3].

3.2 WTT – Wind Tunnel Test

Wind Tunnel testing methodology has not changed substantially over the years and typical wind tunnel tests used for shaping a supersonic aircraft involve low-speed and high-speed wind tunnel entries using dedicated models.

Low speed testing is generally less expensive and more suitable for a highly modular wind tunnel model. Very high angle of attack testing and testing of take-off and landing configuration including landing gear and ground effects, is performed in low speed wind tunnels. The possibilities for rapid prototyping in model manufacturing is large, and utilized to the limit in this project, in order to increase experimental efforts to the left side of Figure 1. High speed testing is generally more expensive with higher requirement on model structural rigidity and therefore less suitable for configuration studies. High speed covers testing in the complete Mach number regime of the aircraft, including supersonic speeds if needed. High speed testing is still a work horse in aerodata model buildup, and used in later stages of development.

4. Shaping of the Loyal Wingman Concept

The total effort that has lead up to the results in this paper includes multidisciplinary work important for the shaping, but outside the scope of this paper. Some examples are engine inlet design and internal weapon bay, which requires advanced CFD methods (e.g. RANS-LES), and radar signature analysis, structural layout, internal packing and flight mechanical analysis based on the aerodynamic data.

The focus of this paper are the longitudinal effects described by the normal force coefficient C_N and the pitch moment coefficient C_m. The lateral and directional coefficients have also been part of the design activities but are not presented here.

The Saab Loyal Wingman concept is designed to a requirement profile with focus on low radar signature, high speed and beyond visual range air-to-air missions. This requires low supersonic drag and internal weapon bays, which is somewhat opposed since low supersonic drag is accomplished with a slender layout, and internal weapon bays typically result in the opposite.

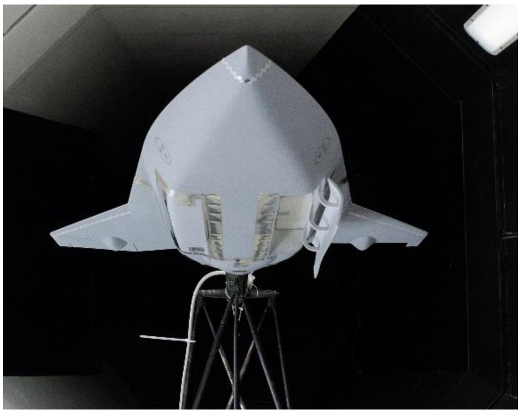

Figure 2: Wind tunnel model with open weapon bay.

The internal layout and packing of the configuration is directly affecting the possibility of slenderness, and a beneficial cross-sectional area distribution. Figure 3 shows a supersonic area rule analysis, compared to an optimum Sears-Haack[1] area distribution. The larger subsystems like weapon bays, engine and landing gear is positioned to give the configuration potential for low supersonic drag.

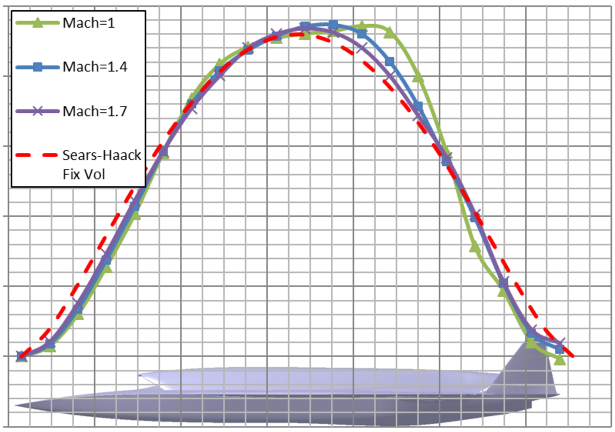

Figure 3: Cross sectional area distribution.

The challenges of supersonic aircraft design is only to a small part directly related to the supersonic drag. Other effects that that need to be taken into account are:

- Stability and controllability at supersonic speed, and its effect on hinge moments.
- Subsonic stability and controllability, and its effect on lift and drag.

The above points might seem disconnected from supersonic drag, but through early wing sizing, all requirements and aerodynamic properties that affect wing size will affect supersonic drag[2]. For example:

- Low aerodynamic efficiency of the wing, even at low speed, leads to a large wing and higher supersonic drag.
- Poor high angle of attack stability and controllability, limiting the aft most center of gravity, will force the design to be overly stable, resulting in reduced lift and increased drag i.e. low aerodynamic efficiency. On top of that, an overly stable design drives supersonic hinge moments.

The aerodynamic design process has included a number of wing design studies with a focus on the wing planform, but also to a smaller extent the double fin layout. The evolution is shown in Figure 4 starting with large variations at the lower part of the figure and gradually refined shapes towards the top of the figure. Shape evolution that can be seen between the different baselines is driven by more than aerodynamic considerations like radar signature, structural layout and internal packing. Although lateral/directional stability and controllability is a consideration, the longitudinal properties are more limiting to the flight envelope for this configuration, and are therefore in focus for this presentation.

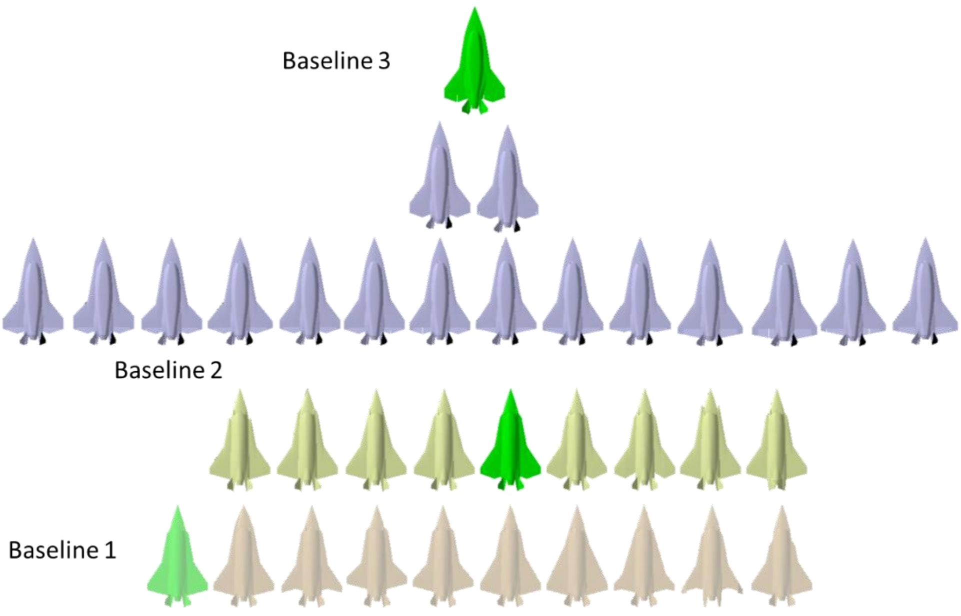

Figure 4: Overall configuration evolution and planform studies.

The last step before the freeze of baseline 3, in Figure 4, is an evaluation of wing position effect on neutral point, done in parallel with wing position effect on center of gravity. This neutral point/center-of-gravity management ensures the balance of the vehicle, and is repeated and refined during the development with maturing weights of subsystems, flight control law design and so on.

4.1 CFD Simulations

The computational meshes are generated according to Saab best practices which have been evaluated and validated in previous projects. No major mesh dependency studies are carried out for each design iteration in this project. The mesh is unstructured with a combination of prismatic and tetrahedral elements. In cases where both Navier-Stokes and Euler computations have been made, the surface mesh is identical and the difference is the inflated prism layers in order to capture the boundary layer. A typical Euler mesh for this geometry contains ~7 million nodes while a typical Navier-Stokes mesh contains ~40 million nodes. Figure 5 shows a typical surface mesh.

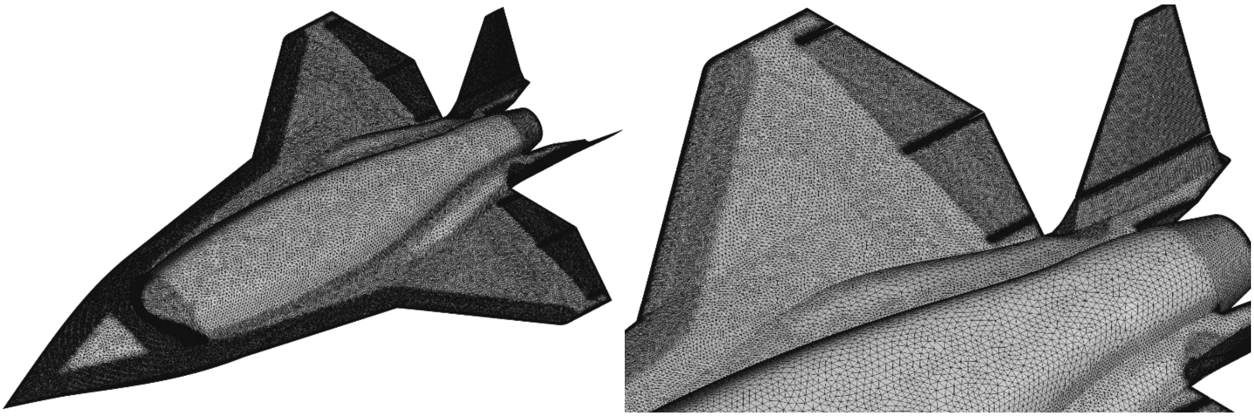

Figure 5: Unstructured surface mesh with refinements around wing edges and control surfaces.

The RANS simulations are run using the M-Edge solver[3] [4] with the Spalart-Allmaras turbulence model until semi-stationary convergence is reached, and then for another couple of thousand iterations for data collection and averaging of results. Post-processing of results is mainly done in Matlab (plotting of aerodynamic coefficients) and Ensight (flow visualization).

One important reason for choosing a double delta wing layout for a supersonic design is that this kind of planform is associated with a low neutral point travel, when going from subsonic to supersonic speeds. One challenge with double outward tilted fins, popular on modern stealth fighter designs, is a risk of destabilizing effect at high angle of attack. The vortex system built up by stealth forebodies, inlets, canards, wings and other lifting surfaces upstream from the fins, are creating an outboard flow around the fins. This leads to a negative lift on fins and aftbody, with a resulting pitch-up. This has been studied and included in the overall shape evolution, by analyzing the configurations with and without fins both in the wind tunnel and in CFD. Flow fields from CFD are also used for visualization of the fins local angle of attack, as presented in Figure 6 where one can see the vortex core spinning counter-clockwise (looking from behind). Adjusting for the angle of the tail, the effect of the vortex on local angle of attack is clearly seen. As global angle of attack increases, the fins are more and more located in a field of negative local angle of attack.

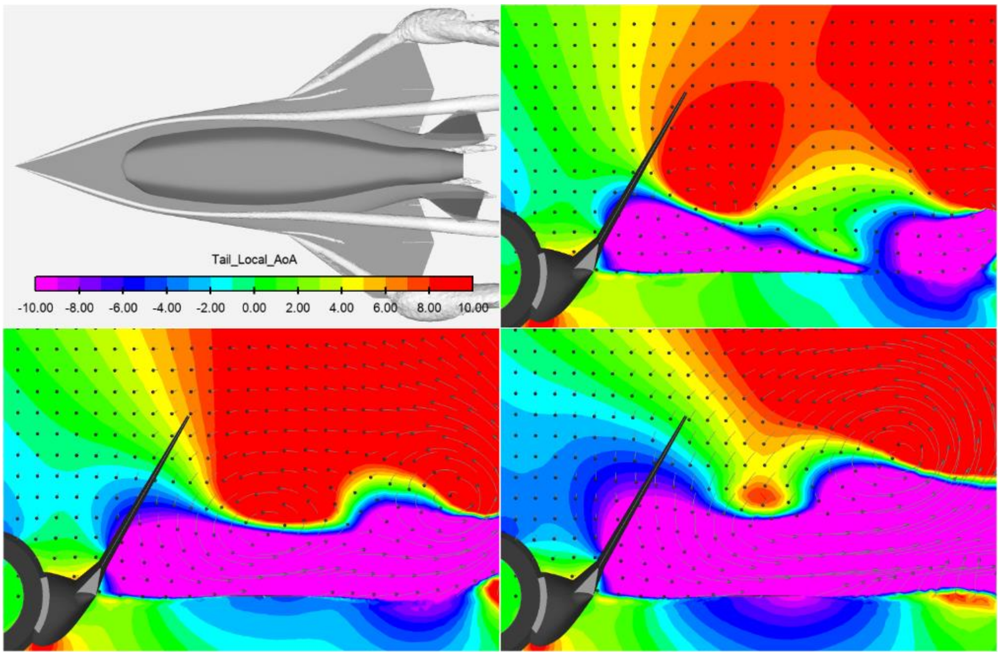

Figure 6: Flow direction evaluated in CFD, as tail (or fin) angle of attack in a plane in front of the fin. The three visualized examples are of increasing global angle of attack which affects the position and strength of the vortex cores, and in turn the local angle of attack.

During the design process, early and quick Euler CFD analysis have gradually moved to Navier-Stokes CFD, with a reduction in productivity but with better physical representation. Figure 7 is showing pitch stability results from Navier-Stokes (top plots) and Euler (bottom plots), from low Mach (left) to high Mach (right).

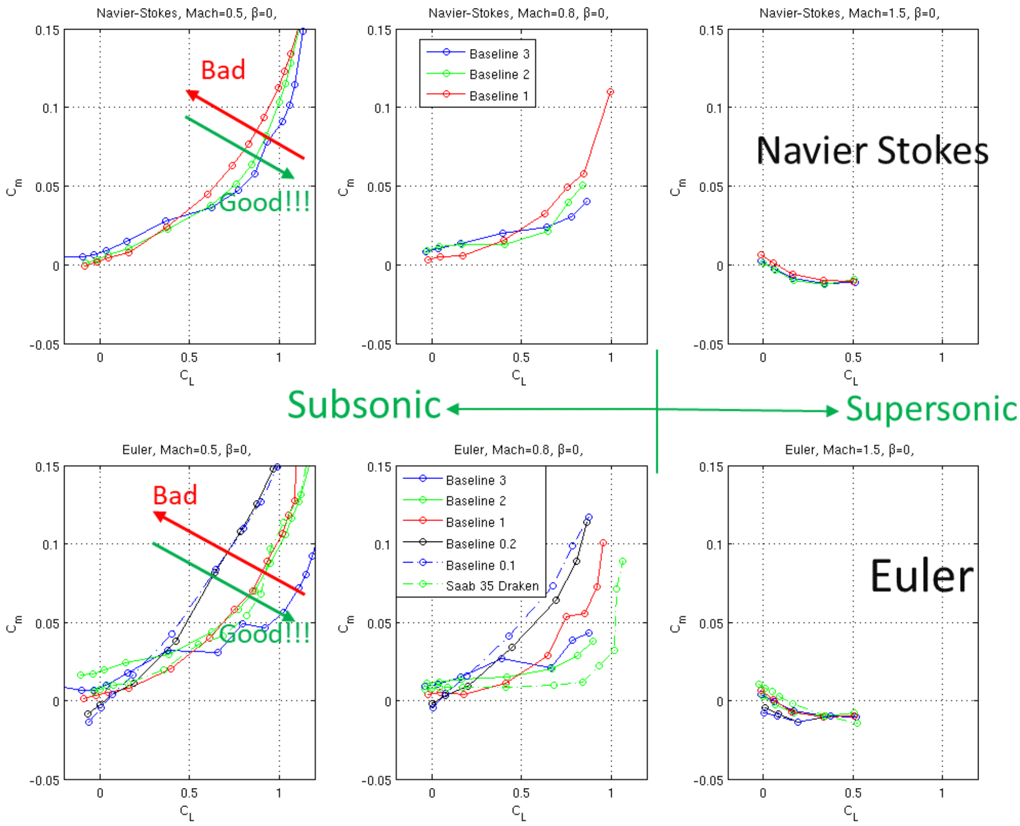

Figure 7: Pitching moment characteristics evolution during shaping.

4.2 Wind Tunnel Test

A wind tunnel test was made within the scope of the loyal wingman concept study. The aim was to produce aerodata input for one of the concepts. The L-2000 wind tunnel at KTH in Stockholm was chosen for the test, which was undertaken in December 2021. The wind tunnel model was designed to be made entirely in PA2200 plastic by additive manufacturing, with the exception of the load carrying balance frame which was made out of aluminum. This part was also the interface towards the balance. The model was mounted on a 6-component internal strain gauge balance. The installation in the wind tunnel is shown in Figure 8.

Figure 8: The Loyal wingman concept in the L-2000 Wind tunnel at KTH, Stockholm.

4.2.1 Model Design

The CAD-geometry of the baseline 3 aircraft was used as input for the wind tunnel model. CFD data was used to produce preliminary loads on the wind tunnel model and a 10% scale was chosen to fit the available balance load range and the wind tunnel. Is was decided not to have flow through the model and a dedicated fairing over the air inlet was designed to achieve this. The shape of the wind tunnel model along with definitions of measured forces and moments are shown in Figure 9.

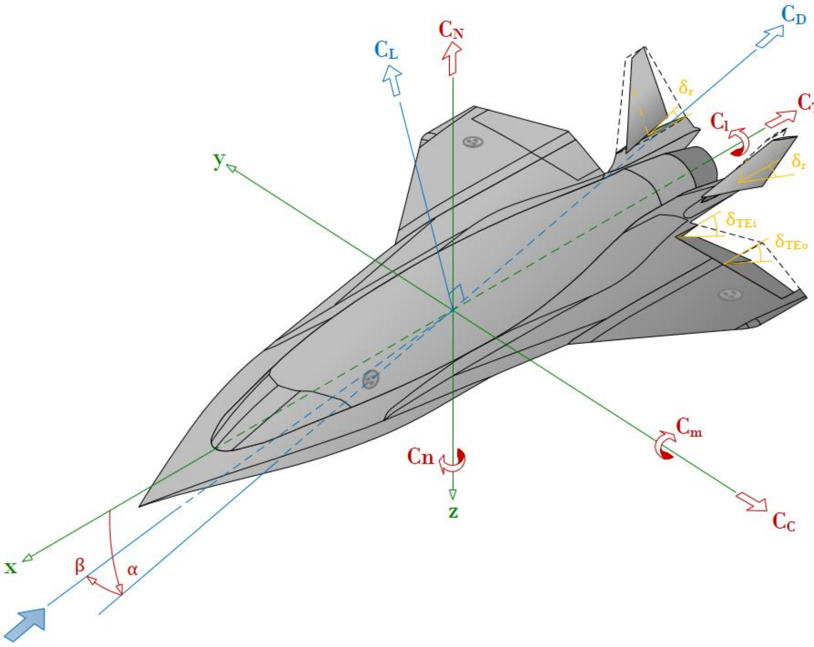

Figure 9: The wind tunnel model and definition of forces and moments measured in the wind tunnel.

Additional material thickness had to be added to wing edges and fin roots in order to add structural rigidity to the parts and to adapt it to the additive manufacturing process, where thin models can lead to bad printing results[5].

In order to change control surface deflections it was decided to change the entire wing including the control surface as one common part. This approach would also support e.g. a quick change of wing planform as a common interface could be used. Changing fin deflection angles was achieved by changing the entire tail section of the model. The model was designed to have one internal weapon bay that could be opened and equipped with a door. The interior parts of the model were designed to achieve a simple balance interface and a simple (cylindrical) shape of the balance cavity if a balance cavity pressure correction would have to be applied. The model fuselage was divided in sections only to fit the build volume of the chosen additive manufacturing machine. In order to get as much structural rigidity as possible the model was 100% filled, which gave the model a gross mass of ca 20 kg.

4.2.2 Wind Tunnel Testing

The wind tunnel test was undertaken in 5 days spread over two calendar weeks. This allowed for a study of model surface roughness as the model was unpainted and in its “out of the printer” state during the first week. The time between the two test entries was used to improve the model surface by paint and the second week of testing was made with a painted model.

A Reynolds number sweep was undertaken at the start of each test week to study the model sensitiveness to Reynolds number. The sweep was made by gradually increasing the free stream velocity in the wind tunnel, while studying the balance loads. It was seen that velocities above 30m/s did not affect the loads to any large extent and 30m/s was consequently chosen as a standard speed for the wind tunnel test.

The main test matrix contained blocks of polars in angle of attack α and side slip angle β for a number of different aircraft configurations, including control surface deflections and an open weapon bay.

The test was undertaken successfully and the model managed the loads from the wind tunnel without problems. Some bending of the outer wing and fin tips was observed at the highest wind speeds and incidence angles, but never came close to a level where the model or balance were deemed at risk. In addition it was desired to keep the model deformations as small as possible to achieve comparable results, and the chosen flow speed of 30 m/s was also chosen to achieve this.

4.2.3 Wind Tunnel Results

Results for the longitudinal aerodynamic coefficients C_N and C_m are presented in this section. Run 60 from the wind tunnel test is used as reference in many plots below, and corresponds to a model with all control surfaces at 0° and IWB closed. The model was painted and gaps and holes covered with aluminum tape. The model also had simple transition markings using zig-zag tape applied. Alpha polars for β=[0°,+10°] are shown in Figure 10 below and corresponding CFD results are shown as thinner lines in the figures.

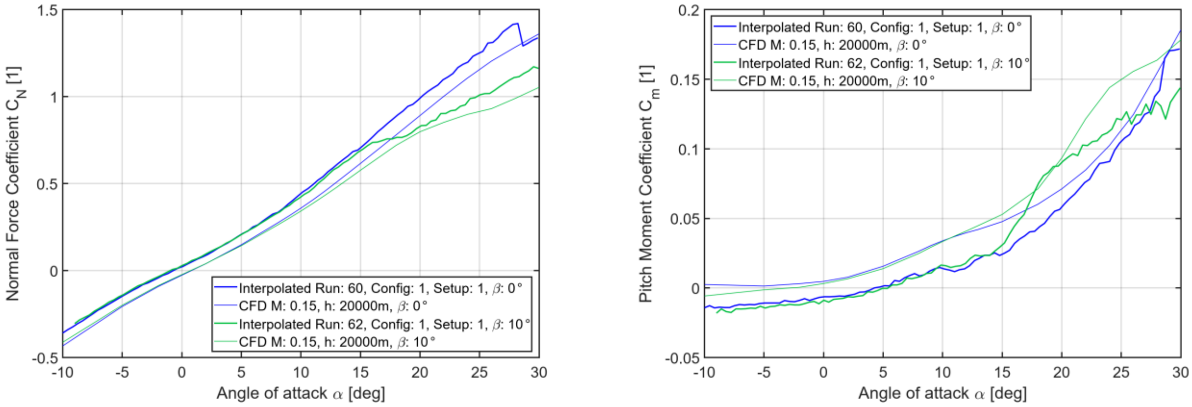

Figure 10: Longitudinal data comparison between CFD and wind tunnel test.

CFD simulation results were compared with wind tunnel test data. The CFD simulations used to compare to wind tunnel data were made using a full scale geometry, Mach number M = 0.15 and a flight altitude of h = 20000m to match the Reynolds number of the wind tunnel.

There is an acceptable degree of conformity between the results. There are small differences seen in the data but these are expected as the wind tunnel data is uncorrected. Further work is needed to apply relevant wind tunnel corrections on the test data. Throughout this paper uncorrected data will be used.

There might also be effects from geometrical deviations such as the air inlet fairing and the sting, present only on the wind tunnel model. In order to study this, a dedicated CFD simulation was made with the air inlet faring and a sting included. The results compared to the wind tunnel data is shown in Figure 11. It is shown that the effect from air inlet fairing and sting are negligible on the normal force, while the pitch moment characteristics for higher angles of attack are somewhat affected if the air inlet faring and sting are included in the CFD simulations.

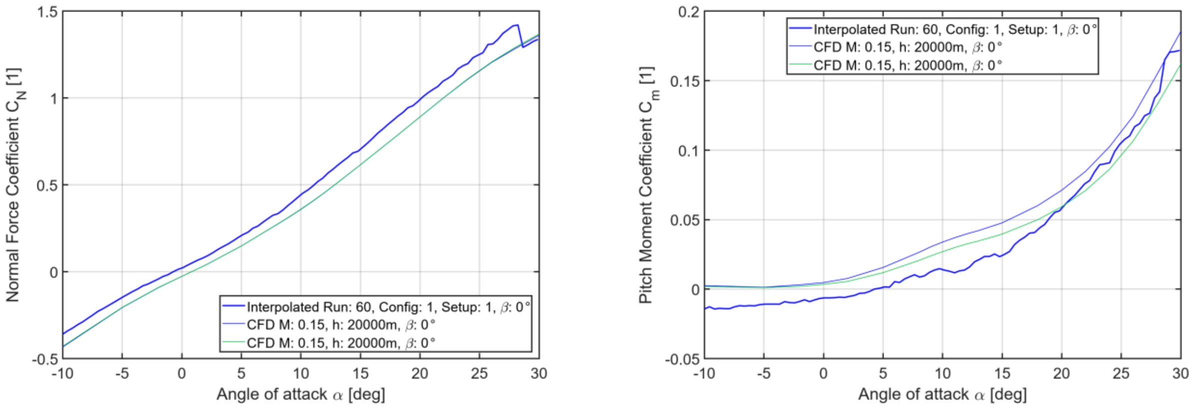

Figure 11: Wind Tunnel data compared with CFD simulations with (green) and without (blue) air inlet fairing and sting.

A study of the effects on the longitudinal coefficients from an open IWB was undertaken and is shown in Figure 12. It is seen that the IWB has a small influence on the longitudinal stability of the aircraft. It can be noted that the CFD data for the open IWB was made at a flight Mach number of M = 0.5 as these were not initially meant for a comparison to wind tunnel data. The Reynolds number difference in the simulations can be seen to be small by comparing to the reference case.

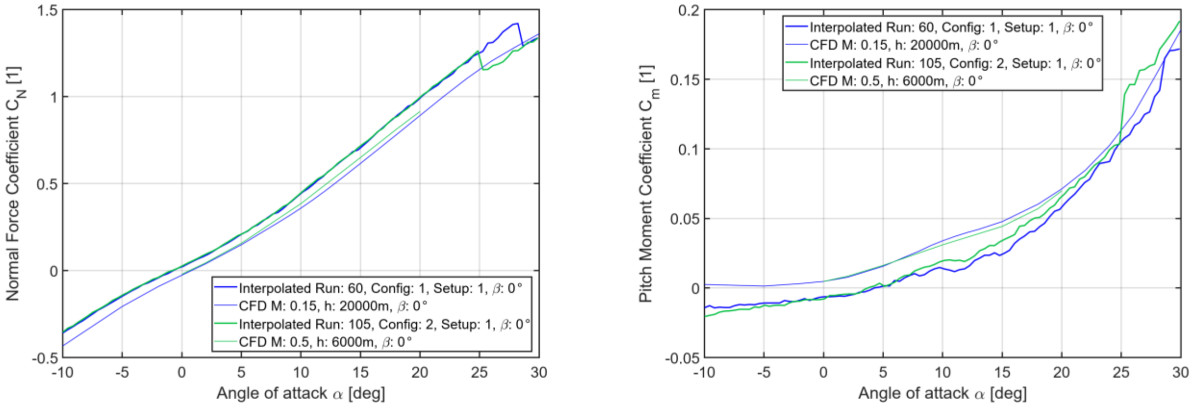

Figure 12: Wind Tunnel data and CFD compared to a configuration with an open IWB.

A study of elevon effects on the longitudinal coefficients was undertaken and is shown in Figure 13. Wind tunnel data for the reference with the port trailing edge elevon angle, dTEP = 0° (Run 60) is shown in blue. Data from runs with deflected elevon angles dTEP = +25° (Run 69) is shown in green and dTEP = -25° (Run 96) is shown in magenta. Corresponding CFD data is also shown in each respective color. The three cases show a good symmetry and the CFD data is also well aligned to the respective wind tunnel case apart from the deviations elaborated upon earlier in this paper. Generally this leads to the wind tunnel under predicting the elevon effectiveness.

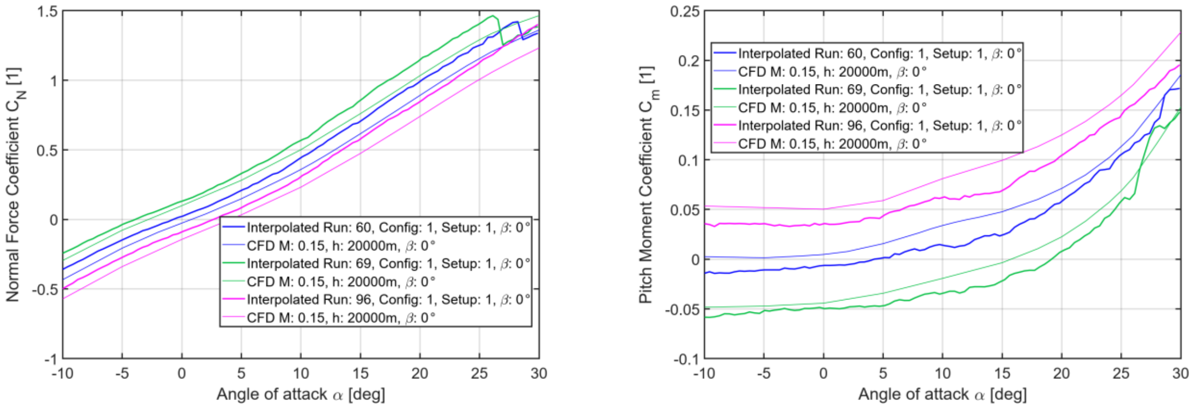

Figure 13: Elevon effect on longitudinal coefficients from Wind tunnel and CFD.

The wind tunnel has produced usable results that are comparable to CFD-simulations and has increased the amount and detail of data available for aerodata modeling, which was the aim of the experimental part of this project. Additional work is needed for application of wind tunnel corrections in order to improve the data usability even further.

4.2.4 Test Planning & Execution

Apart from the successful production of wind tunnel test data, it is also shown that a wind tunnel test can be planned and executed with the limited time and funds available in the project initiation phase. When summarizing the work effort put into the test planning and execution, it is found that in general terms one quarter of 2021 was used, and only by a part of a full time equivalent. A typical production wind tunnel test, including model design, will take approximately a year in total including at least a full time equivalent during that time. It is also believed that a similar test to the one undertaken within the scope of this project can be made even faster in the future.

Considering cost, the use of additive manufacturing along with the use of the wind tunnel at KTH also lead to a cost decrease of ca 90% compared to a commercial wind tunnel test normally used within projects.

4.3 Aerodynamic Data Base Build Up

The exact level of stability and control surface efficiency is evaluated in flight mechanical simulations, which are not presented here. The quick production of aerodynamic data also applies to the aerodynamic data modelling for these simulators, and therefore contributes to a "larger" design loop or process. Similar to the "small loop" aerodynamic design process, early aerodynamic data modelling has been based on Euler analysis (>>1000 CFD cases), and gradually moved to more accurate methods, together with an increased level of detail. The above benchmarking work between the different data sources supports the assessment of the accuracy for the aerodata model at various stages of maturity.

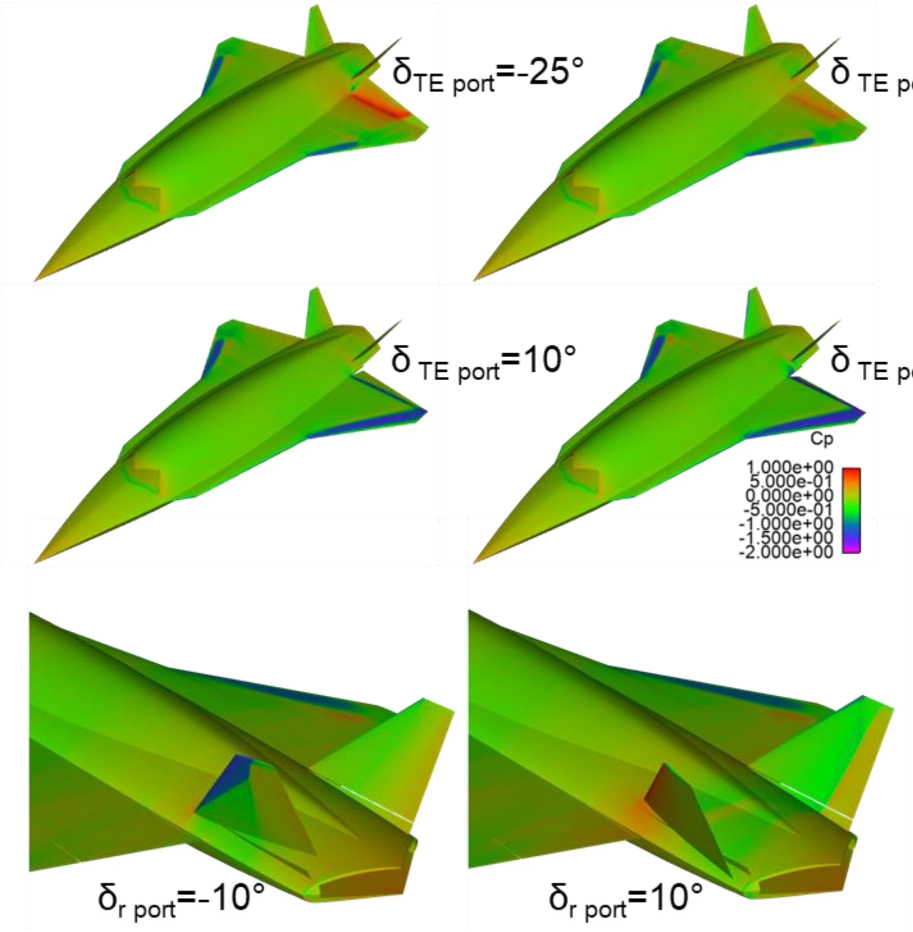

Figure 14: Examples of early aerodata CFD evaluation for a "pre Baseline 1" configuration.

The general evolution of the aerodata build up is in principle:

- Euler data including forces and moments on the aircraft and hinge moments, including some scaling factors for flight mechanical studies.
- Navier-Stokes introduced as a gradual update e.g. basic stability (i.e. control surfaces neutral), and scaling of control surface efficiency. Navier-Stokes effects from control surface deflection or other properties added sparsely or fully depending on time/quality requirements.
- Wind tunnel test and CFD data combined
- Flight test validation and updates

At the writing of this paper, the first two points have been applied. The timescales are increasing exponentially between the bullets in the list, where an initial aerodata base can be produced in days, Navier-Stokes updates takes weeks or months depending on level of detail and resolution. Aerodata built on classical production wind tunnel test in low speed and high speed tunnels, take a year from geometry freeze, while rapid prototyping WTT could start to enter the process already at the second bullet in the list.

5. Conclusions

The results of the studies show that for the double delta, high sweep, vortex dominated flow:

- Euler simulations are catching the overall evolution of both lateral, directional and longitudinal stability levels for large design changes. Absolute values and the effect of small design changes have to be cautiously interpreted.
- Navier-Stokes simulations are a more detailed representation of the external aerodynamics, and are required at some point, both for accuracy and to catch the effect of smaller design changes. Although vortex-dominated flow is generally assumed to be insensitive to Reynolds number, at some level of accuracy it is!
- Non stationary flow, in this study represented by open internal weapons bay, have been investigated by comparing RANS, hybrid RANS-LES and wind tunnel test results. The results are showing that Hybrid RANS-LES or similar turbulence resolving methodology is required for internal weapons bay loads and weapon separation analysis, but not required for early estimate of the weapon bay effect on aircraft stability.
- Wind tunnel test raw results show some offsets to project geometry CFD results, which is partly expected for non-corrected WTT data. Evolution with angle of attack, sideslip and control surface deflection serves as benchmarking for wind tunnel condition CFD, and gives a good indication of accuracy for different levels of CFD modelling. Surface properties of the model show very small effect on the test results.
- A wind tunnel test can be successfully executed in the limited time frame and on the limited budget that exist in typical project initiation activities within Saab.

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7. Copyright Statement

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