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Vortex pairs in the wake of fixed and rotating split-tip wings

D. Schröder^{a*}, T. Leweke^b, R. Hörschemeyer^a and E. Stumpf^a

^a RWTH Aachen University, Institute of Aerospace Systems, Aachen, Germany¹

^b CNRS / Aix-Marseille Université / Centrale Marseille, IRPHE, Marseille, France¹

*Correspondence: schroeder@ilr.rwth-aachen.de

1 Introduction

The flow around lifting surfaces of finite span is associated with the generation of concentrated vortices at their tips. In the case of a fixed wing, a rectilinear trailing vortex is found, whereas a rotating wing (rotor blade) creates a helical tip vortex in its wake. Lift-generated vortex systems have been studied extensively in the context of aircraft and helicopter wakes. For fixed-wing aircraft, the trailing vortex pair can represent a danger to following aircraft, due to the downwash and rolling moment it induces. For helicopters, the interaction between a rotor blade and the tip vortex of the preceding blade can lead to unwanted noise and structural vibrations (Blade-Vortex Interactions – BVI) [1]. Various strategies have been devised to mitigate these negative effects associated with wing tip vortices. One of them aims at modifying the vortex structure, and in particular increasing the vortex core size. This reduces the rotation rate of the core fluid and decreases the velocity gradients, which is beneficial for the induced rolling moment behind a fixed wing and for BVI-related noise generation by rotors. We here present a method which achieves this goal by splitting the concentrated tip vortex into a pair of co-rotating vortices of similar strength, with the help of a tip device in the form of a perpendicular fin (see Fig. 1). Numerical simulations and water channel experiments are used to characterise the evolution of the vortex pair and the resulting final vortex for configurations involving both a fixed and a rotating wing.

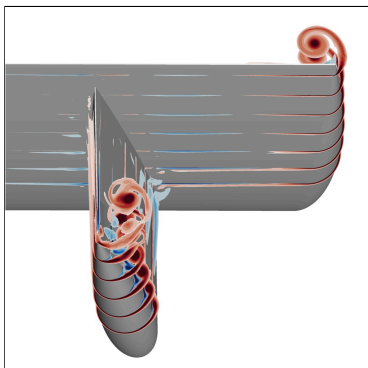


Figure 1: Schematic of the wing tip geometry and vortex formation for the fixed wing, from a RANS simulation [2].

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2 Methods

We consider simple generic wing geometries based on a NACA 0012 profile, constant chord, and rounded tips. The fixed wing has semi-span 290 mm and chord 100 mm, whereas the rotating wing has chord 80 mm and is part of a one-bladed rotor of radius 240 mm, with a twist distribution suitable for operation close to hover conditions. The fin is mounted perpendicularly to the wing near the tip. It has the same NACA 0012 profile, and its geometric parameters (position, height, angle of attack) are varied by exchanging the entire tip geometry. The tip chord-based Reynolds number is of order 10^5 . Numerical simulations using a RANS method with an SSG/LRR- ω Reynolds stress turbulence model, combined with stereoscopic PIV measurements in a water channel, were used to characterise the initial tip vortex system generated for a fixed wing equipped with a fin. The results were then used for the design of the rotating blade, which aimed at producing a similar circulation distribution in the tip region. The downstream evolution of the helical tip vortex pair generated by the rotating wing was investigated experimentally using stereoscopic and volumetric PIV, as well as dye visualizations (Fig. 2).

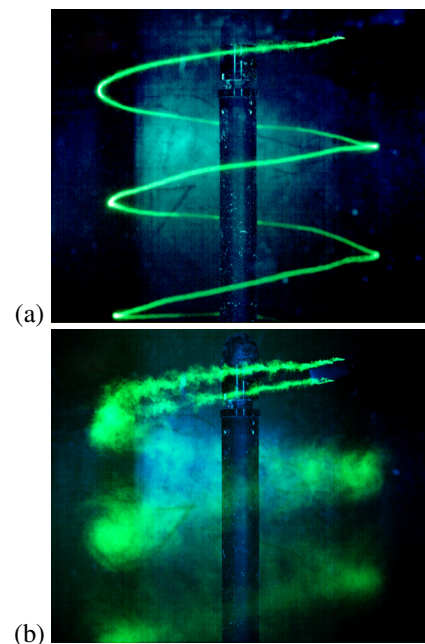


Figure 2: Dye visualization of the tip vortices for the rotating blade, (a) without and (b) with fin [3].

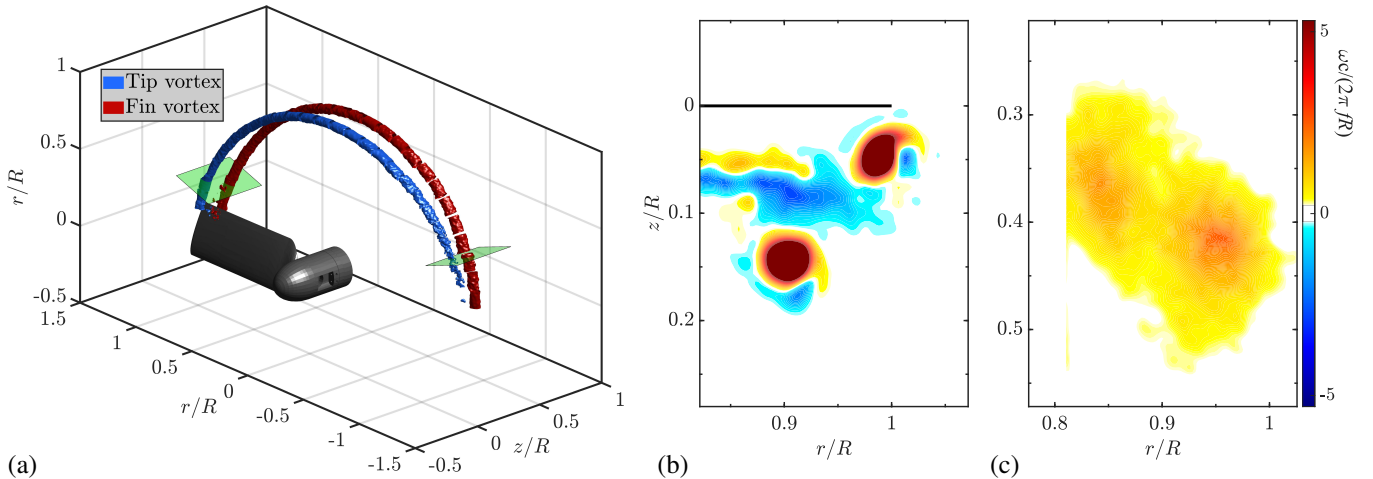


Figure 3: Vorticity from tomographic PIV for the rotating split-tip wing. (a) Volumetric isocontours of vorticity magnitude; (b,c) azimuthal vorticity fields for the two wake ages highlighted in (a). R, f : rotor radius and frequency, c : blade chord.

3 Results

The numerical RANS simulations with the fixed-wing geometry have revealed a tendency for flow separation at the fin root when it is placed on the suction side of the wing [2]. Consequently, all further investigations were carried out with the fin located on the pressure side. Both the numerical and experimental investigations showed that the desired objective of splitting the concentrated tip vortex can be achieved with the presented modification. An experimental parameter study for the fixed wing demonstrated how the characteristics of the resulting tip vortex pair (distance between wing and fin vortices, circulation ratio) are influenced by the parameters of the fin geometry and position. Pairs of co-rotating vortices with similar circulation could be achieved, which are prone to develop interactions which accelerate the core growth and eventually lead to merging into a widened final vortex. The fixed-wing study was limited to the near wake of the wing, where no such interactions and merging were observed.

The experiments with a rotating wing showed that the method of tip vortex splitting also works in this configuration. Two separate vortices are created, whose initial parameters are again influenced by the fin geometry [4]. However, the evolution of the vortex pair strongly differs from the fixed-wing results. For certain configurations, the core radii of both vortices rapidly increase immediately after emerging from the trailing edges, suggesting the presence of an instability phenomenon (see Fig. 2) [3]. PIV results confirm the qualitative observations from the visualizations: an example of a volumetric reconstruction of the wake, as well as two field cuts showing azimuthal vorticity are given in Fig. 3. Comparing the two fields, the rapid core growth and the onset of vortex merging are clearly visible. The merging results in a less concentrated single vortex with strongly decreased peak tangential velocities. A closer analysis of the initial velocity fields reveal that both vortices are subject to centrifugal instability, which arises in vortices whose radial vortic-

ity profile changes sign [5]. The vorticity field in Fig. 3(b) shows that the initial vortex pair is indeed surrounded by regions of opposite-signed vorticity. Its origin can partly be traced back to the interaction between the secondary fin vortex and the blade surface [6]. In addition, contrary to the fixed wing case, the spanwise circulation distribution of the rotating blade leads to a trailing vortex sheet of opposite sign in the inner part of the blade span. Due to the three-dimensional character of the perturbations leading to rapid core growth and merging, the current study uses volumetric measurement techniques to allow a more detailed investigation of the instability and its effects. Further time-resolved measurements, combined with supporting numerical calculations of the rotating system, are planned to obtain a deeper understanding of the underlying physics.

4 Conclusion

A wing tip modification using a perpendicular fin on the pressure side was investigated combining numerical simulations and experiments. For both fixed and rotating wings, a splitting of the tip vortex into a vortex pair was observed, whose characteristics depend on the fin parameters. In the rotating case, a rapid merging occurs into a final vortex with a considerably larger core, a promising result concerning the problem of BVI noise reduction.

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