A CFD study on the strut interference on a regional aircraft wind-tunnel model

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Abstract. The aim of this paper is to investigate the aerodynamic interference effects of typical devices supporting aircraft models during wind tunnel tests by means of CFD tools. This work proposes the use of steady RANS simulations of the flow field in order to predict the interference produced by two different models of struts: (1) one that is made up of two parts and is solidal with the wind-tunnel model for variation of the angles of incidence (α) and of the angles of sideslip (β) and (b) the second that is made up of one part and is fixed for α variations and is solidal with the model for β variations. Low and high Reynolds flow conditions are considered and a typical cruise configuration of a scaled model of regional aircraft is addressed in both power-off and power-on conditions. The strut effect is investigated for several angles of incidence and sideslip. From the numerical point of view, the flow field and forces disturbance caused by the struts are derived by comparing simulations with and without the support. The interference is analysed in terms of global forces and moments coefficients and local quantities, such as pressure coefficients distributions. The main result regarding the comparison between the two models of strut is that the corrections to be applied to experimental data and the effect of both ventral struts on the global aerodynamic forces and moments are small.

1. Introduction

Wind tunnel experiment represents an indispensable tool to predict the aerodynamic performance of single aircraft components as well as the overall configuration and it is a corner stone in the design of new aircraft configurations. In this context extrapolation of the wind tunnel tests to free flight conditions within this process contains certain inaccuracies. The wind tunnel flow does not correspond to the free flight because of wall and model mounting effects. In order to minimize these influences on a large extent, data corrections of the wind tunnel tests are performed, which are usually based on simple procedures and hand book methods. The wind tunnel measurements are performed with scaled models, and the extrapolation to real conditions is done by each aircraft company using their own extrapolation procedures. Aerodynamic performance data resulting from the wind tunnel experiment therefore are still affected by certain systematic errors.

For the last thirty years, computational fluid dynamics (CFD) flow simulation has been further developed. The use of unstructured codes for the flow simulation around complex configurations and geometries can now be handled with the required accuracy and justifiable effort. Thus, the critical
examination of existing wind tunnel correction procedures and their improvement is made possible. In the past, CFD has been used to study the interaction phenomena taking place, in both subsonic and transonic flow conditions, for arrangements such as wing–pylon [1], wing–body [2] [3] and complete aircraft configurations [4].

The present work has been carried out in the frame of the H2020/Clean Sky 2 project called POLITE (grant agreement No 717233, [5]). The objective of the project was to design, manufacture and test a wind-tunnel model of regional aircraft enabling low and high Reynolds WT-tests. The experimental campaign aims at validating technologies developed within CS2 (domain REG) to improve performances in low and high speed. Within the POLITE project, CFD simulations are used to evaluate the various bias present in the experimental wind tunnel data and to reduce the uncertainties related to the determination of the effects due to the presence of the support. The present paper focuses on the application of a methodology to predict the aerodynamic interference effects produced by a single strut supporting the aircraft model in low subsonic flow conditions. The flow field and forces distortion caused by the presence of the sting are derived from comparisons between simulations with and without the support. The wind tunnel model supports (struts) are designed to be as small as possible, under the constraint that they should sustain the forces generated by the model over a wide range of flow conditions and house instrumentation cabling. Furthermore, in the case of powered model, the strut routes the required energy into the model. However, the strut shape can strongly affect the aerodynamic flow field around the model with significant consequences on the accuracy of the measured data [6][7]. Several studies were undertaken in the past [8][9] to determine this effect for numerous configurations. These effects are normally determined by experimental means [10].

In most wind tunnel procedures, the strut effect is accounted for thanks to various corrections methods [11][12]. Unfortunately, the existing methods exhibit several drawbacks [13] because:
- they rely on simplifying hypotheses and/or empirical assumptions, which validity is doubtful for example at high Mach numbers or for unconventional models;
- they differ from one wind tunnel to another, making it difficult to compare final results;
- they call upon dedicated experiments which are expensive and require the introduction of another support, i.e. additional distortions of the flow.

In order to alleviate these shortcomings, several studies [16], some very recent [14][15], have been performed and have showed that advanced numerical simulations can be of support in predicting, understanding and interpreting the effects of interference.

The current study is aimed to predict the effects of the single-strut interference on aerodynamic forces and moments on a scaled model of a turboprop transport aircraft by using a CFD-based approach. Two models of strut are considered: a strut with a pitch mechanism external to the model (used for testing in the RUAG Large Low Speed Wind Tunnel Emmen in Switzerland – LWTE [17]) and a strut with a pitch mechanism located inside the model (for testing in the ONERA F1 wind tunnel in France [18]). A clean configuration representative of a cruise condition is considered and both power-off (i.e. without simulation of propeller effects) and power-on conditions are taken into account.

2. Aircraft model and struts
The aircraft model is represented by a full model comprising the fuselage, the wing with one nacelle (non-powered), the vertical and horizontal tail planes (VTP and HTP). Two configurations of strut will be considered:

1. Strut with EXTERNAL PIVOT (RUAG strut).
   Figure 1 (a) shows a sketch of the WT model as mounted on the strut, represented by the green part. The pitch change mechanism is located in the strut and the pivot point is outside the model. The strut follows the WT model for α and β changes and the model and the strut rotate together.

2. Strut with INTERNAL pivot (ONERA strut).
   Figure 1 (b) shows a sketch of the WT model as mounted on the strut, represented by the red part, equipped with a fairing, represented by the yellow part. The pitch change mechanism
is located inside the model and the pivot point coincides with the origin of the reference frame. The strut follows the WT model at $\beta$ changes but not for $\alpha$ changes. For this reason, for $\alpha$ changes the model rotates and the position of the strut remains unchanged, conversely, for $\beta$ changes, the model and the strut rotate together. The calculation presented in this report consider the only red part of the strut.

Figure 1. Sketch of the WT model and the strut with EXTERNAL (a) and INTERNAL pivot (b)

3. Methodology for strut interference calculations

The strut effect is defined as the difference between the configuration with and the configuration without the strut at the same geometrical angle of incidence and sideslip

$$\Delta C = C_{\text{baseline}} - C_{\text{strut}},$$

$$\Delta \alpha = \Delta \beta = 0,$$

where $C$ represents one of the aerodynamic forces and moments coefficients evaluated with respect to a body reference frame (i.e. $C_x$, $C_y$, $C_z$, $C_{Mx}$, $C_{My}$, $C_{Mz}$) and subscript indices $\text{baseline}$ and $\text{strut}$ refer to the configurations without and with the strut. The above aerodynamic coefficients are derived from the solution of Reynolds-averaged Navier-Stokes (RANS) equations. In details, for each configuration and every $\alpha$ and $\beta$, two numerical simulations are performed by considering the model in the wind-tunnel test section without and with the strut. The CFD analysis produce two sets of coefficients, so called $C_{\text{baseline}}(\alpha, \beta)$ and $C_{\text{strut}}(\alpha, \beta)$, that can be used for the evaluation of the corrections for each strut (see formula 1 and 2).

Conceptually, the correction of the experimental data based on CFD results can be derived by using two different approaches, i.e.

1. the generation of a polynomial surface as function of $\alpha$ and $\beta$;
2. the generation of a fitting surface as function of $\alpha$ and $\beta$.

Both approaches allow the user to apply the correction to configurations in terms of $\alpha$ and $\beta$ which are not evaluated numerically. For every aircraft configuration and aerodynamic coefficient, it is necessary to generate a corresponding (polynomial or fitting surface).

The CFD simulations related to RUAG test campaign have been performed at a Mach number of 0.20 and a Reynolds number of $1.3 \times 10^6$ based on mean aerodynamic chord, while those simulating ONERA test activity at a Mach number of 0.23 and a Reynolds number of $2.5 \times 10^6$. Since both experimental campaigns have been performed in the low subsonic regime and the Reynolds numbers
are of the same order of magnitude, the results obtained from the each CFD analysis can be compared to study the effect of the two different models of strut.

4. Corrections for strut interference

The polynomial (see point 1 of Section 3) and fitting (see point 2 of Section 3) surfaces for $C_x$ and $C_z$ coefficients in the cruise configuration and power-off condition are presented respectively in Figure 2 and Figure 3. Black points in the fitting figures represent the original data points calculated by CFD. The main result derived from these figures is that the corrections to be applied to experimental data and the effect of both ventral struts on the global aerodynamic forces and moments is small. This aspect is especially evident for moderate $\alpha$ and $\beta$ angles, while the corrections increase for conditions that are close to the border of the domain.

The polynomial fit gives smooth surfaces, but they are not forced to pass through the original data points. For this reason, it is possible to observe that, for each aerodynamic coefficient and each strut model, the values of the polynomial and fitting surfaces are very similar in the central region of graph where most of the CFD data points are concentrated. The main differences are observable in the corners of the figures where no data points are evaluated by CFD. In that region, the values of the interpolated surfaces are extrapolated from the data of the CFD points located in the central part. This situation can lead to unacceptable errors at these points. Figure 4(a) contains the values of the error quantity for each simulated $\alpha$ and $\beta$ condition in power-off conditions, $\Delta C_{CFD} - \Delta C_{POL}$, where $\Delta C_{CFD}$ is evaluated from original numerical data and $\Delta C_{POL}$ represents the same quantity derived from the polynomial surfaces. As an example, for the axial force ($C_x$) errors in the order of up 40 drag counts ($40e^{-4}$) are observed. This value could be larger than the accuracy expected from an experimental instrumentation and a wind tunnel test. This problem does not appear if an interpolation approach is used since it forces the surface through all the numerical points. As an example, Figure 4(b) shows the comparison between original and corrected experimental data in terms of $C_x$, $C_z$ and $C_{My}$ for the cruise condition by using the strut with external pivot. As confirmed from the fitting surfaces, the correction applied to original experimental data is very small for all cases, demonstrating the controllable effect produced by the strut.

![Figure 2. $\Delta C_x$ (cruise conf., power-off condition): polynomial (a) and fitting (b) surfaces (left: external pivot; right: internal pivot)](image-url)
Figure 2 and Figure 3 are also interesting for the comparison between the strut with external and internal pivot. By comparing the fitting surface of the struts with external and internal pivot, it is possible to observe that the corrections $\Delta C_x$ show similar behavior in terms of shape and values of the surfaces. The main differences are observable for $C_x$ coefficient: even if the shape of the two fitting surfaces is very similar, it is evident that the strut with external pivot has a lower interference effect than the strut with internal pivot especially at high sideslip angles and moderate angle of attack.

Figure 5 and Figure 6 show the comparison between the configurations with the strut and without it at $\alpha = 8^\circ$, $\beta = 0^\circ$. The pressure contour distribution is divided into two parts by considering the symmetrical axis as reference line: the upper part refers to the configuration with the strut and the lower part to the same without strut. In all the presented cases, most of the pressure distribution remains unaffected by the presence of the strut. The main differences are localized in the bottom part of the fuselage close to the intersection with the strut.

In addition, it is interesting to analyze the contour plot of the following difference, $|C_{p_{\text{strut}}} - C_{p_{\text{nostrut}}}|$, where $C_{p_{\text{strut}}}$ and $C_{p_{\text{nostrut}}}$ are respectively the pressure coefficient distributions in the cases with and without the strut. Figure 7 refer to the cruise configuration at $\alpha = 4^\circ$ and $\beta = 10^\circ$ and strut with respectively external and internal pivot: in details (a) show all the contour levels and (b) is obtained from figures (a) by cutting-off the contour levels below 0.1. They show that the great part of the aircraft surface is characterized by pressure coefficient difference values that are around zero. As expected, the major differences are in the area near to the strut/fuselage junction.

To analyze the effect of the propeller in the configuration with and without the strut by comparing the pressure coefficient contours, it is possible to calculate the following difference, i.e. $\Delta C_p = |(C_{p_{\text{strut}}} - C_{p_{\text{nostrut}}})_{\text{p-off}} - (C_{p_{\text{strut}}} - C_{p_{\text{nostrut}}})_{\text{p-on}}|$. As an example, Figure 8 shows the contour plot of $\Delta C_p$ by cutting-off the contour levels below 0.1, in the case with strut having the internal pivot. The main differences are concentrated in the interference region between the strut and model, because most of the model has $\Delta C_p$ values lower than 0.1. The introduction of the power-on condition does not drastically change the flow field in the configurations with the strut because the effect of the strut is always limited to a small region of the model.
5. Conclusions

This work focuses on the study of the effects of a single-strut interference on all aerodynamic forces and moments on twin engine turboprop transport aircraft model. Two models of strut are considered: a strut with a pitch mechanism external to the model (used for testing in the RUAG Large Low Speed Wind Tunnel Emmen in Switzerland – LWTE) and a strut with a pitch mechanism located inside the model (for testing in the ONERA F1 wind tunnel in France). A clean configuration representative of a cruise condition is considered and both power-off (i.e. without simulation of propeller effects) and power-on conditions are taken into account. One configuration is considered: a clean configuration representative of a cruise condition in power-on and power-off conditions. RANS CFD simulations were used to predict the effect of each single strut on the global aerodynamic forces acting on the model, by including
the effect of the propeller. The interference of the strut is evaluated by considering the difference between the configuration with and without the strut at the same geometrical angles of incidence and sideslip. The results are used to generate polynomial surfaces and/or interpolation surfaces for the correction of experimental data for each $\alpha$ and $\beta$. Polynomial surfaces were shown to produce excessive errors and it is recommended to use interpolated data for the actual corrections of experimental results. The effect of both ventral struts on the global aerodynamic forces and moments was found to be small throughout the range of interest. The comparison between power-off and power-on configurations have demonstrated that power effects are negligible on the support corrections because the effect of the two models of strut is concentrated in the bottom part of the model, near the conjunction between the strut and the model.

![Figure 7. Comparison in terms of $C_p$ contour distribution between the configurations with and without the strut with EXTERNAL pivot (cruise conf. – power-off condition – $\alpha = 4$ deg, $\beta = 10$ deg)](image)

![Figure 8. $\Delta C_p$ (cruise conf. – power-on vs. power-off condition – $\alpha = 4$ deg, $\beta = 10$ deg)](image)

### 6. Acknowledgement

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 717233.
7. Disclaimer
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