Higher Order Dynamic Mode Decomposition to identify decay in trailing vortices

Paloma Gutiérrez Castilllo[1], Manuel Garrido Martín[1], Tobias Bölle[2],
José Hermenegildo García Ortiz[3], Jorge Aguilar Cabello[1] and Carlos del Pino[1,*]

[1]*Department of Mechanical Engineering, Thermal Engines and Fluid Mechanics, University of Málaga, SPAIN*
[2]*Institute of Atmospheric Physics, DLR, Münchener Str. 20, 82234 Wessling, GERMANY*
[3]*Department of Mechanical Engineering and Industrial Design, University of Cádiz, SPAIN*

We conduct three-dimensional measurements of the velocity field using stereo PIV in the turbulent wake of a wing model based on a NACA0012 airfoil, for an angle of attack of 9 degrees, and Reynolds number 40000 up to 32 chords from the wing. These experimental results are compared with theoretical models of trailing vortices, Batchelor [2] and Moore and Saffman [3], to determine the parameters of the turbulent wake vortex. Three different zones are identified based on the vortex strength: near, middle and far fields. We make use of Higher Order Dynamic Mode Decomposition (HODMD) to give a better understanding of the most relevant modes within these three regions. We observe that vortex decay in the middle field is related with the HODMD modes. Thus, the information given by this study is useful to test proof-of-concept of future active control for vortex alleviation.

INTRODUCTION

Lift is fundamental in aerodynamics and provides trailing vortices resulting from the limitation of the length of the wingspan [1]. These trailing vortices can be modelled theoretically [2-5] and they represent significant hazard for following airplanes hence are a main reason for the restrictive rules in air traffic management in landing and taking-off operations in runways at the airport. The possibility to devise efficient means of vortex alleviation is thus very important for safety and economic reasons. We are therefore searching for an effective active control that means to force the vortex from the outside in a way that accelerates its vortex strength reduction [6]. To that end, we propose the analysis of experimental (3D) velocity fields using higher order dynamic mode decomposition (HODMD) [7, 8, 9] thus determining the most relevant modes of the flow structure of this turbulent wake behind the wings. The identification of the modes corresponding to vortex decay is very helpful to improve the forcing mechanism.

EXPERIMENTAL SETUP

We carried out the experimental tests in a towing tank in the Vehicles Aero-Hydrodynamics Laboratory at University of Málaga. Fig. 1 shows the 3D layout of the experimental arrangement. The support (1) allows different angles of attack between the upstream flow and the wing model. All the results shown correspond to a single angle of attack (9 degrees), and a constant chord-based Reynolds number, *Re*=40000. The scaled wing model (NACA0012 airfoil) is a rectangular wing profile has a rounded (half-circular) tip. The main dimensions are a semispan *l*=200 mm and a chord *c*=100 mm, see insets (a), (b) and (c). The towing tank is 10 m long, and 0.5x0.5 m^2 cross-section, in perspex to allow Particle Image Velocimetry (3D-PIV) measurements of the velocity field in the illuminated plane (3). The wing model is vertically assembled on a guide rail (4) that moves (from right to left in the schematic) through the whole towing tank. The electric motor is controlled by a laptop with feedback by means of an encoder (5). The images were recorded by two high-speed cameras located downstream to model movement (6). The towing tank used two rails which were made of iron (7).

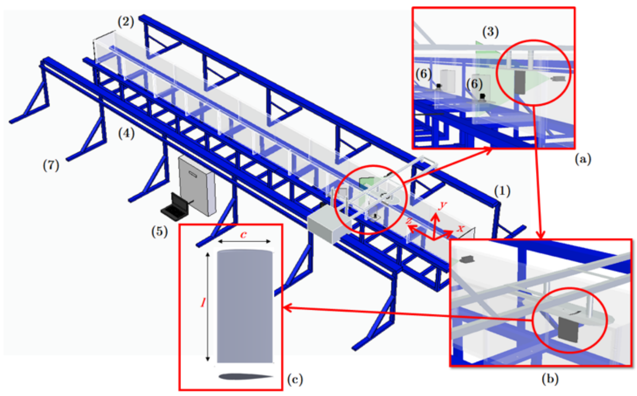

FIG 1. 3D Schematic of experimental setup: NACA0012 wing semispan=2 in a support moving from right to left (1), perspex channel (2), laser sheet (3), guide rail (4), computer to velocity control of guide rail and PIV system (5), high speed cameras (6), and blue iron structure (7). The inset (a) corresponds to zoom in study zone with wing model, cameras, and laser sheet, whereas the insets (b) and (c) show a half-span wing model mounted detail with *c* = 100 mm and *l* = 200 mm.

RESULTS

We have used HODMD to analyze the streamwise vorticity in planes at different distances from the wing tip. Fig. 2 represents in blue the maximum experimental dimensionless vorticity versus the number of frames. It is observed that there are three distinct regions in agreement with the regions where the theoretical vortex intensity parameters (not shown) remain constant (near field, $z^*<6$), decay (intermediate field) and return to constant (far field, $z^*>26$).

HODMD was computed in each of these regions revealing differences in the most physically relevant HODMD modes. The first mode is axisymmetric in every case and structurally similar to the mean flow, see Fig. 3 (left). The second one corresponds to an axisymmetric annular mode, see again Fig. 3 (right), for the middle region while the near and far field do not show this kind of modes. In any case, it is possible to correlate the evolution of the HODMD modes with the vorticity decay. Fig. 2 shows in purple the evolution associated with the HODMD modes on top of the dimensionless vorticity maximum. Additional modes with interesting physical meaning such as dipoles, which appear in every region, are also found.

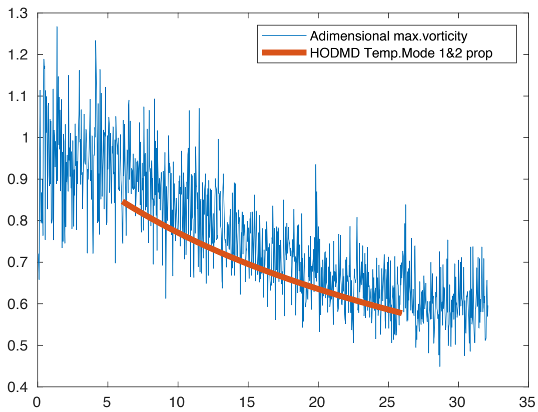

FIG 2. Dimensionless vorticity against distance $z^*=z/c$ along with evolution obtained from HODMD in the middle region ($6<z^*<26$).

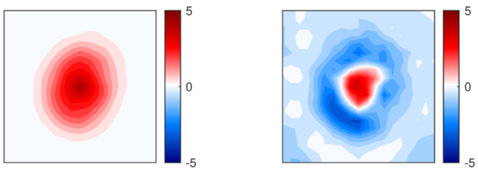

FIG 3. 1&2 Modes with higher amplitude obtained from HODMD in the middle field.

CONCLUSIONS

We have shown how HODMD applied to experimental velocity fields from 3D-PIV in trailing vortices determine the existence of physically relevant modes. It was found that the evolution of these modes is associated with the evolution of the maximum of the vorticity. This interesting result will be useful for the search of active control strategies in future work as a means to alleviate the vortex strength.

—

* cpino@uma.es

[1] Spalart, P. R. (1998) “Airplane trailing vortices”. Annual Review of Fluid Mechancis, **30**, 107—138.
[2] Batchelor, G. (1964) “Axial flow in trailing line vortices”. J.Fluid Mech., **20**, pp. 645—658.
[3] Moore, D., and Saffman, P. (1973) “Axial flow in laminar trailing vortices”. Proc. R. Soc. London, Ser. A, **333**, 403—429.
[4] del Pino, C., Parras, L., Felli, M. and Fernandez-Feria, R. (2011) “Structure of trailing vortices: Comparison between particle image velocimetry measurements and theoretical models”. Physics of Fluids **23(1)**, 013602.
[5] García-Ortiz, J. H., Domínguez-Vázquez, A., Serrano-Aguilera, J. J., Parras, L. and del Pino, C. (2019) “A complementary numerical and experimental study of the influence of Reynolds number on theoretical models for wingtip vortices”. Computers and Fluids **180**, 176—189.
[6] García-Ortiz, J. H., Blanco-Rodríguez, F. J. Parras, L. and del Pino, C. (2020) “Experimental observations of the effects of spanwise blowing on the wingtip vortex evolution at low Reynolds numbers”. European Journal of Mechanics B/Fluids **80**, 133—145.
[7] Le Clainche, S. and Vega, J. M. (2017) “Higher order dynamic mode decomposition”. SIAM Journal on Applied Dynamical Systems **16(2)**, 882—925.
[8] Le Clainche, S. and Vega, J. M. (2017) “Higher order dynamic mode decomposition to identify and extrapolate flow patterns”. Physics of Fluids **29(8)**, 084102.
[9] Kamb, M., Kaiser, E., Brunton, S. L. and Kutz, J. N. (2017) “Time-delay observables for Koopman: Theory and applications”. SIAM Journal on Applied Dynamical Systems **19(2)**, 886—917.