Thrust Vectoring Control of Vertical/Short Takeoff and Landing Aircraft

XiangYang WANG[1], Bin ZHU[2] , JiHong ZHU[1]& ZhiQiang CHENG[1]

[1]Department of Computer Science and Technology,
Tsinghua University, China;

[2]Automation Academy,
Nanjing Unviersity of Science and Technology, China

Overview

1. Introduction
2. Dynamic model of the thrust vectoring system
3. Dynamic model of V/STOL aircraft
4. Flight Control Scheme
5. Simulation and experimental results
6. Conclusions

Background

V/STOL aircrafts are fixed-wing aircrafts which can take-off and land vertically or within short distances.

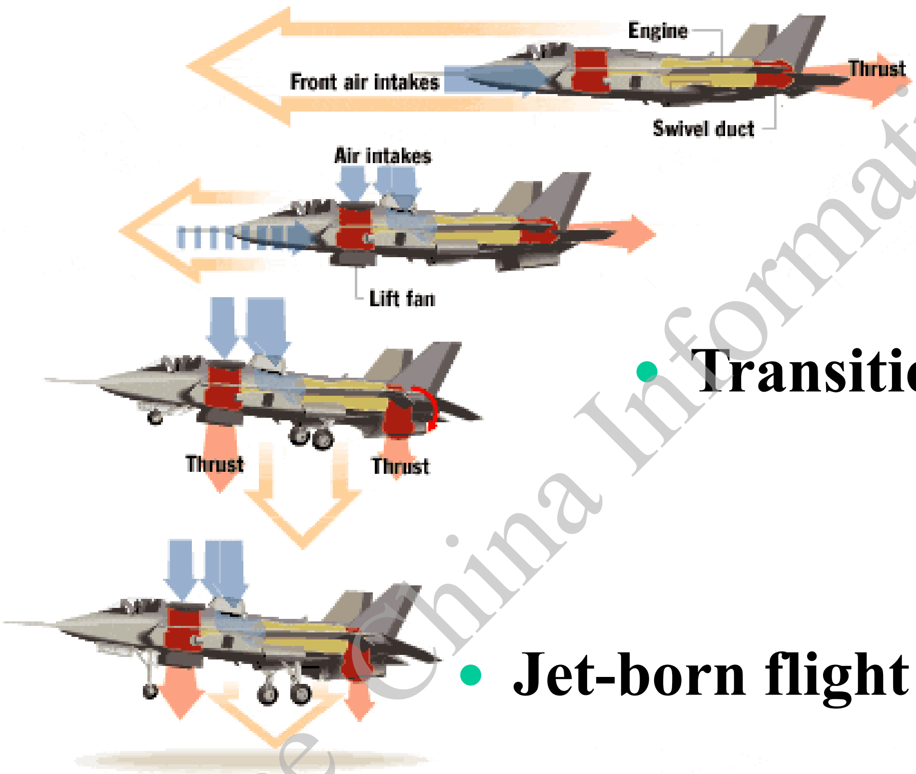
Background

Thrust-vectored V/STOL aircrafts are used as fighters.

F-35B

Yak-141

Flight modes



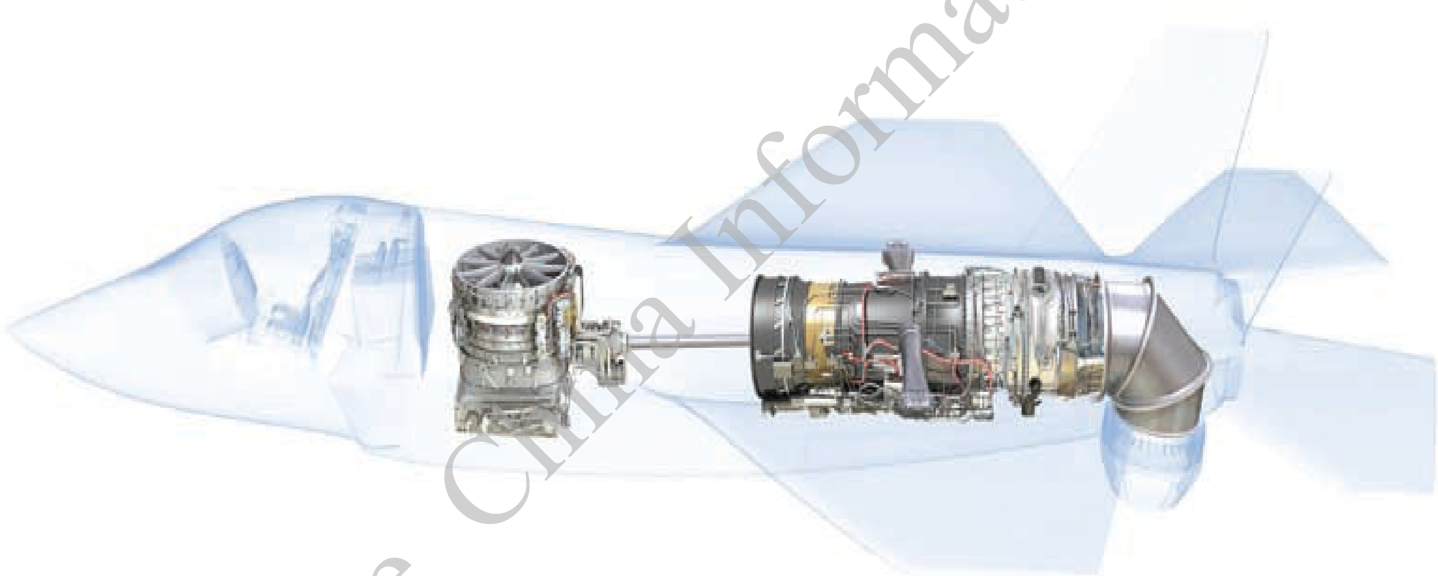
- Wing-born flight
- Transition flight
- Jet-born flight

V/STOL aircraft transit from jet-born to wing-born or backward.

Thrust vectoring system

Vertical lift fan

Main engine + 3-Bearing Swivel Duct (3BSD) nozzle



F-35B

Related works

- Feedback linearization control + control allocation module [2]
- Autonomous transition control strategy based on FBL [3]
- Neural network augmented model inversion [4]
- **Few studies took dynamics of the thrust vectoring system into consideration**

Overview

1. Introduction
2. Dynamic model of the thrust vectoring system
3. Dynamic model of V/STOL aircraft
4. Flight Control Scheme
5. Simulation and experimental results
6. Conclusions

3-Bearing Swivel Duct Nozzle

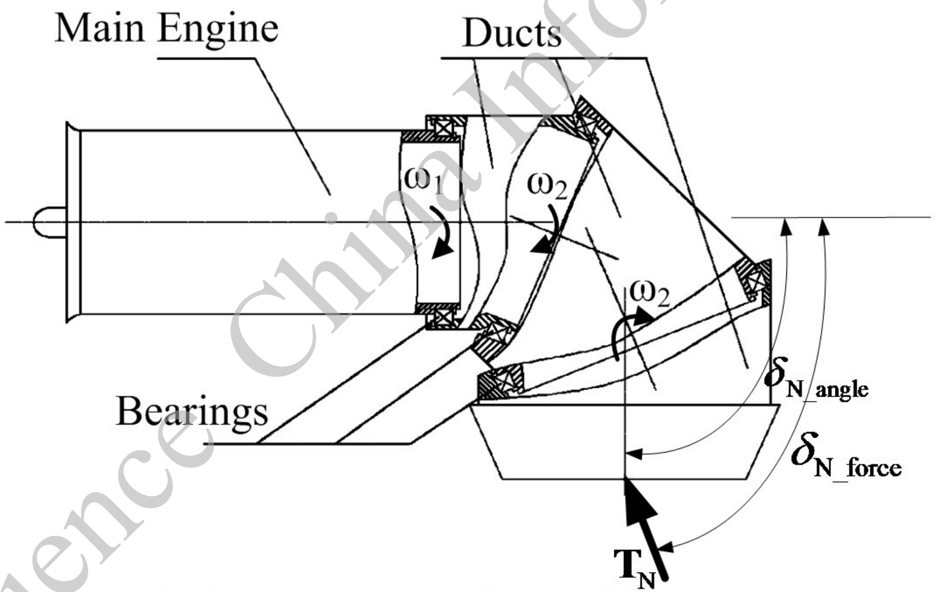
THU-F35B:

	Data
Reference chord (m)	0.57075
Wing Span (m)	1.244
Wing Area (m^2)	0.61048
Max Weight (kg)	20

3-Bearing Swivel Duct Nozzle

3BSD nozzle deflects more than 90 degrees through rotations of three revolute pairs:

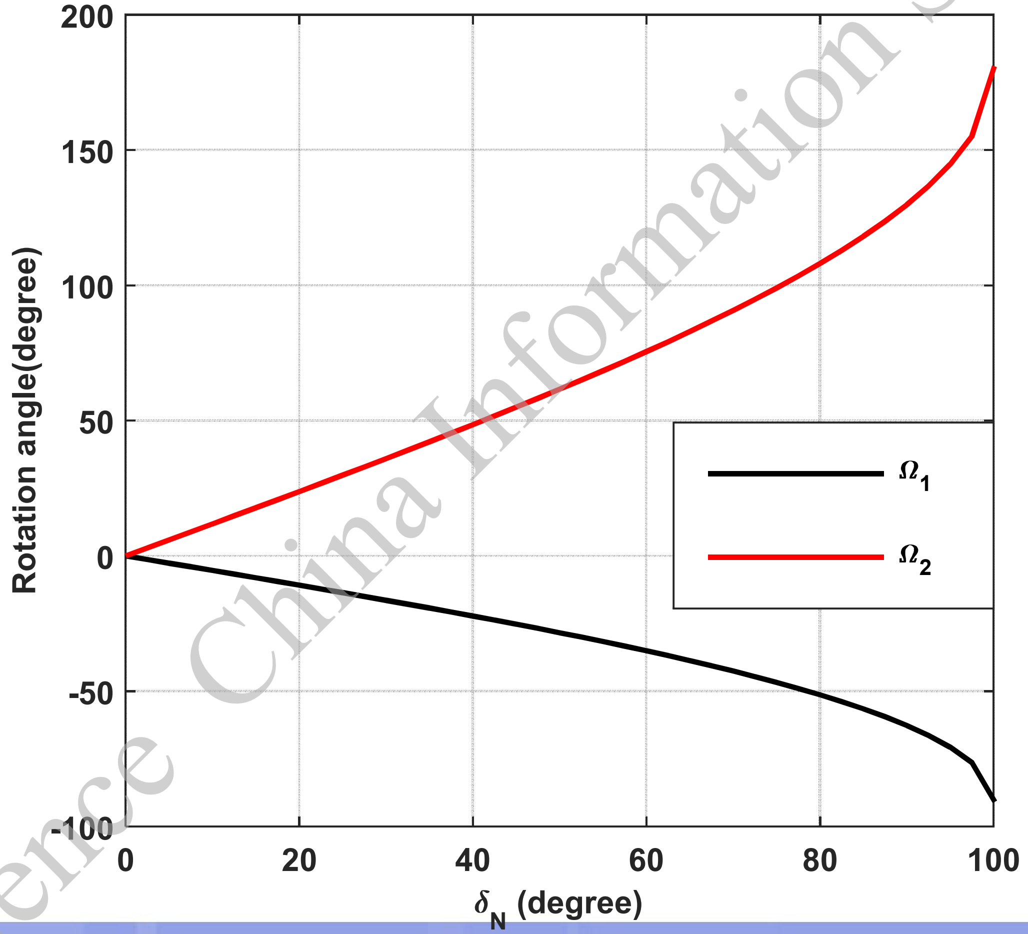
$$\begin{cases} \delta_{\mathrm{N\_angle}} = 2\arccos\left(\sin^2\eta\cos\omega_2 + \cos^2\zeta\right) \\ \delta_{\mathrm{N}y} = \omega_1 + \arctan\left(\tan(\omega_2/2)\cos\zeta\right) \end{cases}$$



3-Bearing Swivel Duct Nozzle

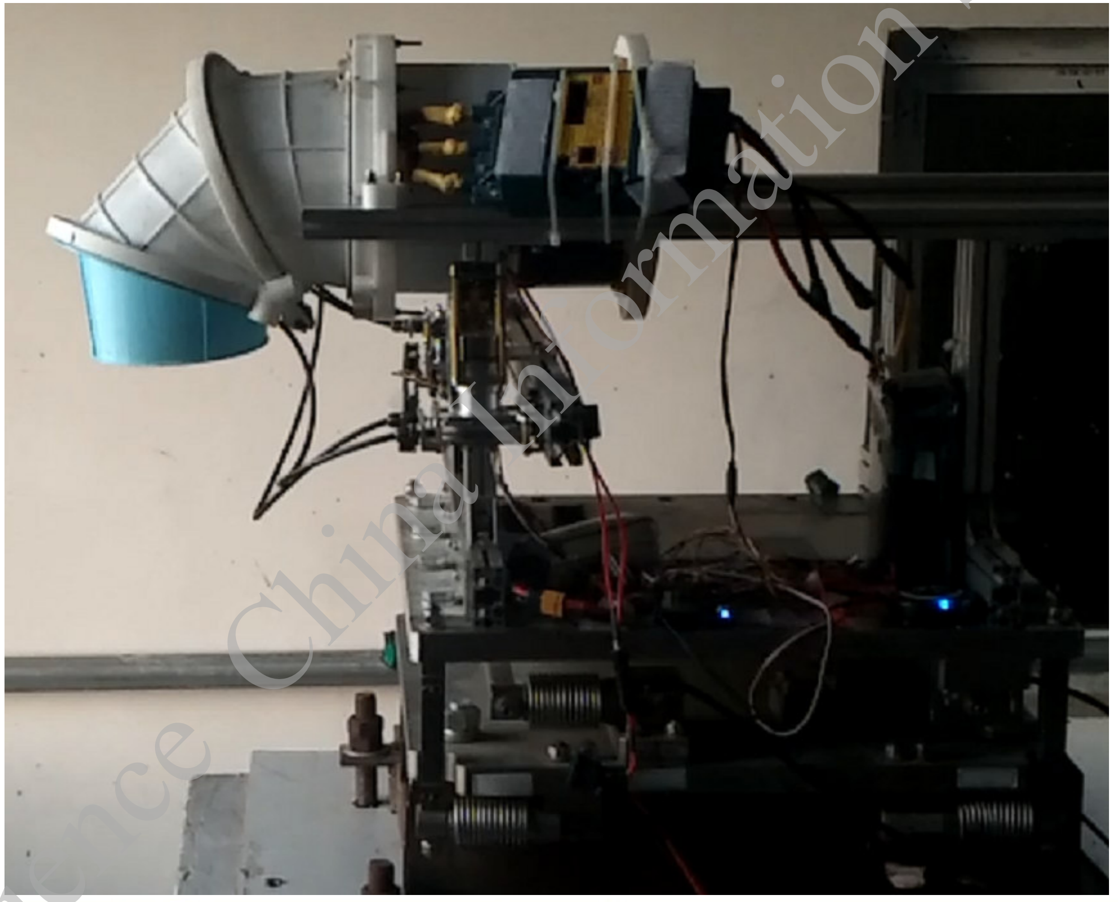
For 3BSD nozzle of THU-F35B:

$\delta_{N\_angle} \in [0,100]$ degrees, $\omega_1 \in [-105,0]$ degrees, $\omega_2 \in [0,180]$ degrees



Static and dynamic tests

Installed on a six-component balance

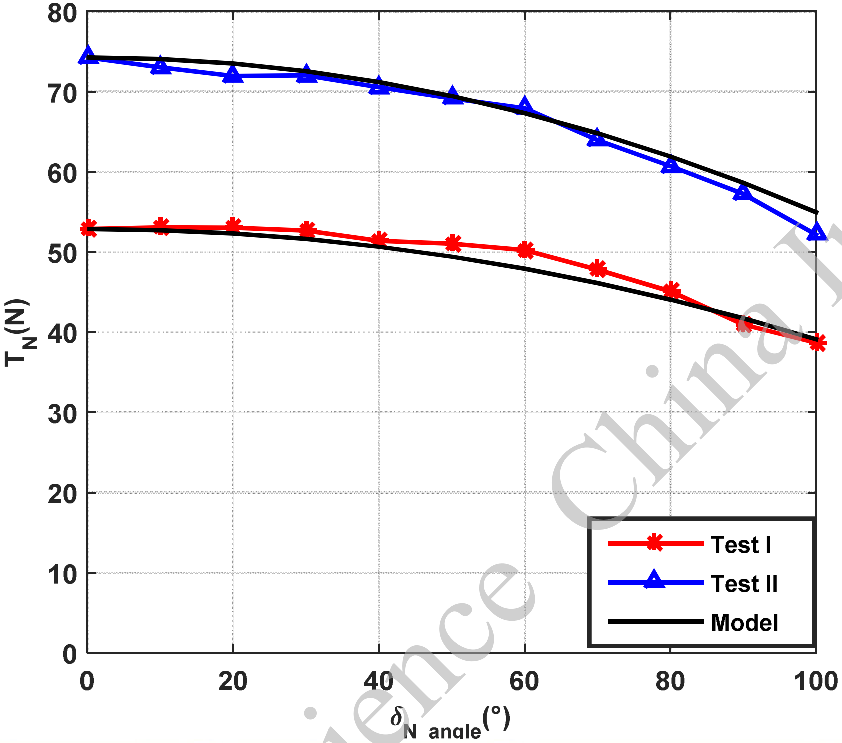


Dynamic model of 3BSD nozzle

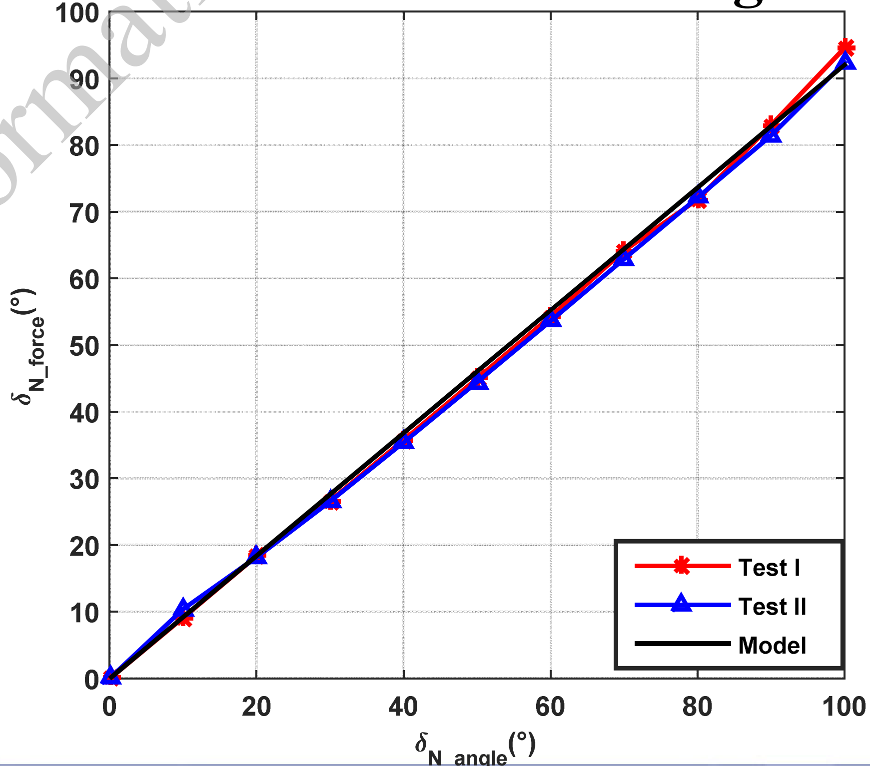
The thrust loss function: $\eta = \eta_0 + \eta_1 \delta_{\mathrm{N\_angle}}^2$

The deflection angle of vectored force : $\delta_{\mathrm{N\_force}} = p_1 \delta_{\mathrm{N}}$

Thrust force



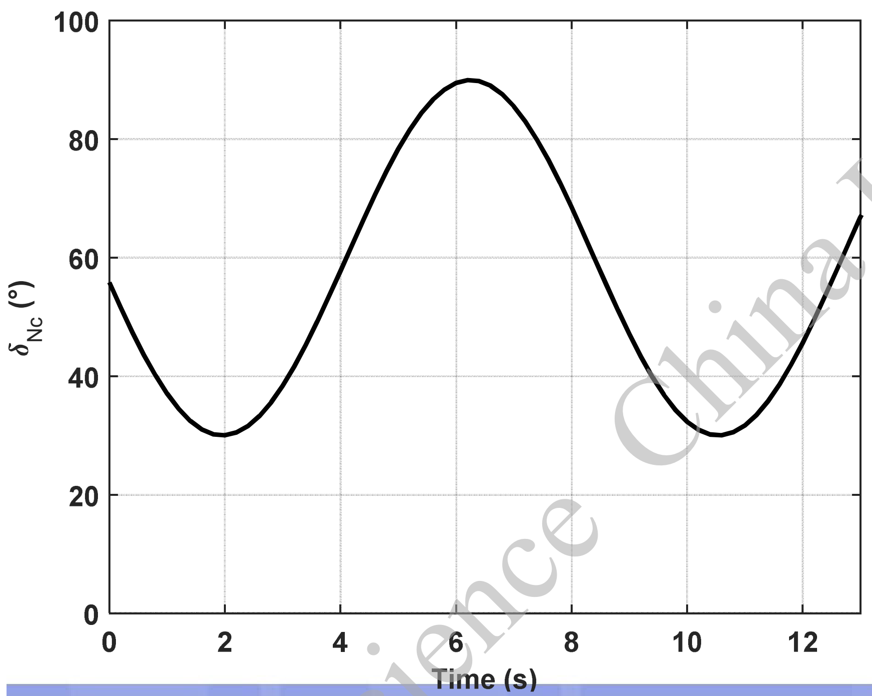
Thrust deflection angle

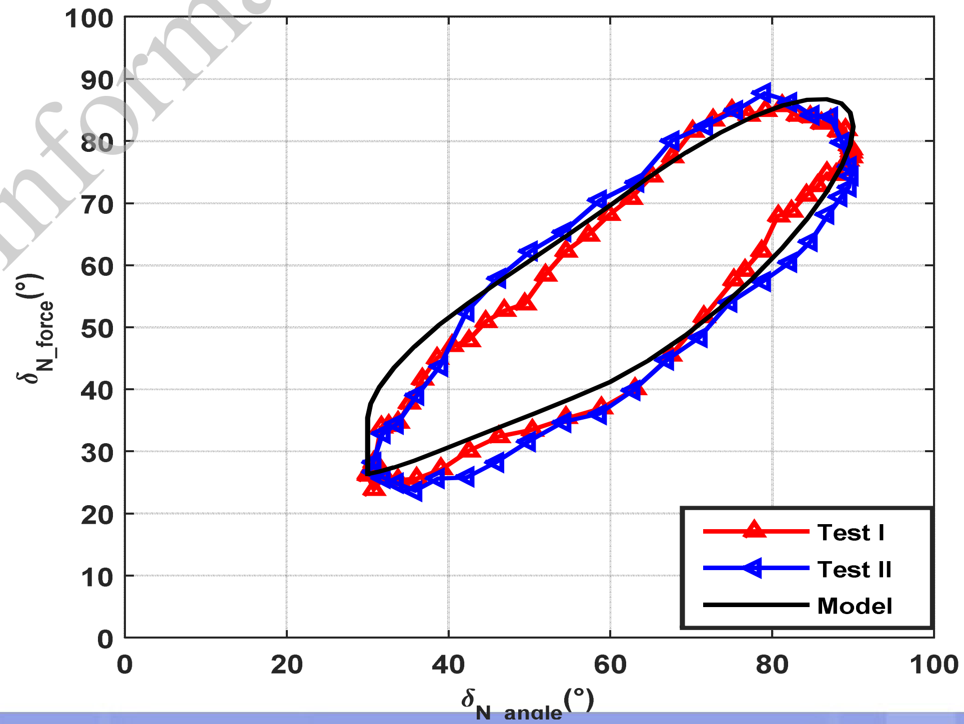


Dynamic model of 3BSD nozzle

The hysteresis characteristics was modeled using first order characteristic model

$$\delta_{\mathrm{N}}(k) = a\delta_{\mathrm{N}}(k-1) + (1-a)\delta_{\mathrm{N\_angle}}, \quad a \in (0,1)$$





Dynamic model of 3BSD nozzle

Components of the vectored forces in the body axis are written as

$$\begin{cases} T_{\mathrm{N}x} = T_{\mathrm{e}}\eta\cos\delta_{\mathrm{N\_force}}, \\ T_{\mathrm{N}y} = T_{\mathrm{e}}\eta\sin\delta_{\mathrm{N\_force}}\sin\delta_{\mathrm{N}y}, \\ T_{\mathrm{N}z} = -T_{\mathrm{e}}\eta\sin\delta_{\mathrm{N\_force}}\cos\delta_{\mathrm{N}y}. \end{cases}$$

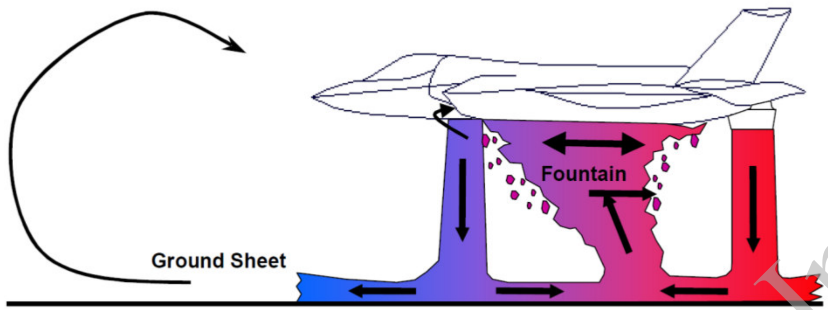
Overview

1. Introduction
2. Dynamic model of the thrust vectoring system
3. Dynamic model of V/STOL aircraft
4. Flight Control Scheme
5. Simulation and experimental results
6. Conclusions

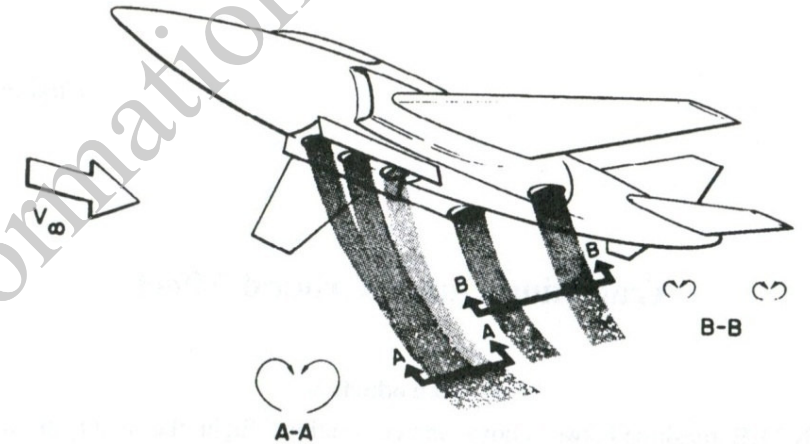
Dynamic model of V/STOL aircraft

Jet-induced effects

Hover



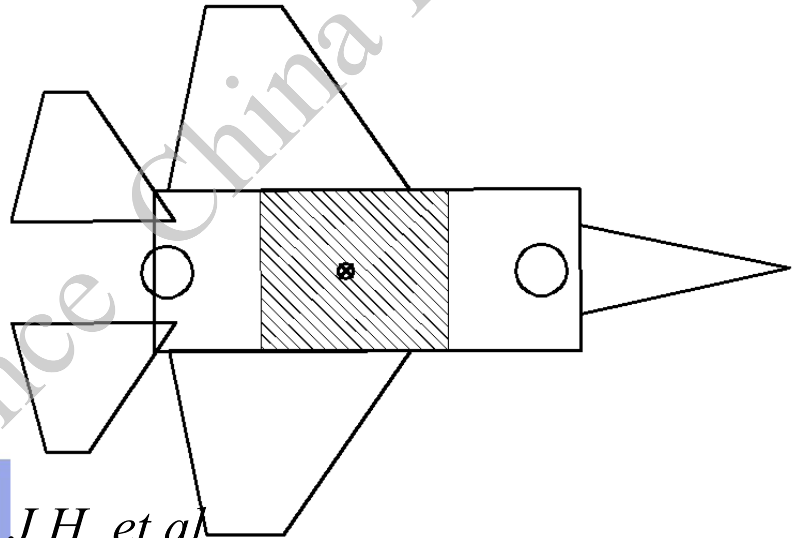
Transition



1. Out of ground effect
2. Suckdown
3. Fountain Effect
4. Transition effect

Aerodynamic forces include jet-induced effects

$$\begin{cases} D = QS(C_{D0} + C_{D\alpha}\alpha + \dfrac{c}{2v_t}C_{Dq}q), \\ L = QS(C_{L0} + C_{L\alpha}\alpha + \dfrac{c}{2v_t}C_{Lq}q) + (\Delta L / T)T, \\ M_{ay} = QSc(C_{m0} + C_{m\alpha}\alpha + \dfrac{c}{2v_t}C_{mq}q) + (\Delta M / TD_e)TD_e \end{cases}$$



Dynamic model of V/STOL aircraft

Dynamic model of V/STOL aircraft in the earth-fixed reference frame

$$\begin{cases} \dot{V}_{xg} = (F_{axg} + F_{Txg}) / m, \\ \dot{V}_{zg} = (F_{azg} + F_{Tzg}) / m + g, \\ \dot{q} = (M_{ay} + M_{Ty}) / I_{yy}, \\ \dot{\theta} = q \end{cases}$$

Taking the nonlinear equations into the above equation, the dynamic model of V/STOL aircraft is rewritten as:

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{u}) + \boldsymbol{D}\boldsymbol{d}, \\ \boldsymbol{y} = \boldsymbol{C}\boldsymbol{x}, \\ \boldsymbol{u}_{\min} \leqslant \boldsymbol{u} \leqslant \boldsymbol{u}_{\max}, \\ |\dot{\boldsymbol{u}}| \leqslant \boldsymbol{u}_{ratmax}(\delta_{\text{N\_angle}}) \end{cases}$$

Overview

1. Introduction
2. Dynamic model of the thrust vectoring system
3. Dynamic model of V/STOL aircraft
4. Flight Control Scheme
5. Simulation and experimental results
6. Conclusions

Flight Control Scheme

Challenges of flight control

(1) Highly cross-coupled system.

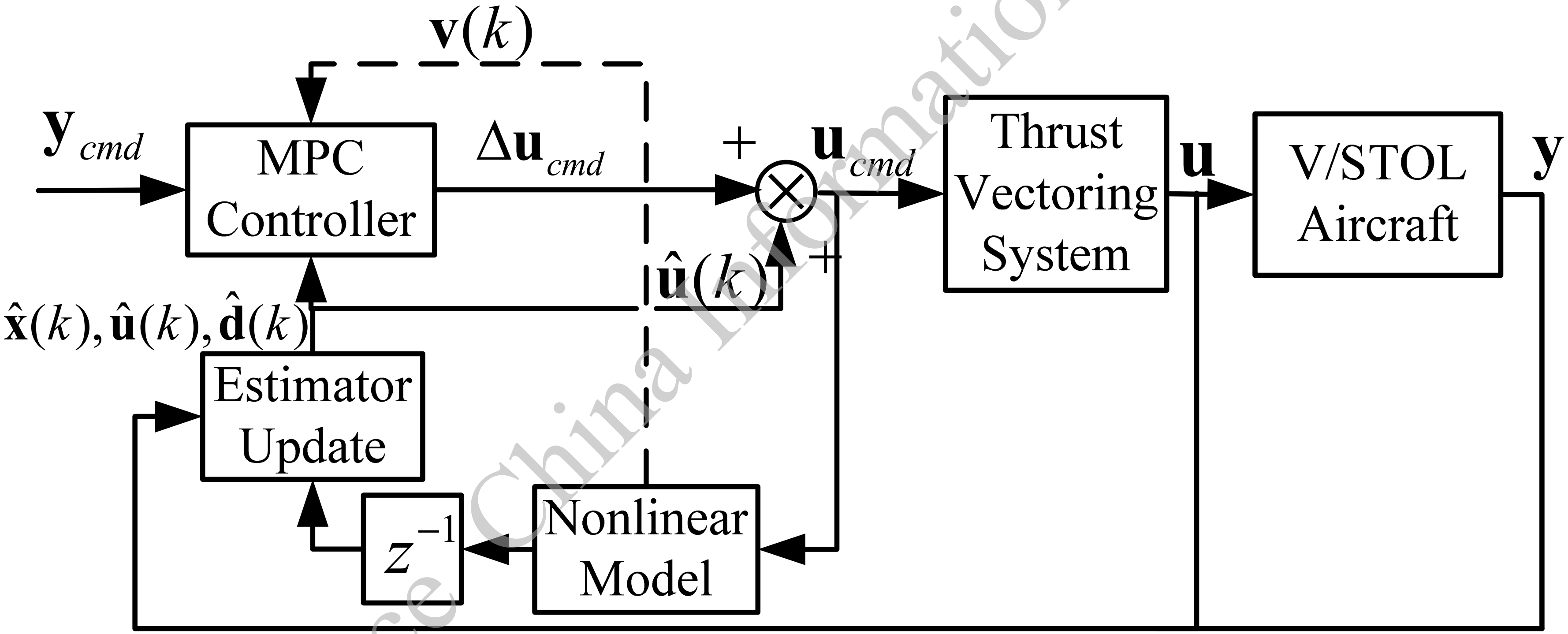
(2) Bandwidth of the thrust vectoring system is much lower than that of aerodynamic actuators. In jet-born and transition flight, effectors' bandwidth requirements are 6 rad/sec for height control, and 20 rad/sec for pitch control.

Fuller, J. Constrained Dynamic Inversion Control and Its Application to Turbomachinery, SAE Technical Paper 2010-01-1737, 2010,doi:10.4271/2010-01-1737.

(1) The performance and weight tradeoffs require the V/STOL aircraft to operate near it's limits of stability, durability, and effectors' rate and position limits.

Flight Control Scheme

Modified LTV MPC control Scheme.



Flight Control Scheme

The LTV approximation of the nonlinear system is written as:

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{A}_k \boldsymbol{x} + \boldsymbol{B}_k \boldsymbol{u} + \boldsymbol{v}_k + \boldsymbol{D}\boldsymbol{d}^*, \\ \boldsymbol{y} = \boldsymbol{x} \end{cases}$$

$$\boldsymbol{A}_k = \partial \boldsymbol{f}/\partial \boldsymbol{x} + \partial \boldsymbol{g}/\partial \boldsymbol{x}|_{\boldsymbol{x}=\hat{\boldsymbol{x}},\boldsymbol{u}=\hat{\boldsymbol{u}}},$$

$$\boldsymbol{B}_k = \partial \boldsymbol{g}/\partial \boldsymbol{u}|_{\boldsymbol{x}=\hat{\boldsymbol{x}},\boldsymbol{u}=\hat{\boldsymbol{u}}},$$

$$\boldsymbol{v}_k = \boldsymbol{f}(\hat{\boldsymbol{x}}) + \boldsymbol{g}(\hat{\boldsymbol{x}}, \hat{\boldsymbol{u}}) - \boldsymbol{A}_k \hat{\boldsymbol{x}} - \boldsymbol{B}_k \hat{\boldsymbol{u}},$$

Flight Control Scheme

Extended dynamic system

$$\begin{cases} \boldsymbol{x}_1(k+1) = \boldsymbol{F}_k x_1(k) + \boldsymbol{G}\boldsymbol{u}_{cmd}(k) + \boldsymbol{\Gamma}\boldsymbol{v}(k) + \boldsymbol{\Phi}\boldsymbol{d}^*(k) \\ \boldsymbol{y}(k) = \boldsymbol{C}\boldsymbol{x}_1(k) \\ \underline{\boldsymbol{u}} \le \boldsymbol{u}_{cmd}(k) \le \overline{\boldsymbol{u}} \\ |\Delta \boldsymbol{u}_{cmd}(k)| \le T_s \boldsymbol{u}_{rat\max} \end{cases}$$

Compute the estimated state and disturbance:

$$\boldsymbol{x}_1(k|k-1) = \boldsymbol{F}_k \hat{\boldsymbol{x}}_1(k) + \boldsymbol{G}\boldsymbol{u}_{cmd}(k) + \boldsymbol{Q}\left[\boldsymbol{v}(k) + \hat{\boldsymbol{d}}^*(k-1|k-1)\right]$$

$$\hat{\boldsymbol{d}}^*(k|k-1) = \hat{\boldsymbol{d}}^*(k-1|k-1)$$

$$\begin{bmatrix} \hat{\boldsymbol{x}}_1(k|k) \\ \hat{\boldsymbol{d}}^*(k|k) \end{bmatrix} = \begin{bmatrix} \hat{\boldsymbol{x}}_1(k|k-1) \\ \hat{\boldsymbol{d}}^*(k|k-1) \end{bmatrix} + \boldsymbol{L}(k)\left[\boldsymbol{y}(k) - \boldsymbol{C}\hat{\boldsymbol{x}}_1(k|k-1)\right]$$

Flight Control Scheme

The performance index to be minimized:

$$J = \sum_{i=1}^{H_p} \| \boldsymbol{Q}_x \left[\boldsymbol{x}_1(k+i) - \boldsymbol{x}_{1,ref}(k) \right] \|_2 + \sum_{i=1}^{H_c} \| \boldsymbol{R}_v \Delta \boldsymbol{u}(k+i) \|_2$$

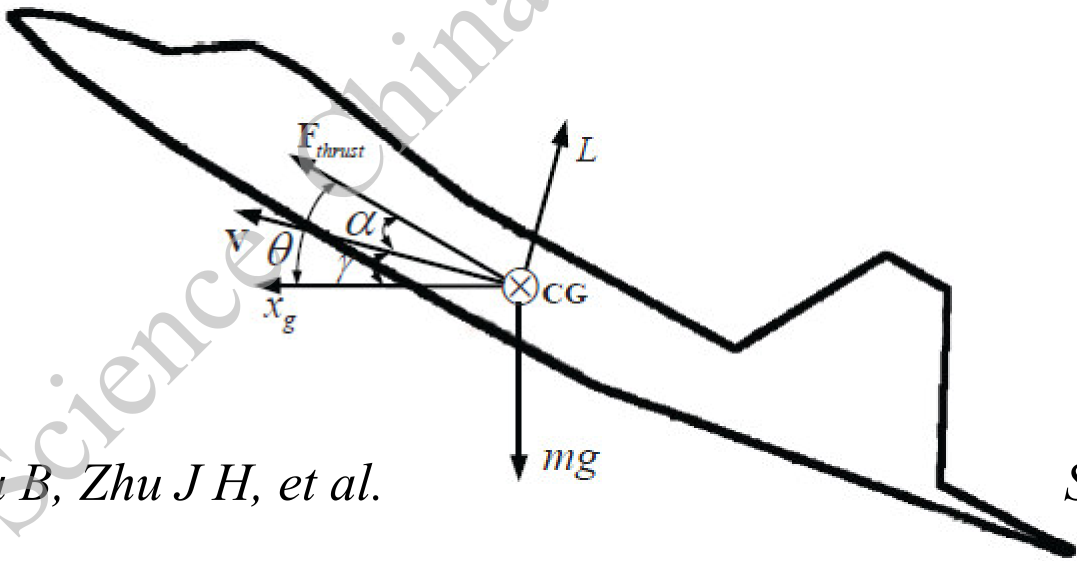
Robust Control Strategy

Choose the reference states V_{xg}, V_{zg}, θ satisfy:

$$L\cos\gamma - mg\cos\theta > 0$$

Design the preferred aircraft and thrust vectoring system states varies with the dynamic pressure. Turn off the thrust vectoring system when the following inequality holds:

$$(T_F / T_{Fmax})^2 + (\delta_N / 90)^2 \leqslant \epsilon$$



Overview

1. Introduction
2. Dynamic model of the thrust vectoring system
3. Dynamic model of V/STOL aircraft
4. Flight Control Scheme
5. Simulation and experimental results
6. Conclusions

Simulation results

Transition from hover to level fight simulation

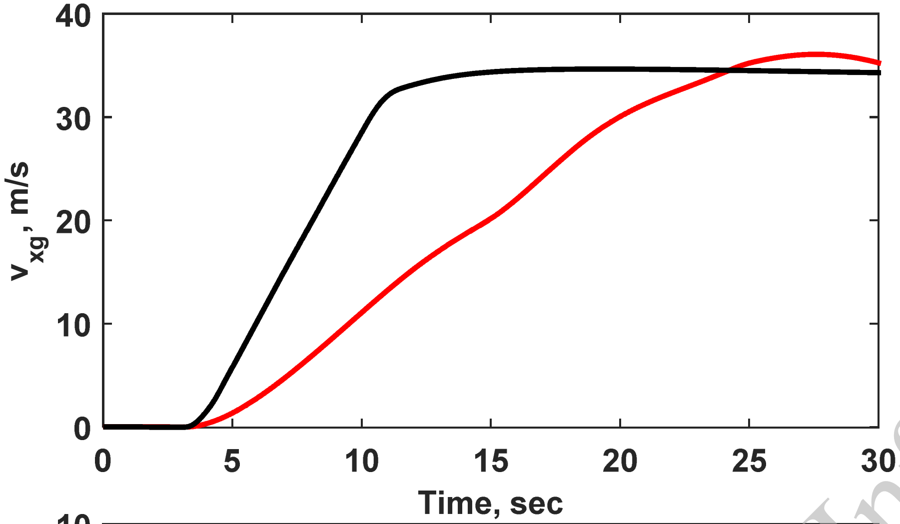
Simulation I: **The proposed controller**

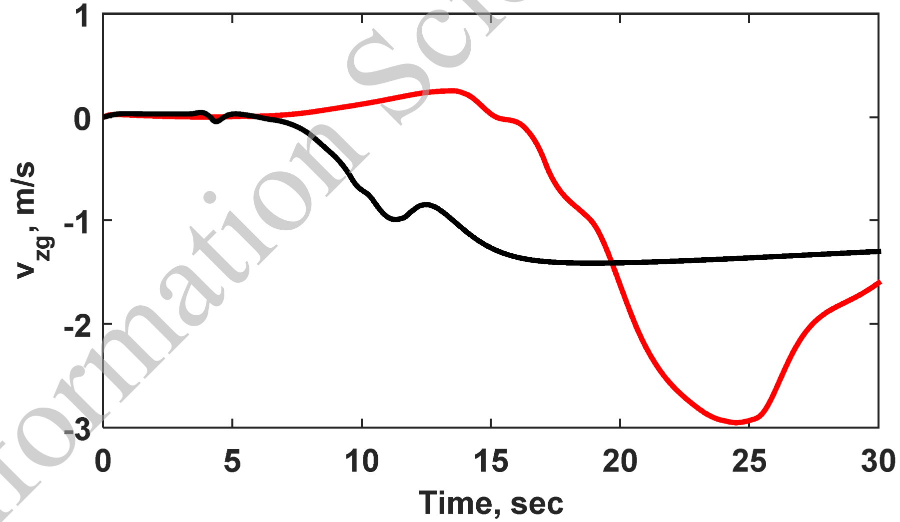
Simulation II: **A FBL controller together with piecewise linear mixed optimization control allocation module**

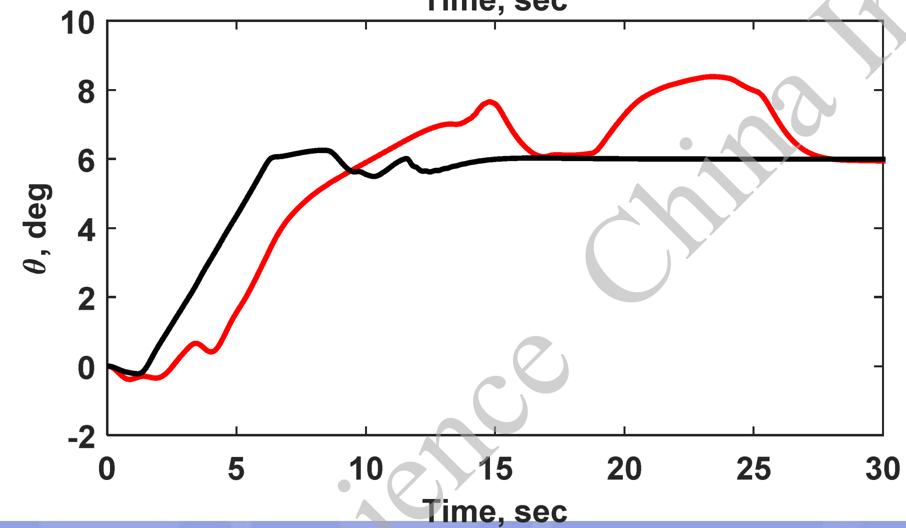
The jet-induced forces/moments are included in the dynamic simulation module, while the dynamic model used for the controllers design assumes these forces/moments are unknown.

Simulation results

Transition from hover to level fight simulation





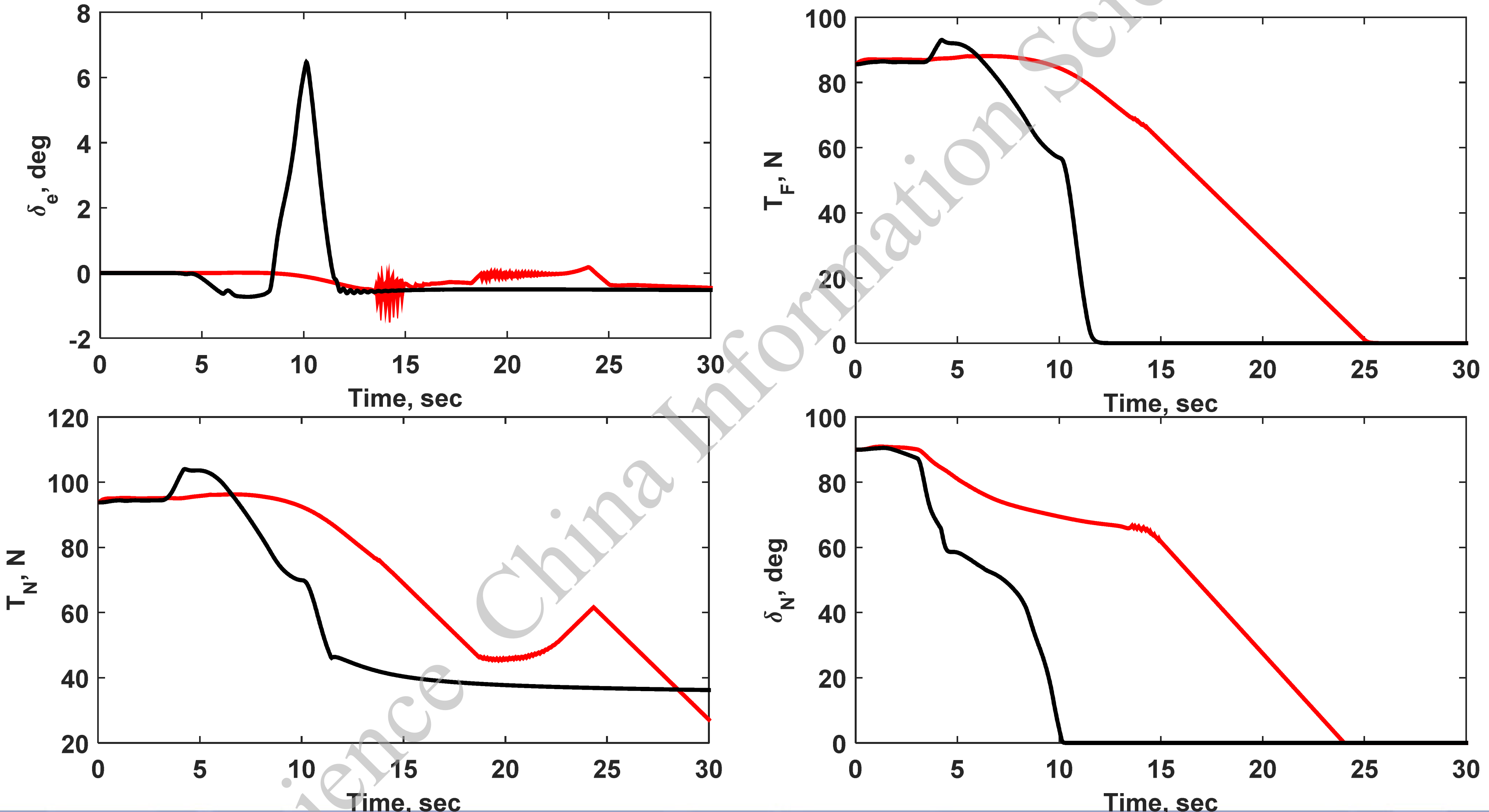


Black Line: The proposed controller

Red Line: FBL controller

Simulation results

Black Line: The proposed controller; **Red Line: FBL controller**

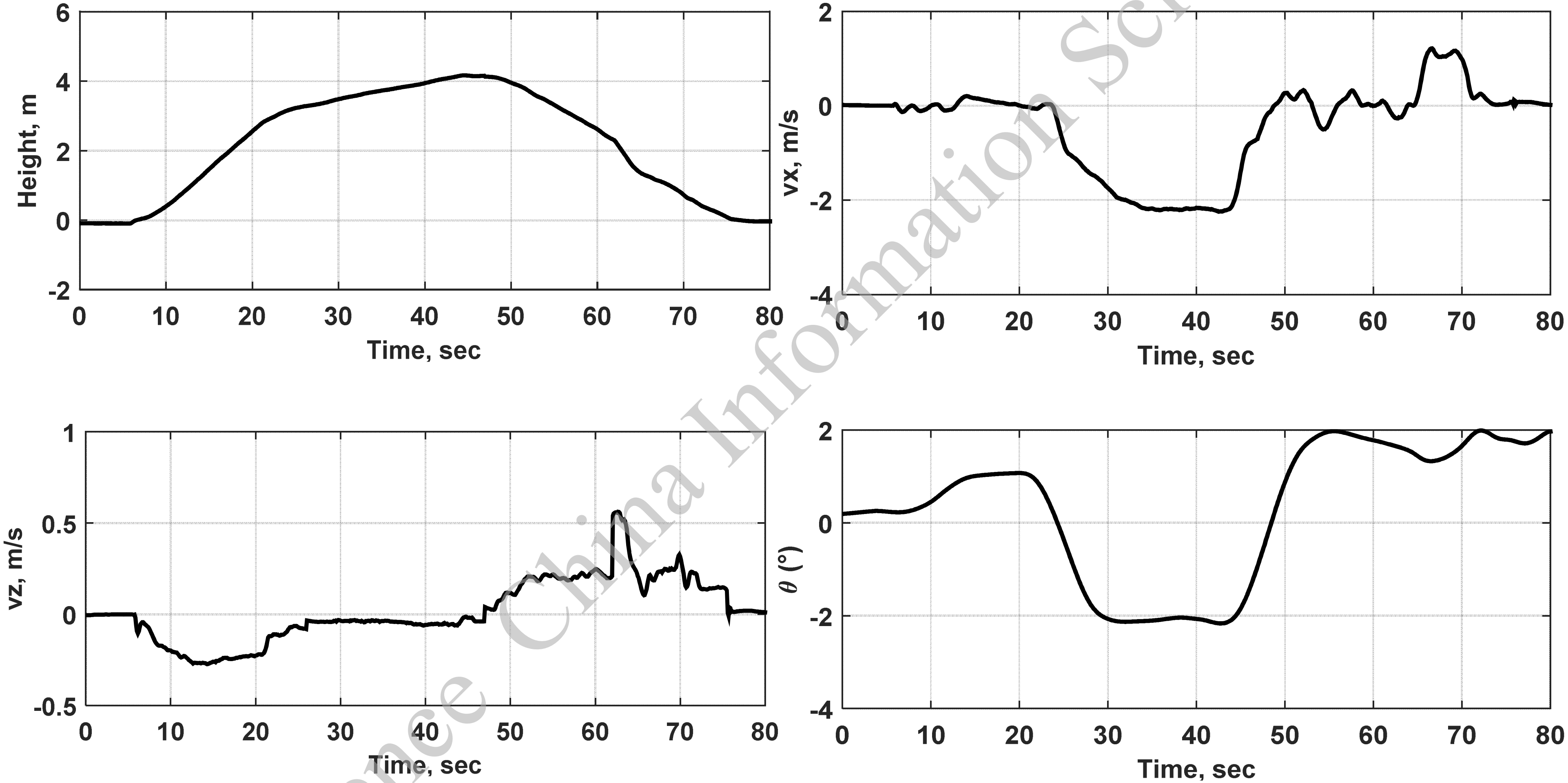


Experimental results

THU-F35B in Hover

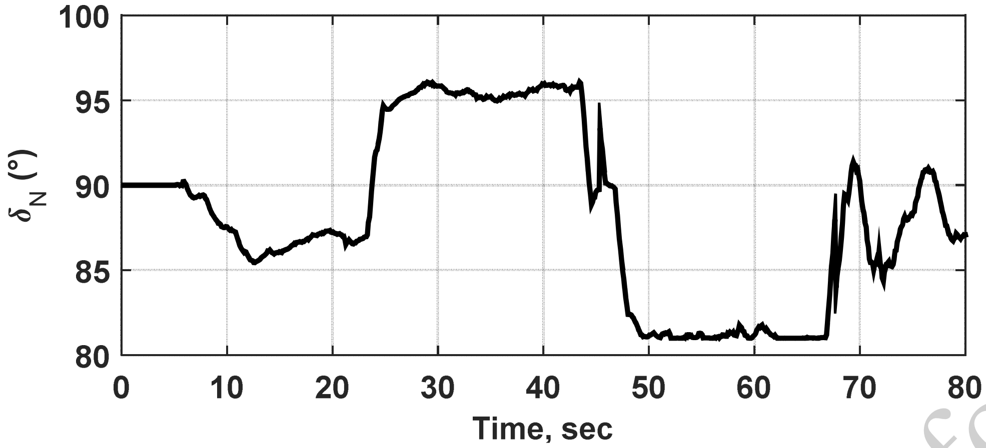
Experimental results

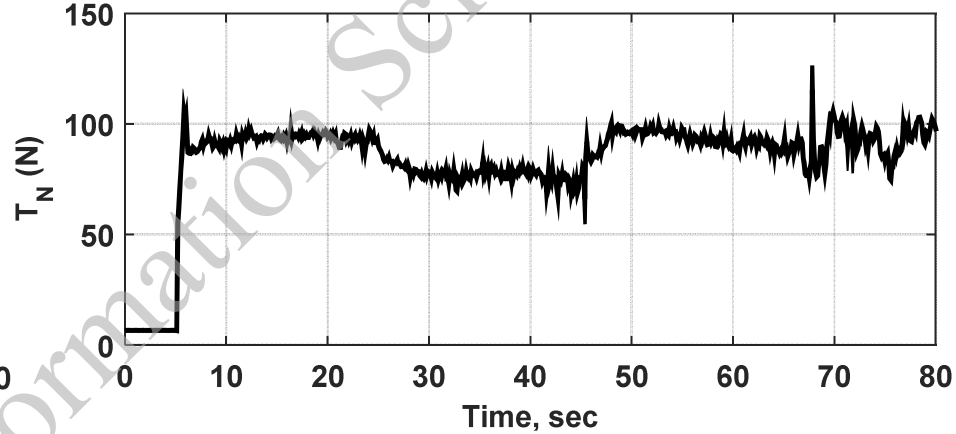
Hover fight

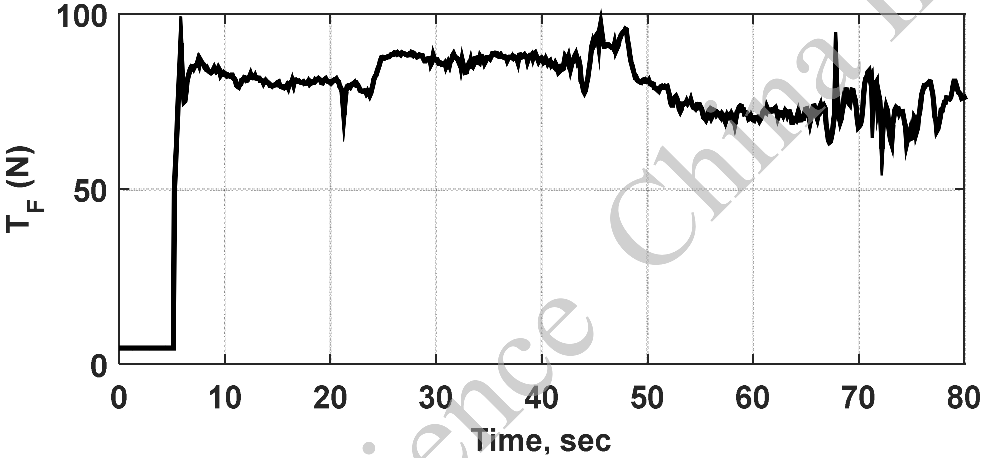


Experimental results

Hover fight







Overview

Conclusions

(1) V/STOL aircraft are nonlinear overactuated systems with low-bandwidth effectors.

(2) Dynamic model of V/STOL aircraft including dynamic characteristic of thrust vectoring system is given.

(3) The proposed LTV MPC is robust to modeling errors and can achieve tight and fast control over numerous limits through integrated optimization.

Thank you!