

# Multi-Axis Pilot Modeling

## Models and Methods for Wake Vortex Encounter Simulations

Technical University of Berlin

Berlin, Germany

June 1-2, 2010

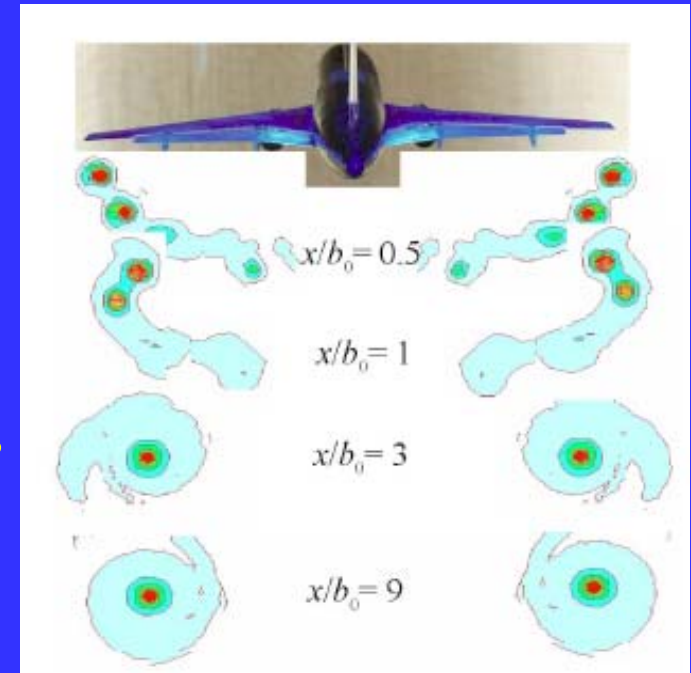
Ronald A. Hess

Dept. of Mechanical and Aerospace Engineering

University of California, Davis

# Outline

- Introduction
- Simplified “Pursuit” Pilot Model
- Modification for Proprioceptive and Vestibular Cues
- Visual Cue Quality
- Task Interference in Multi-Axis Tasks
- Examples:
  - Fighter Aircraft (ICE Vehicle)
  - Rotorcraft (UH-60)
  - Transport Aircraft (Convair 880)
- Conclusions



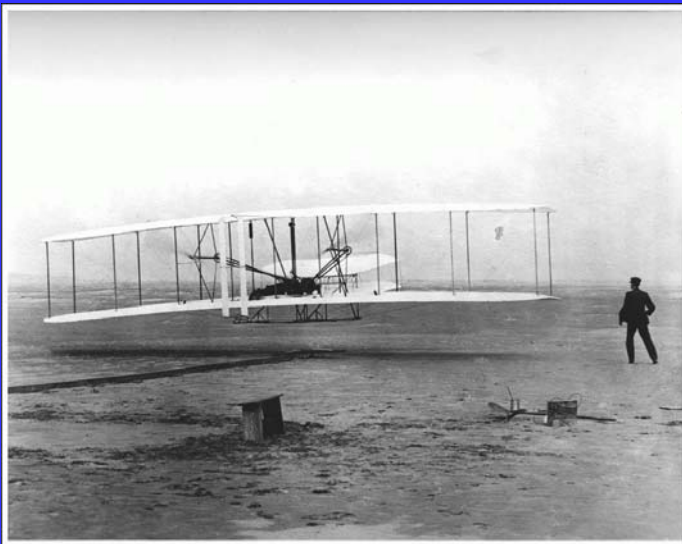
# Introduction

- Goal: Develop pilot modeling procedure that should
  - be able to provide predictions of task performance (i.e., be able to fly the vehicle)
  - be able to simulate varying levels of visual cue quality
  - be able to simulate varying levels of pilot aggression
  - be amenable to multi-axis tasks
  - be able to provide estimates of handling qualities levels
  - be reasonably tractable to use
- All the while remembering that
  - *“The human central nervous system is the most complex structure in the known universe,”*
  - anonymous neurophysiologist

# Introduction

## 107 Years of Pilot/Vehicle Interaction

From Orville Wright in 1903 — to — a Reaper Pilot in 2010



For at least 60 of these 107 years, there has been an interest in pilot modeling

## Introduction

*There appears to be no reason why a complete closed-loop stability analysis of the manually controlled airplane could not be made...The pilot would be represented by a servo system with particular reactions and time constants to signals such as changes in air speed normal and lateral acceleration, etc. By making a reasonable representation of an “average” pilot ...behaviors could be calculated and used to describe the “flying qualities” of the airplane.*

- William Bollay *Fourteenth Wright Brothers Lecture*  
Dec. 16, 1950

# Introduction

*“On the basis of these correlations and explanations it appears possible to define mathematically, within limits, the dynamic behavior of the operator (pilot) for the class of tasks considered.”*

- D.T. McRuer,
  - E. S. Krendel
- “Dynamic Response of Human Operators,”  
WADC TR 56-524, Oct. 1957*

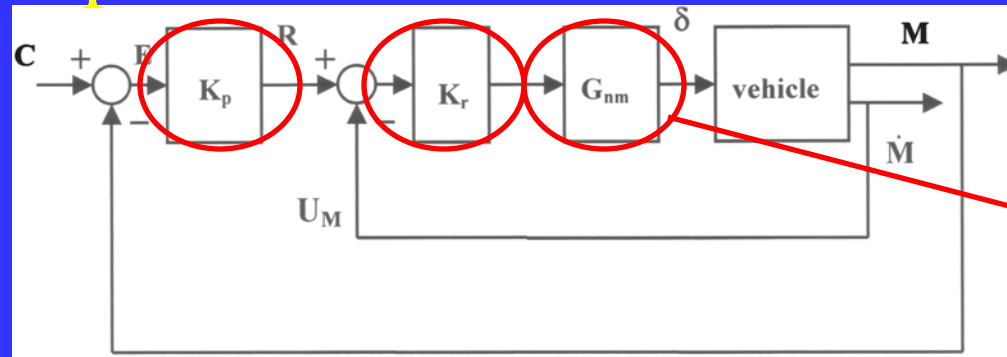
# Introduction

## Why model the pilot?

The proposed model of the human pilot controlling dynamic systems is offered as a tool that has the potential “...*to summarize behavioral data, to provide a basis for rationalization and understanding of pilot control actions, and, most important of all, to be used in conjunction with vehicle dynamics in forming predictions or in explaining behavior of pilot-vehicle systems*”

McRuer, D. T., and Jex, H. R., “A Review of Quasi-Linear Pilot Models,” IEEE Transactions on Human Factors in Electronics, Vol. HFE-8, No. 3, 1967, pp. 181-249.

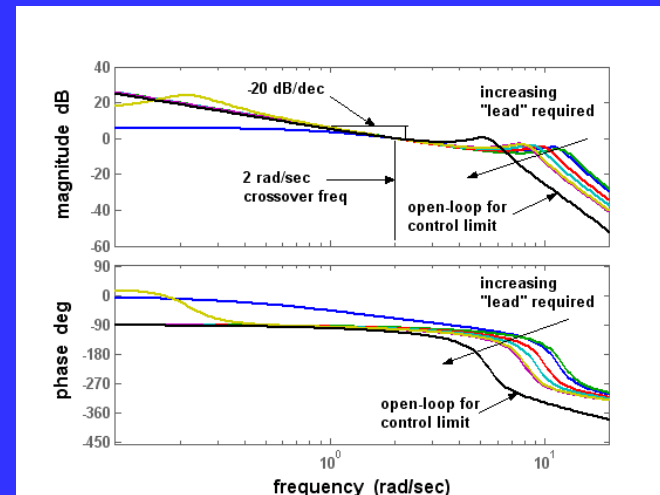
# Simplified “Pursuit” Pilot Model



$$G_{nm} = \frac{10^2}{s^2 + 2(0.707)10s + 10^2}$$

## Pursuit Pilot Model – single axis

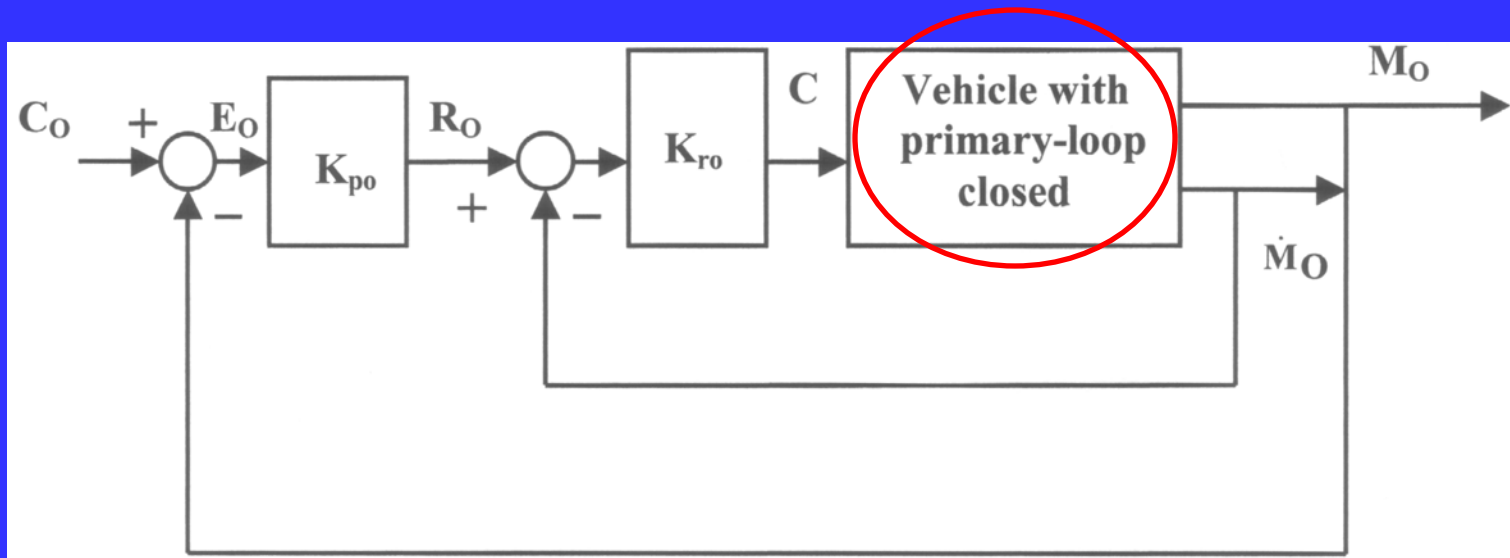
Controlled element	$K_r$	$K_p$
$\frac{1}{s(s+10)}$	20.5	2.91
$\frac{1}{(s^2 + 2(0.707)5s + 25)}$	13.5	3.62
$\frac{1}{s(s+4)}$	11.5	2.56
$\frac{1}{s(s+2)}$	9.19	2.35
$\frac{1}{s^2}$	7.58	1.91
$\frac{0.696(s+0.14)}{s^3 + 0.424s^2 + 0.0353s + 0.397}$	11.3	1.96
$\frac{1}{s^2(s+11)}$	58	1.76



Hess, R. A., “Simplified Approach for Modelling Pilot Pursuit Control Behaviour In Multi-Loop Flight Control Tasks,” *Proceedings of the Institute of Mechanical Engineers, Part G, Journal of Aerospace Engineering*, Vol. 220, No. G2, 2006, pp 85-102

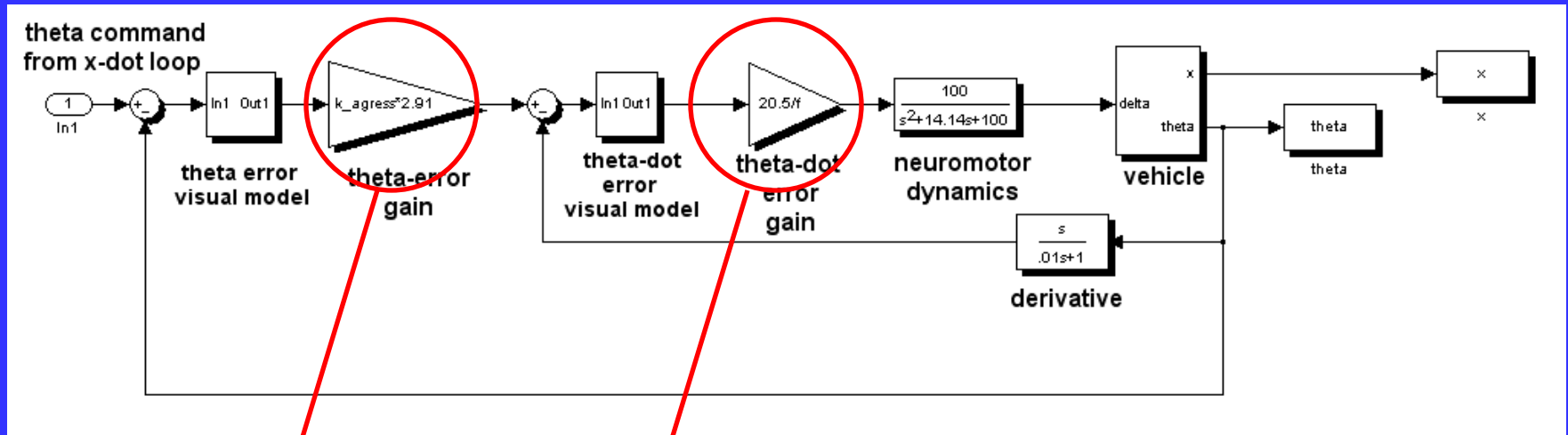


# Simplified “Pursuit” Pilot Model



Pursuit Pilot Model – multi-axis

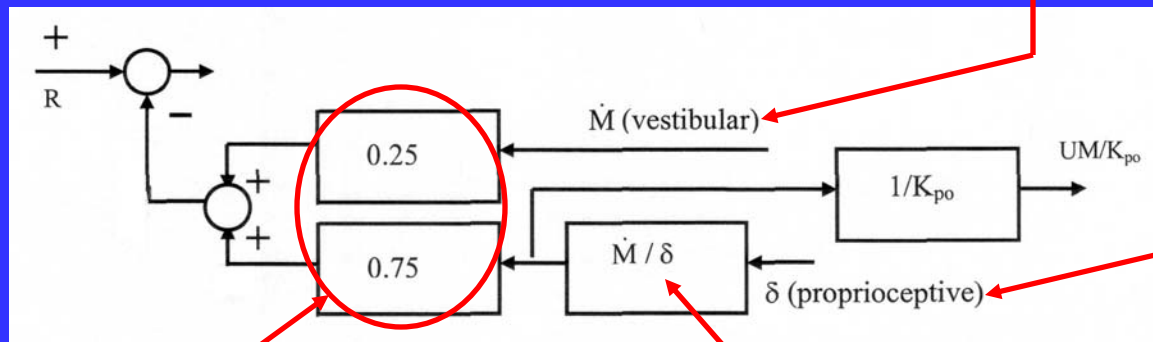
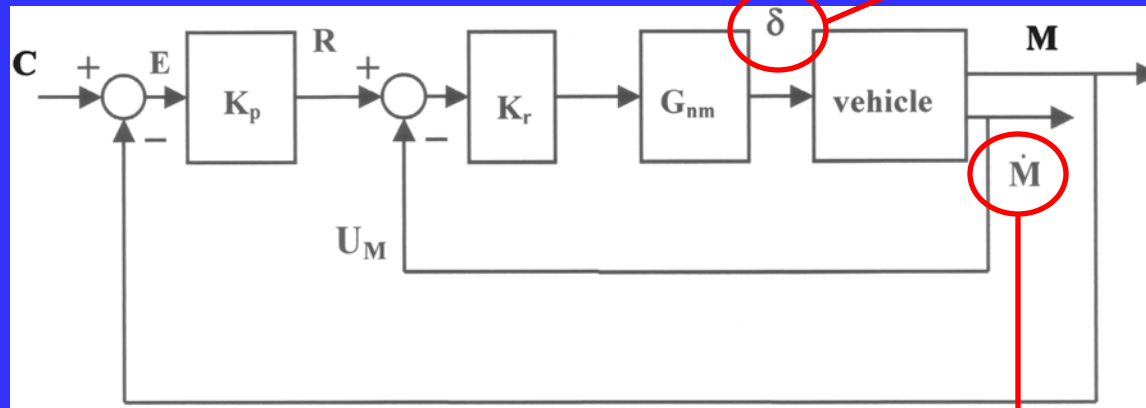
# Pilot Model



$K_r/f$  --  $f$  is part of visual cue model

$K_p K_{agress}$  --  $K_{agress}$  determines pilot  
“aggressiveness” in control

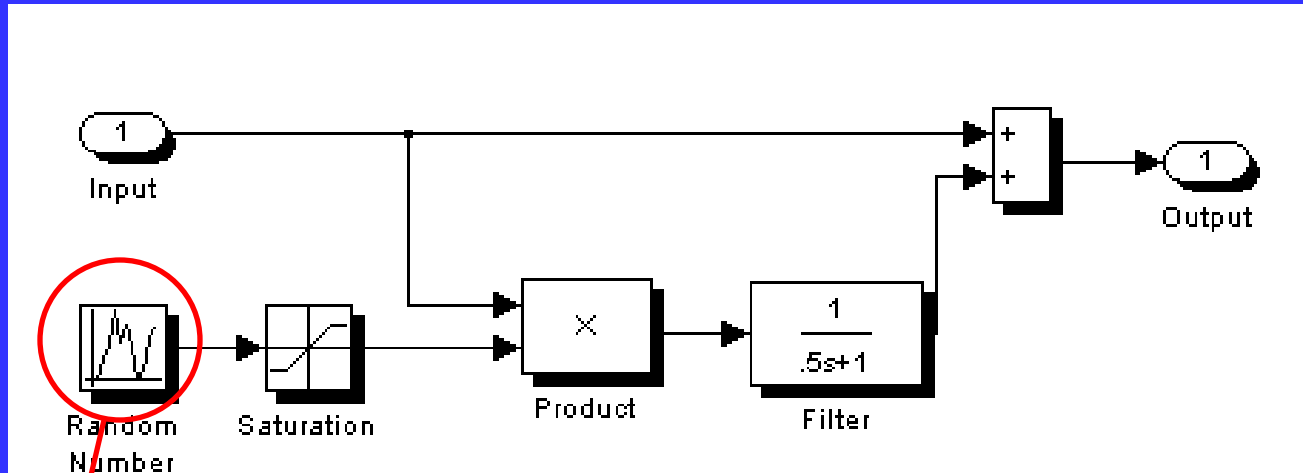
# Modification for Proprioceptive and Vestibular Cues



assumed split

obtained from model of pilot/vehicle system

# Visual Cue Quality



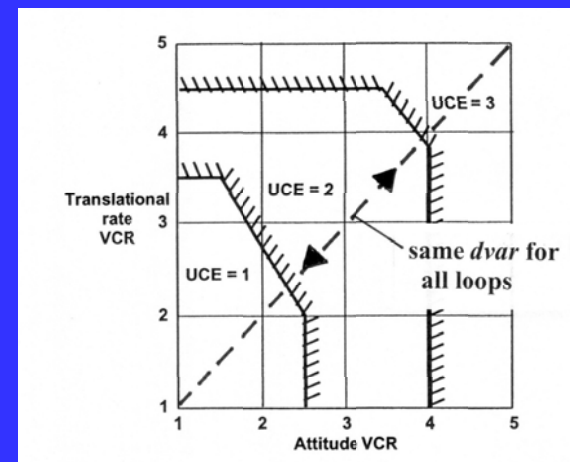
## Visual Cue Model

$\text{variance} = dvar$

If  $0 \leq dvar_{vis} < 0.1$ , UCE = 1

$0.1 \leq dvar_{vis} < 0.2$ , UCE = 2

$0.2 \leq dvar_{vis} < 0.3$ , UCE = 3



# Task Interference in Multi-Axis Tasks

$n$  = number of axes being controlled

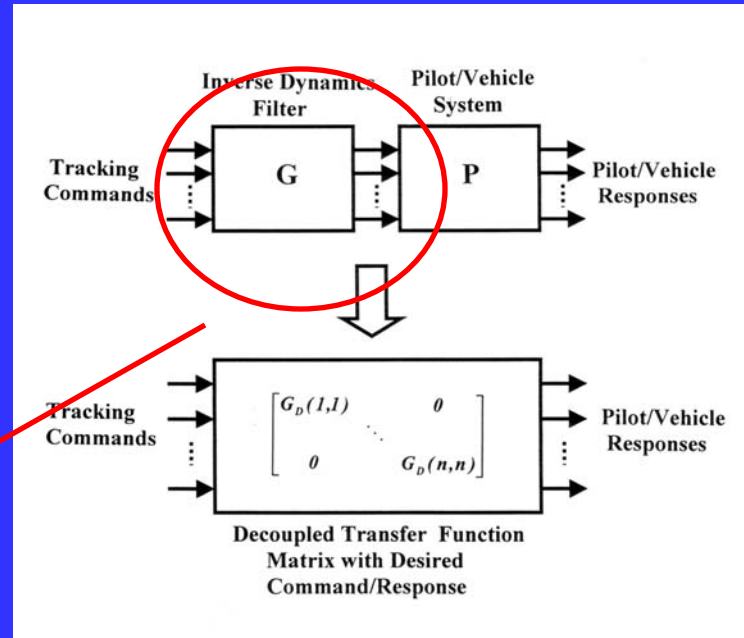
$$\begin{aligned}dvar_{task} &= 0.01n \quad \text{for } n > 1 \\ &= 0 \quad \text{for } n = 1\end{aligned}$$

$$f = 1 + 10(dvar_{vis} + dvar_{task})$$

$f$  factor has following effects on pilot model

- an apparent time delay
- a reduction in crossover frequency

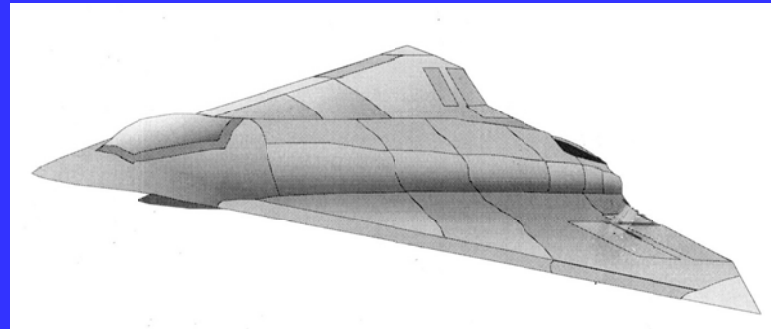
# Higher Levels of Skill Development



linear dynamic inversion

Element "G" transforms tracking commands based upon task description into commands to the pilot/vehicle system "P" that produces pilot/vehicle responses representative of "skilled" pilot behavior

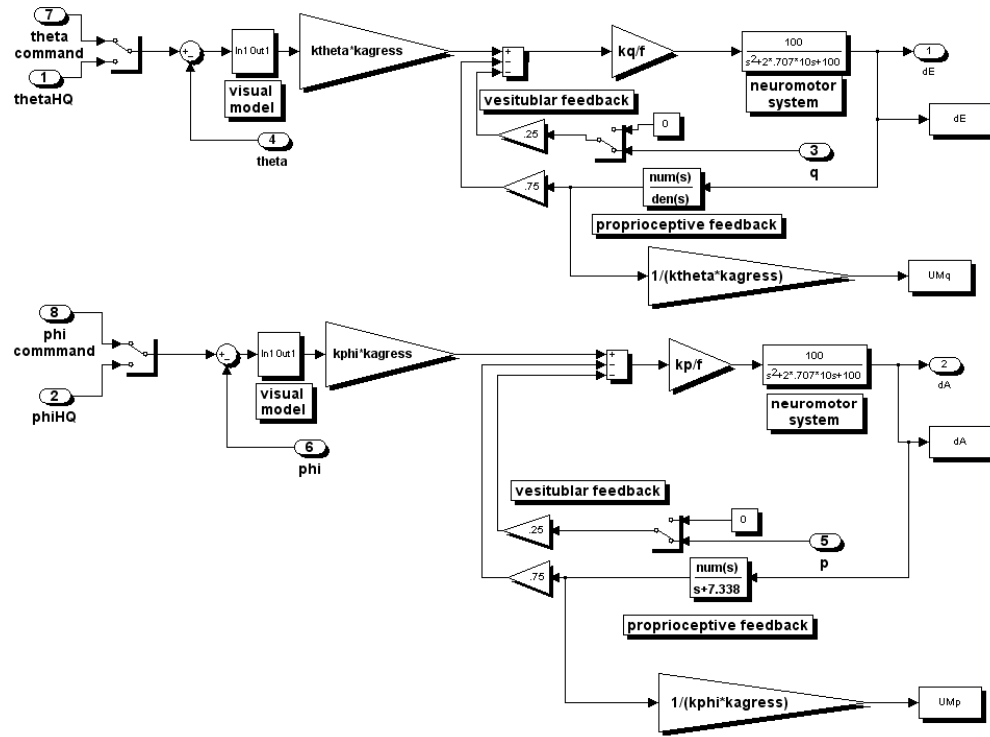
## Example: Fighter Aircraft (ICE Vehicle)



- Flight Condition: Mach No. = 0.3, Alt = 15,000 ft
- Task: Pitch and roll command following (2 control axes)

Hess, R. A., and Marchesi, F., "Pilot Modeling With Applications to the Analytical Assessment of Flight Simulator Fidelity, *Journal of Guidance, Control and Dynamics*, Vol. 32, No. 3, June 2009, pp. 760-777.

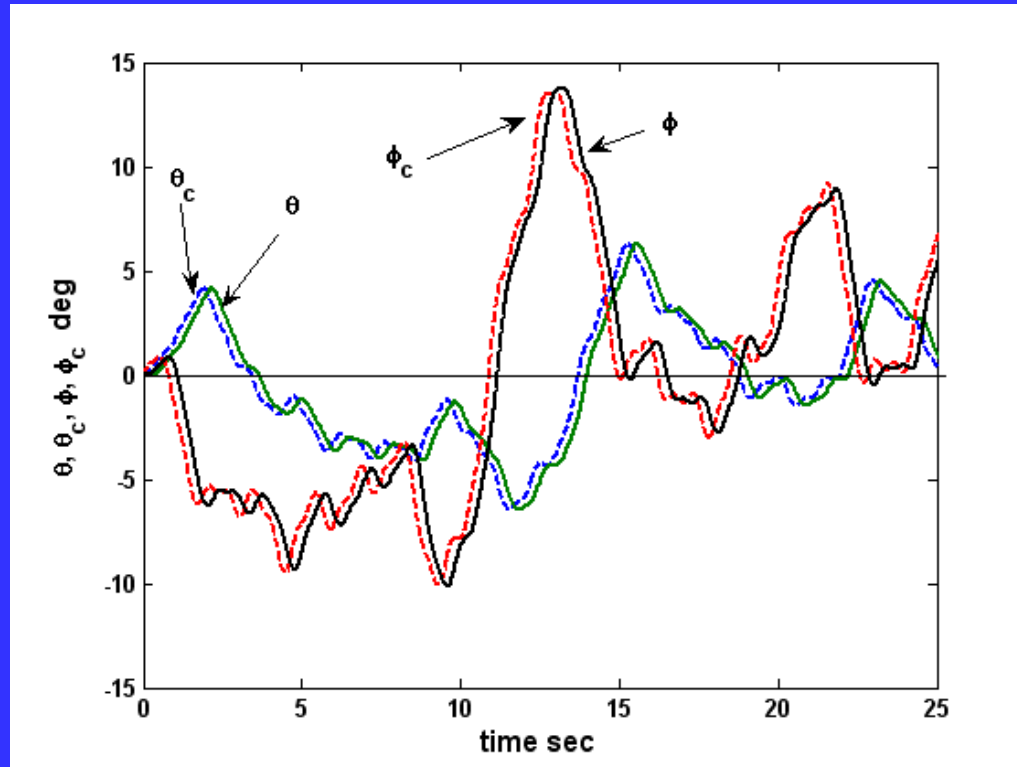
# Example 1: Fighter Aircraft (ICE Vehicle)



pilot model



# Example: Fighter Aircraft (ICE Vehicle)



“nominal” pilot/vehicle tracking performance

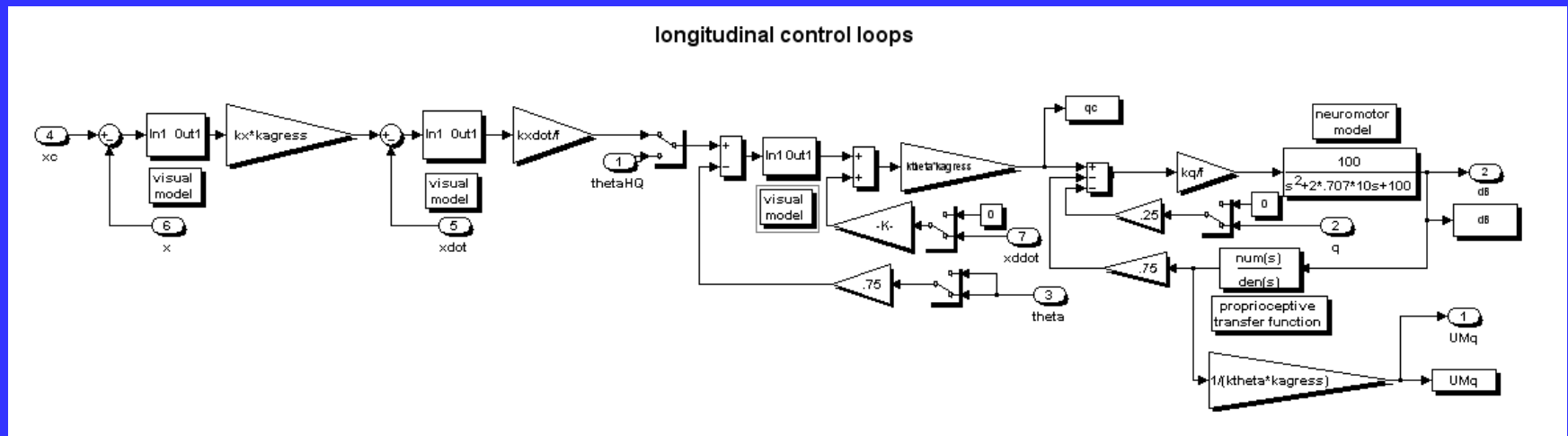
## Example: Rotorcraft (UH-60)



- Example included to demonstrate general applicability of pilot modeling procedure
- Vehicle model has with rotor degrees of freedom – complete model with SCAS is 42<sup>nd</sup> order
- Task: Reposition (4 control axes) with Lusardi/Tischler METS turbulence
- Flight Condition: near hover

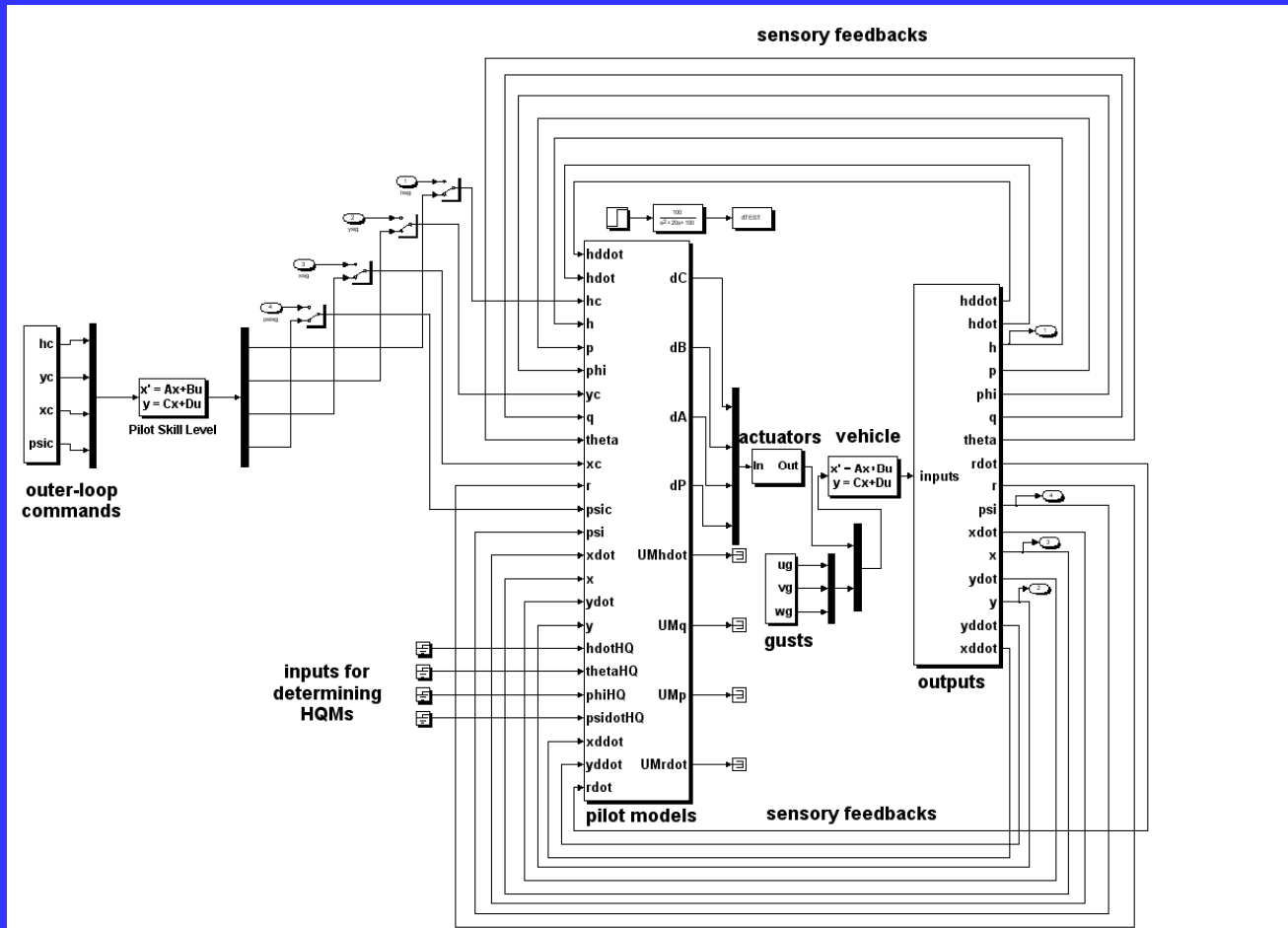
Hess, R. A., “Pilot-Centered Handling Qualities Assessment for Flight Control Design, Invited paper, AIAA Atmospheric Flight Mechanics Conference, Chicago, IL, Aug. 10-13, 2009

# Example: Rotorcraft (UH-60)



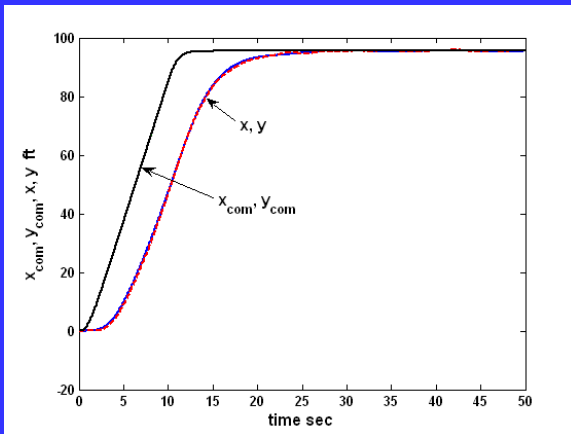
pilot model for pitch and longitudinal translation

# Example: Rotorcraft (UH-60)

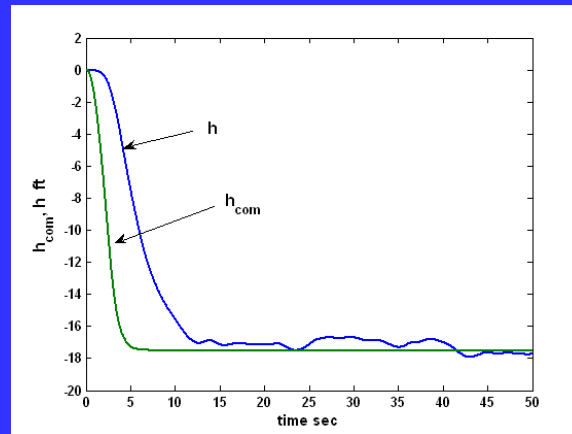


computer simulation model (4 axes)

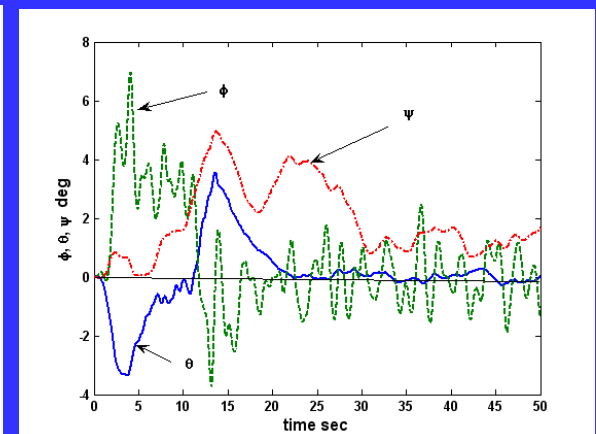
# Example: Rotorcraft (UH-60)



x, y position



h position



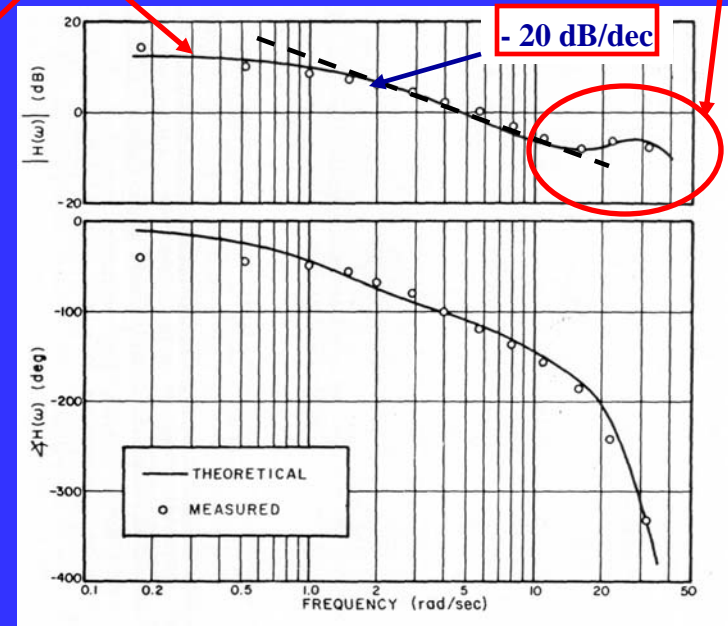
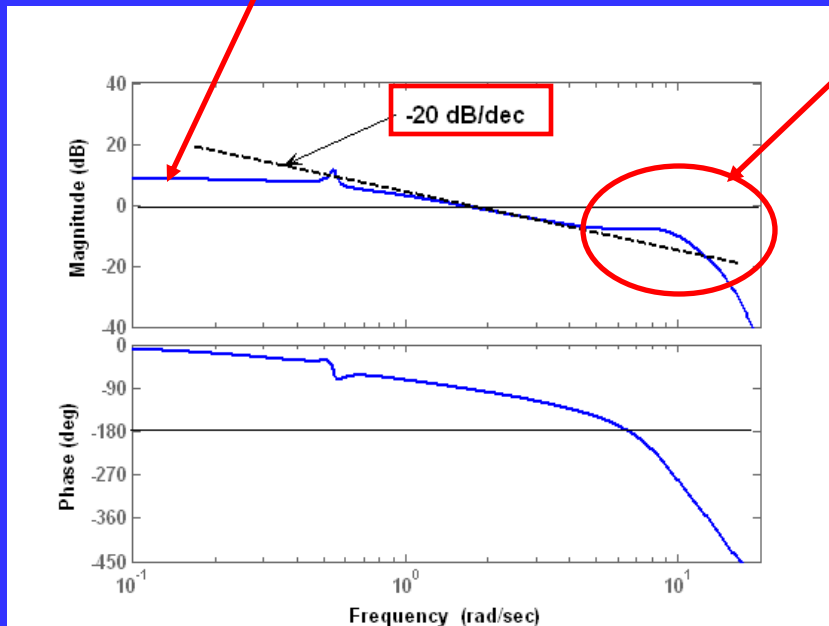
attitudes – showing effects of METS

pilot/vehicle performance

# Example: Rotorcraft (UH-60)

flat @ low frequency

neuromuscular modes



pilot/vehicle dynamics with high bandwidth ATTC/ATTH SCAS

pilot/vehicle dynamics from lab tracking task with  $Y_c = 40/(s+40)$

# Modeling Rotorcraft Interaction with Trailing Vortices – No Pilot Inputs

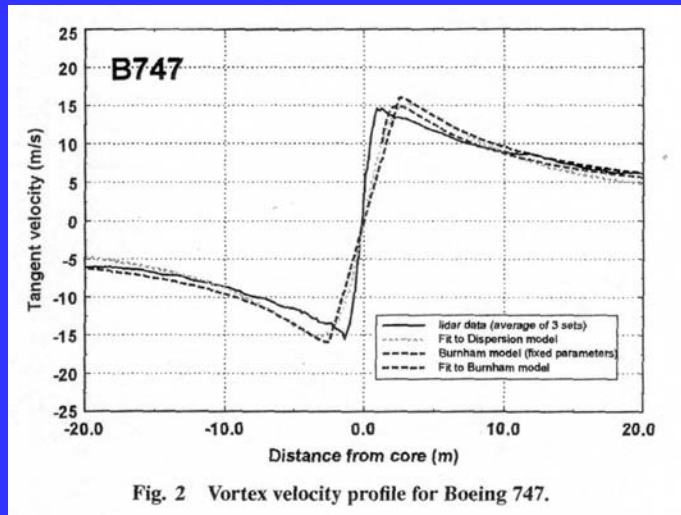
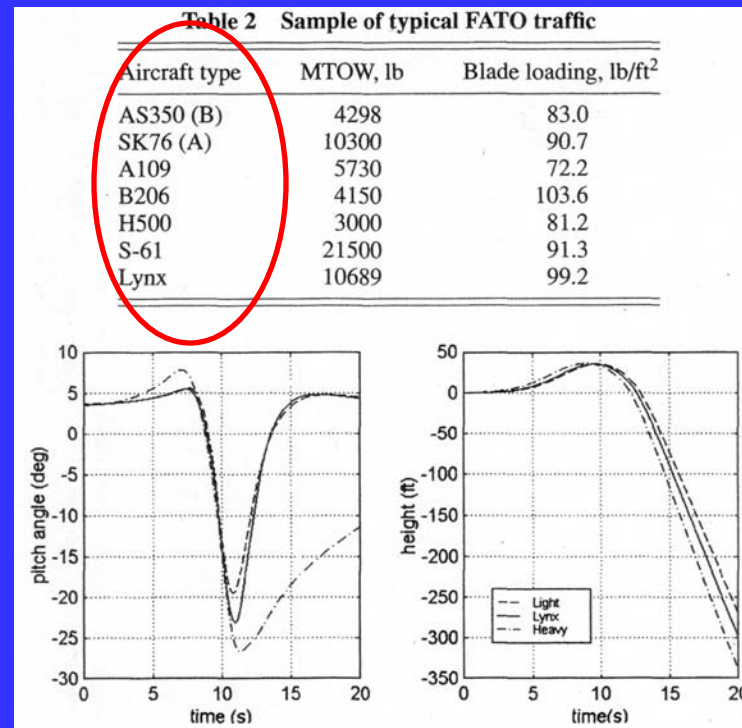


Fig. 2 Vortex velocity profile for Boeing 747.

vortex from B-747

$$r_c = 2.4 \text{ m}, V_c = 14.9 \text{ m/s}$$



rotorcraft pitch and altitude excursions

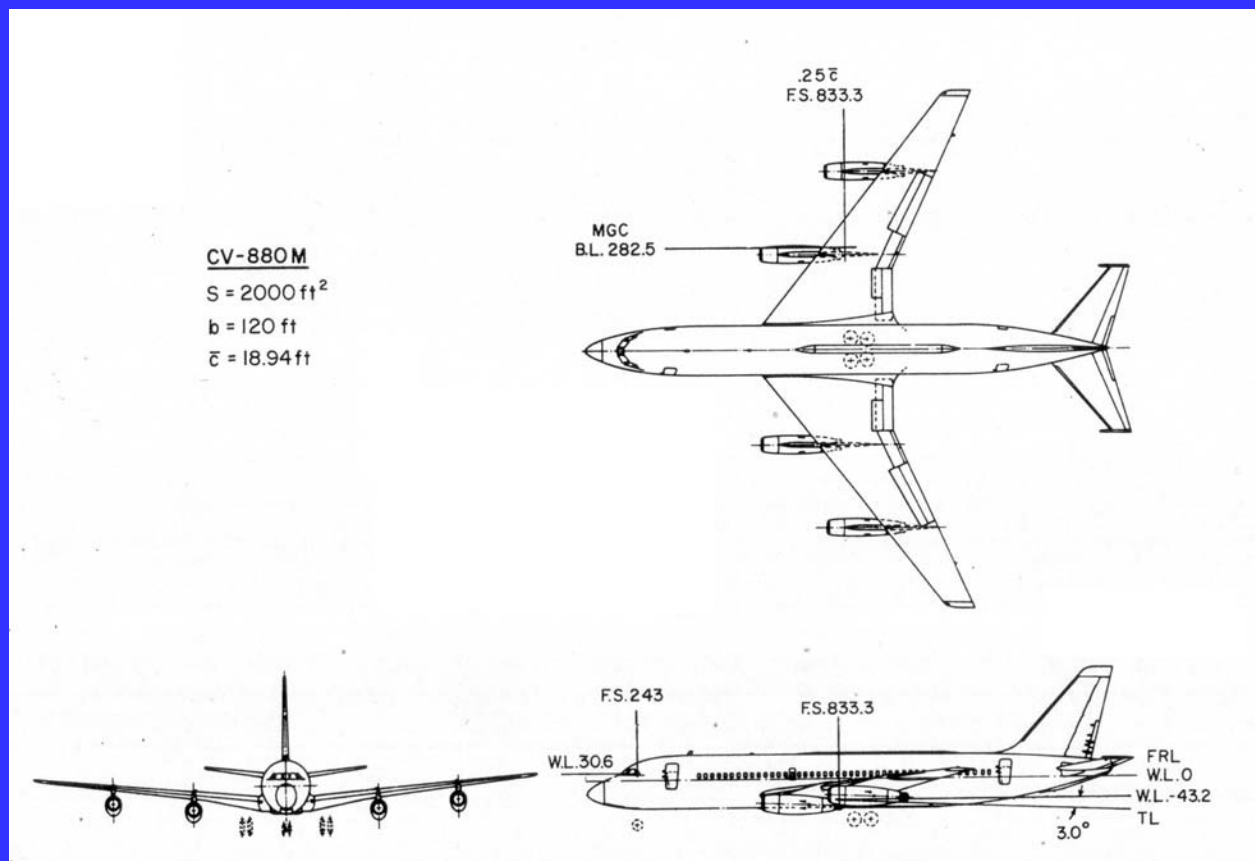
Turner, G P., Padfield, G. D., Harris, M., “Encounters with Aircraft Vortex Wakes: The Impact on Helicopter Handling Qualities,” *Journal of Aircraft*, vol. 39, No. 5, 2002, pp. 839 – 849.

# Example: Transport Aircraft (Convair 880)

Data from "Aircraft Handling Qualities Data," NASA CR-2144, Dec. 1972

Flight Condition: Alt: Sea Level,  $M = 0.249$

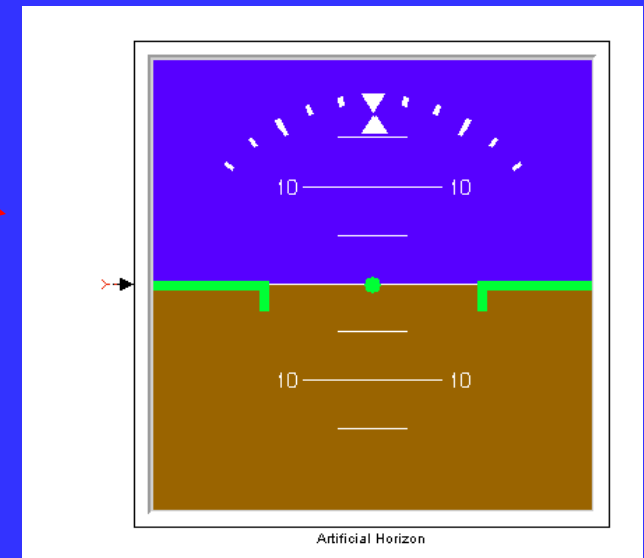
yaw-damper included in model





# Example: Transport Aircraft (Convair 880)

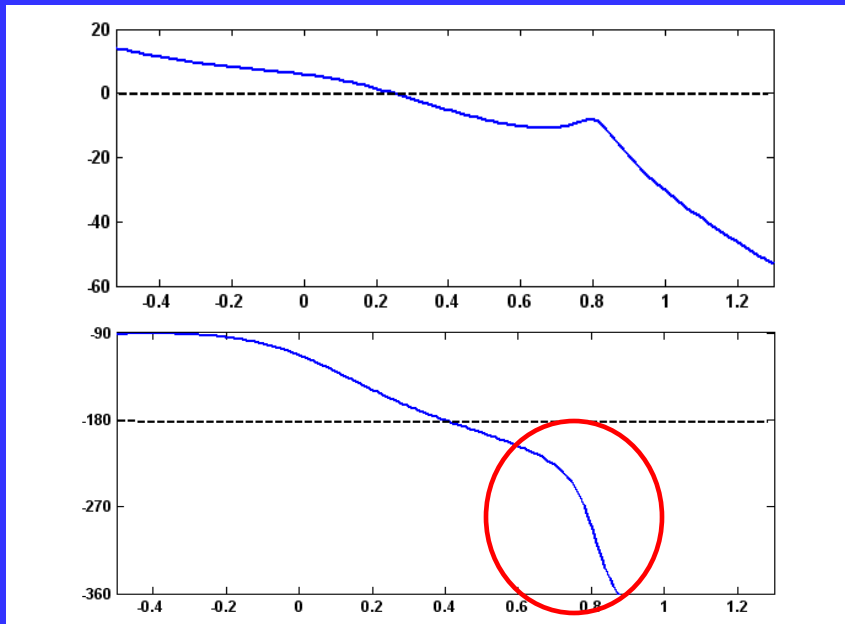
## Laptop Simulation



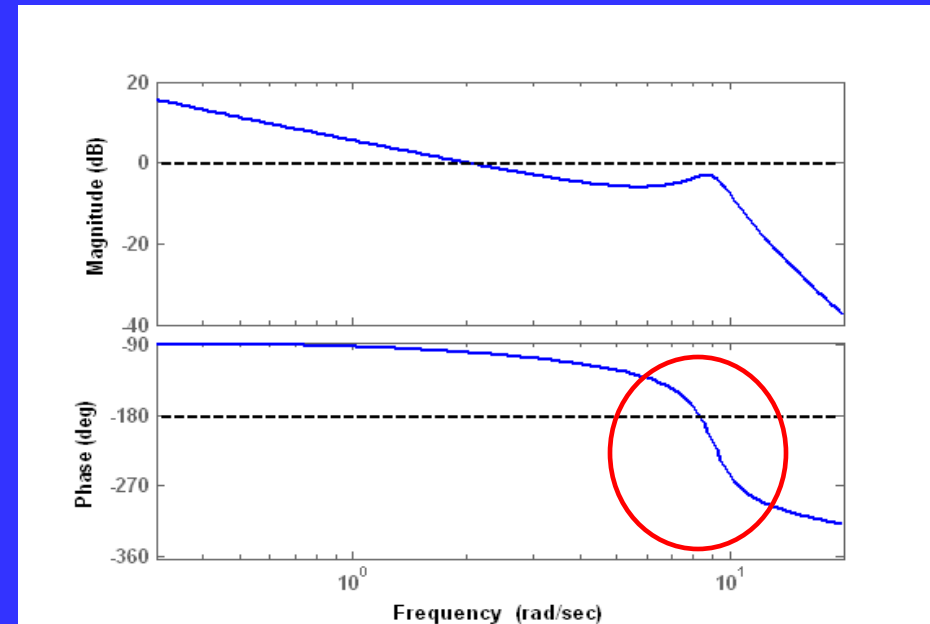
# Example: Transport Aircraft (Convair 880)

## laptop simulation vs pilot model

- Task: Maintain trim attitudes in presence of random turbulence
- Control inputs: elevator and aileron



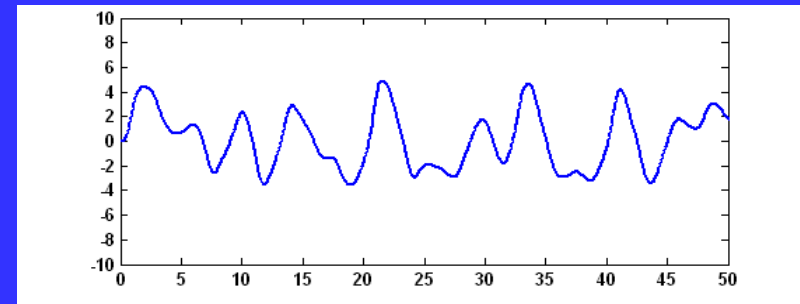
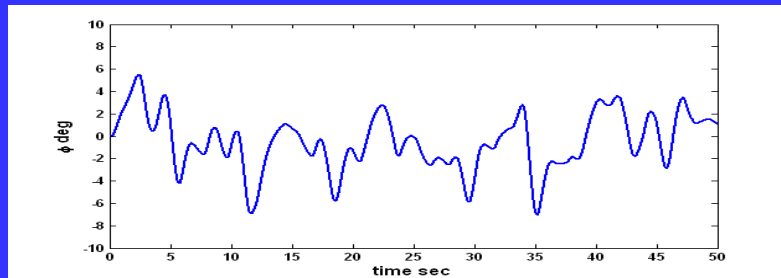
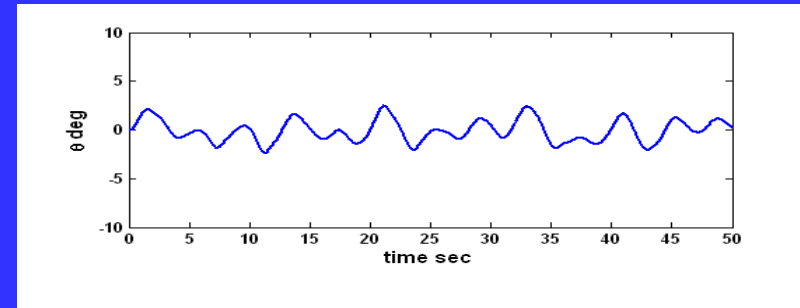
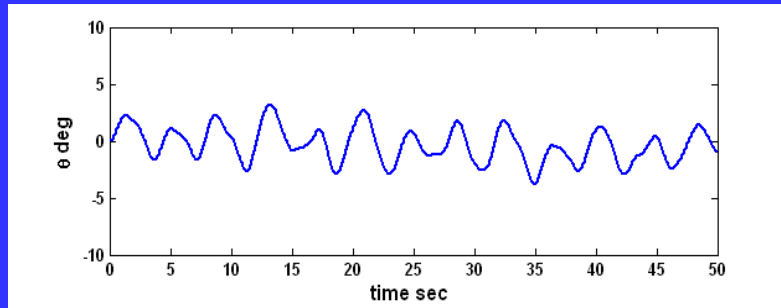
pitch tracking pilot/vehicle loop transmission  
identified from laptop simulation



pitch tracking pilot/vehicle loop transmission  
obtained from multi-axis pilot model

# Example: Transport Aircraft (Convair 880)

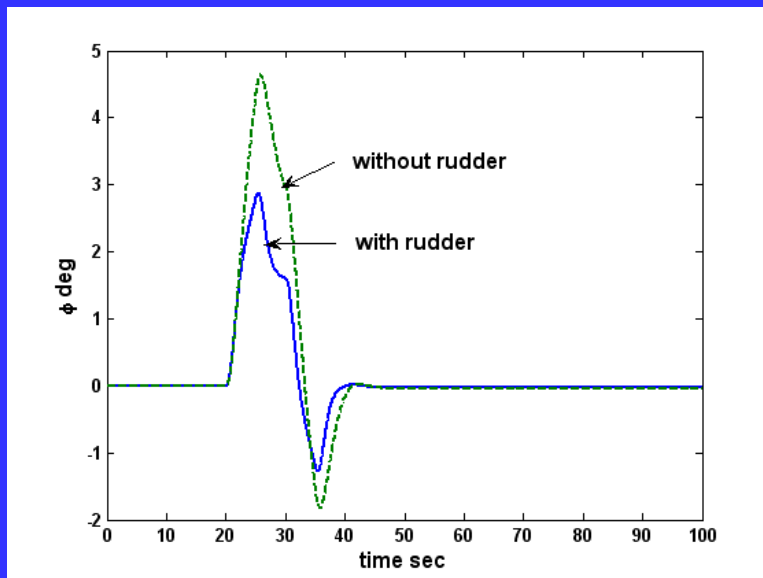
## laptop simulation vs pilot model



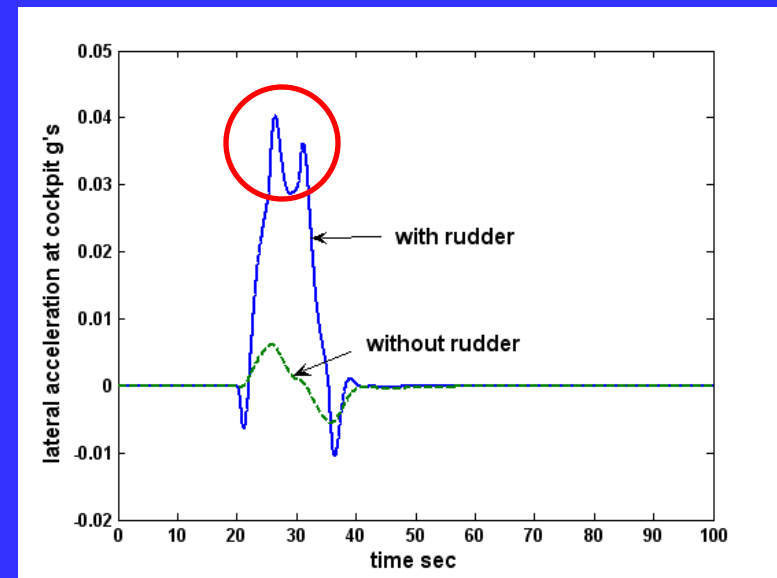
laptop simulation

pilot model

Example: Transport Aircraft (Convair 880)  
 pilot model - simulated encounter with a “roll-rate”  
 gust ( $p_{g-max} = 0.25$  rad/sec lasting 5 sec at peak value)



roll response with and without  
rudder input



lateral g's at cockpit with and without  
rudder input

# Pilot Technique

## (Regarding Use of Rudder for Up-and-Away Flight)

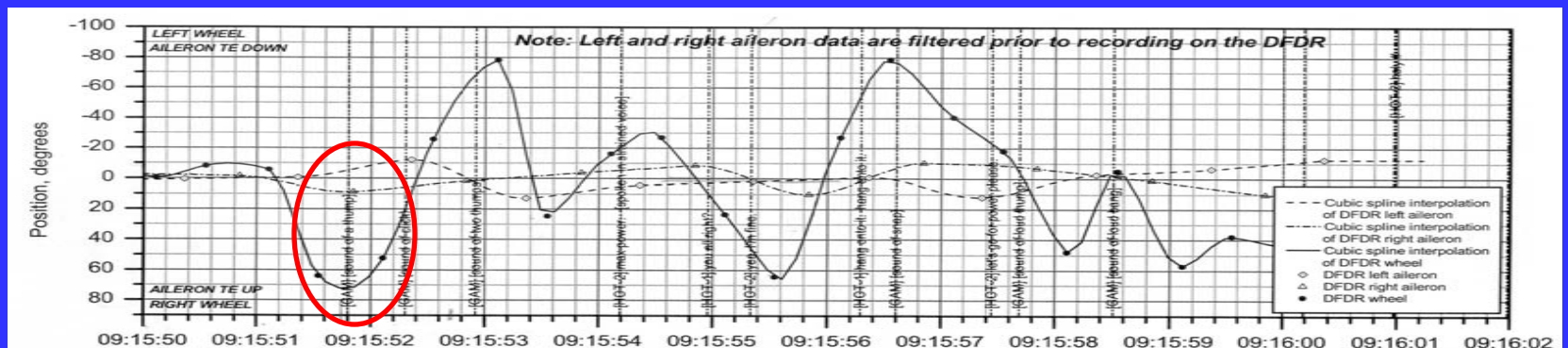
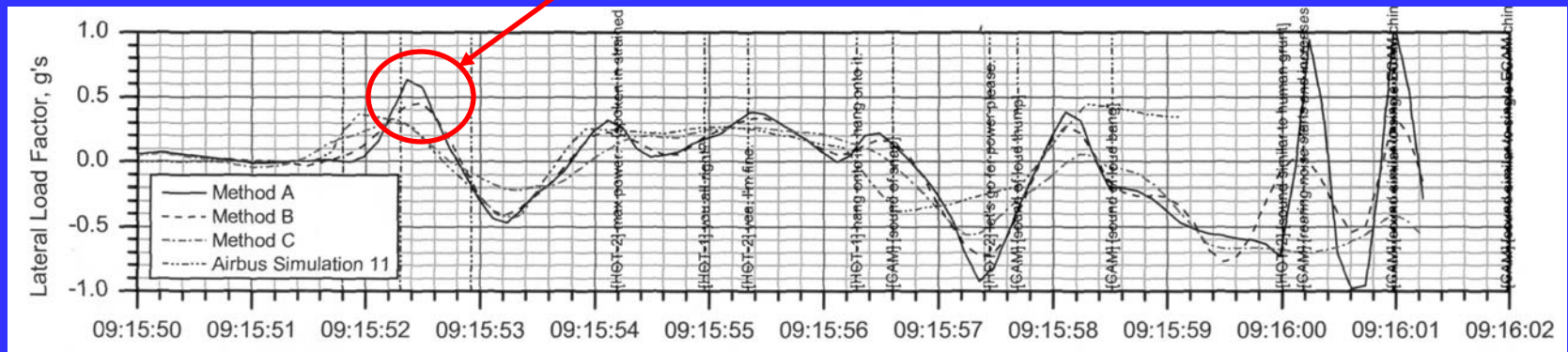
From presentation by Roger Hoh of Hoh Aeronautics, Inc.

- FAA Sponsored Simulation Study
  - Study summarized at SAE/IEEE Aerospace Control and Guidance Systems Committee Meeting, March, 2010, Charlottesville VA.
  - Summarizing piloted simulation study in NASA Vertical Motion Simulator to develop transport aircraft rudder control system requirements...22 pilots participated
- 
- Pilots are instructed to stay off rudder during up-and-away flight
  - Assertion: If roll disturbance exceeds roll authority pilot WILL use rudder to augment aileron
  - Developed task so roll disturbance exceeded aileron authority – similar to an extended wake vortex
  - **EVERY pilot used rudder**

# Example: Transport Aircraft (Airbus A-300)

## American Airlines Flight 587

PIO triggering event?



lateral acceleration at cockpit in g's at second wake vortex encounter  
initiated by large rudder input

# Conclusions

- Multi-axis pilot model developed that incorporates primary sensory information available to the human pilot:
  - Visual
  - Proprioceptive
  - Vestibular
- Model design begins with the simplified “pursuit” model of pilot
- Model can be created in a loop-by-loop process with the primary tool being the Bode plot
- Multi-loop (as opposed to multi-axis) pilot structure based upon serial loop closures with crossover frequency separation
- Area of concern to this speaker: the ability of a vortex encounter to create a “triggering event” for a pilot-induced-oscillation (PIO).