Kernel-based Identification of Periodically Parameter-Varying Models of Power Kites

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In airborne wind energy (AWE) systems, control design is usually conducted with linearized or simplified kinematic models. The model mismatch in model-based control design may lead to severe performance deterioration in practice. Therefore, it is desired to assess the closed-loop performance from experimental trajectory data with a model of the AWE system in closed loop with the designed controller. Such a model would make it possible to simulate and analyze the performance of existing flight systems analytically. Furthermore, additional control loops can be designed to refine the performance based on the identified closed-loop model.

In this work, we are interested in the identification of the power generation phase where the system is controlled to fly along a periodic or close to periodic orbit. In this phase, the closed-loop dynamics can be modelled as a limit cycle oscillation, a common phenomenon of nonlinear dynamical systems with periodic, locally-stable, and self-sustained state trajectories. However, identification of nonlinear systems like power kites purely from data is in general a hard problem, which requires prior knowledge of model structure, and/or complex nonlinear optimization schemes with tractability issues. Alternatively, since knowledge of the periodic orbit is available, nonlinear dynamics around the limit cycle can be modelled as a periodic system parametrized with the location on the limit cycle. If we are only interested in the performance close to the orbit, such a periodic system can then be described by a locally linearized model. Motivated by this idea, this work proposes an approach to identifying the local dynamics in the power generation phase with a linear periodically parameter-varying model from experiment trajectory data.

The approach consists of decomposing the dynamics into two parts: one along the limit cycle, and one lying on a transversal hyperplane of the limit cycle. That is, the dynamics are described in the so-called transverse coordinates (Manchester (2011)). Let the state of the kite be x, and the nominal periodic trajectory be $\{x(\tau)\,|\,\tau\in[0,T)\}$ parametrized by the time τ, where T is the period. Define $S(\tau)$ as a hyperplane transversal to the orbit with an origin at $x(\tau)$. Then for each state x, there exist τ such that $x\in S(\tau)$. The state can thus be decomposed as $(\tau, x_\perp)$, where $x_\perp$ is the coordinate of x on $S(\tau)$. The dynamics of the decomposed states take the following form:

$$\begin{cases}\dot{x}_\perp &= A(\tau)x_\perp + O(|x_\perp|^2),\\ \dot{\tau} &= 1 + g(\tau)x_\perp + O(|x_\perp|^2),\end{cases} \tag{1}$$

From an AWE perspective, (1) describes a closed-loop model of a power kite around the orbit which is tracked by the controller. Different sets of state x can be selected to obtain different levels of model fidelity. It can be used to extract important information on the system such as sensitivity to disturbances, time constants, and general performance limits.

Taking (1) as the model parametrization, the proposed system identification method consists of identifying the parameter-varying objects ($A(\tau)$ and $g(\tau)$) in the linear dynamics as smooth functions of τ. Assuming full-state observation, the measured data are decomposed in transverse coordinates and are thus available as trajectories $(x_\perp(t_i), \tau(t_i))_{i=1}^N$. The problem is recast in this way as a function learning problem, where basis function decomposition and the kernel method are applied to identify the model. This approach also handles cases where exogenous inputs (e.g. wind gusts, additional actuation) are present and the measurement data are noisy. With the kernel method, the identified model can be further augmented with other parameters of the operating condition (e.g. radius, nominal speed).

The identification algorithm is tested on simulation data generated by a simulation model of tethered kites with a multi-loop control design developed in existing work (Wood et al. (2015)). Results show that the proposed approach is able to identify model (1) effectively and thus obtain reliable predictions of trajectories under various scenarios. A sample comparison between analytical model parameters and identified ones is shown in Figure 1. We believe that this can be a useful tool to analyze the closed-loop performance of AWE systems by taking into account dynamic effects that are often neglected in first-principles approaches. Besides analysis, these models can be employed to quantify the mismatch of the first-principles models with the true system and, in view of this, to inform a redesign.

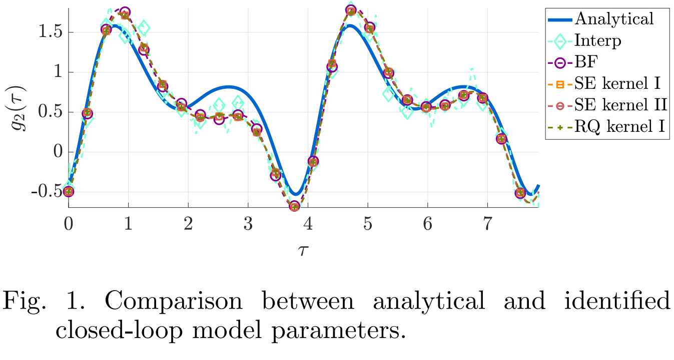

Fig. 1. Comparison between analytical and identified closed-loop model parameters.

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