

Identification of Airship Aerodynamic Models from Flight Data: Preliminary Investigation and Identifiability Analysis

Carlo E.D. RIBOLDI^{1,a*}, Stefano CACCIOLA^{1,b}, Yan POZHANKA^{2,c}
and Mostafa HASSANALIAN^{2,d}

¹Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy

²New Mexico Institute of Mining and Technology, 801 Leroy Pl., Socorro, New Mexico, via La Masa 34, 20156

^acarlo.riboldi@polimi.it, ^bstefano.cacciola@polimi.it, ^cyan.pozhanka@student.nmt.edu,

^dmostafa.hassanalian@nmt.edu

Keywords: Lighter Than Air, LTA, Airship, Aerodynamics, Aerodynamic Model, Dynamic Modeling, Simulation, Parameter Identification, Identifiability, Output Error

Abstract. In this research, a preliminary identification testing of some modelling parameters pertaining to the aerodynamic model proposed by Munk-Jones-DeLaurier for airships has been carried out. Identification trials have been carried out in virtual environment employing an output-error method, solving a non-linear optimization problem on the norm of the error between the output of an estimated model and that corresponding to a reference model, assumed as ground-truth. The practical results show how some of parameters in the aerodynamic model appear identifiable even employing a rather limited dataset also in presence of noise.

Introduction

The availability of accurate and reliable simulators represents a key-asset in the design, performance assessment and certification of any flying system. Lighter-than-air (LTA) flying vehicles are no exception. However, the substantial absence of well-validated and proven simulators accepted at an industrial level is just a result of complexity of embracing all airships via a simple unified theory (like the lifting line for slender wings, or BEM for rotors). Actually, the practical realization of LTA [1] may range significantly in terms of overall shape (including a larger or smaller fineness ratio, multi-lobed envelopes, multiple and freely positioned fins, etc. [2] [3] [4]) as well as in terms of the values of the Reynolds number, spanned in the typical speed domain of flight operations [5]. The latter, in combination with the relative bluntness of the envelope (which has to be compared in this regard to higher lift-to-drag bodies like a wing), provokes separation phenomena on the tail cone of the airship envelope. These are typically present also in standard forward flight for an airship, and their modelling is generally not trivial. Actually, where potential-flow-based theory, with corrections for cross-flow motion is still the reference for aerodynamic modelling (at least for computationally-fast flight dynamics simulators), the actual assignment of the parameters in that class of models is generally not easy to perform. In a similar fashion, the modelling alternative represented by aerodynamic specifications assigned as lumped coefficients (e.g. stability and control derivatives) is generally coupled for airships with CFD computational models, or data coming from experimental (i.e. wind tunnel) testing, which provide predictions not spared from a strict dependence on the specific geometry and flight regime (i.e. Reynolds number).

These considerations point out the need for model tuning procedures, which are especially required in the fine tuning phase of the setup of a virtual model for airship dynamics. For LTA flying vehicles, the employment of such techniques has been attempted only sporadically and with



mixed results, in association primarily with the identification of lumped parameters in a simplified (linearized) dynamic formulation [6].

In the present work, the focus is moved to the tuning of a model based on the Munk-Jones-DeLaurier theory [7] [8], which basically mixes potential-flow aerodynamics with cross flow effects from cylinders and fins. The literature indicates that some coefficients in this formulation can be only guessed in a preliminary phase (for instance, when the airship is under design and no practical data is available), yet they need to be corrected when possible, by mixing experimental data and what is more accurately known of the model.

After shortly reviewing the features of the aerodynamic model of interest, the present paper shows a proposed application of a parameter estimation method which might be employed for the task. Finally, some preliminary results showing the potential of the proposed technique will be presented.

Methodology

A model capable of capturing the driving aerodynamic phenomena intervening on an airship in flight, with sufficient accuracy for flight dynamic computations, has been elaborated from the original theory of Munk [7] by Jones and DeLaurier [8]. Munk's theory has been developed from Lamb's solution of the potential flow around a generic ellipsoid [9], where the axis of the ellipsoid is misaligned with the prevalent direction of the flow. The contribution from Jones and DeLaurier has been the inclusion of separation phenomena, to supply the non-viscid (potential) theory with information of the separation effects taking place both on the envelope and on the tails on board an airship. This allows to correctly account for effects typically found at higher angles of attack or sideslip, which are typical to airships especially at low speed and in terminal maneuvers (i.e. close to hovering conditions). Besides the validation of the theory via fluid dynamics testing, including the experimental verification of effects bound to a rotary motion of a scaled test airship specimen (i.e. when the components of the rotational speed are not all zero) [8], the results of this aerodynamic modelling approach have been applied to the Lotte airship in the early 2000s [10]. In the latter case, experimental results in the wind tunnel have proven the generally very good likelihood obtained through this modelling approach, in that case in static flight conditions, yet considering the complete setup of the airship (i.e. including the tails) and flight at very high angle of attack, where separation phenomena are clearly intense [5].

An implementation of this aerodynamic model has been included in the Airship class of SILCROAD (SImulation Library for CRAFT-Object Advanced Dynamics) [11] [12] [13] [14], an object-oriented flight simulation library working in Matlab®/Simulink, conceived for the computationally fast simulation of interacting flying objects.

Among the parameters that define the aerodynamic characteristics of the airship, according to this model, are the following related to the airship hull (including interference effects from the tail) [8]:

- $C_{D_0}^{hull}$, $C_{D_{cf}}^{hull}$. These represent the components of the hull drag coefficient accounting for viscosity in attached flow, typically modelled from a thin plate analogy, and cross-flow, obtained from the estimation of cylinder cross-flow.
- η_k^{hor} , η_k^{ver} . These represent an interference effect between the tail and the hull. In particular, in the original theory [8] only a single parameter was included for the entire fin, whereas in the SILCROAD implementation a slightly more refined model was introduced, allowing to split the two contributions, thus potentially allowing for a more elaborated and generic arrangement of the empennages in a specific design.
- k_1, k_2, k_3, k'_3 . These represent the apparent inertia coefficients, and for the specific case of a slender body obtained as a solid of revolution have been tabulated by Munk starting from Lamb's solution of potential flow [7] [9].

Due to the uncertainties typically associated to these quantities, they have been shortlisted as interesting candidates within a parameter estimation effort.

This work has been carried out in virtual environment (future developments will make use of data made available through the first flying demonstrator now available at Politecnico di Milano within project IPROP [15]). In this context, the virtual model of an airship test-bed has been assembled, and a preliminary estimation of the identifiability of these parameters has been carried out, perturbing one by one the candidate parameters for estimation, and employing a doublet on elevator and rudder controls. The results of this preliminary analysis have allowed assembling Fisher's information matrix. The latter confirmed the likely good identifiability of the parameters k_2, k_3, k'_3 (notably, $k_2 = k_3$ for an axial-symmetric body), as well as η_k^{hor} , η_k^{ver} . Conversely, parameters $C_{D_0}^{hull}$, $C_{D_{cf}}^{hull}$ have tested harder to identify according to this analysis, possibly indicating that the proposed doublet on aerodynamic controls of the tail empennages (i.e., elevator and rudder controls) is not effective in stimulating the effect on dynamics of these two parameters.

In this work, after evaluating possible ways of carrying out parameter identification [16] [17] [18], an output-error approach was selected [19]. The parameters selected for identification have been collected in an array $\mathbf{p} = \{\eta_k^{hor}, \eta_k^{ver}, k_3, k'_3\}$. The output-error approach calls for the definition of an optimal problem, where parameters $\mathbf{p}$ are iteratively corrected by an optimal solver so as to obtain the best matching of the simulated system output and field data, when both the real machine and the simulated model are subject to the same input. In this case, the input was the same for which the analysis of Fisher's matrix had been carried out, i.e. a doublet of elevator and rudder.

In analytical terms, the response of the system $\mathbf{y} = \mathbf{g}(\mathbf{p}, \mathbf{x}, \mathbf{u})$ is a function of the parameters, as well as of the system state $\mathbf{x} = \mathbf{x}(t)$ and controls $\mathbf{u} = \mathbf{u}(t)$. The time history of controls is assigned (i.e., the doublet on elevator and rudder, other controls are not stimulated), whereas the state solves the dynamic equilibrium equation $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{p}, \mathbf{x}, \mathbf{u})$. Assuming to know the output $\mathbf{z} = \mathbf{z}(t)$ from a test in the field, carried out subjecting the real machine to the same input as the value as the simulated system, it is possible to compute a quadratic norm of the error $\mathbf{e}(t) = \mathbf{z}(t) - \mathbf{y}(t)$, as

$$J = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} \mathbf{e}(t)^T \mathbf{Q} \mathbf{e}(t) dt, \quad (1)$$

where the diagonal matrix $\mathbf{Q}$ is employed as a weight matrix, which might be set as the inverse of the squared covariance of the noise of each channel in array $\mathbf{e}(t)$. The identification of the parameters is then configured as the optimal problem

$$\min_{\mathbf{p}} J. \quad (2)$$

Working in virtual environment, the actual value of the coefficients, named $\mathbf{p}^*$, is known. Therefore, instead of employing data from the field, a simulation where $\mathbf{z} = \mathbf{g}(\mathbf{p}^*, \mathbf{x}, \mathbf{u})$ is employed as a ground-truth dataset. For added realism, the channels in the so-obtained $\mathbf{z}(t)$ have been artificially polluted with random noise.

Results

In this work, a virtual model of the Lotte airship [5] has been employed as a test-bed. Reference values of the measures $\mathbf{z}(t)$ have been produced by running the simulation model in SILCROAD in forward, horizontal, steady and symmetric flight, at a reference horizontal speed of 8 m/s. A corresponding trimmed solution has been computed automatically. A time history $\mathbf{z}(t)$ extending from $t_0 = 0$ s to $t_f = 20$ s has been obtained running an integration over time on a model of the airship, with assigned values of the parameters $\mathbf{p}^* = \{1.0, 1.0, 0.86, 0.69\}$, corresponding to the Lotte airship.

The measures considered in the identification process are the three body velocities, the three body rotational rates, the attitude angles and the position of a point (center of buoyancy) with

respect to a ground observer (12 channels in total). All these quantities are realistically obtainable even from a relatively cheap, small-scale airship test-bed, like the one currently available within project IPROP [15].

The optimal problem in Eq. (2), based on the norm in Eq. (1), has been solved numerically, based on a gradient algorithm, starting from an initial guess artificially polluted so as to simulate an uncertainty in the values of the parameters. In particular, the initial guess $\mathbf{p}_0 = \{1.05, 1.05, 0.93, 0.77\}$, where the latter two values, referring to k_3 and k'_3 respectively, have been chosen from Munk's tabulated functions [7] so that they correspond to a higher fineness ratio of the hull than the actual one.

The period of the doublet on elevator and rudder controls have been selected so as to excite respectively the two oscillatory modes of the airship, namely the pendulum in the longitudinal domain (via the elevator control), and the roll mode in the lateral-directional domain (via the rudder control) [6]. For the test-bed at hand, the corresponding (positive) intervals of the doublet is 6.92 s for the elevator and 0.85 s for the rudder. A deflection amplitude (positive) of 1.0 deg has been employed for both controls, and the behaviour of the airship in flight was visually checked not to diverge towards unrealistic flight conditions over the duration of the simulations. In this regards, however, it should be remarked that, thanks to employing buoyancy as a lifting force, the range of flight dynamics states for an airship is generally much broader than for winged aircraft.

Several cases corresponding to different levels of artificial noise in the measures have been considered. Considering the different nature of the sensors providing the measures, the following reference noise levels have been considered:

- for velocity components (GPS differentiation), a $\sigma_v = 0.01$ m/s
- for rotational rate components (IMU), a $\sigma_\omega = 0.002$ rad/s
- for attitude angles (IMU), $\sigma_a = 0.001$ rad
- for position (GPS), $\sigma_p = 0.05$ m

The value of σ_p is comparatively higher on account of the low-value/low-accuracy of GPS sensors commonly employed on low-budget measurement units, like for scaled flying models [15].

Table 1 summarizes the results of the identification analysis, for changing values of the actual noise levels, artificially added to the measure channels in the reference simulation, and scaled by a same multiplier to simulate a generally higher or lower noise level in the measures. As it can be argued from Table 1, an identification of the selected parameters is indeed possible, and remarkably so even when employing (as done here) a very reduced dataset, corresponding to a single run on the reference test-bed. The most reduced error can be obtained in identifying Munk's parameters k_3 and k'_3 , even starting from a rather offset initial condition. A comparatively lower accuracy can be observed in the identification of the tail-to-hull interference parameters η_k^{hor} , η_k^{ver} , even though the change on the initial values computed by the solver is acting in most cases in the correct direction (i.e., the artificially-boosted initial values are changed by the algorithm towards the correct value).

Table 1 Results of identification runs, for changing values of the overall noise level multiplier.

Parameter ($\mathbf{p}$)	Real value ($\mathbf{p}^*$)	Init. Value ($\mathbf{p}^0$)	Estimated value ($\bar{\mathbf{p}}$) – No noise (0% of reference)		Estimated value ($\bar{\mathbf{p}}$) – Noise 1% of reference		Estimated value ($\bar{\mathbf{p}}$) – Noise 10% of reference		Estimated value ($\bar{\mathbf{p}}$) – Noise 100% of reference	
	Value		Value	Error [%]	Value	Error [%]	Value	Error [%]	Value	Error [%]
η_k^{hor}	1.0	1.05	0.9847	-1.5300	1.0022	0.2200	1.1082	10.8200	1.0571	5.7100
η_k^{ver}	1.0	1.05	0.9022	-9.7800	0.9694	-3.0600	1.0282	2.8200	1.0489	4.8900
k_3	0.86	0.93	0.8694	1.0930	0.8741	1.6395	0.7689	-10.5930	0.7999	-6.9884
k'_3	0.69	0.77	0.6808	-1.3333	0.7854	13.8261	0.7039	2.0145	0.7367	6.7681

To better interpret the results, it should be noted that the dataset (i.e., the simulations) with noise is only one for each overall noise scaling factor, hence the results just presented are not enough for a statistical analysis of correlation between the error on identification and the level of noise. They just serve to preliminary assess the general identifiability of the parameters in the problem at hand, and in this sense they look extremely promising.

As an example, the plot in Figure 1 show the time histories of longitudinal and lateral-directional states, and of controls, corresponding to the reference test-bed ($\mathbf{p} = \mathbf{p}^*$, in blue, barely visible under the green curves corresponding to estimations), the polluted initial condition ($\mathbf{p} = \mathbf{p}_0$, in amber), and the set of estimated parameters $\mathbf{p} = \bar{\mathbf{p}}$ (in green), corresponding to the result of the identification procedure. The figure is referring to a 1% of-reference-noise condition.

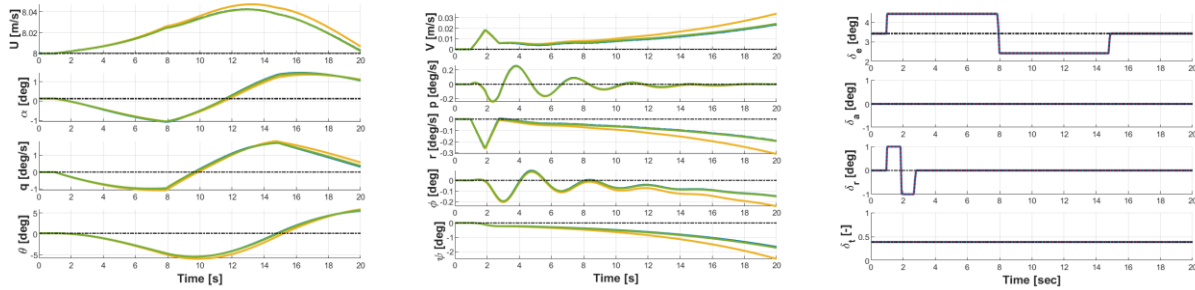


Figure 1 Time histories of longitudinal states (left), lateral-directional states (centre) and controls (right) for a simulation with a noise scaling factor of 1% in the reference test-bed. Blue: test-bed (barely visible under the green line). Yellow: starting point of identification. Green: result of identification.

As noted from Table 1, the result in the figure shows an a clear amelioration of the estimated parameters over the initial condition, with a very good likelihood of the output of the reference model corresponding to $\mathbf{p} = \mathbf{p}^*$ and the estimated one corresponding to $\mathbf{p} = \bar{\mathbf{p}}$.

Conclusions

A parameter identification method based on the output-error approach has been employed for the estimation of some parameters appearing in a mid-fidelity aerodynamic model of an airship. Following a shortlisting of the candidate identifiable parameters, and a preliminary synthesis of a time history of controls suitable for stimulating their expression in the dynamic response of the airship, the identification has been carried out employing as a test-bed the virtual model of the Lotte airship. Results obtained up to the present state of the research support the suitability of the technique selected for identification, which can easily work on the free response of the airship, taking advantage of the reduced tendency of barely stable or unstable airships to diverge fast from a trimmed condition even when non artificial stabilization is employed. The excitation input, based on doublets, appears to provide a dataset sufficiently rich for identification purposes, as far as the shortlisted parameters η_k^{hor} , η_k^{ver} , k_3 , k'_3 are considered. The effect of noise has been preliminarily evaluated in view of an application of the proposed technique to the identification of parameters pertaining to an existing airship prototype, designed and built in Spring 2025 at DAER-Politecnico di Milano within project IPROP.

Future short-term developments will involve the investigation of additional maneuvers, such to allow the identification of the relevant drag-related coefficients $C_{D_0}^{hull}$, $C_{D_{cf}}^{hull}$, and possibly involving the use of thrusters instead of aerodynamic surfaces.

Acknowledgments

This work was partly funded by the IEC Pathfinder project IPROP under grant N.101098900.

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