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Unsteady aerodynamics modeling for aircraft maneuvers: A new approach using time-dependent surrogate modeling

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A new approach for computing the unsteady and nonlinear aerodynamic loads acting on a maneuvering aircraft is presented based on linear and nonlinear indicial response methods. The novelty of this approach relies on the use of a grid motion technique for CFD calculation of response functions and the development of a *time-dependent* surrogate model that fits the relationship between flight conditions (Mach number and angle of attack) and responses calculated from a limited number of simulations (samples). The reduced-order model, along with the surrogate model, provides a means for rapid calculation of response functions and predicting aerodynamic forces and moments during maneuvering flight. The maneuvers are generated using a time-optimal prediction code, each covering a different range of angle of attack and motion rates. The side-slip angle ranges from −5° to 5° for all maneuvers, and the model assumes that the lateral aerodynamics is linear with side-slip angle over this range. Results presented show that the aircraft studied in the current paper exhibits highly nonlinear roll moments even at low angles of attack which the linear model fails to predict. The results of the new model provide some evidence that, for a certain range of input parameters, in certain maneuvers considered, the predictions match quite well with URANS CFD predictions. The models were at least better than traditional quasi-steady predictions. However, for aircraft maneuvering at high angles of attacks, discrepancies are found in lateral coefficients between the model and CFD. At these conditions, the lateral airloads become highly nonlinear with side-slip angle and the model fails to predict these effects. Also, the results show that the CFD calculation of response functions in the high angle of attack flight regime remains a challenging task.

1. Introduction

Computational Fluid Dynamics (CFD) tools have become credible for the computation of aerodynamics experienced by a maneuvering fighter with time history effects. This allows for CFD to reduce the amount of wind tunnel and flight testing time required for aircraft development. At the highest practical level, a full-order aerodynamic model can be developed based on the direct solution of the discretized Reynolds-Averaged Navier–Stokes (RANS) equations coupled with the dynamic equations governing aircraft motion [27]. First attempts at this approach were limited to two-dimensional test cases, while with recent advances in computing techniques and the capabilities provided by high performance computing resources, the coupled CFD-flight dynamics of a full aircraft has been studied [39,14]. However, full-order modeling is an infinite-dimensional problem because the solution at each time depends on all of the states at times prior to the current state and the flow equations describe the motion of the fluid at infinitely many points [27,47]. Also, an aerodynamic model for stability and control requires a large number of coupled computations for different values of motion frequency and amplitude which makes full-order simulation a very expensive approach.

To make timely progress in the use of CFD for aircraft design, efforts over the last few years have been spent mainly on the development of a Reduced Order Model (ROM) using CFD from an appropriate training maneuver(s) and an accurate System IDentification (SID) approach [28,30,5]. The objective of the ROMs is to develop a model that significantly reduces the CFD simulation time required to create a full aerodynamics database, making it possible to accurately model aircraft static and dynamic characteristics (within the range of data used for model generation) from a number of time-accurate CFD simulations. These models need an initial or upfront cost to estimate, or identify, the unknown parameters. Once the model has been created, however, the aerodynamics

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Nomenclature

$a(t)$	indicial response function	
b	wing span	m
C_L	lift coefficient, $L/q_\infty S$	
C_{L0}	zero-angle of attack lift coefficient	
$C_{L\alpha}$	lift coefficient derivative with angle of attack	1/rad
C_{Lq}	lift coefficient derivative with normalized pitch rate	1/rad
C_l	rolling moment coefficient, $\bar{L}/q_\infty Sb$	
$C_{l\beta}$	rolling moment derivative with side-slip angle	1/rad
C_{lp}	rolling moment derivative with normalized roll rate	1/rad
C_{lr}	rolling moment derivative with normalized yaw rate	1/rad
C_m	pitching moment coefficient, $\bar{M}/q_\infty Sc$	
C_{m0}	zero-angle of attack pitching-moment coefficient	
$C_{m\alpha}$	pitching moment derivative with angle of attack	1/rad
C_{mq}	pitching moment derivative with normalized pitch rate	1/rad
C_n	yawing moment coefficient, $\bar{N}/q_\infty Sb$	
$C_{n\beta}$	yawing moment derivative with side-slip angle	1/rad
C_{np}	yawing moment derivative with normalized roll rate	1/rad
C_{nr}	yawing moment derivative with normalized yaw rate	1/rad
C_Y	side-force coefficient, $Y/q_\infty S$	
$C_{Y\beta}$	side-force derivative with side-slip angle	1/rad
C_{Yp}	side-force derivative with normalized roll rate	1/rad
C_{Yr}	side-force derivative with normalized yaw rate	1/rad
c	mean aerodynamic chord	m
f	forcing function	
$H(t)$	unit step function	
I_{ij}	moments of inertia	kg m^2
L	lift force	N
M	Mach number	V/a
$\bar{L}, \bar{M}, \bar{N}$	rolling, pitching, and yawing moment	N m
p, q, r	normalized roll, pitch, and yaw rate	rad
q_∞	dynamic pressure, $\rho V^2/2$	Pa
Re	Reynolds number, $\rho V c/\mu$	
S	reference area	m^2
s	normalized time, $2Vt/c$	
t	time	s
V	free-stream velocity	m/s
v_0	initial aircraft velocity	m/s
v_a	aircraft reference point velocity	m/s
Y	side force	N
x, y, z	aircraft position coordinates	

Greek

α	angle of attack	rad
β	side-slip angle	rad
ϕ	roll (bank) angle	rad
θ	pitch angle	rad
ψ	yaw angle	rad
ρ	density	kg/m^3
μ	air viscosity	

prediction of a wide range of maneuvers can be determined in order of a few seconds.

ROMs can be grouped into two different categories of parametric and nonparametric depending on the system identification method used. The parametric types provide a structure for representing aerodynamic forces and moments in the aircraft equations of motion. On the other hand, nonparametric models are concerned with the measured input/output behavior of the aircraft dynamics. The current paper aims to assess the accuracy of predictions of a parametric reduced order model based on indicial response method of Tobak [43].

The transient aerodynamic response due to a unit step change in a forcing parameter, such as angle of attack or pitch rate is a so-called "indicial function". A distinction should be made between indicial and response functions; a response corresponds to the response of a system to a general input, but an indicial response is the specific system response due to a unit step change in the input (such as angle of attack). Assuming that the indicial functions are known, the linear aerodynamic forces and moments induced in any maneuver can be estimated using the well-known Duhamel's superposition integral [26]. Note that aerodynamic predictions by using Duhamel's integral are only valid for linear regimes of flow. To overcome this problem, Tobak [43,47] formulated a nonlinear indicial response model for predicting aerodynamic responses to an arbitrary angle of attack variation. These models have then been used as a fundamental approach to represent the unsteady aerodynamic loads, in particular for two-dimensional airfoils. There have been only limited reports of using these models for aerodynamics modeling of three-dimensional configurations due to limitations of the identification methods of response functions for aircraft configurations. Among these works are the well-known studies of Klein and Norderer [22,23] who applied the indicial response method to an aircraft small-amplitude motion around a trim point. Klein and Murphy [21] and Pamadi et al. [31] later extended this model for aerodynamic modeling of the F-16XL aircraft at high angles of attack. They approximated aircraft responses (including indicial responses) by exponential functions and then identified the unknowns using wind tunnel and flight test data. However, an exponential function is not valid to represent the initial behavior of response functions. Also, wind tunnel and flight test data are expensive and typically only available late in the aircraft design cycle.

Recently, CFD solutions for the indicial response of airfoils and wings have been reported (see for example, Singh and Baeder [40] and Raveh [32]). Also, Ghoreyshi et al. [15] described an approach based on a grid motion technique for CFD-type calculation of linear and nonlinear response functions with respect to angle of attack and pitch rate. Ghoreyshi and Cummings [12] later used this approach to generate indicial functions due to longitudinal and lateral forcing parameters of a generic unmanned combat air vehicle (UCAV) and used these functions for predicting the unsteady aerodynamic responses to aircraft six degrees of freedom maneuvers. They showed that while unsteady lift, side-force and pitch moment (all estimated from indicial response methods) match quite well with full-order simulations in the linear regime, the roll and yaw moments (again estimated from indicial response methods) do not match even at low angles of attack. For the vehicle studied, the roll and yaw moment variation with the angle of attack and Mach number is highly nonlinear [6]. The objective of this paper is to develop a framework for approximating time-dependent response (including indicial) functions in the input design space (angle of attack/Mach). This framework allows rapid calculation of response functions and predicting aerodynamic forces and moments during maneuvering flight.

Having a ROM to predict the aerodynamic responses to any arbitrary motion over a wide flight regime could become a very expensive approach because a large number of response func-