HYBRID MULTI-STEP STRATEGY FOR ROTORCRAFT IDENTIFICATION FROM FLIGHT DATA

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Abstract: The availability of suitable methods for system identification from flight data of rotorcraft models is a key factor to enhance the competitiveness of the rotorcraft industry in the development process of new vehicles. Indeed, reliable simulation models provided by the identification techniques can be used for the design and validation of the vehicle flight control system. It allows minimizing the number of in flight experimental tests and consequently reducing costs and risks related to flight testing.

Much of the published works on rotorcraft identification deals primarily with frequency-domain methods, which work well at mid and high frequencies associated with the dynamics of the vehicle control inputs and the aero-elastic behavior of the blades. On the other hand, time-domain methods provide accurate models at the low frequency scale that is related to the vehicle flight mechanics.

In this paper a hybrid time-frequency identification approach is proposed. The identification process is carried out in the framework of a multi-step strategy and a specific methodology is selected to comply with each step objective. The hybrid time-frequency approach allows exploiting the advantage of both time and frequency methods, maximizing the information content extracted from the flight data and obtaining an identified model applicable in the whole frequency range of interest. Furthermore the multi-step strategy decomposes the complex starting problem in simplified sub-problems.

The proposed methodology was applied to simulated data of the UH60 Black Hawk, generated using the FLIGHTLAB multi-body simulation environment. Preliminary results show the effectiveness of the proposed identification strategy in terms of convergence and capability of extracting from flight data relevant information on the vehicle dynamic behavior. Current work is focused on the refinement of the rotorcraft model structure used for identification purpose, in order to further improve the already promising preliminary results.

1 INTRODUCTION

Rotorcraft system identification is still a challenging task, mainly due to the complexity of the model used to describe the vehicle dynamics. In fact, rotorcraft aeromechanical analyses are usually based on highly nonlinear coupled multi-body models ([1]), which include both slow flight mechanics scales and faster aero-elastic ones. Furthermore the rotorcraft models are typically unstable, at least in certain flight conditions ([2]). For those reasons, suitable identification techniques have to be developed to get high fidelity simulation models of rotorcraft dynamics, which could be used to improve the performance, stability and handling qualities of the vehicle and to design the control systems by minimizing the number of flight tests, with a consequent reduction of risks and costs in the development process of new products.

Dynamics identification methodologies generally fall into two categories: frequency-domain and time-domain. Each approach has inherent strengths and weaknesses. Much of the published works on rotorcraft system identification deals primarily with frequency domain methods ([1]). Frequency-domain identification uses spectral techniques to determine frequency responses between selected input and output pairs. The MIMO frequency response matrix constitutes a nonparametric model of the system, since it fully characterizes the input-to-output behavior without the need for defining a priori the model structure or determining the model parameters ([3]). In order to obtain closed-form analytical models of the transfer-functions of linearized input to output processes, least-squares fitting techniques are used in the frequency domain to match the Bode plot of the frequency response. The semi-logarithmic frequency format of the Bode plot, and subsequent transfer function fit, makes the identified models most accurate at mid and high frequencies, whereas low-frequency and steady-state response prediction is generally not very good ([3]). On the other hand, time-domain methods are widely used for the identification of fixed wing vehicles ([4]) and can be applied to the identification of rotorcrafts ([2]), too. Time-domain approach requires the definition of a model, which involves considerations about the model structure, selection of significant parameters and inclusion of important nonlinearities. Time-domain identification inherently weights low-frequency dynamics much greater than high-frequency ones, for that reason the identified model is accurate at low and mid frequencies ([3]).

In this paper we propose a new hybrid time-frequency technique for rotorcraft system identification, performed in the framework of a multi-step strategy ([5]). The approach allows to exploit the advantage of both time and frequency methods and, together with the selection of a suitable vehicle model structure, permits to obtain an identified model applicable in the whole frequency range of interest (from low to high frequencies). Furthermore the multi-step strategy decomposes the complex starting problem in simplified sub-problems, which are easier to be solved.

In what follows, Section 2 is dedicated to the presentation of the rotorcraft model selected for identification purpose, whereas the identification strategy and methodologies are described in Section 3. Section 4 is focused on the presentation of the case study used to test the proposed technique. In Section 5 identification results are showed and discussed. Finally, a section of conclusions, also describing the ongoing work, ends the paper.

2 ROTORCRAFT MODEL FOR IDENTIFICATION PURPOSE

The rotorcraft model we adopt in this paper is composed of:

- nonlinear rigid body equations of motion, to describe fuselage dynamics;
- main rotor nonlinear model;
- model of the global force and moment acting on the fuselage.

Since we aim at identifying the open loop model of the rotorcraft, the flight control system is not modeled. Figure 1 presents the functional blocks of the model to be identified.

The main rotor model simulates coning, longitudinal and lateral flapping dynamics in multi-blade coordinates. They are modeled through coupled first order nonlinear system, which includes unknown parameters to be estimated from flight data. Inputs to the rotor model are the control inputs (longitudinal and lateral cyclic pitch, main and tail rotor collective pitch) and the fuselage velocity and angular rates, which are introduced to take into account the effect of the fuselage on the main rotor. The set of inputs, as well as the nonlinear terms included in the model, are selected on the basis of physical meaning and engineering judgment. The outputs of the model (that is, coning longitudinal and lateral flapping) are inputs for the computation of the force and moment acting on the fuselage. In this way the fuselage/main rotor coupling is correctly taken into account by the model.

The external forces and moments are modeled through a lumped parametric model, in which each force or moment is expressed as parametric function of the flight measurements of the vehicle state vector and the control inputs. Based on physical considerations and sensitivities analysis, the functional dependence on many inputs is neglected, dramatically reducing the number of the unknowns to be estimated. The preliminary structure of the model is static and linear; we are refining this structure in order to include nonlinear terms and to introduce a time delay on the control signals, with the aim to take into account all the un-modeled dynamics (such as the inflow, for example). The delay will be estimated in the identification process together with the model's parameters.

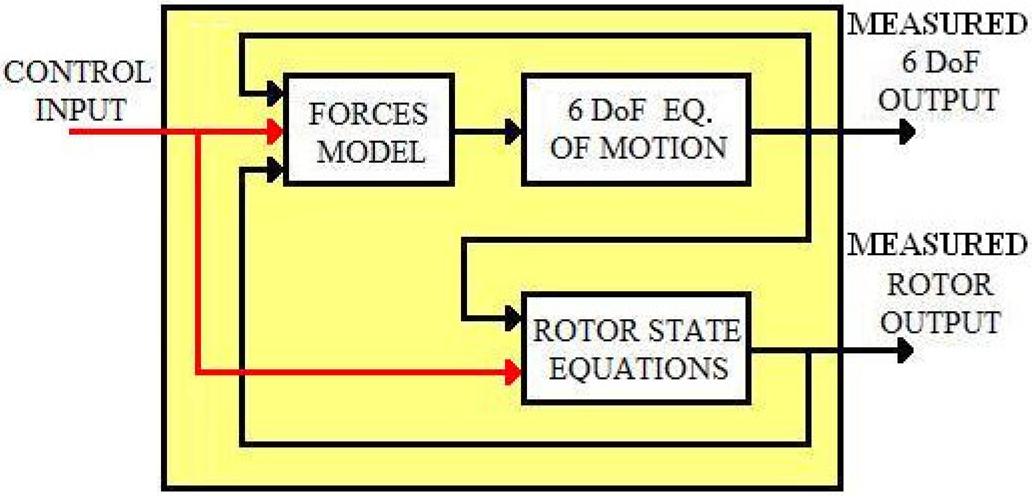

Figure 1: Rotorcraft model functional blocks

3 IDENTIFICATION METHODOLOGY

In this paper we propose a new hybrid time-frequency technique for rotorcraft system identification, which is performed in the framework of a three-step approach. The identification steps are aimed at estimating:

- the time history of the global external forces and moments acting on the vehicle's fuselage during the flight (first step)
- all the unknown parameters of the main rotor model and the unknown parameters of the forces model related to the high frequency dynamics (second step)
- all the unknown parameters of the forces model associated to the low and mid frequency dynamics (third step).

The Flowchart of the identification process is shown in Figure 2, which is followed by the description of and the methodologies applied in each identification step.

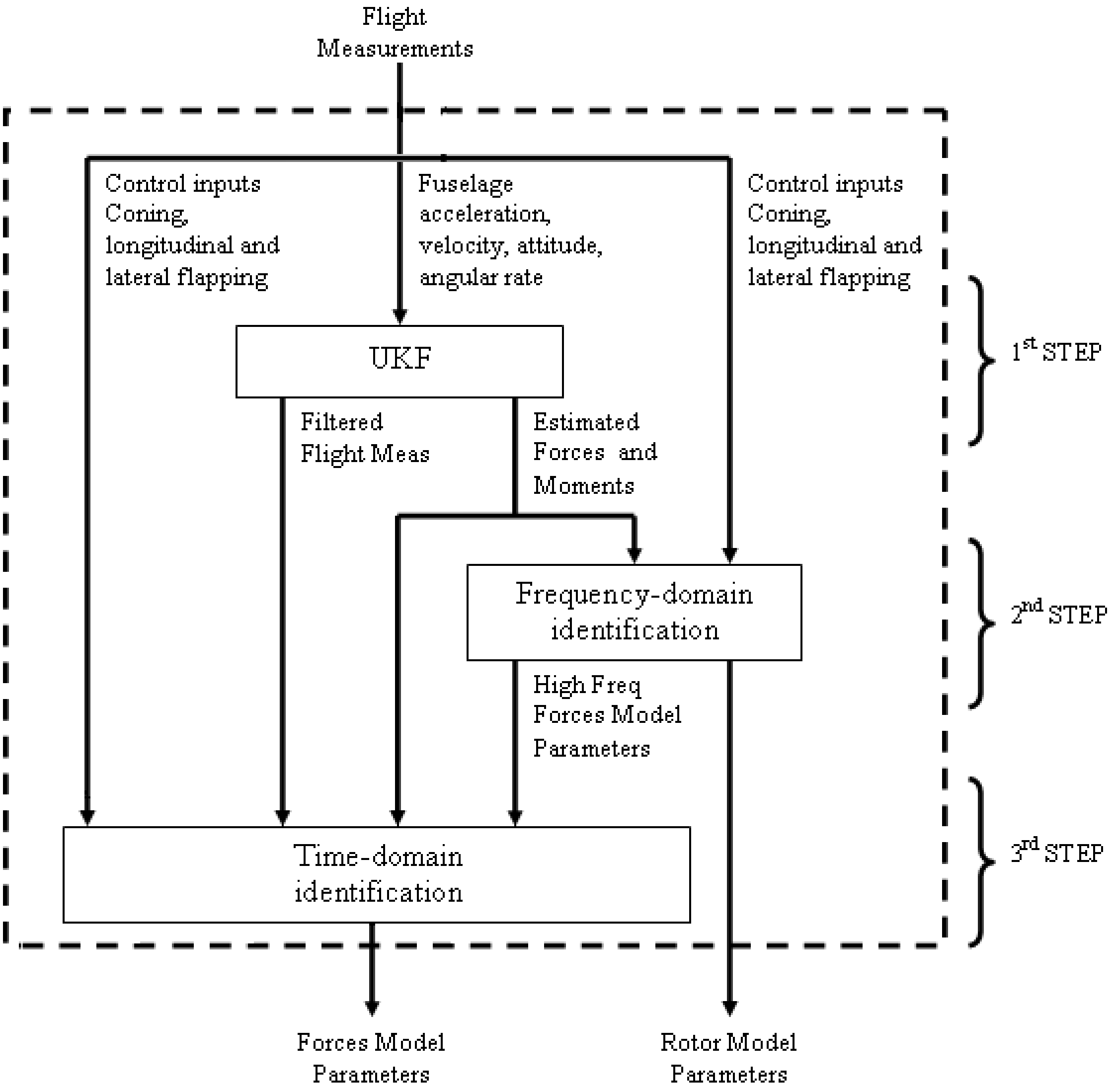

Figure 2: Flowchart of the identification process

The first step is carried out in the time-domain using a filtering approach based on the Unscented Kalman Filter (UKF) ([6]). In this work the filtering is performed using a non-augmented algorithm for the UKF, in order to reduce the filter state vector dimension, and process and measurement noises are assumed white Gaussian and additive. To avoid a loss of information on the effect of process noise on output, two concatenated UTs are executed to account for the transformation of mean and covariance throughout the nonlinear process equations and measurement equations ([7]). The filter's model is composed of the 6 DoF equations of motion plus the model of the sensors used to gather the flight measurements (output equations). A by-product of the first step is a filtered (then more reliable and accurate) set of these flight measurements and the associated estimation error characterization.

Second identification step is performed in the frequency-domain using the Fourier Transform Regression methodology, proposed by Morelli ([9]). This technique is an equation error method which estimates the unknown parameters by minimizing the sum of square differences between measured data and corresponding values provided by the model on a selected frequency range. The choice of the frequency range allows focusing on the estimation of the parameters associated to the mid-high frequencies. Moreover the technique is applicable to linear and nonlinear system, however linear in the unknown parameters. Finally, being an equation error method, it doesn't require an initial estimate for the unknown parameters. The proposed approach applies this technique to estimate all the parameters of the main rotor model and to the parameters of the forces model related to the high frequency dynamics. It is assumed that the measurements of command inputs, coning flapping, longitudinal and lateral cyclic flapping are available.

In the third step the remaining unknown parameters of the forces model are estimated. The identification is performed in the time-domain by means of the Maximum Likelihood Estimation (MLE) technique, based on bounded-variable Gauss-Newton optimization method. The subset of parameters estimated in the second step is provided in input to this step, together with the estimation of force and moment performed in the first step.

Results of the identification process are used to implement the rotorcraft simulation model in MATLAB/SIMULINKTM environment. The first level diagram of the model is shown in the following figure.

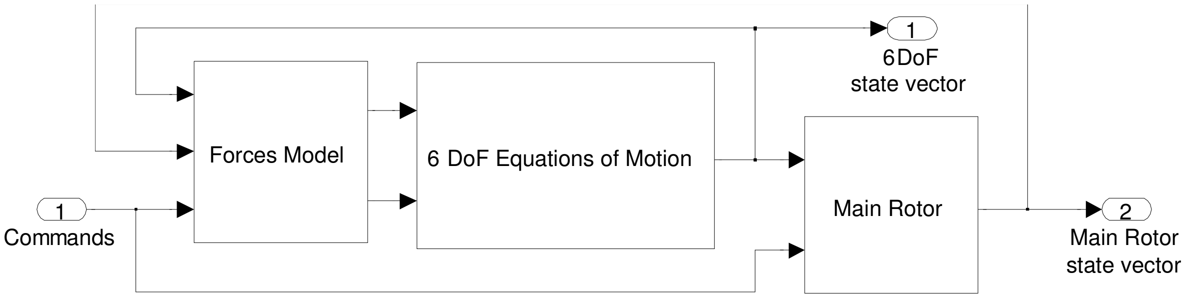

Figure 3: SIMULINK block diagram of the identified rotorcraft model

4 CASE STUDY

The FLIGHTLAB Software Environment is used to build a simulation model for flight data generation. The rotorcraft model is nonlinear with characteristics similar to the ones of the UH60 Black Hawk ([10]). It includes main rotor, tail rotor and fuselage. The main rotor is four-bladed with flap and lag articulation provided at the blade root by electrometric bearings. The rotor blade elastic characteristics are introduced via nonlinear flexible beam elements and the rotor aerodynamic model includes a 2-D indicial formulation to account for the blade sectional air loads unsteadiness. The rotor induced-flow dynamics is modeled using the Peters-He finite state wake model with 15 state variables ([11]).

Several flight tests are performed. For each of them, flight data are gathered over a time range of 15s at sampling frequency of 154 Hz and corrupted by white zero mean Gaussian noise, introduced to simulate the sensors measurement errors. Three types of identification maneuvers are carried out, perturbing a hover trimmed condition at 90 ft altitude:

- 3-2-1-1-type perturbation (applied to each of the four rotorcraft controls);
- doublet-type perturbation (applied to each of the four rotorcraft controls);
- collective sweep.

The amplitude of the perturbation is equal to 10% of the maximum control deflection. In the final version of the paper, the model will be identified not only in proximity of the hover, but also in forward flight for moderate velocity conditions.

Due to the possible instability of the vehicle, identification test maneuvers are performed while flight control system is active, degrading the optimality of the flight test.

5 PRELIMINARY IDENTIFICATION RESULTS AND DISCUSSION

A preliminary subset of identification results are presented in this section.

The first identification step is performed independently on each flight test. Examples of the UKF results are presented in Figure 4, where the estimated force is compared with the true one for the 3-2-1-1 lateral cyclic flight test. True and estimated trajectories are undistinguishable, confirming that the estimation results are very good. In the same figure, the estimation error (right column) is compared with the 3σ uncertainty on the estimation, also provided by the UFK. The characterization of the estimation error is consistent with the actual estimation error.

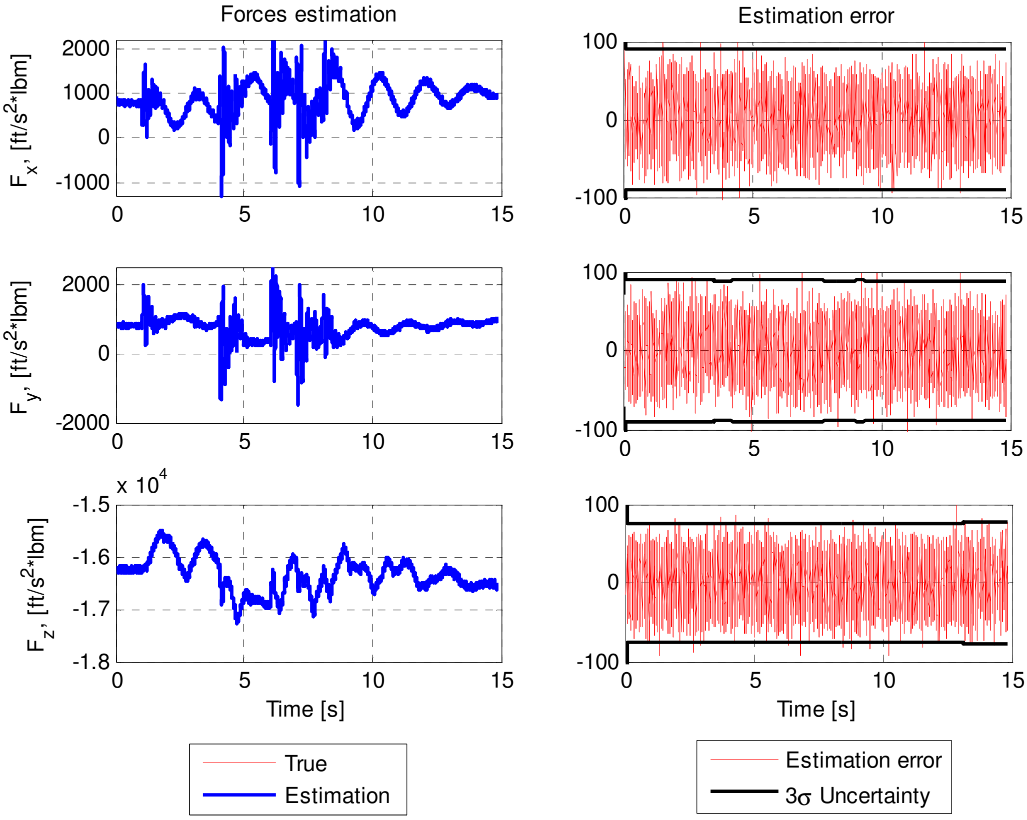

Figure 4: Comparison between true and estimated force components in body axes

For the second step we present the preliminary results concerning the identification of lateral cyclic flapping. The obtained results are checked comparing the measured flapping trajectory with the one provided by the estimated model. The comparison is executed on flight data not used for the model identification (acid test). As shown in the following figure, the model reproduces almost exactly the main rotor dynamics, and this is the first relevant result of the proposed approach.

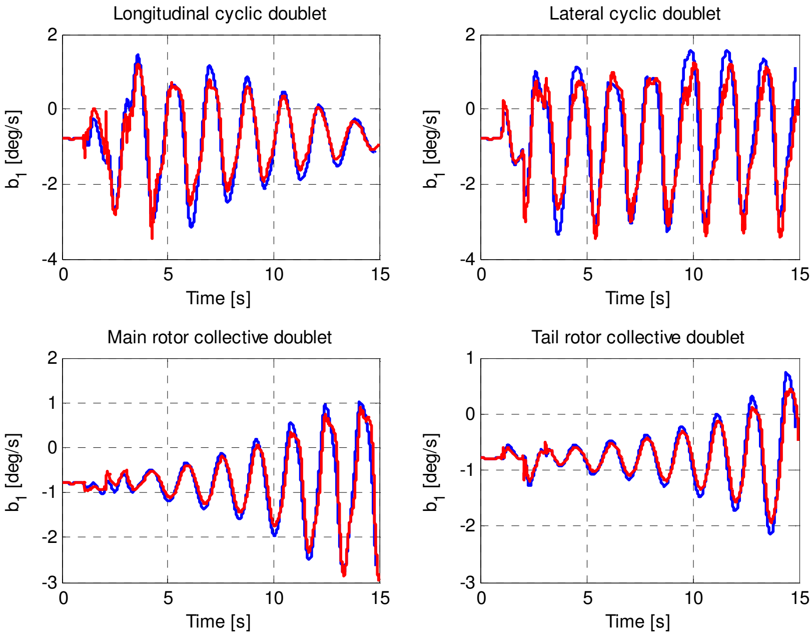

Figure 5: Lateral flapping: comparison between measured time histories (red) and the one provided by the model (blue) along four maneuvers which were not used for the identification

For the third identification step, the identified pitching moment model is presented. The true time histories are compared with the one provided by the model, for flight tests not used in the identification process. The matching is good in mean, also if high frequency oscillations (often present during the execution of the maneuver) and nonlinear behavior are not reproduced exactly. These phenomena are under investigation and will be addressed in the final version of the paper. Concerning the high frequency oscillations, they are probably related to the dynamics of the main rotor blades which is not fully modeled in the current model (only the tip path plane dynamics are considered). The optimization of the model structure instead could probably mitigate the model nonlinear error. Although the estimation could be improved, the preliminary results seem to be promising.

The complete model obtained by assembling the whole set of estimation results is validated through an open loop simulation. The capability of the model to reproduce the measured flight data is evaluated. The validation is carried out through an acid test, therefore a maneuver that is not used for identification, neither for partial validation of single step results, is selected. The chosen test consists of a frequency sweep in the range [0.05-2] Hz of the main rotor collective command. The maneuver lasts 6 seconds, whereas the simulation is stopped after 8 seconds. The time histories of the vehicle commands are provided in input to the identified model and the outputs of that model are compared with the corresponding flight measurements. This type of validation is very critical because small identification errors could translate in dramatic differences in the simulation outputs, due to the absence of a flight control system which allows tracking the reference trajectory, that is, the measured one. The acid test validation results are shown in the following figures.

The model behavior is very good, with some minor errors which could be further reduced. If the simulation time is extended, results slightly degrade, but this is acceptable because it is due to the time integration of the small errors on which enhancements are already foreseen.

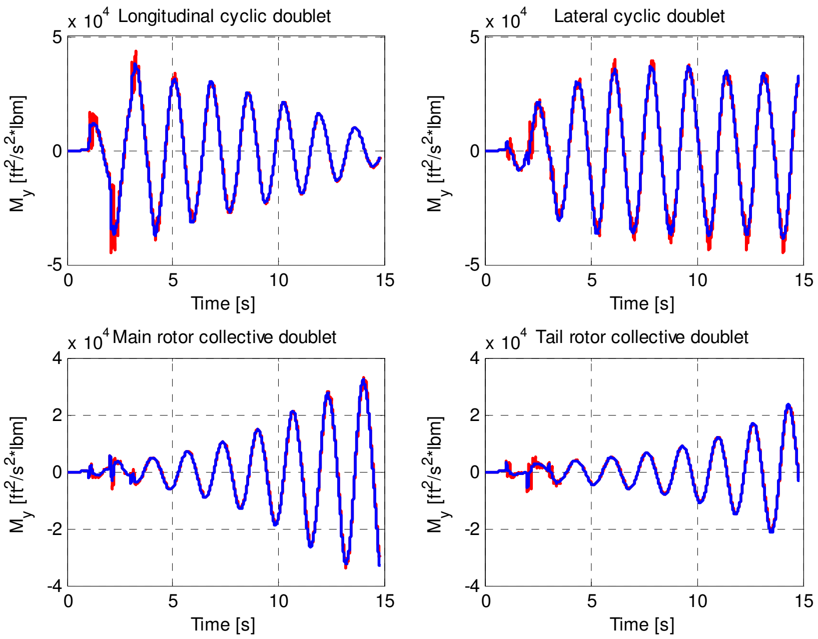

Figure 6: Comparison between true time histories (red) of the pitching moment and the one provided by the model (blue) (maneuvers not used for the model identification)

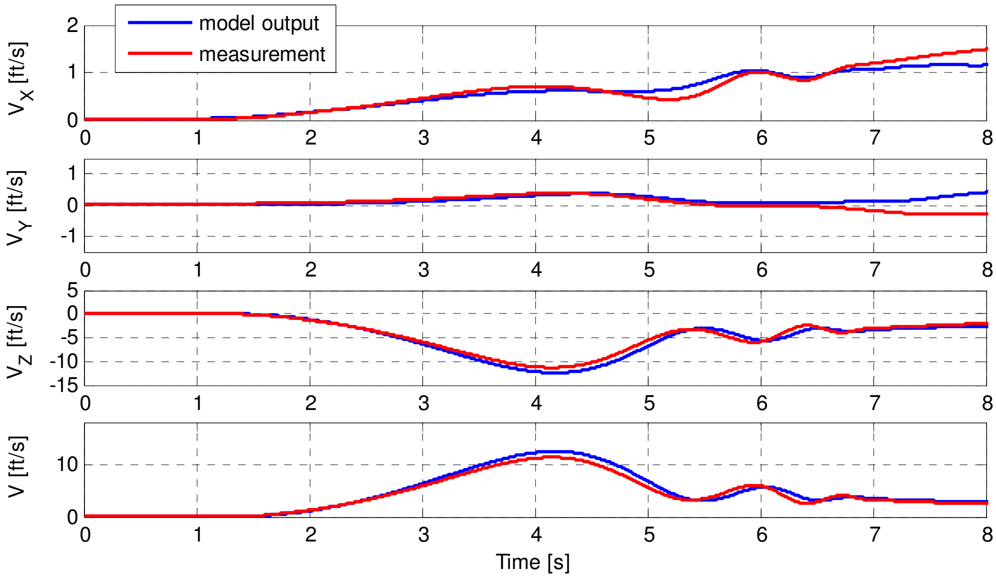

Figure 7: Comparison between the true time histories of the velocity and the corresponding time histories provided by the identified model (maneuver not used for the model identification)

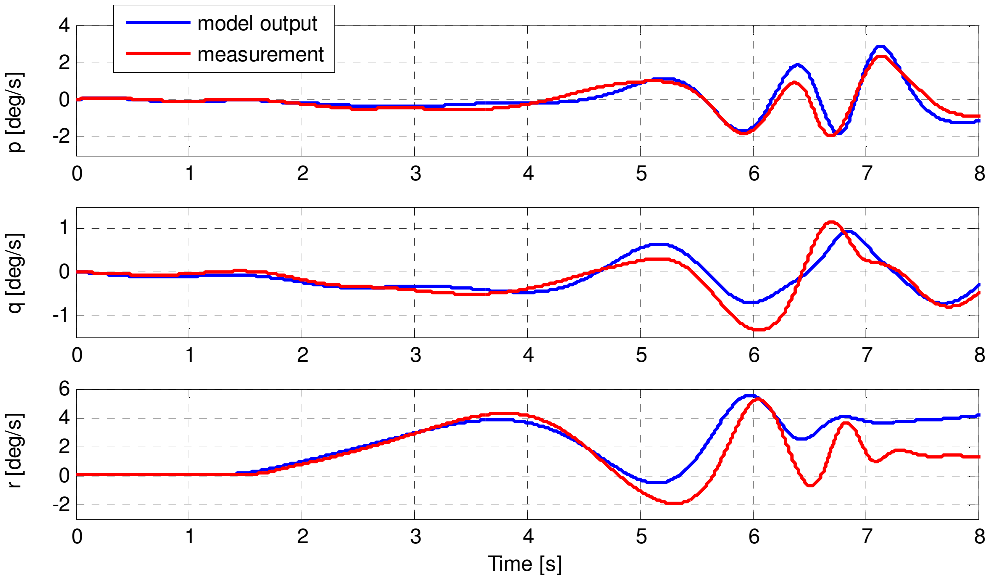

Figure 8: Comparison between the true time histories of the angular rate and the corresponding time histories provided by the identified model (maneuver not used for the model identification)

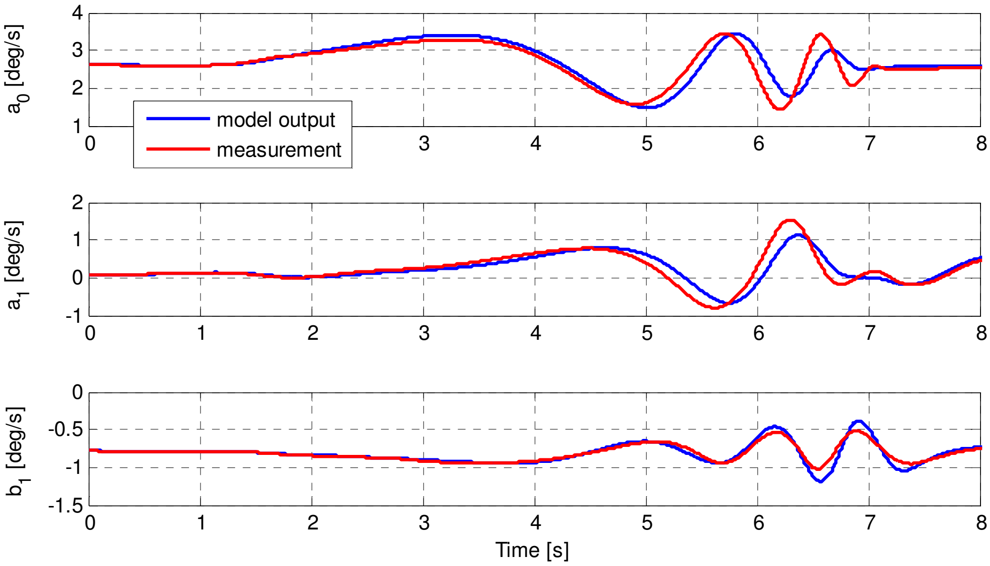

Figure 9: Comparison between the true time histories of the rotor dynamics and the corresponding time histories provided by the identified model (maneuver not used for the model identification)

6 PRELIMINARY CONCLUSION AND CURRENT WORK

A new three-step hybrid time-frequency strategy for rotorcraft model identification from flight data has been proposed in this paper. Each step can be performed by using the best suitable identification methodology and exploiting the advantage of both time and frequency identification techniques.

The application of the methodology to simulated flight data demonstrated the effectiveness of the proposed technique, providing highly promising results, even if they represent just a preliminary step and the identification process should still be optimized.

In the final version of the paper we will also present the results of the current work, which is focused on the refinement of the force model structure. The final model will be nonlinear, also including further inputs which are still not considered, in order to enlarge the frequency range of applicability. Moreover the vehicle control inputs will be affected by time delay, which is introduced to take into account un-modeled dynamics (such as the inflow).

Finally the technique will be applied to wider set of data, in order to extend the applicability of the identified model to forward flight in moderate speed conditions.

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