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Navier–Stokes predictions of dynamic stability derivatives for air-breathing hypersonic vehicle

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ABSTRACT

Dynamic derivatives are important parameters for designing vehicle trajectory and attitude control system that directly decide the divergence behavior of vibration of the aircraft open-loop system under interference. After calibration model validation, the dynamic behavior of air-breathing hypersonic vehicle WR-A is characterized. The unsteady flow field of aircraft forced simple harmonic vibration (SHV) is simulated using N–S equation. The direct damping derivatives, cross derivatives, acceleration derivatives and rotary derivatives of WR-A under different frequencies, amplitudes and positions of centroid are obtained. Research demonstrates that the proportion of acceleration derivatives, which represents the flow time lag effect, in the direct damping derivatives can be as high as 40% but is opposite to the damping derivative value symbols in some cases, contributing to dynamic instability. Numerical simulation on large-amplitude forced vibration of WR-A indicates that the aerodynamic behavior predicted by the dynamic derivative model agrees well with unsteady calculations. The inlet performance parameter derivatives are solved using the Etkin theory. The inlet performance parameters under large-amplitude vibration are successfully predicted using the dynamic derivative model. This offers a guideline for characterizing the dynamic internal flow field and unsteady inlet performance.

1. Introduction

In aircraft design and development, it is difficult and costly to achieve dynamic stability within the flight envelop. Shock wave-induced separation, swirling motion and rupture and the interaction between them lead to strong unsteady and nonlinear behaviors of fluid motion, which generally results in aerodynamic effect beyond expectation and even some overwhelming consequences. In the aircraft design stage, it is hard to foresee the boundaries of dynamic operation stability and the severity level of dynamic problems, most of which are not discovered until in the flight test stage. This directly leads to multiplication of the aircraft design cycle, significant increase of design cost and detrimental effects on performance [1]. In order to meet the demand of future aerospace development for launch vehicle technology, hypersonic airframe-propulsion integrative vehicle technology is a hotspot within the aerospace community [2,3], yet dynamic stability has remained a problem behind it [4]. Research on space launch vehicle X-33 discovered obvious lateral instability in its liftbody configuration. Hypersonic vehicle HTV-2 displayed rolling/yawing coupling motion at the reentry-glide transition due to inadequate flight stability and maneuverability, inducing far greater overshot yawing/rolling moment than practically controllable, which eventually led to out-of-control attitude [5,6]. The analysis report on the flight failures of X-43A and X-51A revealed that the aerodynamic force of specially-configured vehicles has far greater nonlinearity than

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anticipated, and inaccurate aerodynamic modeling is believed to be one of the key contributors to flight failures. To better understand the causes of flight stability deterioration from the fluidity mechanism horizon, unsteady aerodynamic mathematic model has been widely applied to the studies to dynamic flight quality issues [7]. A mature, reliable package of unsteady aerodynamic mathematic models enables us to evaluate and select different aircraft design plans so as to minimize the aircraft design cost and mitigate risk exposure [8].

To solve flight stability, Bryan [9] introduced the concept of stability and dynamic derivative in 1911, which has been applied to flight motion equation for a century as a traditional aerodynamic model. Dynamic stability parameters are important parameters for vehicle maneuverability and stability analysis [10]. Dynamic derivatives are needed for engineering because [11]: a. Dynamic derivatives are important parameters for trajectory design and calculation of hypersonic vehicles; b. Dynamic derivatives are important parameters for attitude control system design of hypersonic vehicles, during which the amplification factor or gain factor is often based on dynamic stability parameters; c. Dynamic derivatives are important basis for dynamic stability analysis and flight quality analysis of hypersonic vehicles. As many as ten-plus dynamic stability parameters are involved in the attitude control system design and ballistic trajectory design of hypersonic vehicle. Table 1 lists the dynamic stability derivatives of the moment coefficient [11], where C_l, C_m, C_n represent rolling, pitching and yawing moment coefficients, respectively; α and β are the angle of attack and angle of sideslip; p, q and r are the angular speed components of the rolling axis, pitching axis and yawing axis.

The importance of the derivatives in Table 1 may vary with the aerodynamic configurations or aspect investigated. So far, most dynamic derivative calculation directly targets at direct damping derivatives, involving little numerical calculation of cross derivatives or cross coupling derivatives. The cross derivative of the vehicle reflects its longitudinal and lateral cross coupling. As its magnitude is small and uncertainty is high, numerical approaches are needed to ensure accurate simulation of its flow asymmetry. Literature [12] provides the calculation method for these derivatives. As little has been done to predict cross derivatives by calculation and experiment, not many data are available on the comparison between calculation and experiment. In this paper, further studies are carried out in this respect to improve the reliability of cross derivative prediction.

The direct damping derivative of the vehicle is the combination of its rotary derivative and acceleration derivative. Presently, considerable attention is paid to direct damping derivative in the calculation and experiment of dynamic derivatives, in which rotary derivative is separated from acceleration derivative in the proportion of 70–30% following the traditional engineering practice. However, as an air-breathing hypersonic vehicle has more complex exterior design and motion mechanism as well as higher flow nonlinearity and non-steadiness than its traditional counterpart, the rationality of this method is receiving increasing doubts. Numerical simulation of acceleration derivatives for hypersonic re-entry capsules [13], winged underwater vehicles [14] and hybrid lift-buoyancy airships [15] has indicated that the proportion of acceleration derivatives in the combination derivative is not stationary but varies between 30% and 50%. In some cases, however, the symbol of the acceleration derivative is the opposite to that of the combination derivative, which acts as a negative damping and causes dynamic instability. In our study, numerical simulation is conducted on the rotary derivatives and acceleration derivatives of integrated-flow vehicles. Our dynamic derivative prediction and stability forecasting will provide important aerodynamic parameters for the control system design, dynamic instability boundary analysis and dynamic stability criteria research of the vehicle.

Currently, the configuration commonly used for dynamic derivative calculation is mostly the relatively simple configuration of a body of revolution, such as the configuration of a re-entry capsule [16], circular cone [17], hyperballistic shape HBS [18], the 25-mm M910 TPDS-T subprojectile [19], the 0.50-cal. projectile [20]. The dynamic derivative calculation of complex configuration major focus on conventional aircraft which does not include internal flow, such as Basic Finner Missile [21], DLR-F12 [22], SDM [23]. For a hypersonic airframe/propulsion integrative vehicle, its configuration is much more complex than conventional aircraft that does not include internal flow. At present, the difficulty with dynamic derivative calculation is typically decided by how complex the unsteady flow field is, and the calculation methods mainly include fast engineering calculation [24], linear frequency domain method [25–27], non-Linear frequency domain method [28,29] and precision time-domain prediction [30]. As both of these methods are the simplified

Table 1
Dynamic stability derivatives of the moment coefficient [11].

	Rotation derivatives	Acceleration derivatives	Vibration around a fixed axis		
			Direct derivatives	Cross derivatives	Cross-coupling derivatives
Roll moment derivatives	C_{lp}, C_{lq}, C_{lr}	$C_{l\dot{\alpha}}, C_{l\dot{\beta}}$	$C_{lp}+C_{l\dot{\beta}}\sin\alpha$	$C_{lr}+C_{l\dot{\beta}}\cos\alpha$	$C_{lq}+C_{l\dot{\alpha}}$
Pitch moment derivatives	C_{mp}, C_{mq}, C_{mr}	$C_{m\dot{\alpha}}, C_{m\dot{\beta}}$	$C_{mq}+C_{m\dot{\alpha}}$		$C_{mr}+C_{m\dot{\beta}}\cos\alpha$ $C_{mp}+C_{m\dot{\beta}}\sin\alpha$
Yaw moment derivatives	C_{np}, C_{nq}, C_{nr}	$C_{n\dot{\alpha}}, C_{n\dot{\beta}}$	$C_{nr}+C_{n\dot{\beta}}\cos\alpha$	$C_{np}+C_{n\dot{\beta}}\sin\alpha$	$C_{nq}+C_{n\dot{\alpha}}$