Control Force Compensation in Ground-Based Flight Simulators

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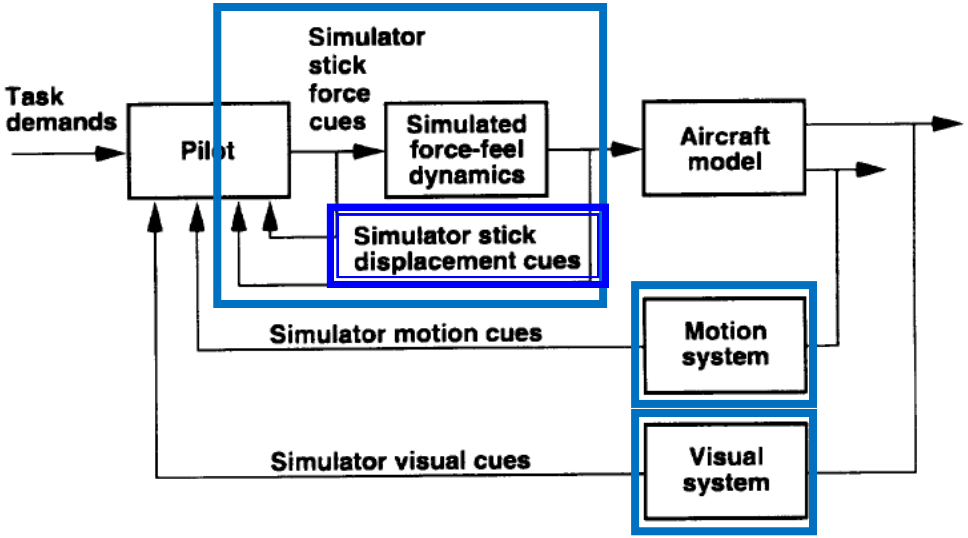
Background

Ground-Based Flight Simulation



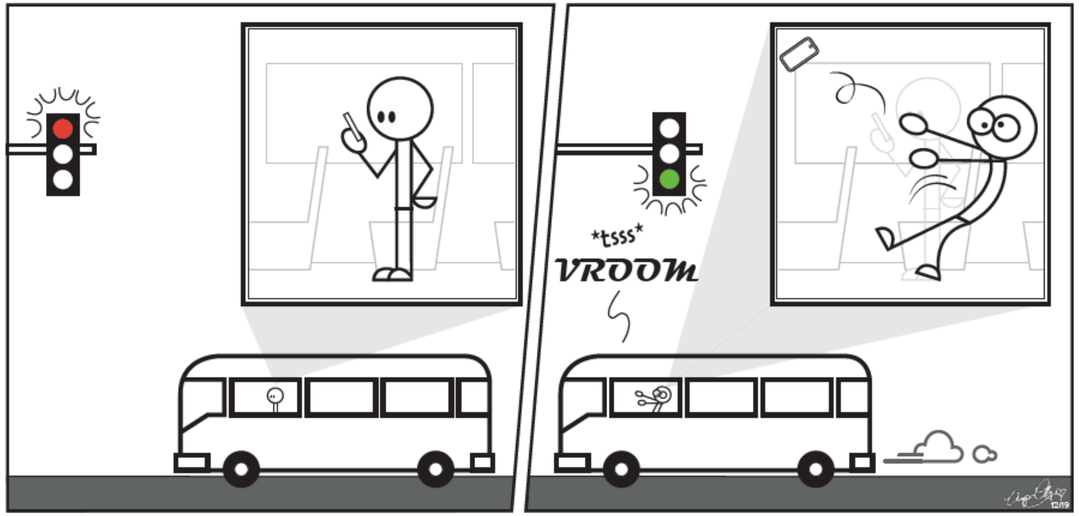
1. Motion is perceived from visual cues with the eyes.
2. The pilot perceives motion from the vehicle's acceleration.
3. Pilot can infer, or predict motion, via the kinesthetic force and position cues that the vehicle's force feel system provides. The latter is often neglected, but important, cueing source.

Schroeder, J. A., "Helicopter Flight Simulation Motion Platform Requirements, " NASA TP-1999-208766

Background (Cont’d)

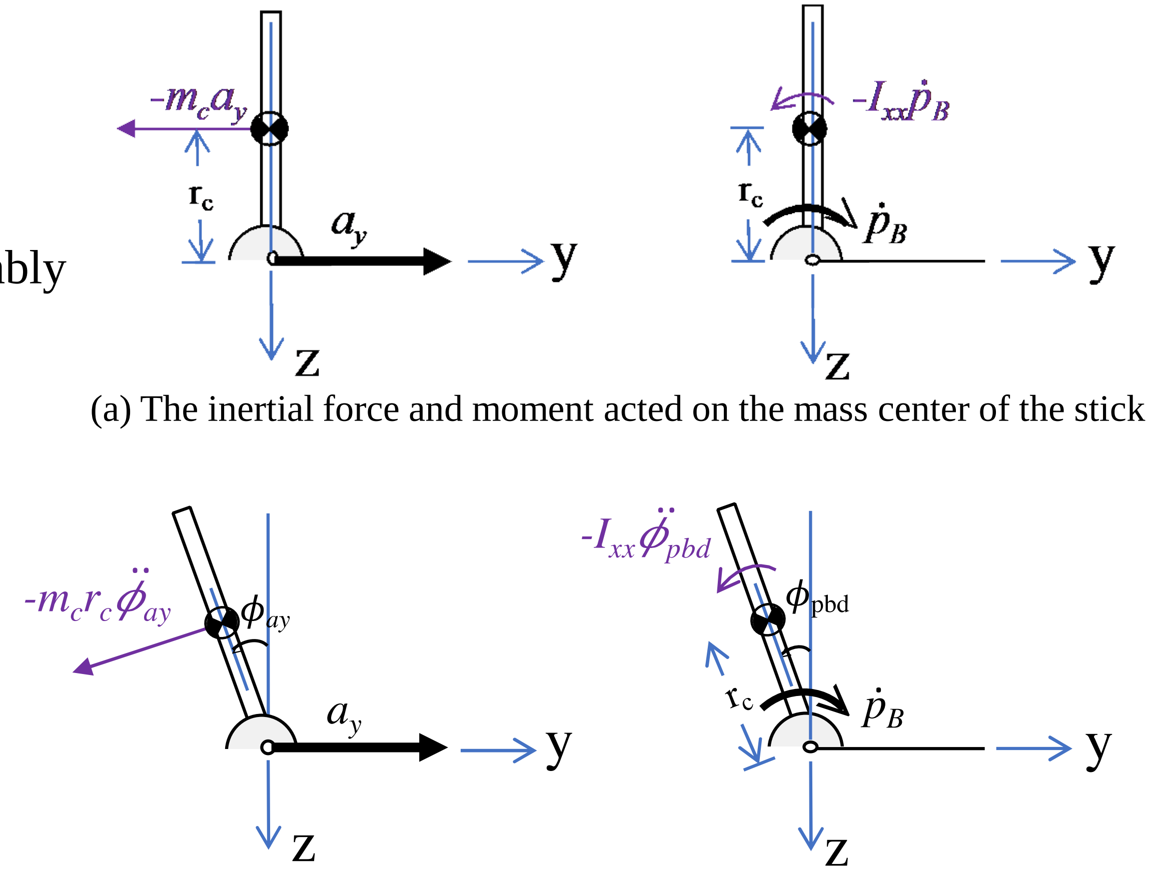
Newton’s First Law

Every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force. This is normally taken as the definition of **inertia**.



The Force Compensation

- ⊗ c.g. of the mass of the lateral stick rotational assembly
- r_c the distance between the lateral stick's pivot point and c.g. of the mass of the stick assembly



(a) The inertial force and moment acted on the mass center of the stick

(b) Resulted stick displacement due to the inertial force and moment

The Force Compensation (Cont'd)

Stick displacement due to a_y

$$\boldsymbol{\Phi}_{ay} = \frac{-\dfrac{m_c\, r_c}{I_{xx}}\, a_y}{s^2 + \dfrac{\zeta_y}{I_{xx}} s + \dfrac{k_y}{I_{xx}}}$$

Stick displacement due to $\dot{p}_b$

$$\boldsymbol{\Phi}_{pbd} = \frac{-\,\dot{p}_b}{s^2 + \dfrac{\zeta_y}{I_{xx}} s + \dfrac{k_y}{I_{xx}}}$$

Total displacement compensation
is added to the stick's trim command

$$\boldsymbol{\Phi}_c = \boldsymbol{\Phi}_{ay} + \boldsymbol{\Phi}_{pbd}$$

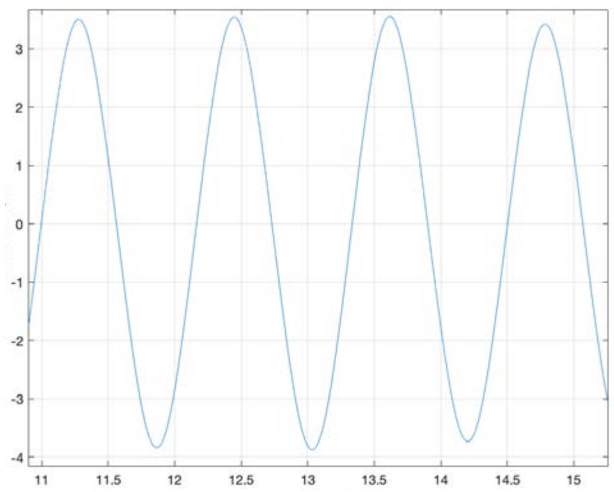
The Force Compensation (Cont’d)

From a previous experiment (NASA TP-1999-208766), $\zeta_y = 0.136\ lb_f\text{-s/in}$ and $k_y = 0.6\ lb_f/in$

$$\Phi_{ay} = \frac{-\dfrac{m_c\, r_c}{I_{xx}}\, a_y \to 0}{s^2 + \dfrac{\zeta_y \to 0}{I_{xx}} s + \dfrac{k_y}{I_{xx}}}$$

$$\omega_n = \sqrt{k_y / I_{xx}} \quad \text{or} \quad I_{xx} = k_y / \omega_n^2$$

Lateral Stick, in



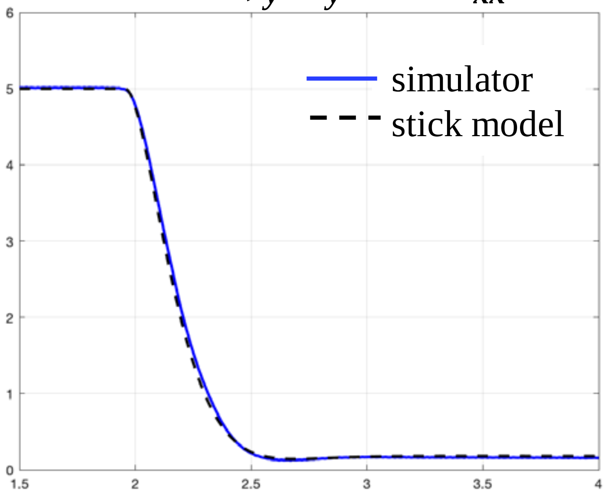
Time (sec)

$\omega_n = 7.5$ rad/sec

$I_{xx} = 2{,}577\ lb_m\text{-in}^2$

Pull-and-release check verifies ζ_y, k_y, and I_{xx}

Lateral Stick, in



Time (sec)

The Force Compensation (Cont’d)

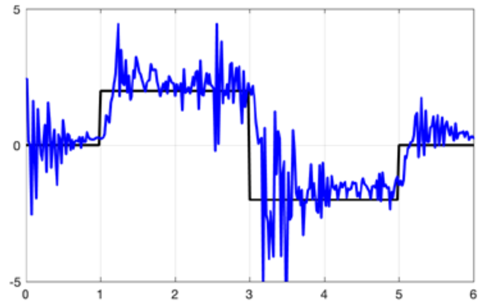
Verification of the force compensation models

Simulator command
Simulator response
Calculated compensation

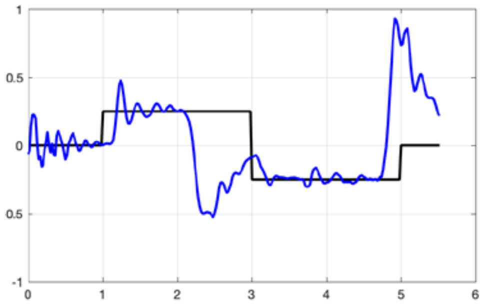
2.5 ft/s^2 lateral acceleration command

0.25 rad/s^2 roll angular acceleration command

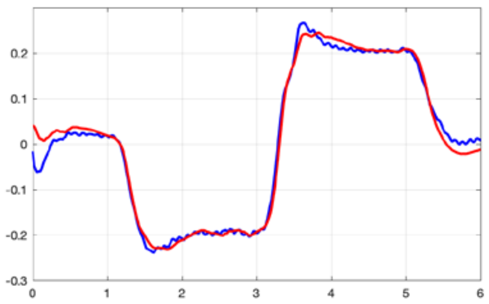
Lateral acceleration ft/sec^2



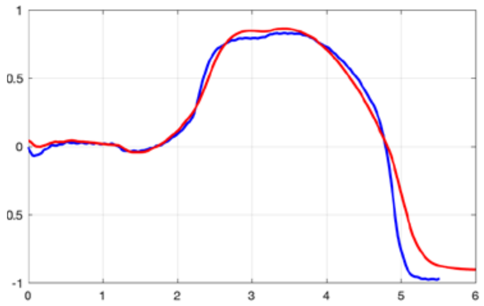
Roll Acceleration rad/sec^2



Lateral stick displacement inch



Lateral stick displacement inch



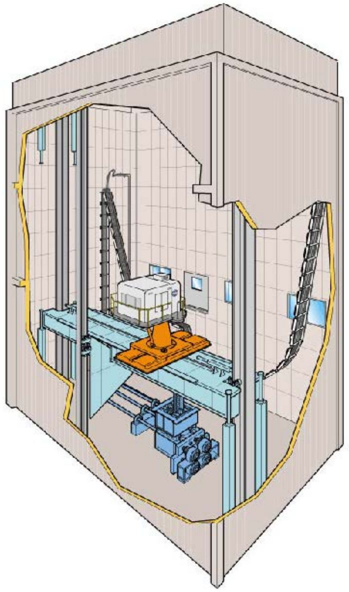
Time (sec)

Time (sec)

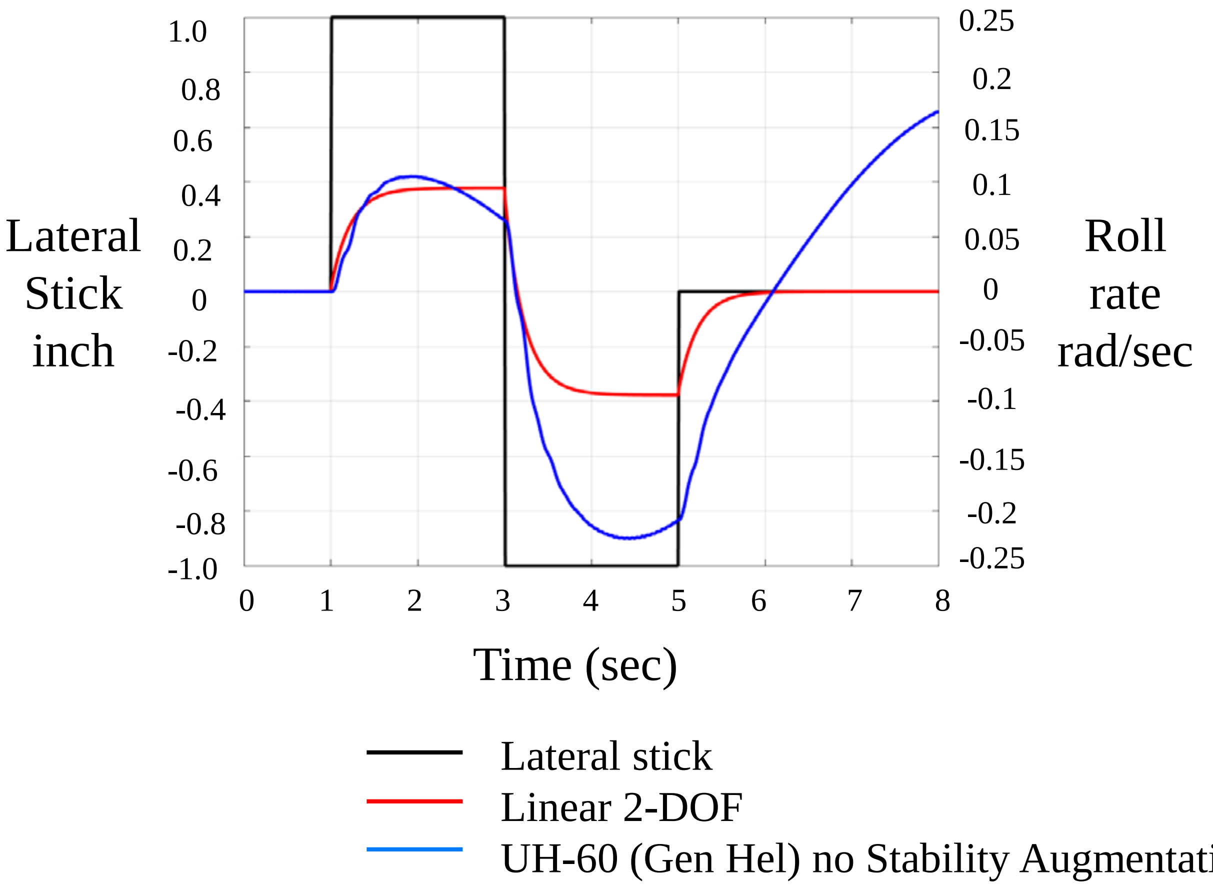
Experiment Setup

A 20-foot sidestep

- **Translation over in 5 seconds**
- **Station-keeping for 10 seconds**



Experiment Setup (Cont'd)



Linear 2-DOF Model

from NASA TP-1999-208766

$$\ddot{\phi} = -4.5\dot{\phi} + 1.7\ \delta_{lat}$$

$$\dot{v} = g\sin\phi$$

Experiment Setup (Cont'd)

	Configuration				Force Feel Characteristics	
Model	High-Fidelity Motion	Medium-Fidelity Motion	Low-Fedility (Fixed-Base)	Low-Fidelity + Compensation	Breakout Force (lb_f)	Force Gradient (lb_f-in)
Linear 2-DOF	Config. 1	Config. 2	Config. 3	Config. 4	0.3	0.6
UH-60 GenHel	Config. 5	Config. 6	Config. 7	Config. 8	1.0	1.0

High-Fidelity Motion: Used more than 20 feet of lateral travel
Medium-Fidelity Motion: Typical hexapod motion (used about 5 feet)
Low-Fidelity: Fixed-base (no motion)
Low-Fidelity + Compensation: Fixed-base with the force compensation

- **Seven experienced rotorcraft pilots**
- **Test configurations were given in random order six times for each pilot**

Results

Performance Evaluation Parameters

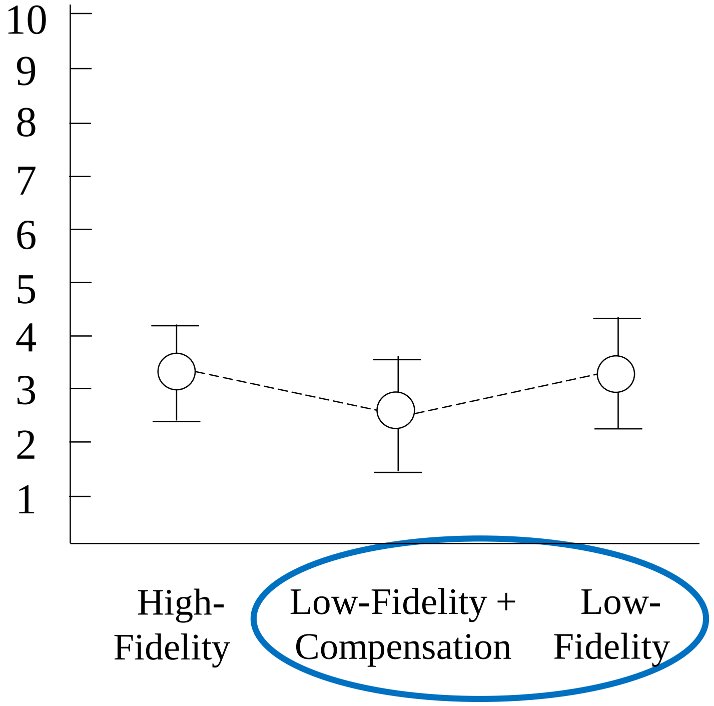
1. Handling Qualities Rating (HQR)
2. Pilot cut-off frequency
3. Station-keeping performance
    i. Lateral position error
    ii. Lateral velocity
    iii. Bank angle
    iv. Roll rate

Results (Cont’d)

Only Linear Model was tested with HQR

No significance was found among tested configurations

HQR - Translational



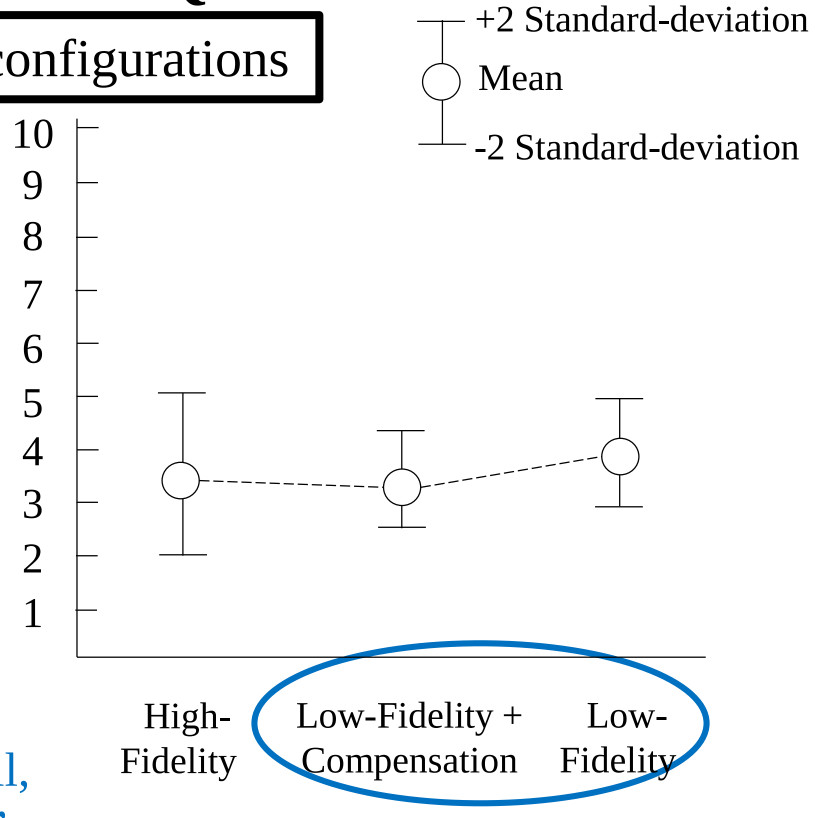
Motion Fidelity

HQR- Station-keeping

Low Fidelity + Compensation

“Handles pretty well, definitely better”

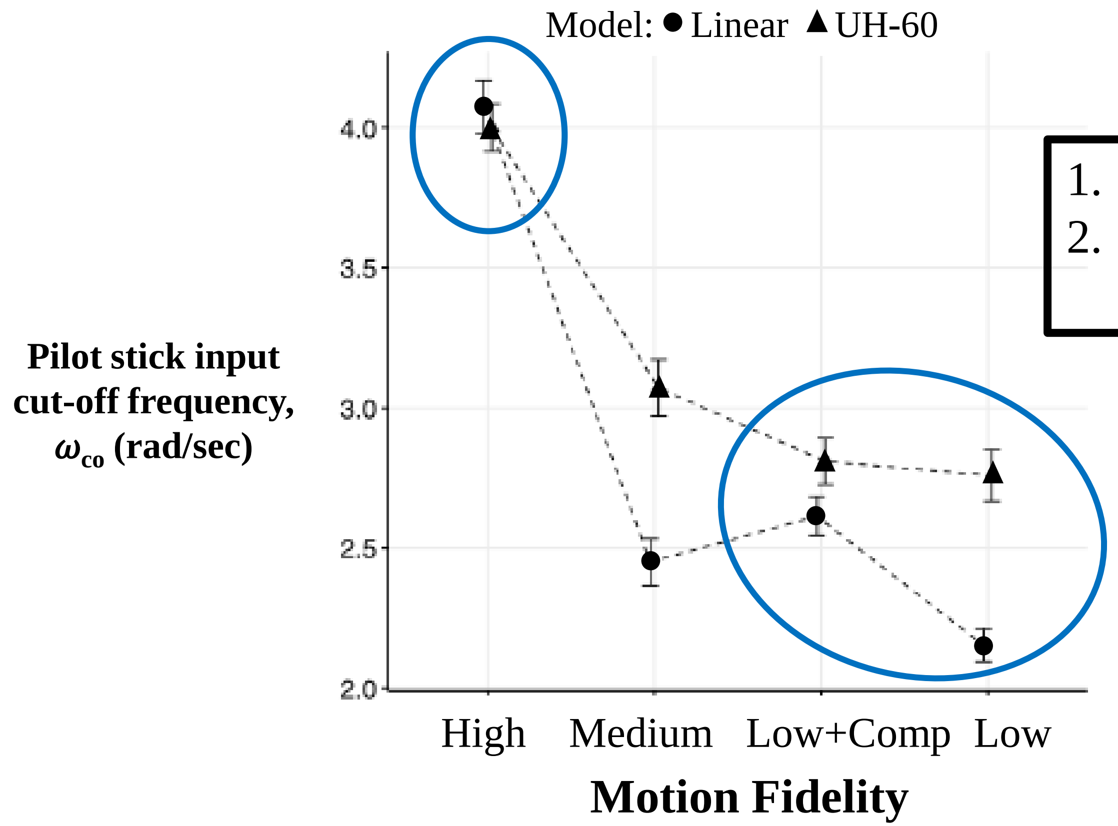
“Feel is better and fly sportier”



Motion Fidelity

Results (Cont'd)

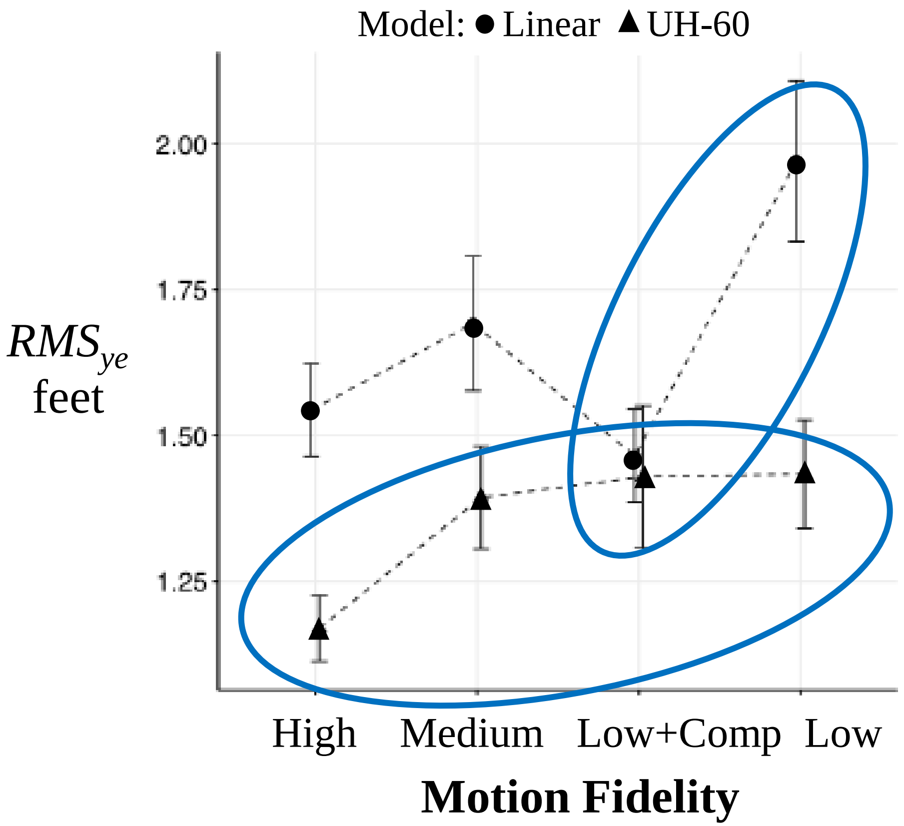
Cut-off frequency of pilot's lateral stick input, ω_{co}



1. ω_{co} is significantly higher with the high-fidelity motion
2. ω_{co} is significantly higher for the low-fidelity motion with compensation than the low-fidelity with no compensation

Results (Cont'd)

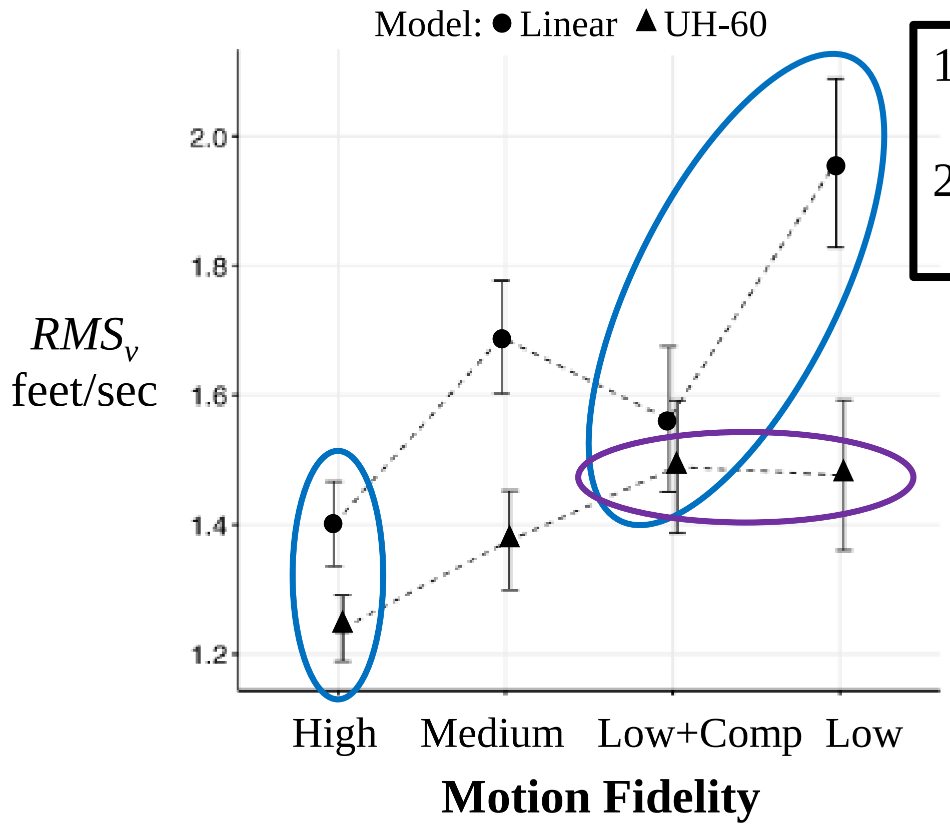
Lateral position error at the station-keeping, RMS_{ye}



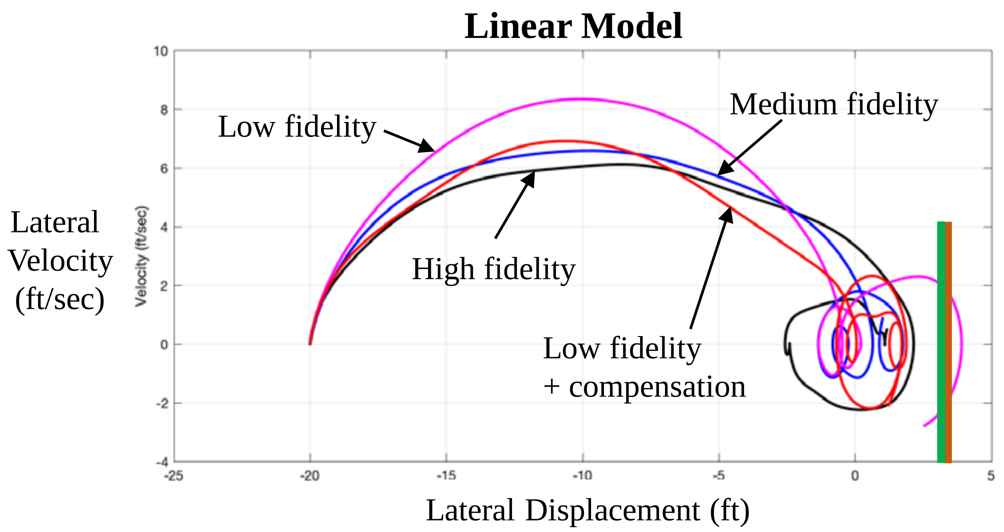
1. For the Linear model, the RMS_{ye} from Low+Comp is significantly lower than the Low with no compensation
2. The RMS_{ye} from UH-60 is significantly lower than the Linear model

Results (Cont’d)

Lateral velocity at the station-keeping, RMS_v

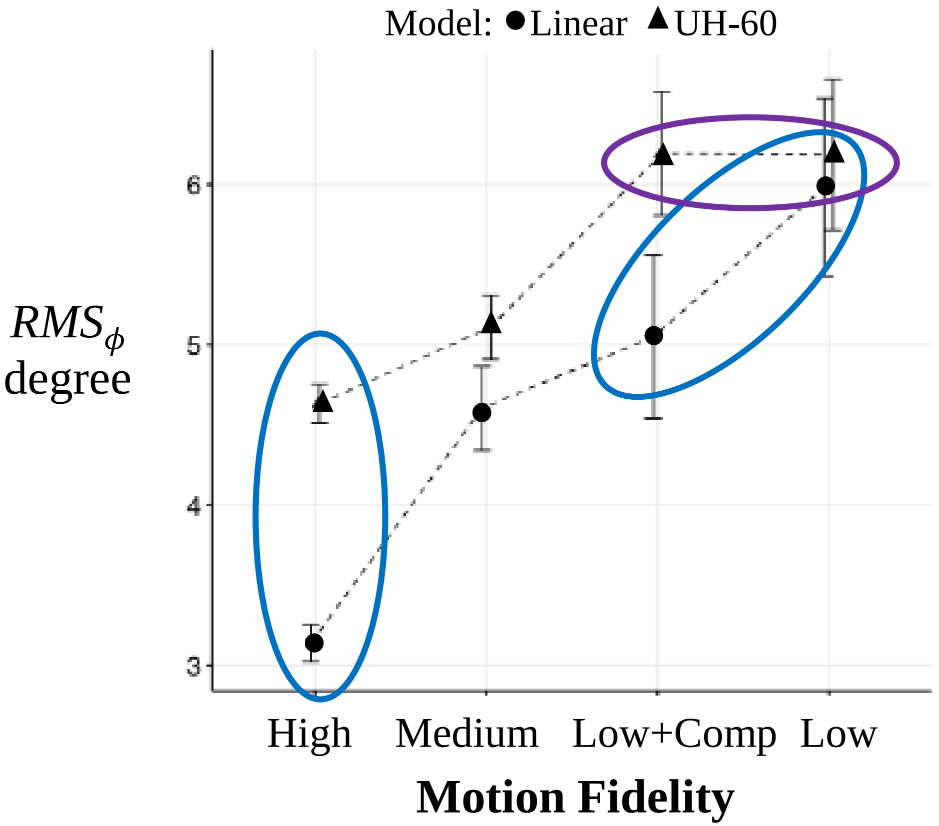


1. High-fidelity has significantly lower RMS_v than all other conditions
2. The effect of the compensation in the low-fidelity cases depends on the model



Results (Cont'd)

Bank angle during the station-keeping, RMS_ϕ



1. The $\boldsymbol{RMS_\phi}$ from the high-fidelity condition is significantly lower than the other conditions
2. The RMS of the roll angle was significantly lower for the Linear model in the low-fidelity with compensation

Conclusions

1. The inertial control force compensation introduced significant differences in some of the dependent measures, mainly for the Linear model.
2. The inertial control force compensation had minimal effects to the UH-60
3. High-fidelity motion has effects in some of dependent measures against other conditions

BACKUP SLIDES