Identification from Flight Data of the Aerodynamics of an Experimental Re-entry Vehicle

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Post flight data analyses are essential activities in aerospace projects. In particular, there is a specific interest in obtaining vehicle aerodynamic characteristics from flight data, especially for re-entry vehicle, in order to better understand theoretical predictions, to validate wind-tunnel test results and to get more accurate and reliable mathematical models for the purpose of simulation, stability analysis, and control system design and evaluation. Indeed, due to atmospheric re-entry specificity in terms of environment and phenomena, ground based experiments are not fully exhaustive and in-flight experimentation is mandatory. Moreover pre-flight models are usually characterised by wide uncertainty ranges, which should be reduced. These objectives can be reached by performing vehicle's model identification from flight data.
This chapter presents a novel analytical model for describing the aerodynamics of a re-entry vehicle in subsonic, transonic and supersonic regimes, and an innovative methodology for the estimation of model parameters from flight data.

The Italian Aerospace Research Centre (CIRA) has faced the problem of re-entry vehicle model identification from flight data within the framework of its Unmanned Space Vehicle (USV) program. The main objective of this program is designing unmanned Flying Test Beds, conceived as multi-mission flying laboratories, in order to test and verify innovative materials, aerodynamic behaviour, advanced guidance, navigation and control functionalities as well as critical operational aspects peculiar of the future Reusable Launch Vehicle. The first vehicle of USV program, named FTB_1, is unmanned and un-powered and has been developed for investigating the terminal phase of re-entry mission, that is, subsonic, transonic and low supersonic flight regimes. The FTB_1 is a winged slender configuration, with two sets of aerodynamic effectors: the elevons, that provide both pitch control when deflected symmetrically and roll control when deflected asymmetrically, and the rudders, that deflect only symmetrically to allow yaw control. Lateral-directional stability is enhanced by means of two ventral fins. A Hydraulic Actuator System (HYSY) controls the aerodynamic effectors.
The FTB_1 vehicle already performed two test missions, in winter 2007 and in spring 2010. Both mission profiles were based on the release of the vehicle from a high altitude scientific balloon at nominal mission altitude (about 20 km for the first mission and 24 km for the second one), followed by a controlled gliding flight down to the deployment of a recovery parachute. In the first mission the transonic regime of flight was reached (Mach ~1.05) while

holding the angle of attack at a constant value. No lateral directional manoeuvres were foreseen and the flight was very short, lasting only about 40s. Based on first mission experience, second mission was more complex. After release, the vehicle performed a pitch-up manoeuvre to reach and hold predefined angle of attack while accelerating up to Mach 1.2 at about 15 km altitude; then a pull down manoeuvre was performed to keep the Mach number constant while a sweep in angle of attack was executed. Such manoeuvre allows the verification of the aerodynamic behaviour of the vehicle at constant Mach and variable angle of attack in full transonic regime as it would happen in a wind tunnel facility. At the end of this manoeuvre the vehicle began a pull up manoeuvre to decelerate to very low speeds (below Mach 0.2) and reached an altitude lower than 5 km where a low-cost subsonic parachute was opened, allowing a safe water splashdown of the vehicle.

Data gathered during the FTB_1 missions were analysed by means of innovative model identification techniques. Model identification of a re-entry vehicle is a very challenging task for the following main reasons

1. The aerodynamics of a re-entry vehicle are characterised by complex flow structure that produces significant variations of all the aerodynamic coefficients depending on Mach number and angle of attack, making it difficult to model the vehicle aerodynamic behaviour, particularly in transonic regime.
2. Experimental re-entry missions are typically performed once, providing a limited number of suitable data, and the experiment cannot be repeated in the short term. Therefore, it is difficult to refine the vehicle model in the whole flight envelope.
3. Due to safety constraints, manoeuvres specifically suited to the purpose of model identification are minimised.

The first two issues call for structured parametric models based on physical considerations, where the flow field characteristics in the regimes of interest are represented with adequate accuracy. As a major advantage, such a model would extend the results obtained from the analysis of a single trajectory to the whole flight envelope. Structured models where the aerodynamic coefficients are expressed using some interpolation technique as functions of Mach number, aerodynamic angles and control surfaces deflection are usually proposed in the literature for the purpose of identification. Since these models are not based upon first principles, they cannot, in general, be applied outside of the region of the flight envelope where flight trials are undertaken. On the other hand, the third topic above requires that as much as possible information is extracted from low excitation inputs, and is thus related to the effectiveness of the adopted identification methodology.

In this chapter a novel parametric aerodynamic model is proposed, the structure of which is based on first principles and specifically accounts for the peculiarities of a slender winged body configuration like the FTB_1 vehicle. The model provides a continuous and regular analytical representation of nondimensional aerodynamic force and moment coefficients acting on the vehicle in the three regimes of subsonic, transonic and supersonic flow. It is based on the Kirchoff theorem, which in origin was formulated for incompressible streams and is based on the linear property of the continuity equation. This theorem states that, for an incompressible flow, the local fluid velocity around an obstacle is a linear function of the peculiar velocities of the problem. To study the vehicle aerodynamics in the compressible regimes, the Kirchoff theorem is properly extended here to the compressible streams, taking into account that the local velocity depends on the fluid compressibility through the von

Kármán equation. The model allows expressing each aerodynamic coefficient as nonlinear function of Mach numbers, aerodynamic angles, control angles, angular rates, and a set of constant aerodynamic parameters. The nonlinear behaviour stems from the effect of Mach number in the transonic regime and from the aerodynamic characteristics of the FTB_1 low aspect ratio, lifting-body configuration.

The estimation of the parameters of the aerodynamic model is carried out as follows. First, they are determined before flight, fitting a pre-flight aerodynamic database, built upon wind-tunnel test data and CFD analysis. Next, a subset of the model parameters is identified form flight data analysis, in order to update their pre-flight values and to reduce the related uncertainty level. To this end, an original model identification methodology is presented, which works in the framework of a two-step strategy called Estimation Before Modelling (EBM). In the first step of EBM, the aerodynamic coefficients and some atmospheric properties (such as local wind experienced during the mission) are estimated. This step is formulated as nonlinear filtering problem and solved using the Unscented Kalman Filter (UKF). The nonlinearity arises from the vehicle nonlinear equations of motion. The UKF enables a complete and structured statistical characterization of the estimated variables, leading to a reliable evaluation of uncertainties on the unknowns. The availability of the aerodynamic coefficients with related uncertainty allows validating pre-flight aerodynamic databases and models. Concerning the implementation of the filter, we adopt a non-augmented algorithm for the UKF, in order to reduce the number of filter states; moreover, to avoid a loss of information on the effect of process noise on output, two concatenated Unscented Transformations are carried out to account for the estimate propagation throughout nonlinear process and measurement equations. The second step receives in input the aerodynamic coefficients (and related uncertainties) calculated in the previous step, and provides an estimation for a subset of the aerodynamic model parameters that, as said before, is valid throughout the whole flight envelope of interest. The subset of parameters is selected using a sensitivity analysis based on the evaluation of the Cramer Rao Bounds. The parameters estimation could be performed using the UKF again as well as the simpler Least Mean Squares techniques. When the estimation is carried out, the uncertainties on the aerodynamic coefficients identified in the first step are treated as measurement noise. They are rigorously propagated through the second step, whatever the applied estimation methodology is, in order to get reliable characterisation of the identified aerodynamic model. In conclusion, the proposed methodology allows to deal independently with the estimation of global aerodynamic coefficients and parameters of the aerodynamic model, performed in the first and second step, respectively. Moreover, it guarantees an accurate statistical characterisation of the estimates, that is, it calculates both the nominal value and the related estimation uncertainties of the aerodynamic parameters, by using all the available pre-flight information and in-flight gathered data. In this way, the identified model is completely defined and the identification process generally allows getting values of the aerodynamic uncertainties that are lower than the pre-flight ones.

The application of the above described aerodynamic modelling and identification methodologies to the flight data of the first two missions of the FTB_1 vehicle provided interesting results in terms of estimation convergence, reduction of uncertainty with respect to pre-flight model and capability of extracting useful information content on the vehicle aerodynamics from a rather limited set of flight data in different flow regimes.