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Smooth tracking control for the conversion mode of tilt-rotor aircraft with switching modeling

Key words: Tilt-rotor aircraft; State-tracking control; Switched linear systems; Time-scheduled multiple Lyapunov function approach; Smooth interpolation

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Motivation

1. Tilt-rotor aircraft is a new type of aircraft with advantages of both helicopters and fixed-wing aircrafts, and has been applied in many fields. To ensure a safe flight, it is important to focus on the control problem of the conversion mode and complete the smooth switching of the flight modes.

2. A switched linear model of the tilt-rotor aircraft is built, so that the tilting features can be better described, and the control design is simplified based on the switched linear model.

3. A bumpless transfer (BT) method is necessary to reduce the controller bumps. To satisfy the BT performance, a time-scheduled method is developed to construct an improved multiple Lyapunov function (MLF), and the linear interpolation approach is adopted in certain intervals. Compared with the conventional BT technique, the reference input is no longer essential.

Method

By selecting five operating points in the conversion corridor, trimming the nonlinear model of the conversion mode, and using the Jacobian linearization, a cluster of linear models can be obtained.

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}_{\sigma(t)}\boldsymbol{x}(t) + \boldsymbol{B}_{\sigma(t)}\boldsymbol{u}(t) + \boldsymbol{H}_{\sigma(t)}\boldsymbol{\omega}(t)$$

Table 1 Trimming results of the selected operating points

Mast angle	Air speed	System state				Control input		
β_{M}	V (ft/s)	u (ft/s)	w (ft/s)	q (rad/s)	θ (rad)	θ_{b} (rad)	θ_{a} (rad)	δ_{e} (rad)
0°	101.21	101.1160	−4.3608	0	−0.0431	0.5661	0	0.1011
12°	135.02	134.2099	14.7686	0	0.1096	0.4576	0	−0.1847
35°	168.78	164.1370	39.3157	0	0.2351	0.2658	0	−0.4413
52°	202.53	198.0255	42.4769	0	0.2113	0.2183	0	−0.3906
90°	270.04	266.6466	42.6757	0	0.1587	0.2432	0	−0.2821

1 ft=0.3048 m

Method

Select the proper switching signal that satisfies the mode-dependent dwell-time (MDDT) constraint.

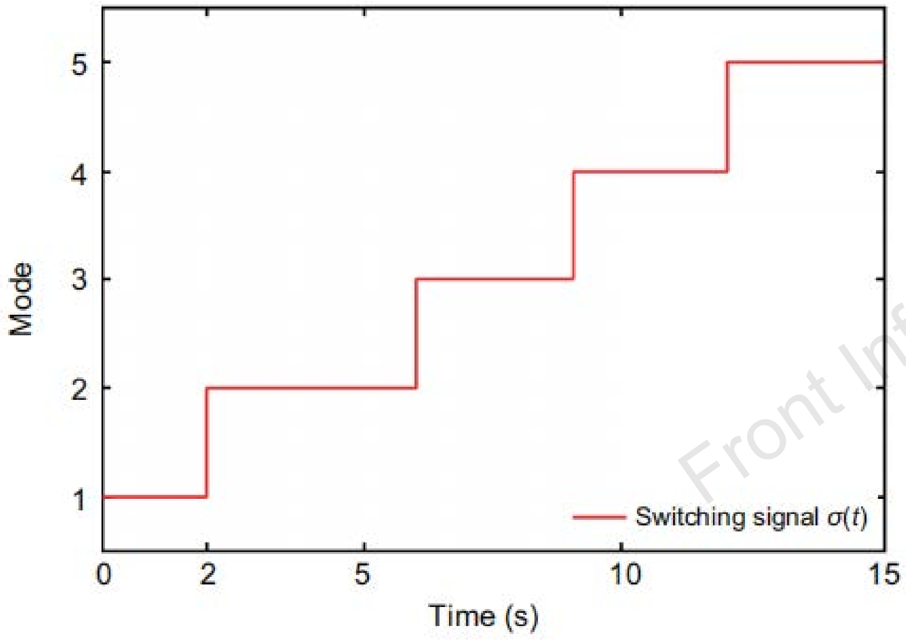

Fig. 1 Switching signal $\sigma(t)$

Introduce a transition interval and develop the interpolation process during the interval to design time-scheduled controllers.

$$\tilde{\chi}_{1ij}=\begin{bmatrix}\tilde{\chi}^{11}_{1ij} & \boldsymbol{H}_i & \boldsymbol{T}_{jL}\\ * & -\gamma^2\boldsymbol{I} & \boldsymbol{0}\\ * & \boldsymbol{0} & -\boldsymbol{I}\end{bmatrix}<0,$$

$$\tilde{\chi}_{2ij}=\begin{bmatrix}\tilde{\chi}^{11}_{2ij} & \boldsymbol{H}_i & \boldsymbol{T}_{i0}\\ * & -\gamma^2\boldsymbol{I} & \boldsymbol{0}\\ * & \boldsymbol{0} & -\boldsymbol{I}\end{bmatrix}<0,$$

$$\bar{\chi}_{1ij}=\begin{bmatrix}\bar{\chi}^{11}_{1ij} & \boldsymbol{H}_i & \boldsymbol{T}_{il}\\ * & -\gamma^2\boldsymbol{I} & \boldsymbol{0}\\ * & \boldsymbol{0} & -\boldsymbol{I}\end{bmatrix}<0,$$

$$\bar{\chi}_{2ij}=\begin{bmatrix}\bar{\chi}^{11}_{1ij} & \boldsymbol{H}_i & \boldsymbol{T}_{i(l+1)}\\ * & -\gamma^2\boldsymbol{I} & \boldsymbol{0}\\ * & \boldsymbol{0} & -\boldsymbol{I}\end{bmatrix}<0,$$

$$\chi_i=\begin{bmatrix}\chi^{11}_{i} & \boldsymbol{H}_i & \boldsymbol{T}_{iL}\\ * & -\gamma^2\boldsymbol{I} & \boldsymbol{0}\\ * & \boldsymbol{0} & -\boldsymbol{I}\end{bmatrix}<0,$$

$$\begin{aligned}
\tilde{\chi}^{11}_{1ij} =&\mathrm{He}\{\boldsymbol{A}_i\boldsymbol{T}_{jL}+\boldsymbol{B}_i\boldsymbol{U}_{jL}\}+\varsigma_{\mathrm{u}i}\boldsymbol{T}_{jL}-\frac{\boldsymbol{T}_{i0}-\boldsymbol{T}_{jL}}{\tau_{\mathrm{h}}},\\
\tilde{\chi}^{11}_{2ij} =&\mathrm{He}\{\boldsymbol{A}_i\boldsymbol{T}_{i0}+\boldsymbol{B}_i\boldsymbol{U}_{i0}\}+\varsigma_{\mathrm{u}i}\boldsymbol{T}_{i0}-\frac{\boldsymbol{T}_{i0}-\boldsymbol{T}_{jL}}{\tau_{\mathrm{h}}},\\
\bar{\chi}^{11}_{1ij} =&\mathrm{He}\{\boldsymbol{A}_i\boldsymbol{T}_{il}+\boldsymbol{B}_i\boldsymbol{U}_{il}\}+\varsigma_{\mathrm{s}i}\boldsymbol{T}_{il}-\frac{\boldsymbol{T}_{i(l+1)}-\boldsymbol{T}_{il}}{\tau_{\mathrm{l}i}},\\
\bar{\chi}^{11}_{2ij} =&\mathrm{He}\{\boldsymbol{A}_i\boldsymbol{T}_{i(l+1)}+\boldsymbol{B}_i\boldsymbol{U}_{i(l+1)}\}+\varsigma_{\mathrm{s}i}\boldsymbol{T}_{i(l+1)}\\
&-\frac{\boldsymbol{T}_{i(l+1)}-\boldsymbol{T}_{il}}{\tau_{\mathrm{l}i}},\\
\chi^{11}_{i} =&\mathrm{He}\{\boldsymbol{A}_i\boldsymbol{T}_{iL}+\boldsymbol{B}_i\boldsymbol{U}_{iL}\}+\varsigma_{\mathrm{s}i}\boldsymbol{T}_{iL},
\end{aligned}$$

Method

The controller gain matrices are obtained, and the tracking performances of those four states are obtained.

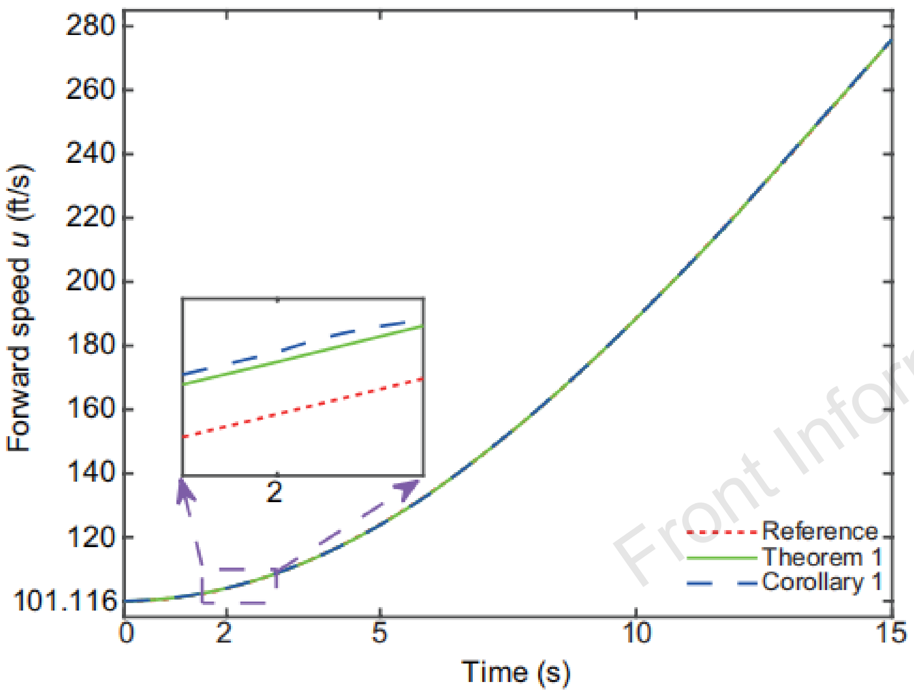

Fig. 2 Forward speed u (1 ft=0.3048 m)

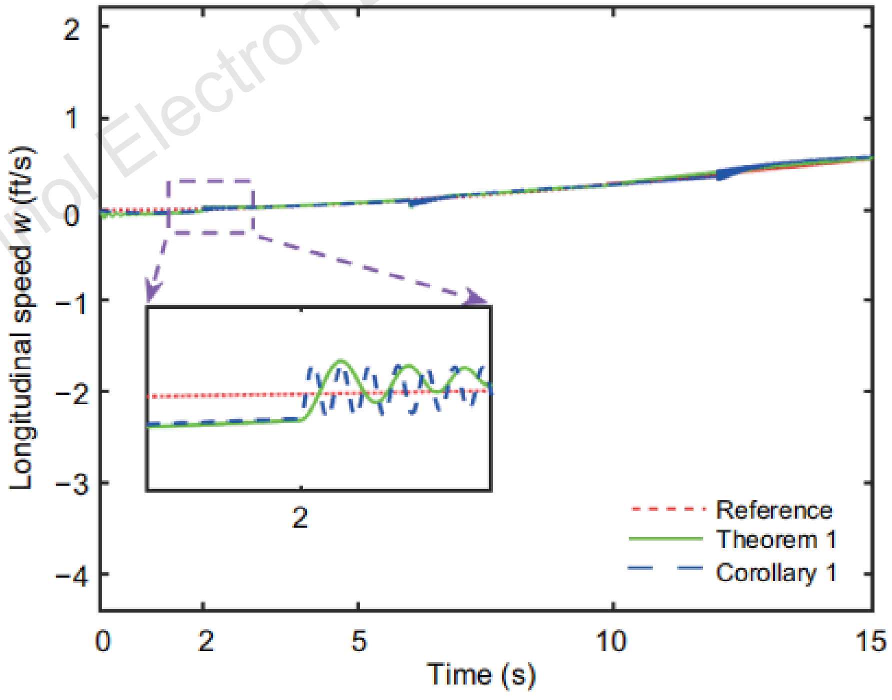

Fig. 3 Longitudinal speed w (1 ft=0.3048 m)

Method

Based on the developed smooth tracking control scheme, the tracking performances are further improved.

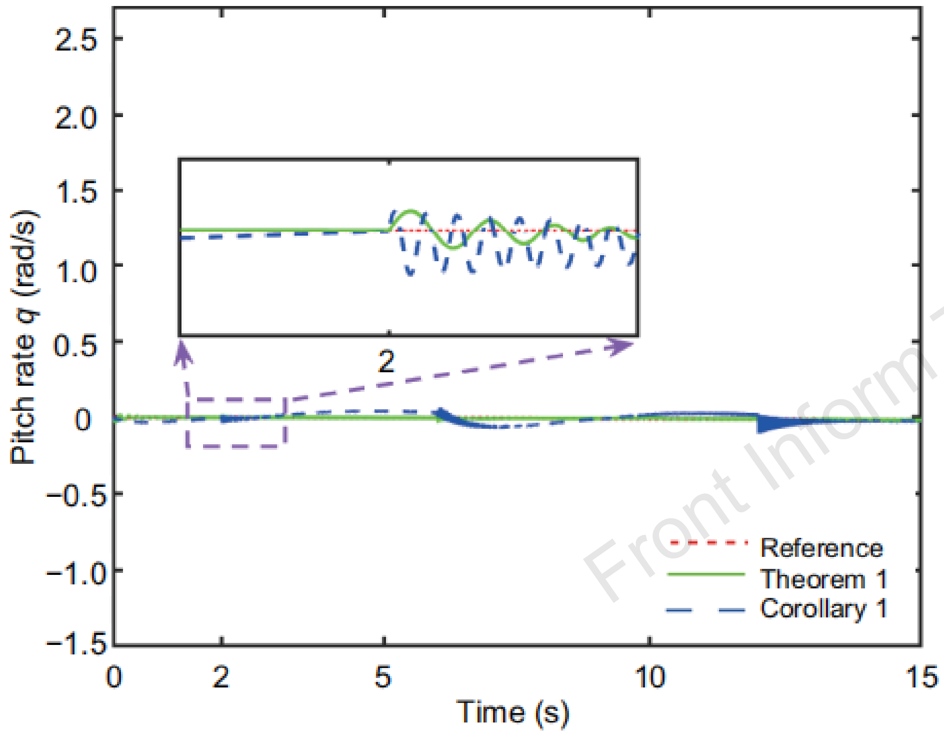

Fig. 4 Pitch rate q

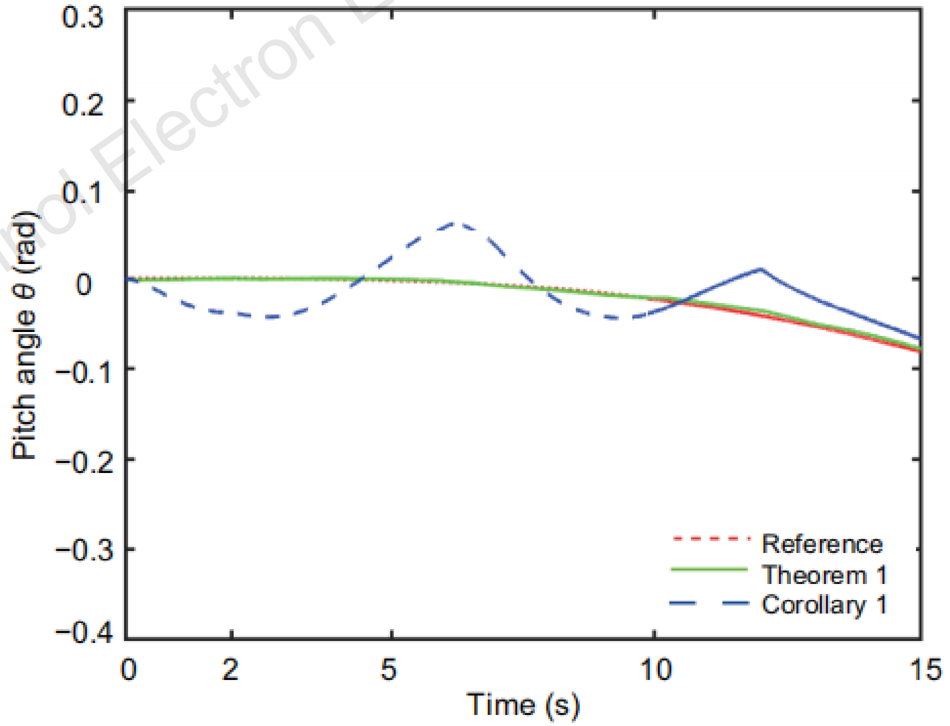

Fig. 5 Pitch angle θ

Conclusions

1. We adopted the switched linear model for modeling the tilt-rotor aircraft in conversion mode, and designed a proper switching signal.
2. We developed the time-scheduled method to construct an improved MLF, and adopted the linear interpolation approach to resolve the BT issue.
3. We designed the smooth state-tracking control scheme, and achieved the improved tracking performances.

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