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Forced motions design for aerodynamic identification and modeling of a generic missile configuration ☆

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ARTICLE INFO

Article history:
Received 16 October 2017
Received in revised form 5 April 2018
Accepted 6 April 2018
Available online xxxx

Keywords:
Generic missile configuration
System identification
CFD
Forced motion
Dynamic derivatives

ABSTRACT

This article is focused on the design of forced motions and developing models that can accurately and rapidly predict the aerodynamic stability derivatives of air vehicles over a wide range of air speeds using time-accurate computational fluid dynamic (CFD) simulations. The test case is a generic missile configuration known as the Army–Navy (basic) Finner (ANF) missile. Longitudinal stability coefficients are available from a combination of free-flight and wind tunnel tests for Mach numbers in range of 0.5–4.5. Estimating stability derivatives of this vehicle requires a large number of static and dynamic CFD simulations using a brute-force approach. The present study instead uses a single forced motion to estimate vehicle's stability derivatives over a wide range of speed regimes. The results of this study show that identification of aerodynamic coefficients from time-accurate simulation of the forced motions requires significantly less computational time. A new aerodynamic model is also proposed that captures the aerodynamic coefficients' dependence on the angle of attack, pitch rate, time rate of change of angle of attack, and Mach number including the transonic region. The results presented show that the model predictions agree well with experimental data and those calculated from a brute-force approach. The methods of this work could reduce the computational cost of estimating stability derivatives up to 90%.

1. Introduction

The prediction of aerodynamic stability derivatives using computational fluid dynamics (CFD) has become increasingly feasible as computational speed has steadily increased. However, CFD still remains time-consuming and expensive from a computational resource perspective. As such, the integration of CFD into the aircraft design process, which requires thousands of CFD simulations [1], has been slow. The aircraft design process still relies heavily on experimental testing of scaled prototypes. Therefore the design process is time consuming and expensive as a new aircraft is iteratively redesigned and re-tested in response to poor aerodynamic behavior. Additionally, wind tunnel tests are limited to low Reynolds and Mach numbers, and motions that can be achieved in the tunnel and suffer from model support interference effects [2]. The numerical solution of the unsteady Reynolds-averaged Navier–Stokes (RANS) equations is a powerful tool for estimating the stability derivatives of aircraft. However, increased efficiency is needed in predicting the aerodynamic coefficients of complex aircraft configurations in order for CFD to be more readily integrated into the aircraft design process.

The current techniques for aerodynamic coefficient prediction using CFD involve running numerous static computations at discrete flight conditions in order to determine the stability and control characteristics of the aircraft over its flight envelope. This process is two-fold: steady state computations are completed to determine static stability coefficients, and time accurate simulations of sinusoidal pitching and plunging behavior are completed to predict dynamic and acceleration derivatives. Creating an aerodynamic model over the entire flight envelope requires numerous time-accurate and RANS simulations, often adding up to millions of CPU hours.

Some efforts on reducing the computational cost to estimate aerodynamic derivatives are reported in Ref. [3]. Specifically, recent works have tried to extend the application of derivative-based aerodynamic models to advance fighter aircraft using CFD simulations [4–7]. These new models use a global nonlinear parameter modeling technique proposed by Morelli [8] that describes the functional dependence between a motion and its computed aerodynamic response in terms of force and moment coefficients. The

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https://doi.org/10.1016/j.ast.2018.04.014
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Please cite this article in press as: J. Allen, M. Ghoreyshi, Forced motions design for aerodynamic identification and modeling of a generic missile configuration, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.04.014

Nomenclature

C_m	pitching moment coefficient	
$C_{m\alpha}$	pitching moment curve slope	1/rad
C_{mq}	pitch moment due to normalized pitch rate	1/rad
$C_{m\dot{\alpha}}$	pitch moment due to normalized time-rate change of angle of attack	1/rad
$C_{m\dot{\alpha}} + C_{mq}$	pitch damping moment	1/rad
C_N	normal force coefficient	
$C_{N\alpha}$	normal force curve slope	1/rad
C_{Nq}	normal force due to normalized pitch rate	1/rad
$C_{N\dot{\alpha}}$	normal force due to normalized time-rate change of angle of attack	1/rad
$C_{m\dot{\alpha}} + C_{Nq}$	pitch damping force	1/rad
C_x	axial force coefficient	
C_{x0}	axial force coefficient at zero angle of attack	
D	diameter of missile – Reynolds length	m
f	frequency	Hz
k	reduced frequency, $\frac{\omega D}{2V}$	
M	Mach number	
$\bar{q}$	pitch rate	rad/s
q	normalized pitch rate	
t	time	s
u, v, w	velocity components in inertial X, Y, and Z directions	m/s
V	free-stream velocity	m/s
Greek		
α	effective angle of attack	deg or rad
θ	pitch angle	deg or rad
ω	angular velocity	deg/s or rad/s

current work is also focused on similar system identification methods and using CFD simulation of several motions as training data. Forced motion simulations in CFD potentially offer a significant reduction in the computational cost needed to determine an aircraft's aerodynamic behavior. While each static run typically needs several thousand time steps to converge, a dynamic motion simulation that sweeps over the range of an input parameter (e.g., Mach number or angle of attack) costs about the same as a few static runs.

Forced motion (also known as prescribed motion) is a numerical technique used in CFD solvers where the grid is numerically translated and rotated with respect to the reference conditions of the simulation. This allows for the free-stream velocity to be manipulated to any desired speed and any incident angle with time accuracy. This creates the opportunity to use a forced motion to vary Mach number, angle of attack, acceleration terms, and angular rates in a single computation. A forced motion can be thought of as a computational flight test, but without the flow (e.g., post stall) and kinematic restrictions (e.g., G-force) of the aircraft or pilot.

Forced motion simulations are used commonly in CFD, and previous works in literature have shown that prescribed motion is an effective way to identify the aerodynamic coefficients over certain ranges of the flight envelope. Using forced motions for changes in angle of attack and pitch angle, aerodynamic models have been developed with good accuracy in predicting both experimentally and computationally determined coefficients [7,9–11]. However, studying the influence of Mach number on the aerodynamic behavior of an aircraft using forced motions has not been extensively studied, especially for an aircraft with a transonic flight envelope. This work therefore applies the forced motion approach to determine the dependence of both static and dynamic aerodynamic coefficients on Mach number for the ANF missile.

This study specifically focuses on new forced motion designs that could accurately predict the ANF longitudinal stability derivatives with the least computational time. The impacts of motion design and aerodynamic models on predictions are investigated. The computational costs are compared with those calculated from a brute-force approach. This work is organized as follows: first the test case and available experimental data are described. Next, the flow solver and some definitions and notations are presented. Finally, the results are discussed and some concluding remarks are provided.

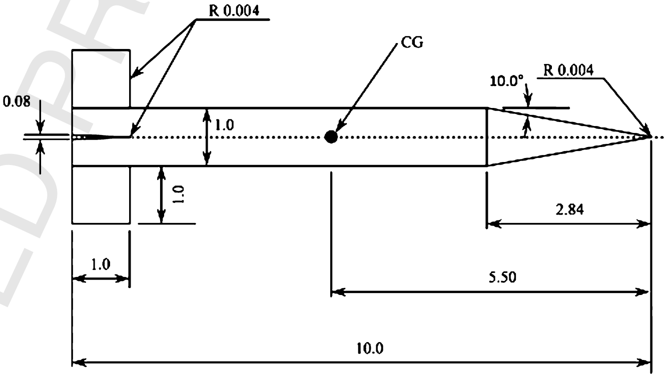

Fig. 1. The Army–Navy (Basic) Finner missile geometry from Ref. [12]. Dimensions are in calibers.

2. Test case

The ANF missile is shown in Fig. 1. The design has an overall length of 10 calibers (1 caliber = 30 mm) with a 20°, 2.84-caliber long cone. The ANF has four rectangular, uncanted, 1-cal × 1-cal fins mounted level at the base of projectile. The fins are wedge-shaped with very sharp leading edges (0.004 calibers radius) and thicknesses of 0.08 calibers at the trailing edge. The center of gravity is located at 5.5 calibers (165 mm) from the nose of the projectile. This configuration has been used as a reference projectile in many studies because the aerodynamics and flight mechanics data are well known and readily available [12].

Experimental aerodynamic data of the ANF were obtained from a combination of free-flight tests in a ballistic range and wind tunnel measurements at different test facilities, including Defense Research and Development Canada (DRDC) [12,13] for Mach numbers in range of 0.5–4.5. A nominal flight condition of standard sea level was used with pressure of 101,325 Pa and temperature of 293.15 K. The main aerodynamic coefficients measured include C_{x0}, the axial force coefficient at zero angle of attack, $C_{N\alpha}$, the normal force curve slope at zero angle of attack (or linear range of AoA), $C_{m\alpha}$, the pitch moment curve slope at zero degrees angle of attack about the center of gravity, and the pitch damping derivatives, $C_{Nq} + C_{N\dot{\alpha}}$ and $C_{m\dot{\alpha}} + C_{mq}$.

The computational grid used in this work is shown in Fig. 2. This grid has around 20.7 million cells and a y^+ value less than one at Mach 4.5. Note that test conditions of this missile covers subsonic, transonic, and supersonic flight regimes. Transonic regime has a mixture of subsonic and supersonic flow. For the ANF missile, transonic speed regime is in the approximate

Please cite this article in press as: J. Allen, M. Ghoreyshi, Forced motions design for aerodynamic identification and modeling of a generic missile configuration, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.04.014