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Title

Flight dynamics analysis and trajectory optimization of some gliding phases

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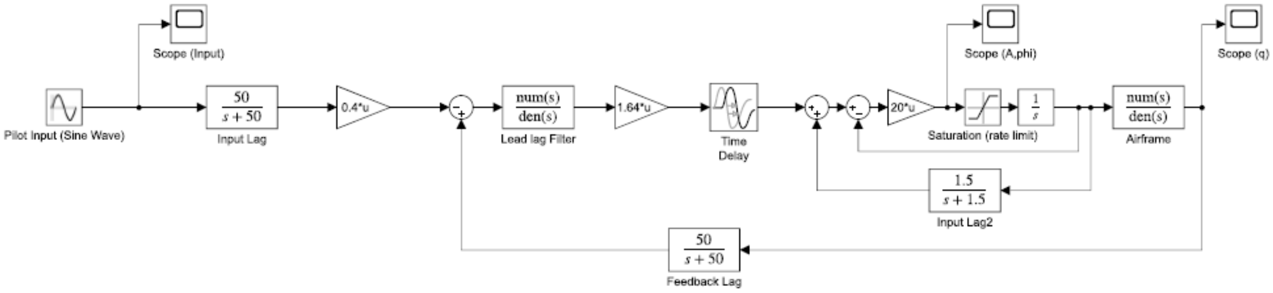
Abstract

As far as the gliding phases are concerned, the specificities of the aircraft flight dynamics and the surrounding aerology must be taken into account seriously, especially since no propulsion is at disposal to cope with possible problems.
In this study, several issues are examined. On the one side, pilot induced oscillations of the space shuttle command channel are expertized and on the other side, a performance (range, mean velocity) is maximized for a sailplane in an environment with a given repartition of thermals (or wind). Even if the study is more applied mathematics oriented, the results are interesting for engineers and pilots since it helps to take in-flight decisions and to make pre-flight preparations.

The analysis of some issues coming from nonlinear flight dynamics is accomplished here by means of the bifurcation theory and continuation algorithms. Some nonlinear features are related to the inner flight dynamics, others are actually due to couplings with pilot reaction. Concretely these nonlinear features may imply unexpected events and it is then important to evaluate whether there are dangerous or not.
The main topic of this part concerns *pilot-aircraft couplings* for a configuration with forced oscillations as inputs [3]. The application concerns the space shuttle which meets some issues in its gliding phase [4]. The analysis of the command channel with a rate-limited actuator reveals the presence of *jumps* (flying qualities cliffs), indeed a little variation of the input pulsation ω may imply large variation (of amplitude and phase), as illustrated in figure 1. According to the *describing function method* (DFM), a continuation algorithm allows to predict the amplitude A (and the phase shift ϕ) at the entry of the actuator thanks to the resolution of an *harmonic balance equation* (HBE) (like equation (1)) which involves the transfer functions of the different parts and the describing function of the nonlinearity (saturation or *rate limiting*).

$$Ae^{j\phi} = \frac{Filter(j\omega)}{1 - N(A,\omega)Actuator(j\omega)Airframe(j\omega)Feedback(j\omega)Filter(j\omega)}\, Feedforward(j\omega)\ Input \qquad (1)$$



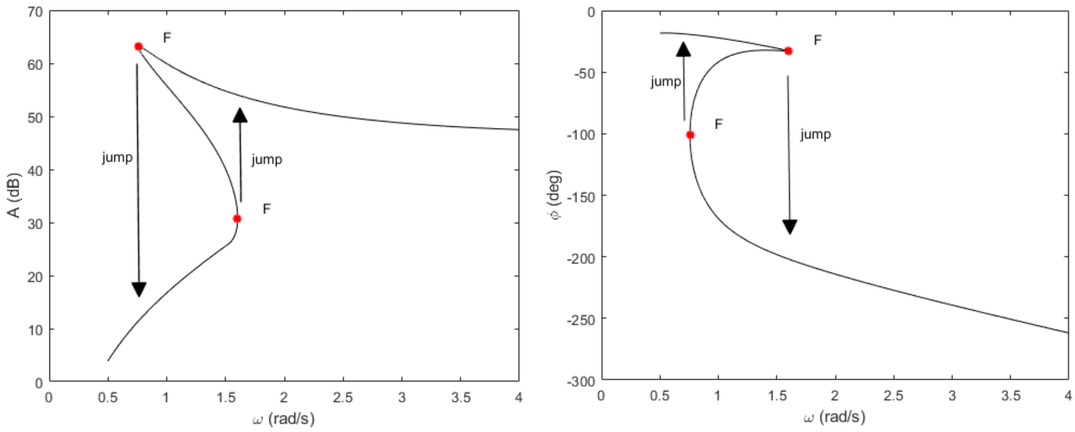


Figure 1: Command channel of the space shuttle (top figure).
Amplitude A and phase ϕ at actuator entry in function of the pulsation ω of the pilot inputs according to DFM (bottom figures).
Diagnosis of jumps due to a rate limited actuator in the space shuttle command channel.

Besides another topic is the flight trajectory optimization of a sailplane. When (the mean velocity is) calculated in a stationary environment with only one vertical thermal, it is associated to the so-called *McCready* speed, whereas configurations with several thermals raise some questions such as the optimal speeds and the best strategy to adopt (which speed to take or which thermals to target, in which order, etc).
Another strategy might be to realize a *dolphin-style gliding* and keep on flying (in thermals). In this case, *optimal control* can furnish the best speeds (and altitudes) to follow during a longitudinal flight (in the vertical plane), as illustrated in figure 2. Here the equations of flight dynamics (1) includes the magnitude $W_z(x)$ of the vertical wind.

$$\frac{dV_a}{dt} = -\frac{1}{2m}\rho S V^2 C_X - \frac{dW_Z(x)}{dt}\sin\gamma - g\sin\gamma\,, \frac{d\gamma}{dt} = \frac{1}{2m}\rho S V C_Z - \frac{dW_Z(x)}{dt}\frac{\cos\gamma}{V} - \frac{g\cos\gamma}{V} \tag{1}$$

When the objective consists in flying as far as possible, the performance to optimize (altitude loss in fact) can be re-written $J = \int_0^{t_f}(W_Z + V\sin\gamma)\,dt = \int_0^{x_f}\left(\frac{W_Z + V\sin\gamma}{V\cos\gamma}\right)dx$.

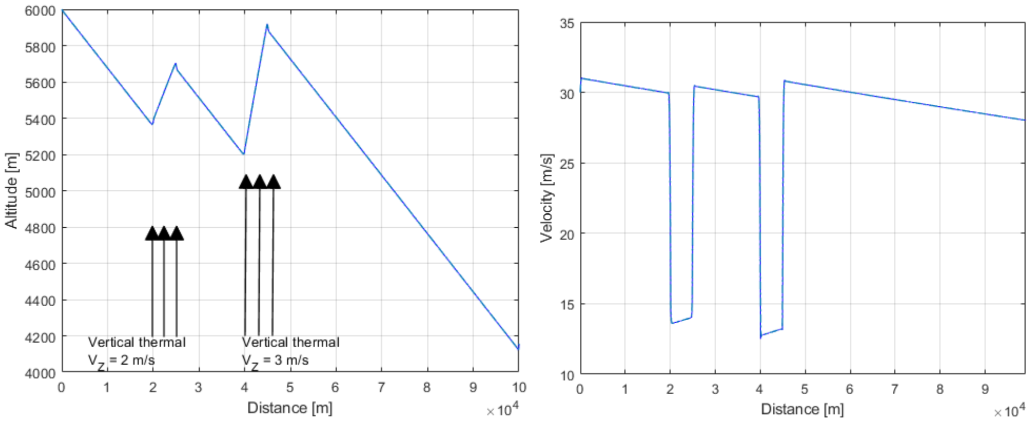


Figure 2: Best speeds to adopt in order to maximize the range of a glider in a calm environment with two stationary ascending thermals.
Results obtained thanks to optimal control of dolphin soaring.

Finally for such studies, one hope is surely to help pilots to make wise in-flight decisions and to prepare as well as possible the gliding phases taking into consideration the amount of data and their level of precision at disposal but also to compare different scenarios and to avoid unscheduled off-field landing and more generally to diminish soaring risks. The mathematical analysis, optimization and underlying physics are explained in theoretical and practical terms in order to be valuable for mathematicians and aerospace specialists. The pilot viewpoint is also considered and some (training) scenarios (on simulator for example) may be exposed.

References

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