Dynamics of a Simplified Wing-Body Junction Flow

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Abstract

In this paper, a simplified wing body junction at $Re_c = 3.10^5$ is designed and investigated experimentally and numerically using a wide range of approaches, ranging from a one-transport-equation RANS model to Large Eddy Simulation. The focus is put on the physical properties of the flow in three critical areas. The dynamic properties of the vortices observed are scrutinized and a global motion of the main horseshoe vortex is unveiled. Furthermore, the study of the corner area emphasizes the failure of usual RANS models to accurately predict the flow for this configuration.

1 Introduction

Junctions areas, for instance at the wing-fuselage junction, are of utmost importance for aircraft designers. However, the aerodynamics of such intersection regions still remains unclear and challenging to predict, both experimentally and numerically. Therefore, this study aims at identifying and analysing the origins and properties of the phenomena involved within junctions as well as to evaluate the reliability of RANS and LES approaches on such configurations.

Only main results are introduced in this paper, for further details (including numerical settings, details on the experimental study, grid convergence of the RANS computations, validation of the Large Eddy Simulation, etc.) the reader is invited to refer to the original publications[1, 2, 3].

2 Major results

A generic organization of a junction flow is proposed in figure 1. Three areas of interest can be identified : the leading edge area, where a horseshoe vortex is created due to the skewing of the incoming boundary layer, the convection area of the horseshoe vortex past the wing and the area near the corner where a corner separation may occur. In the following study, we investigate each of these areas separately, then their interactions is questioned to unveil the global dynamics of the vortex. Furthermore, the investigation of the corner area indicates the limitations of the RANS models used for the present study in the framework of junction flows.

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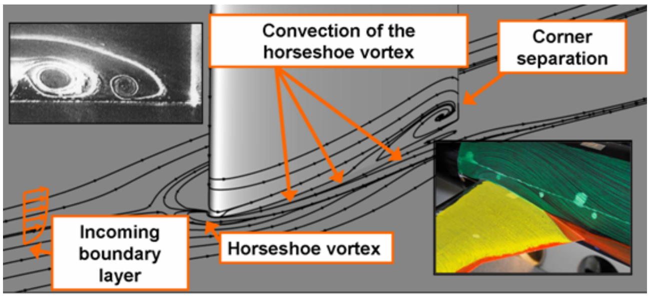


Figure 1: Proposed generic organization of a junction flow

2.1 Physics of the junction flow

Leading edge area In the leading edge area, the skewing of the incoming boundary layer results in the formation of a so-called horseshoe vortex. This flow feature is well documented [4, 5, 6] and the LES simulation performed in this study accurately reproduces the properties of the horseshoe vortex. For instance, the aperiodic switch between two equilibrium states is captured as illustrated in figure 2 (phenomenon named bimodal behaviour by Devenport *et al.* [6]).

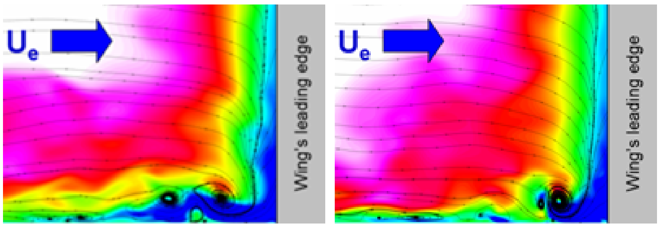


Figure 2: Evidence of the bimodal behaviour of the horseshoe vortex in the symmetry plane (negative axial velocity in blue)

Convection area Downstream of the leading edge, the horseshoe vortex is convected around the wing. Oscillations of the core of the horseshoe vortex in transverse planes can be identified in figure 3 where the vorticity magnitude is plotted at two different times in a transverse plane at the trailing edge. The location of the core of the vortex evolves in time as suggested by the right hand side picture of figure 3 where the evolution of the pressure fluctuations along a rake crossing the vortex is depicted. This behaviour, similar to the meandering of wing-tip vortices except the vortex is embedded in a turbulent boundary layer in this case, appears to have a broadband energy distribution [1].

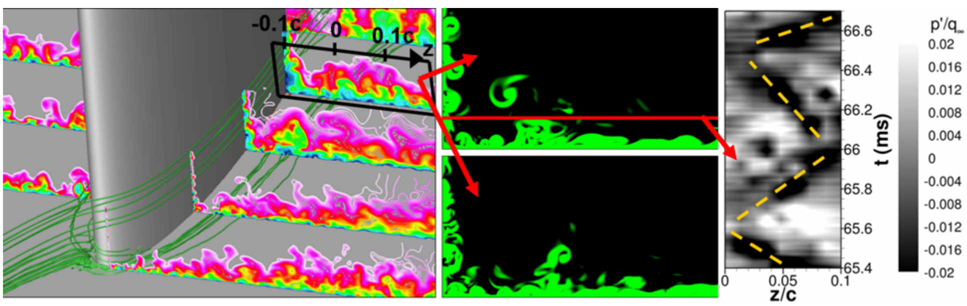


Figure 3: Idenfication of transverse oscillations of the horseshoe vortex in the convection area

Corner area In the corner area, no separation was observed during the wind tunnel tests as shown in figure 4. As a matter of fact, a corner separation would induce high total pressure losses in the corner. The same behaviour is observed in the LES simulation whereas all RANS models investigated (ranging form Spalart Allmaras to Speziale, Sarkar and Gatski RSM) predict the onset of a separation. This issue has been attributed partly to the high anisotropy of the boundary layers in the corner which is not accounted for by the RANS models (and actually cannot be by Boussinesq-hypothesis-relying closures, only RSM type models are theoretically suited to do so), see [1, 2] for further details.

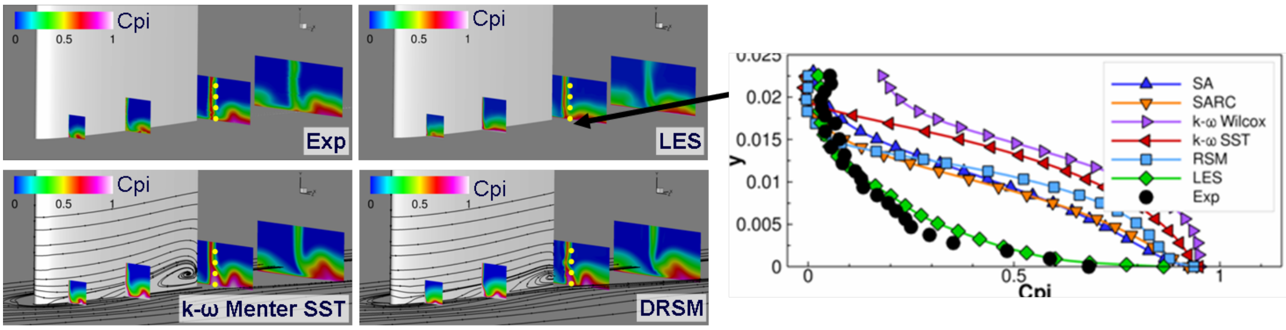


Figure 4: Turbulence modelling effect in the corner area, total pressure losses are displayed

Interactions between areas of interest A spectral analysis has been made for signals acquired during the LES simulation in the leading edge area and in the convection area within the vortex core. The spectra show that the instabilities observed (the horseshoe vortex bimodal behaviour and its transverse oscillations) have a broadband energy distribution. However, a cross-spectra analysis shows evidence of a coherent motion of the vortex. The instabilities seem to be included in a global motion of the horseshoe vortex.

3 Conclusion

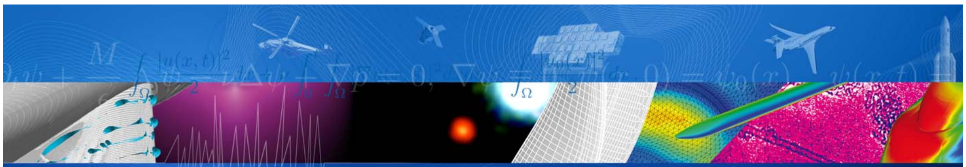
A simplified wing body junction has been investigated. In this paper, only the main results have been introduced since more detailed studies have already been published [1, 2, 3].

The dynamics of the flow has been assessed thanks to the use of a LES simulation, which has been validated against an experimental database. The global dynamics of the horseshoe vortex as well as the complex structure of the turbulence in the near-corner region have been observed and quantified.

These properties illustrate the intricacy of junction flows, which justifies future work devoted to in-depth analysis of other cases presenting corner separations as well as turbulence modelling to improve RANS predictions for such configurations.

A Appendix : slides presented during the symposium

In addition to the brief summary of the study given in the present paper, the slides presented during the symposium are provided below. The reader is encouraged to refer to references [1, 2, 3] for more details on this study.



2nd Symposium on Wing and Nacelle Stall
21st-22nd June 2012

Dynamics of a Simplified Wing-Body Junction Flow

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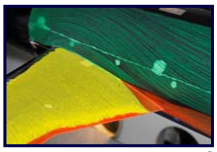
ONERA
THE FRENCH AEROSPACE LAB
return on innovation

Background

- A major and recurring issue
  - Corner separation at junctions
  - Matters of concern: aircraft design/certification, drag,…
  - During design stages: inability to predict corner separations in a reliable way → wind tunnel verifications

Key areas

Key areas



DLR F6

➔ Need for physical understanding of these configurations and assessment of numerical models

- First step (2007-2010) « Dynamics of turbulent junction flows », Ph.D. F. Gand
  - *Flow Dynamics Past a Simplified Wing Body Junction Flow*, Physics of Fluids 22, 2010
  - *A Combined Experimental, RANS and LES Investigation of a Wing Body Junction Flow,* AIAA Paper 2010-4753, 2010 (+ enhanced version accepted for publication in AIAA Journal)

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Outline

1. Generic organization of a junction flow and underlying experimental and CPU cost issues

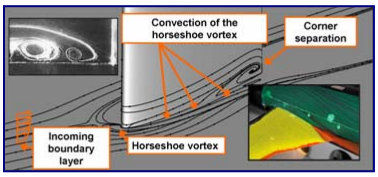
2. Main PhD results
   - Test case investigated
   - Methods
   - Modeling issues
   - Physics of the junction flow

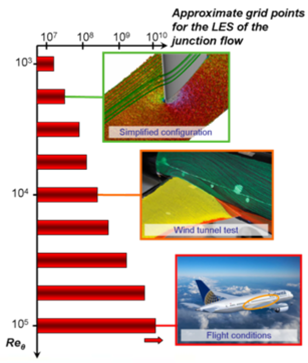
3. Conclusion and on-going activities

Generic organization of a junction flow

- Two major phenomena
  - Horseshoe vortex
  - Corner separation
  - 3 areas of interest
- CFD databases issues
  - Need to account for wall turbulence on the body and on the wing
  - CPU cost issue
  - Grid requirements for the LES of a simplified wing body junction flow
- Experimental databases issues
  - Optical accesses required to the corner to perform LDV, PIV…

➔ Difficulties to generate databases to understand the physical mechanisms





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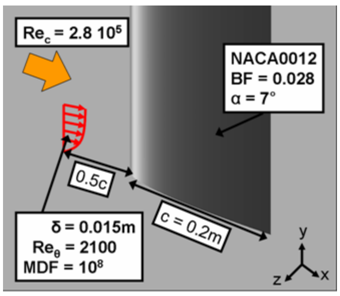
PhD results
Test case

- NACA0012 : simple, aerodynamic behavior at mid span well documented

- Re_c and incoming boundary layer set up
  - LES grid points requirements *vs* super-computing capacities

- α=7°



PhD results
Methods

- Wind tunnel experiments
  - S2L at Meudon, 5 hole pressure probe

- Steady RANS simulations (***elsA***)
  - Numerics: 1 order time scheme / 2nd order space scheme
  - Turbulent closures:
    - Spalart-Allmaras, Spalart-Allmaras with rotation correction, k-ω of Wilcox, k-ω SST of Menter, RSM of Speziale Sarkar and Gatski
  - Grid:
    - Structured, grid convergence study: 7.10^6, 12.10^6, 60.10^6 → 12.10^6 selected
- LES simulations (Flu3M)
  - Numerics: 2 order time and space schemes
  - Turbulence: Selective mixed scales
  - Wall turbulence generation at inlet: Synthetic Eddy Method
  - Grid
    - $\Delta x+=50$, $\Delta y+=1$, $\Delta z+=25$, $Lz/\delta_0=30$
    - 63.10^6 grid points
  - 20,000 h CPU on 8 NEC SX8 cores

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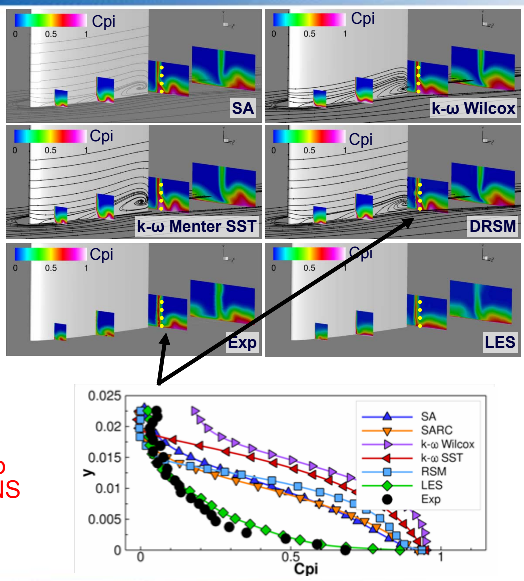
PhD results
Modeling issues

- RANS
  - Limited effect of the turbulence model
  - Horsehsoe vortex and corner separation co-exisiting
- Wind tunnel & LES
  - No corner separation
  - LES in fairly good agreement with WTT

➔Need to analyze the flow physics to understand the reasons of the RANS prediction failure

➔Investigation of the 3 areas of interest



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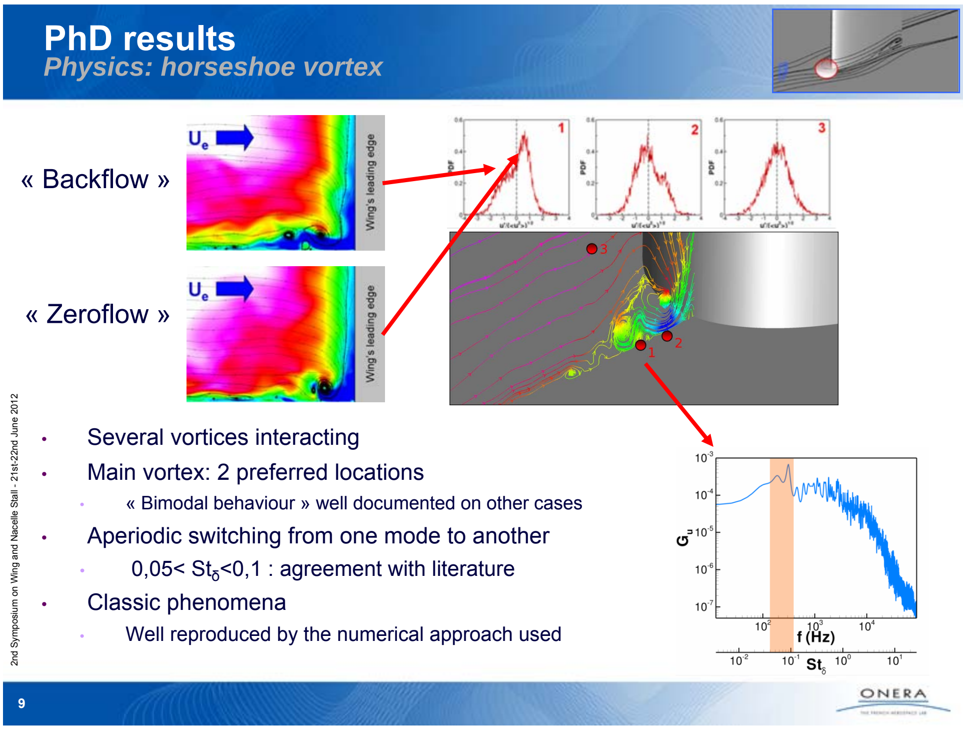
PhD results
Physics: horseshoe vortex
« Backflow »
« Zeroflow »
Wing's leading edge
Several vortices interacting
Main vortex: 2 preferred locations
« Bimodal behaviour » well documented on other cases
Aperiodic switching from one mode to another
0,05< St$_\delta$<0,1 : agreement with literature
Classic phenomena
Well reproduced by the numerical approach used
f (Hz)
St$_\delta$
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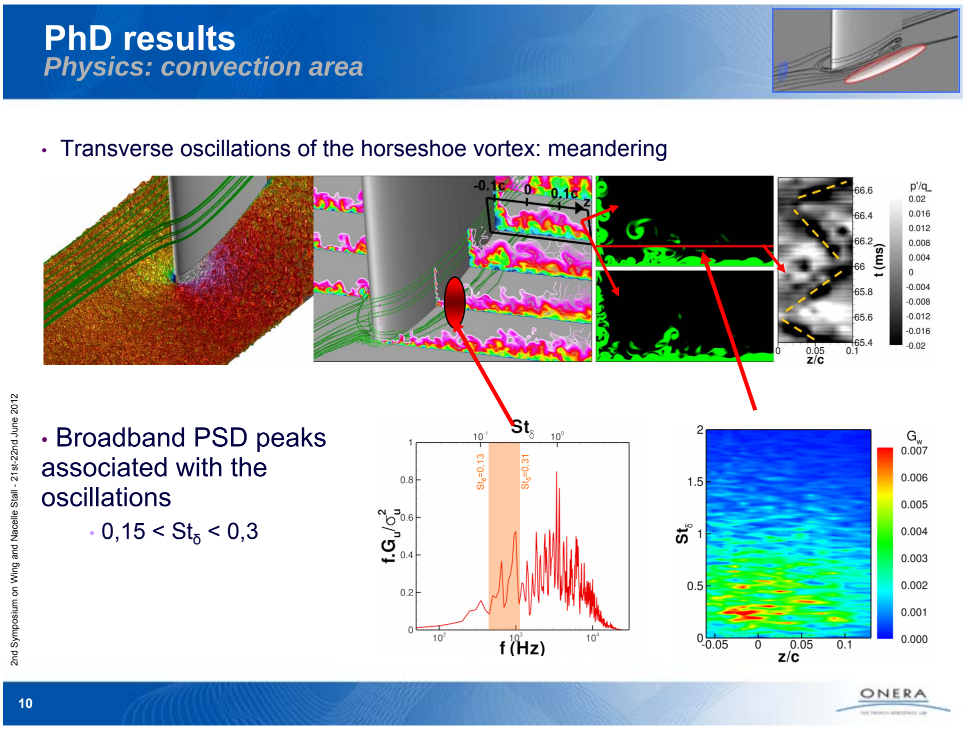
PhD results
Physics: convection area
Transverse oscillations of the horseshoe vortex: meandering
Broadband PSD peaks associated with the oscillations
0,15 < St$_\delta$ < 0,3
f (Hz)
z/c
t (ms)
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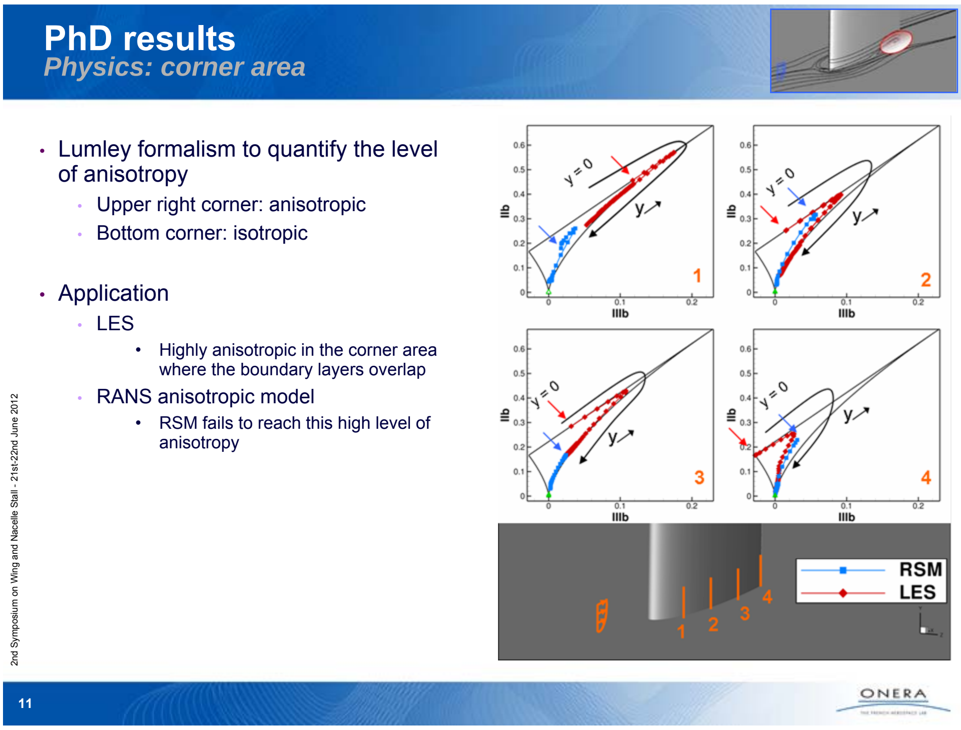

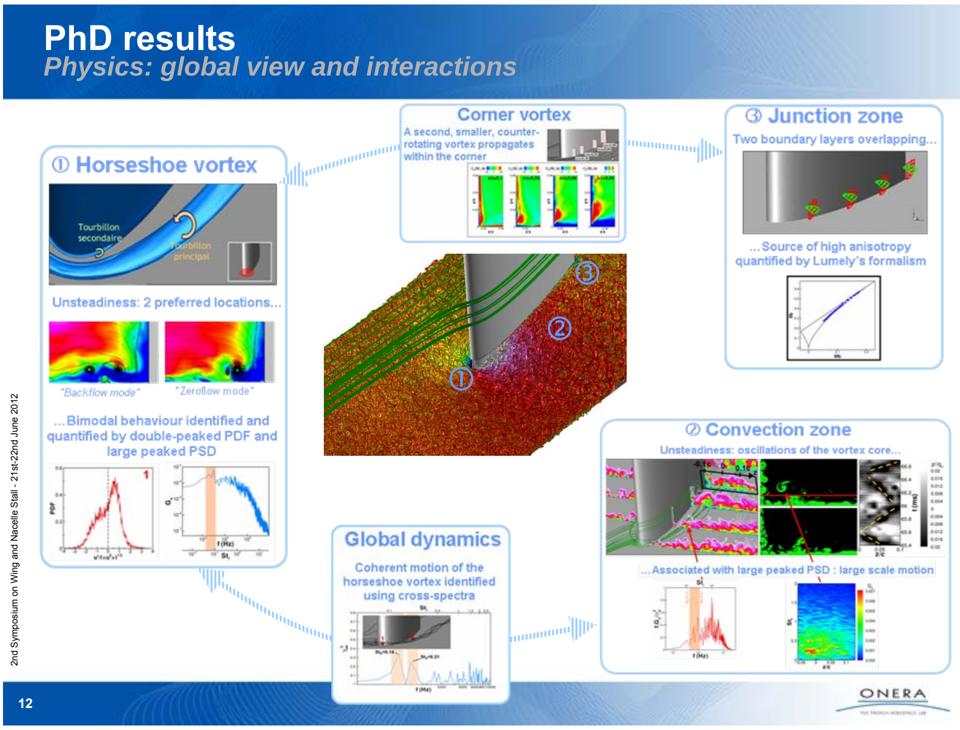

Acknowledgments

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References

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[2] F. Gand, V. Brunet, and S. Deck, "A Combined Experimental, RANS and LES Investigation of a Wing Body Junction Flow," *40th Fluid Dynamics Conference and Exhibit, 28 June - 1 July 2010, Chicago, Illinois, AIAA Paper 2010-4753*, 2010.

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[6] W. Devenport and R. Simpson, "Time Dependent and Time Averaged Turbulence Structure Near the Nose of a Wing/Body Junction," *Journal of Fluid Mechanics*, vol. 210, pp. 23–55, 1990. doi:10.1017/S0022112090001215.