13th ERCOFTAC SIG 33 Workshop, Progress in Flow Instability, Transition and Control
March 6-8, 2018, Paraty, Brazil

OPTIMAL GUIDANCE OF BUOYANCY-CONTROLLED BALLOONS IN TURBULENT FLOWS USING A NON-QUADRATIC OBJECTIVE AND DISCONTINUOUS ACTUATION

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Meteorological forecasting of extreme phenomena like hurricanes could strongly benefit from sensor-laden vehicles (typically, balloons) that could be guided to remain in the geographical area of interest for a few days at a time, rather than a dozen minutes or so as is the case with today's free-flying balloons and dropsondes. A promising energy-sparing technology consists of balloons with mechanically-adjustable volume [1] which can reversibly provide increased or decreased buoyancy and move to an altitude where the prevailing wind blows in the desired direction. In previous work we have shown that a) guidance of balloons in specified orbits, and even in orderly formations, can numerically be achieved in realistic hurricane simulations [2], and b) a control objective proportional to the absolute value of the inflation rate, more representative of required electric power than its square, leads to the choice of a discontinuous control law where the balloon is left most of the time at a constant volume and only inflated or deflated for abrupt short periods (ideally, in a discontinuous way) [3, 4].

Whereas the optimal control of a linear system, disturbed by white noise, towards a quadratic objective can be mathematically proved to require a linear feedback control and to lead to gaussian statistical distributions of all the quantities involved, a non-quadratic objective removes all these nice mathematical properties, and in particular the optimal controller can no longer be assumed to be linear even when the system to be controlled is linear. In this context, result (b) mentioned above was achieved by extremely simplifying the dynamics, to the point that the entire turbulent flow was replaced by a white noise with its spectral amplitude as the only tunable parameter. A more realistic approximation must at least involve a spectrum that more closely resembles a turbulent flow. It is an almost forgotten result that the lagrangian correspondent of the Kolmogorov $k^{-5/3}$ spatial spectrum of turbulent energy is a temporal spectrum proportional to ω^{-2} [5]. An ω^{-2} power spectrum implies an ω^{-1} amplitude spectrum, and is quite easy to achieve in a lumped numerical simulation by passing white noise through an integrator.

The simplest abstract model of the motion of a balloon in a hurricane is then a two-degree-of-freedom mechanical system disturbed by once-integrated white noise. The power spent to inflate and deflate the balloon is proportional to the absolute value of vertical velocity, and its integral is the energy to be minimized. This nonquadratic objective makes even such a simplified system nontrivial to analyze; its optimization implies solving a partial differential Fokker-Planck equation for the statistical distribution function of position and velocity, a mathematical technique often referred to as dynamic programming. The numerical solution of this problem and the resulting discontinuous, stepwise optimal control strategies will be discussed at the conference.

References

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