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A robust nonlinear output feedback control method for limit cycle oscillation suppression using synthetic jet actuators

Natalie Ramos Pedroza [a], William MacKunis [a], Vladimir Golubev [b]

[a] Physical Sciences Department, Embry–Riddle Aeronautical University, Daytona Beach, FL 32114, United States
[b] Aerospace Engineering Department, Embry–Riddle Aeronautical University, Daytona Beach, FL 32114, United States

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ABSTRACT

A synthetic jet actuator-based output feedback control method is presented, which achieves asymptotic limit cycle oscillation regulation in small unmanned aerial vehicle wings, where the dynamic model contains uncertainty and unmodeled external disturbances. In addition, the proposed control method compensates for the parametric uncertainty and nonlinearity inherent in the synthetic jet actuator dynamics. Motivated by the limitations characteristic of small unmanned aerial vehicles, the control method is designed to be computationally inexpensive, eliminating the need for time-varying parameter update laws, function approximators, or other computationally heavy techniques. To this end, a computationally minimal robust-inverse control method is utilized, which is proven to compensate for the uncertainties in both the aerial vehicle dynamics and the synthetic jet actuator dynamics. By endowing the robust-inverse control law with a bank of dynamic filters, asymptotic limit cycle oscillation regulation is achieved using only pitching and plunging displacement measurements in the feedback loop. The result is an asymptotic synthetic jet actuator-based limit cycle oscillation regulation control method, which does not require velocity measurements, adaptive laws, or function approximators in the feedback loop. To achieve the result, a detailed mathematical model of the limit cycle oscillation dynamics is utilized, which includes nonlinear stiffness effects, unmodeled external disturbances, and dynamic model uncertainty, in addition to the parametric uncertainty in the synthetic jet actuator dynamic model. A rigorous Lyapunov-based stability analysis is utilized to prove asymptotic regulation of limit cycle oscillations, and numerical simulation results are provided to demonstrate the performance of the proposed control law.

1. Introduction

The design of limit cycle oscillation suppression systems is extremely important in aircraft applications, since limit cycle oscillations can cause dynamic instability that could result in catastrophic damage [1,2]. To ease readability in this paper, the following four acronyms will be defined: limit cycle oscillations **(LCO)**; synthetic jet actuators **(SJA)**; small unmanned aerial vehicle **(SUAV)**; and angle of attack **(AoA)**. LCO, or flutter, is characterized as pitching (rotational) and plunging (vertical) displacements in an airfoil. A synthetic jet actuator (SJA)-based LCO suppression method is presented in this paper, which is designed to be practically implementable in small unmanned aerial vehicle (SUAV) flight applications, where onboard space and computational power is limited.

LCO suppression systems are usually designed based on the assumption that the full state (i.e., pitching and plunging displacement and velocity measurements) is available for feedback [3–8]. Although the availability of velocity measurements is a standard assumption, velocity information can be difficult to obtain accurately due to system faults and/or low sensor measurement resolution [9]. Motivated by this fact, eliminating the need for velocity measurements is important in LCO suppression system design [10]. Moreover, the inherent space limitations involved in SUAV applications motivate the development of control laws that can be implemented with a reduced computational cost and space requirement.

To reduce cost, weight, and mechanical complexity over standard mechanical control surfaces (e.g., ailerons and elevators), SJAs are becoming increasingly popular in SUAV control applications. SJAs transfer linear momentum to a flow system using a piezoelectric membrane inside a cavity, which creates trains of air vortices through the alternating ejection and suction of air through a small orifice. A key benefit of SJA is that they are capable of achieving momentum transfer with zero net mass flux across the flow boundary. For this reason, SJAs do not require space for a fuel supply, and this feature reduces the space and weight requirements

E-mail address: ramosa66@my.erau.edu (N. Ramos Pedroza).

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when used in SUAV applications. These SJAs can be utilized to achieve LCO suppression by modifying the boundary layer flow field near the surface of an aircraft wing. SJAs can also improve SUAV maneuverability by expanding the usable range of angle of attack (AoA) [11]. However, one of the challenges in SJA-based control design is that the SJA actuator dynamic model is nonlinear and includes parametric uncertainty. For further details regarding SJA operation and modeling, readers are referred to [12–15] and the references therein.

The contribution in this paper is a SJA-based output feedback control method, which achieves asymptotic LCO regulation in SUAV wings in the presence of uncertain SUAV dynamics and unmodeled external disturbances. In addition, the proposed control method compensates for the parametric uncertainty and nonlinearity inherent in the SJA actuator dynamics. Motivated by the limitations characteristic of SUAV applications, the control method is designed to be computationally inexpensive, eliminating the need for time-varying parameter update laws, function approximators, or heavy computations. To this end, a robust-inverse control method [12] is utilized, which is proven to compensate for the SUAV and SJA uncertainties using a simplified controller structure. By endowing the robust-inverse control structure with a bank of dynamic filters, asymptotic LCO regulation is achieved using only pitching and plunging displacement measurements in the feedback loop. The result is an asymptotic SJA-based LCO regulation control design, which does not require velocity measurements, adaptive laws, function approximators, or heavy computations in the feedback loop. To achieve the result, a detailed mathematical model of the LCO dynamics is utilized, which includes nonlinear stiffness effects, unmodeled external disturbances, and SUAV model uncertainty. An additional challenge addressed in the control design is the parametric uncertainty and nonlinearity that is inherent in the SJA dynamic model. A rigorous Lyapunov-based stability analysis is utilized to prove the theoretical result, and numerical simulation results are provided to demonstrate the performance of the proposed control law.

2. Dynamic model and properties

In this section, a detailed mathematical model of the pitching and plunging dynamics in an airfoil will be presented, which incorporates nonlinear stiffness effects, unmodeled nonlinear external disturbances, and the uncertain nonlinear SJA actuator dynamics. To facilitate the control design, the LCO dynamics will be expressed in an advantageous form, which will be utilized to design the LCO suppression control law.

The equation describing LCO in an UAV wing can be expressed as [16]

$$M_s\ddot{p} + C_s\dot{p} + F(p)p + d(t) = \begin{bmatrix} -F_L \\ M \end{bmatrix} \tag{1}$$

where the coefficients $M_s, C_s \in \mathbb{R}^{2\times 2}$ are the structural mass and damping matrices; $F(p(t)) \in \mathbb{R}^{2\times 2}$ is a nonlinear stiffness matrix; and $p(t) \triangleq \begin{bmatrix} h(t) & \alpha(t) \end{bmatrix}^T \in \mathbb{R}^2$ denotes the state vector, where $h(t), \alpha(t) \in \mathbb{R}$ denote the plunging [m] and pitching [rad] displacements, respectively. In (1), $d(t) \in \mathbb{R}^2$ represents a general unknown, norm-bounded, nonvanishing disturbance.

Assumption 1. The disturbance $d(t)$ is bounded and sufficiently smooth such that $d(t), \dot{d}(t) \in \mathcal{L}_\infty$ throughout closed-loop operation.

Property 1. The structural mass matrix M_s is positive definite and symmetric (see [16] and [17]).

In (1), the structural linear mass, M_s, structural linear damping, C_s, and the nonlinear stiffness, $F(p)$, matrices are described as [16]

$$M_s = \begin{bmatrix} m & mx_\alpha b \\ mx_\alpha b & I_\alpha \end{bmatrix},\ C_s = \begin{bmatrix} C_h & 0 \\ 0 & C_\alpha \end{bmatrix},\ F(p) = \begin{bmatrix} K_h & 0 \\ 0 & K_\alpha(\alpha) \end{bmatrix} \tag{2}$$

where $x_\alpha \in \mathbb{R}$ denotes the non-dimensional distance measured from the elastic axis to the center of mass, $b \in \mathbb{R}$ is the semi-chord of the wing [m], $m \in \mathbb{R}$ is the mass of the wing section [kg], and $I_\alpha \in \mathbb{R}$ is the mass moment of inertia of the wing about the elastic axis [kg·m^2]. The parameter $C_h \in \mathbb{R}$ denotes the structural damping coefficient in plunge due to viscous damping [kg/s], and $C_\alpha \in \mathbb{R}$ denotes the structural damping coefficient in pitch due to viscous damping [kg·m^2/s]. The $K_h \in \mathbb{R}$ is the structural spring constant in plunge [N/m]; and $K_\alpha(\alpha(t)) \in \mathbb{R}$ is the nonlinear torsion stiffness coefficient [N·m/rad], which is defined via the polynomial

$$K_\alpha = 2.82(1 - 22.1\alpha + 1315.5\alpha^2 - 8580\alpha^3 + 17289.7\alpha^4). \tag{3}$$

Remark 1. The exact polynomial definition for the nonlinear torsion stiffness coefficient in (3) is provided for completeness in defining the dynamic model only [17]. The polynomial in (3) is assumed to be unknown and is not used in the control design. The proposed robust nonlinear control law compensates for the uncertainty associated with nonlinear torsion stiffness.

Also in (1), the control force $F_L(t) \in \mathbb{R}$ and control moment $M(t) \in \mathbb{R}$ are defined as

$$F_L = \rho U^2 s_p b c_{l_\alpha}\left[\alpha + \frac{\dot{h}}{b} + \left(\frac{1}{2} - a\right) b\frac{\dot{\alpha}}{U}\right] + \rho U^2 s_p b c_{l_\beta}\beta \tag{4}$$

$$M = \rho U^2 s_p b^2 c_{m_\alpha}\left[\alpha + \frac{\dot{h}}{b} + \left(\frac{1}{2} - a\right) b\frac{\dot{\alpha}}{U}\right] + \rho U^2 s_p b^2 c_{m_\beta}\beta \tag{5}$$

where $U \in \mathbb{R}$ denotes forward velocity [m/s], $s_p \in \mathbb{R}$ is the wing span [m], $c_{l_\alpha} \in \mathbb{R}$ is the lift coefficient per angle of attack, $c_{m_\alpha} \in \mathbb{R}$ is the moment coefficient per control surface deflection, $c_{l_\beta} \in \mathbb{R}$ is the lift coefficient per control surface deflection, $c_{m_\beta} \in \mathbb{R}$ is the moment coefficient per control surface deflection, and $a \in \mathbb{R}$ is the non-dimensional distance from the mid-chord to the elastic axis. In (4) and (5), the term $\beta(t) \in \mathbb{R}$ denotes the control surface deflection [deg].

Property 2. The control surface deflection $\beta(t)$ in (4) and (5) will be generated by means of SJA arrays. In the following Section 2.1, the nonlinear dynamic model for the *virtual* surface deflection due to arrays of SJAs will be described. To simplify the following discussion, it will be assumed that the virtual surface deflection is generated by $m = 2$ arrays of SJAs; however, the control design can be easily extended to handle any number $m \geq 2$ SJA arrays with little modification (e.g., using the pseudo-inverse of a matrix).

After some rearranging of (1), the LCO dynamics can be expressed as

$$M_s\ddot{p} = \chi(t) - d(t) + Bu \tag{6}$$

where the unknown, unmeasurable, nonlinear auxiliary signal $\chi(t) \in \mathbb{R}^2$ is defined as

$$\chi(t) \triangleq -C_s\dot{p} - F(p)p \tag{7}$$

where $F(p)$ is the nonlinear stiffness. In (6), $u(t) \triangleq \begin{bmatrix} u_1(t) & u_2(t) \end{bmatrix}^T \in \mathbb{R}^2$ denotes the virtual surface deflection angle due to the SJA arrays; and $B \in \mathbb{R}^{2\times 2}$ is an uncertain control

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