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Control for Novel 3-DOF Flight Testing in a Wind Tunnel

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***Abstract*—A long standing ambition in the aerospace industry is to flight test aircraft in wind tunnels. We propose a robotic manipulator system that can be operated with an aircraft wind tunnel model that replicates the longitudinal dynamics of the aircraft in free flight. A nonlinear aircraft-manipulator dynamics model developed with the Euler-Lagrange method is combined with the inverse kinematics to produce the relative joint angles for the robot manipulator to reproduce free flight trajectories in the wind tunnel working section. Simple PI control is used for the manipulator joint control to replicate the translational degrees of freedom, whilst the aircraft pitch is controlled via the aircraft elevator. The proposed scheme is tested in simulation and the results demonstrate the effectiveness of the proposed scheme.**

I. INTRODUCTION

Manipulators have often been proposed for use in wind tunnel experiments for various reasons, for example to provide dynamic responses so that unsteady aerodynamic effects can be investigated. Aircraft dynamic wind tunnel tests are of two methods, passive tests where the aircraft glide freely about its constraints and active tests where the aircraft model performs manoeuvres under feedback control of its dynamic states. The motive for the latter approach is to mimic flying parameters termed dynamic equivalence modelling which is essential for time-dependent aerodynamics and control experiments. For example, [1] developed a 2-DOF passive robot model to experiment lateral motion of a delta wing and [2] developed a 3-DOF manipulator actuated with commands sent to the corresponding motor for variable angles of pitch, roll and yaw. [3] developed a dynamic wind tunnel test apparatus consisting of a momentum arm attached to a rigid frame, allowed to rotate about a gimbal for pitch and yaw with a wrist designed for roll. It demonstrated phugoid motion with a kinematically restricted model multi-degree-of-freedom wind tunnel rig. [4] modelled unforced pitch-axis non-linear behaviour in a 1-DOF dynamic wind tunnel test rig. [5, 6] presented recent development of a novel multi-DOF dynamic manoeuvre rig for time dependent aerodynamics in a wind tunnel.

Recent experiments propose the use of robotics framework with advanced capabilities in wind tunnels [6]. Suitably, an active controlled aircraft-manipulator model to coordinate flight motion within the wind tunnel to experiment real-time aerodynamic experiments. Here, we propose a concept for wind tunnel flight using a 3-DOF aircraft-manipulator system. Novelty infuses aerodynamics and robotics dynamic nonlinearities for the aircraft manipulator to reproduce free flight in real-time when the tailplane is perturbed in wind flow resulting to a dynamic response of the aircraft-manipulator. A PI controller tracks the flight trajectory through the manipulator joints angular positions defined with initial conditions of phugoid mode. It is envisaged that the system can be used for testing flight control laws, handling qualities and parameter identification of model aircraft. Parameter optimization improves the dynamic performance of modern aircraft through data. This concept demonstrates feasibility and uniqueness for prototyping and real-time applications.

II. FLIGHT DYNAMICS MODELLING OF A SCALED AIRCRAFT

The aircraft model shown in Figure 1 is a 1/12th scaled BAe Hawk aircraft with active control surfaces (ailerons, rudder, and all-moving tailplane). A 3-DOF longitudinal free-flight dynamics model based on [7] is developed and coded in Simulink. The model parameters were estimated from dynamic wind tunnel testing using a 4-DOF rig shown in Figure 2. Trim conditions and free flight trajectories are obtained from the Simulink model.

Figure 1: 1/12th scaled BAe Hawk

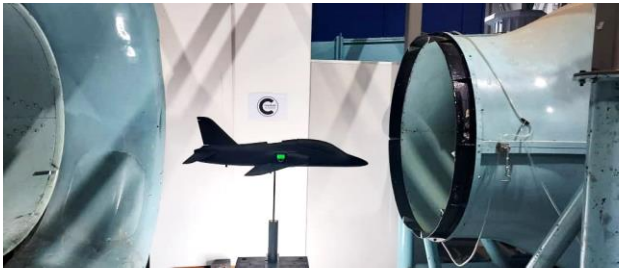

Figure 2: Passive test of a 4-DOF BAe Hawk model in wind tunnel

III. MODELLING OF WIND TUNNEL TESTING ROBOT

In order to replicate the free flight trajectory in the wind tunnel, the aircraft-manipulator system shown in Figure 3 is modelled. The first and second manipulator joints are actuated by rotary motors, providing direct control of joint angles θ_1, θ_2. The aircraft lateral dynamics are constrained, and the aircraft is free to pitch about joint O which is located at the aircraft centre of gravity and is not actuated. Instead, the aircraft tail is effected to provide the pitch control. Hence the system has 3-DOF to match the 3-DOF of the free flight dynamics, namely pitch, heave, and surge.

The coupled aircraft manipulator dynamics model is developed with Euler-Lagrange method and is given by,

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$$m_I(\theta)\ \ddot{\theta} = \tau_n + \tau_a + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) \qquad (1)$$

where τ_n is the control torque required at the joints, τ_a is the aerodynamic torque produced by the aircraft, m_I is the mass inertia matrix of each link, C is the Coriolis effect relative to each link and G is the gravitational effect on each link.

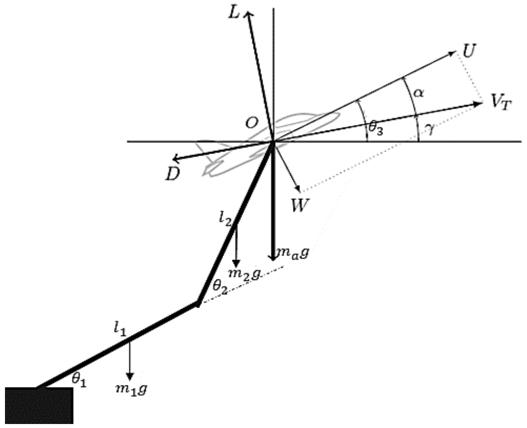

Figure 3: Configuration of DEA model for wind tunnel experiments

The vertical and horizontal velocity components $[\dot{x}_s\ \dot{z}_s]$ of the aircraft at joint O is given by,

$$\dot{x}_s = -l_1\omega_1 \sin\theta_1 + l_2\omega_2 \sin(\theta_1 + \theta_2) \qquad (2)$$

$$\dot{z}_s = l_1\omega_1 \cos\theta_1 + l_2\omega_2 \cos(\theta_1 + \theta_2) \qquad (3)$$

where l_1 and l_2 are the respective link lengths, and $\omega_1 = \dot{\theta}_1$ and $\omega_2 = \dot{\theta}_2$ are the angular rates. From the aircraft velocities from the free flight simulation, the manipulator joint positions are calculated by inverting the kinematic equations (2) and (3).

A PI controller is tuned for each manipulator joint to track the joint states and rates that replicate longitudinal trajectory. The control model with unity feedback is shown in Figure 4.

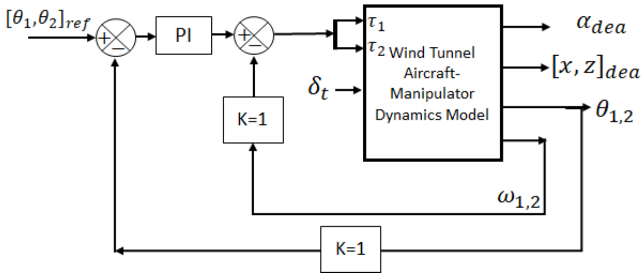

Figure 4: DEA trajectory control model with a PI controller

IV. RESULTS

The flight model at trim perturbed with a pilot input on the elevator developed into time-varying pitching oscillations. Transients in the dynamic model resulted into SPPO and phugoid modes with displacements in [*x*, *z*] coordinates. These coordinates from the aircraft model are transformed into joint angles for the manipulator links with inverse kinematics. Similarly, considering the orientation of the aircraft and manipulator links at trim states set by initial conditions, the aircraft-manipulator dynamics perturbed with equal value of elevator input acquires aerodynamic forces. These forces and moments are transferred into the robot dynamics to replicate the flight model. Wind tunnel trajectory $[x_s \quad z_s]$ of the model dynamic response characterized by joint angular positions $[\theta_1 \quad \theta_2]$ relates to phugoid mode.

The feedback system with a PI controller accurately tracked the reference joint angles with steady aircraft motion until steady state. Figure 6 shows the control torques and moment.

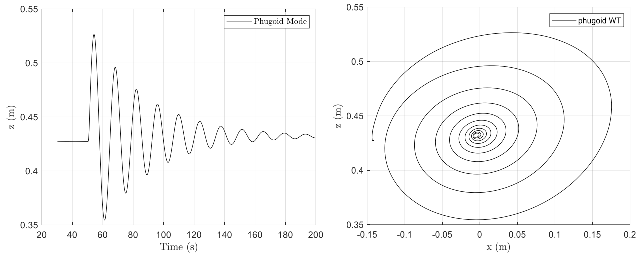

Figure 5: Phugoid trajectories for aircraft and wind tunnel models

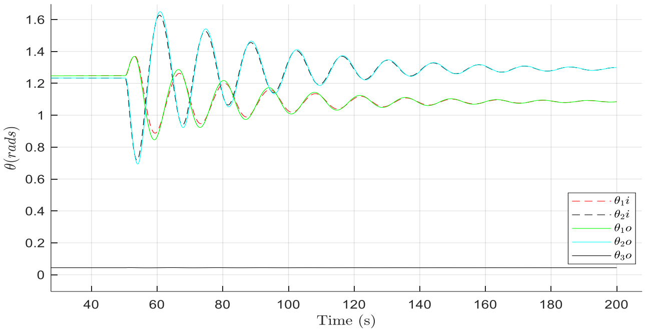

Figure 6: PI controller tracking DEA joint angles for phugoid mode

CONCLUSIONS

A concept for aircraft models effected for surge and heave by a manipulator and for pitch by the aircraft control surface for the purpose of wind tunnel testing is proposed. By means of simulation, it is shown that the system can replicate the longitudinal free flight dynamics of the aircraft, that being both the short period and phugoid modes. The range of the heave and surge are, of course, limited by the constraints of the wind tunnel.

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