Simulator Integration

Frank Cardullo

Professor - Department of Mechanical Engineering

SUNY Binghamton

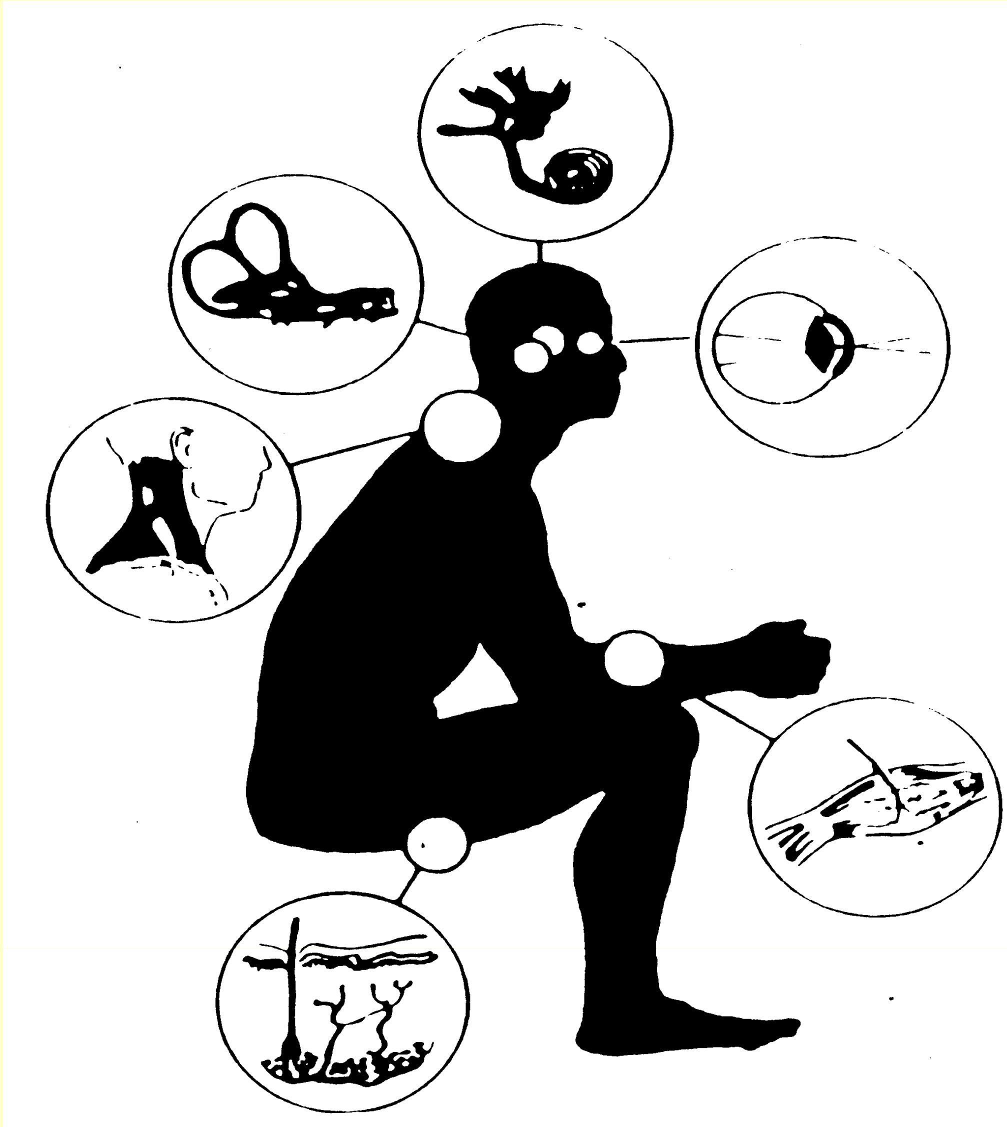
cardullo@binghamton.edu

January 27,2017

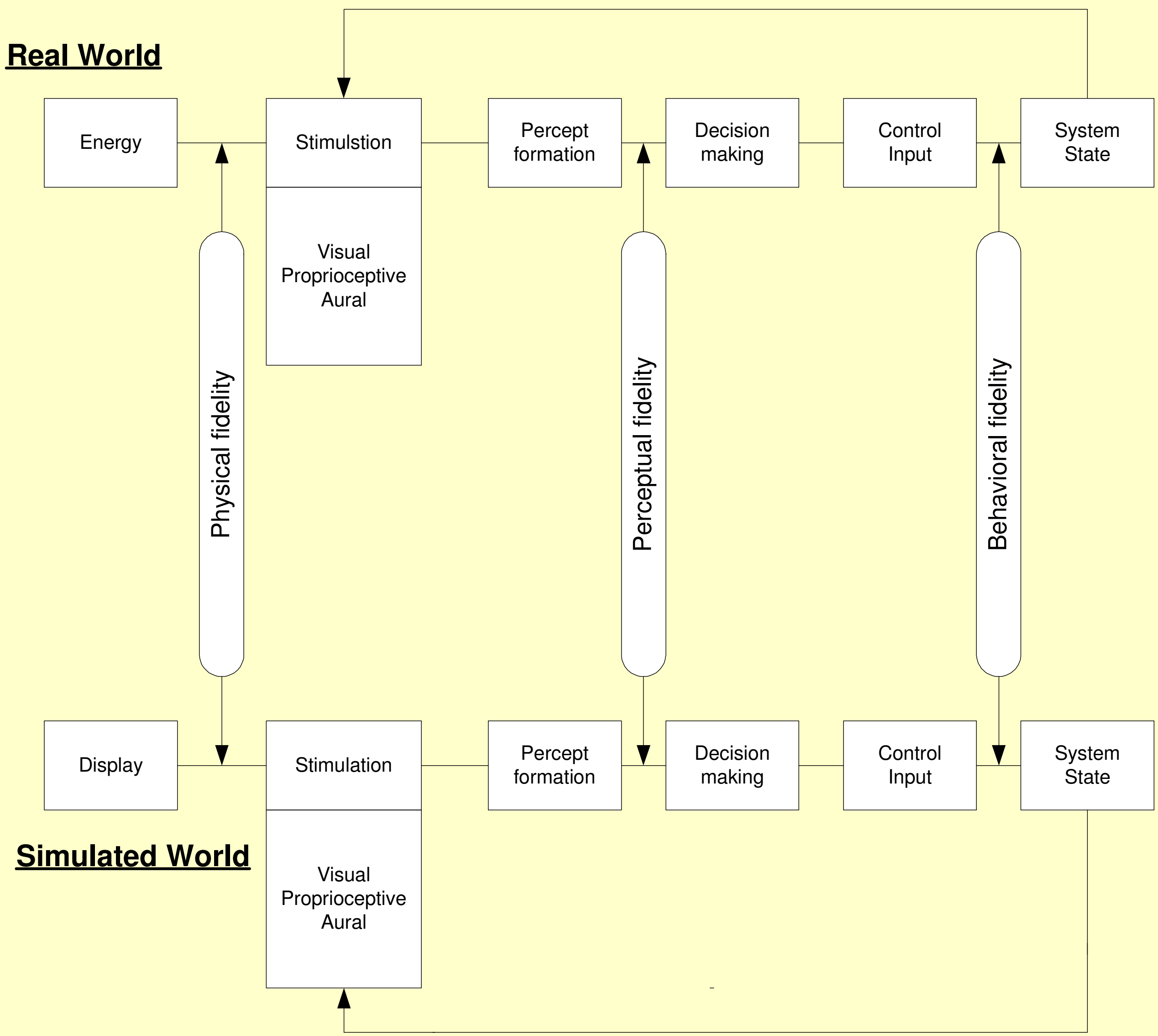
Outline

- Introduction
- Perceptual/Behavioral Framework
- Integration Factors
- Temporal Integration
  - Transport delay characterization
  - Sources/Manifestation/Consequences
  - Mitigation Techniques
- Simulator Sickness
  - Background
  - Etiology
  - Measurement and consequences
  - Mitigation Techniques
- Measurement and Evaluation of Integration/Fidelity

Human Perception Is an Integrated Process



Simulation Fidelity Concept



Working Definitions

- **Cue**

  - Stimulus elements or patterns which give an indication of system state.

- **Integration:**

  – Ensuring that the critical cues are included

  – Deleterious cues are eliminated

- **Synchronization:**

  - Ensuring that critical temporal relationships are maintained

Two Types Of Integration Errors

Including Spurious Cues

- **Visual Anomalies**
  - Sharp Surface Definition
  - Level Of Detail Switching
  - Aliasing
  - Transport Delay
  - Highly Saturated Colors
  - Etc.
- **Motion Anomalies**
  - Cueing Algorithm
  - Hardware
  - Control Force

Omitting Necessary Cues

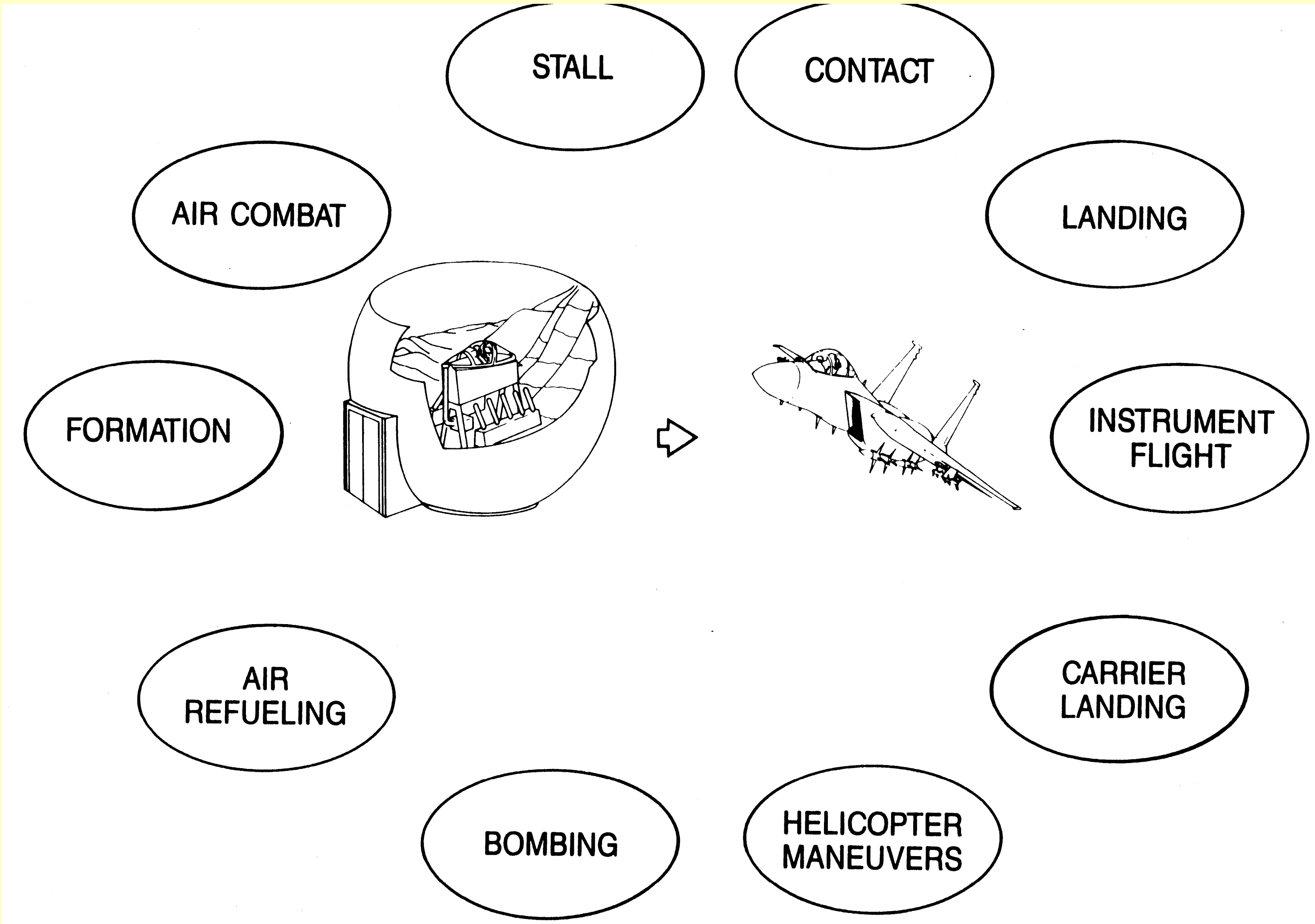
- Limited Scene Content
- Limited FOV
- Limited Resolution
- No Motion and/or Force Cues when needed

NB This is not an exhaustive list, but rather an exemplar list

Task and Feature Benefit

- Tasks showing transfer to aircraft
  - Piloting tasks
- Features showing performance benefit
  - Simulator features
- Features showing transfer benefit
  - Quasi-transfer
  - Transfer to aircraft

Tasks Showing Transfer to Aircraft

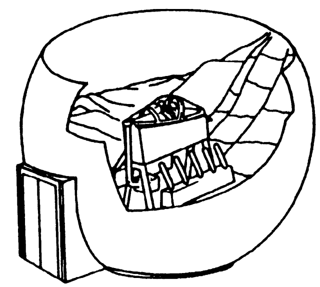


Features Showing Performance Benefit

SCENE DETAIL
- BOMBING
- HELICOPTER SHIP LANDING
- LANDING
- CARRIER LANDING

TEXTURE
- LANDING
- TF/TA

MOTION
- TURBULENCE
- ENGINE OUT
- EMERGENCY
- MARGINAL STABILITY

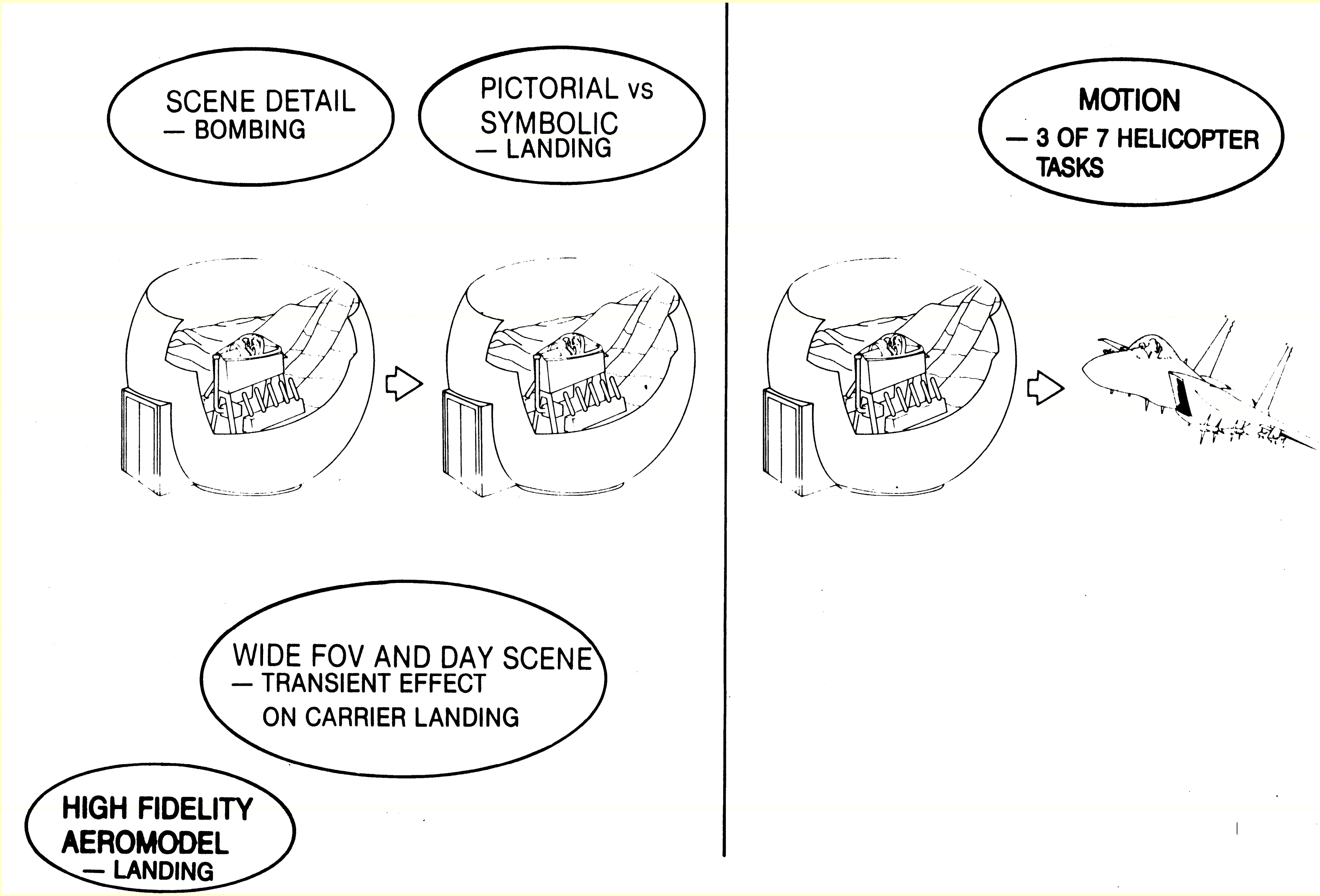


HIGH FIDELITY AERO MODEL
- HELICOPTER SHIP LANDING

WIDE FOV
- MANUAL REVERSION
- BASIC MANEUVERS
- CARRIER LANDING
- HELICOPTER SHIP LANDING
- TARGET ACQUISITION WITH HMD

VERTICAL OBJECTS
- TF/TA

Features Showing Transfer Benefit



Temporal Integration

Delay vs Lag

Do they mean the same thing?

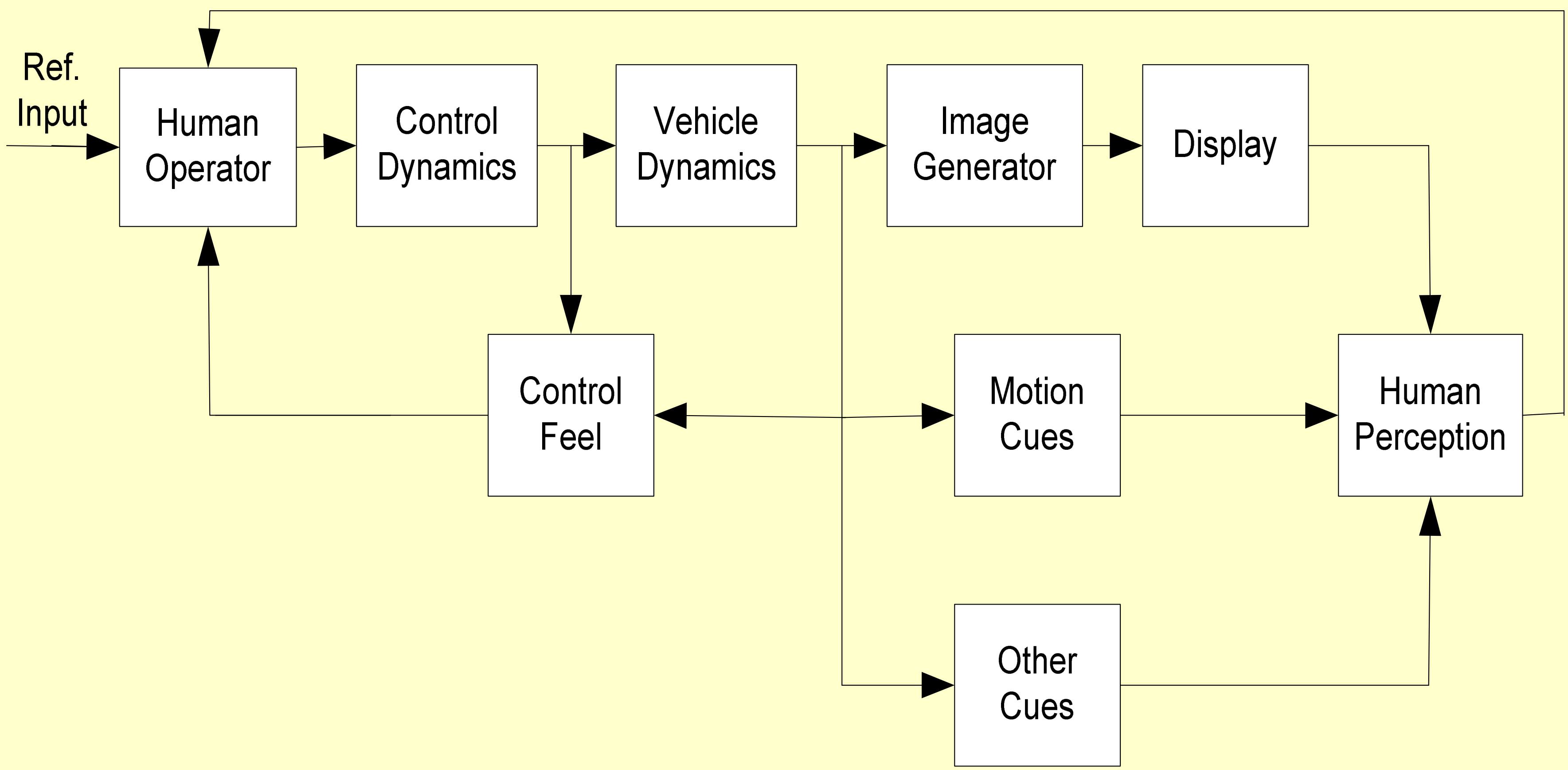
Delay/Lag Definitions

- **Delay** is the dead time between an event and a reaction to that event, which is associated with sampling and computation.
- **Lag** is the phase shift resulting from;
  - System dynamics
  - System delay

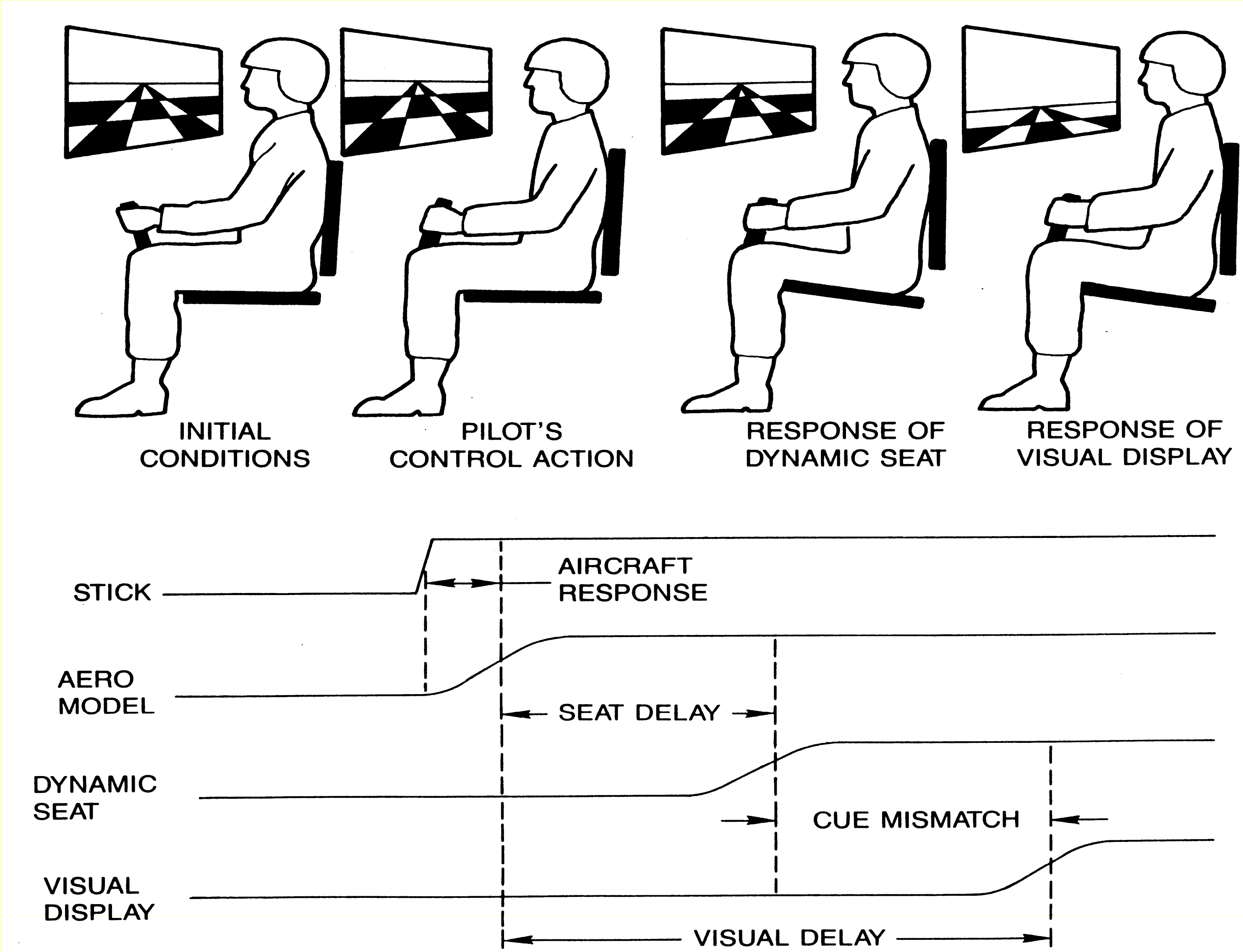
Sources of Delay

- Digital computer sampling
- Asynchronous computation
- Visual pipeline
- Motion cueing algorithm and closed loop control.

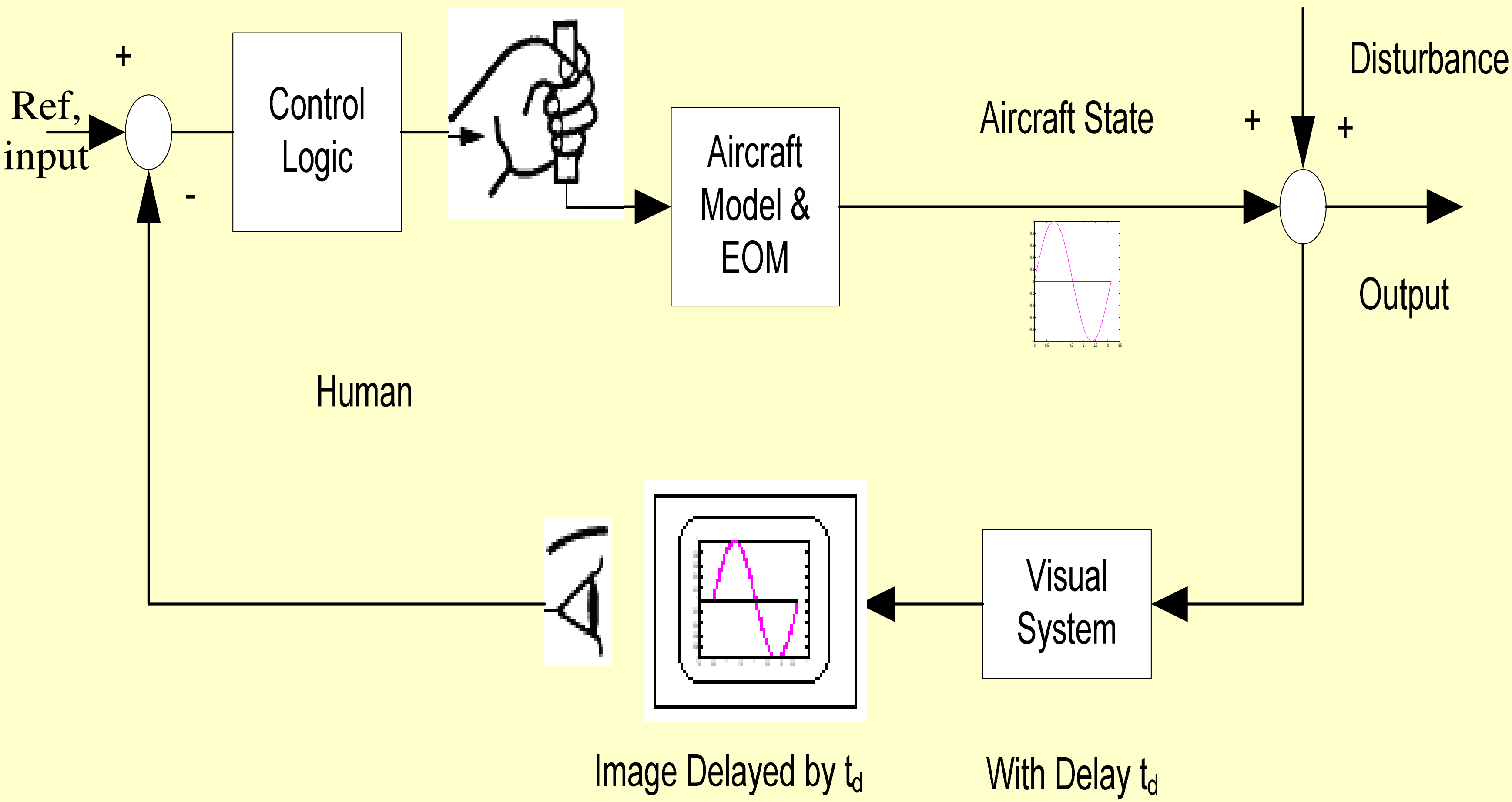
Simulation Block Diagram



Cue Synchronization



System with Delay



Measurement Of Temporal Distortions

- Two Measurement Domains
  - Time domain
  - Frequency domain
- Time Domain Techniques Are Most Often Used
- FAA Specifies Time Domain Measures for Level A-D Ratings
- Simulators May Be Optimized for Either Domain

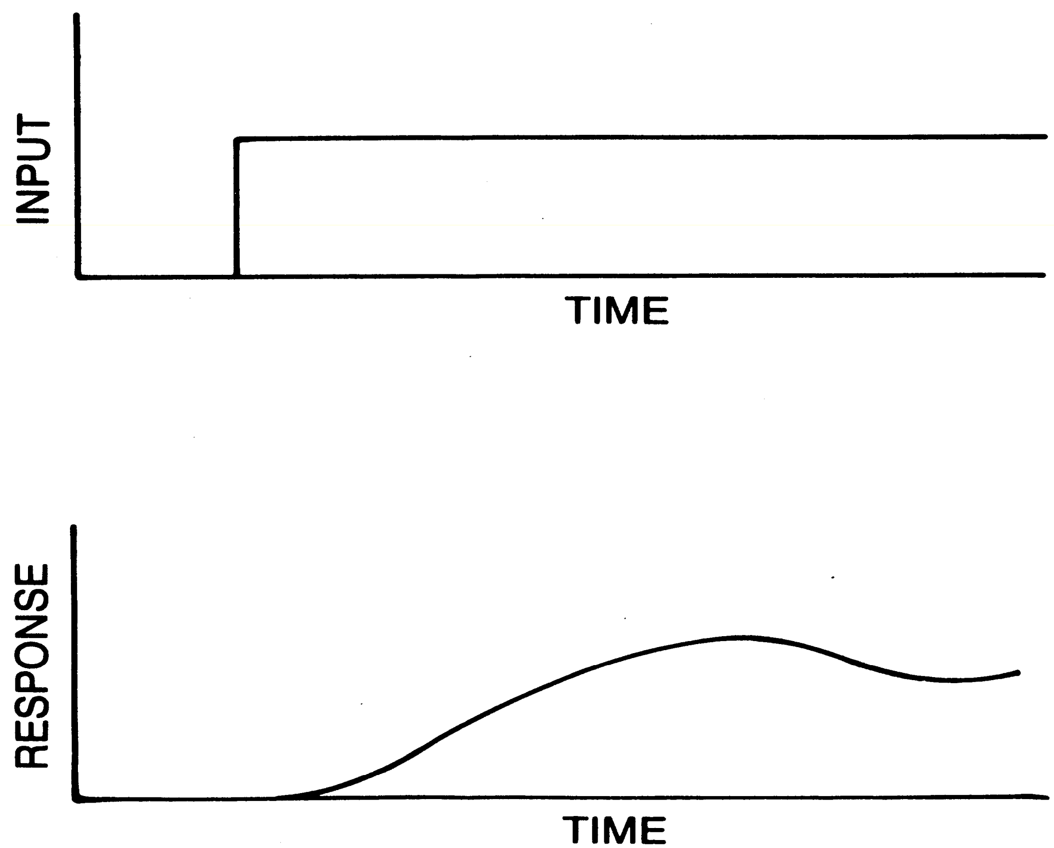
Mathematical Representation of Delay

$$G(s) = \frac{E_0(s)}{E_i(s)} = e^{-Ts}$$

$$G(j\omega) = e^{-jT\omega} = e^{-j\Phi}$$

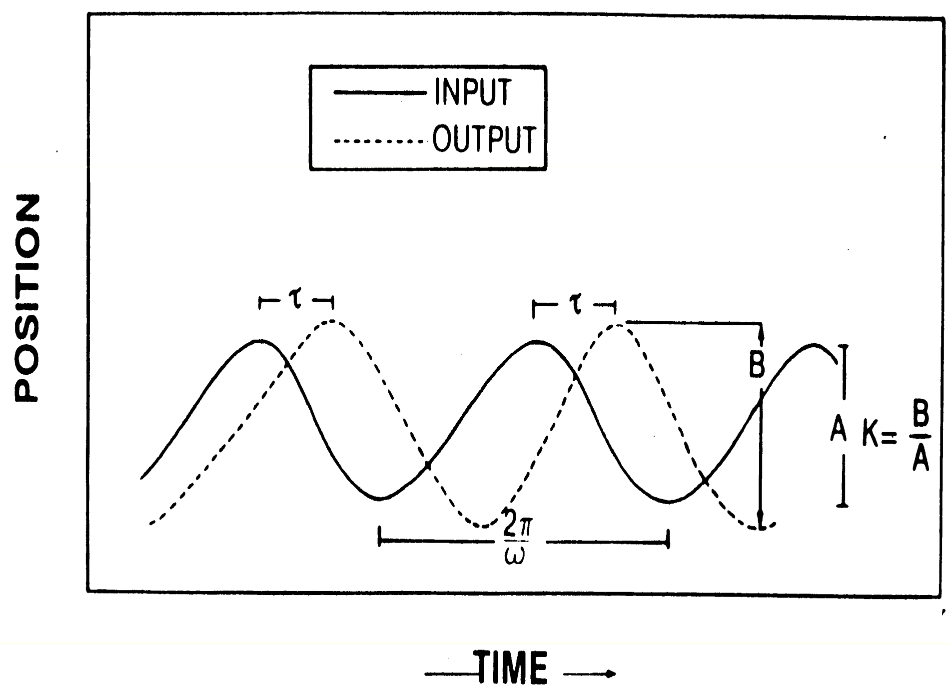
$$\therefore \Phi = \omega T$$

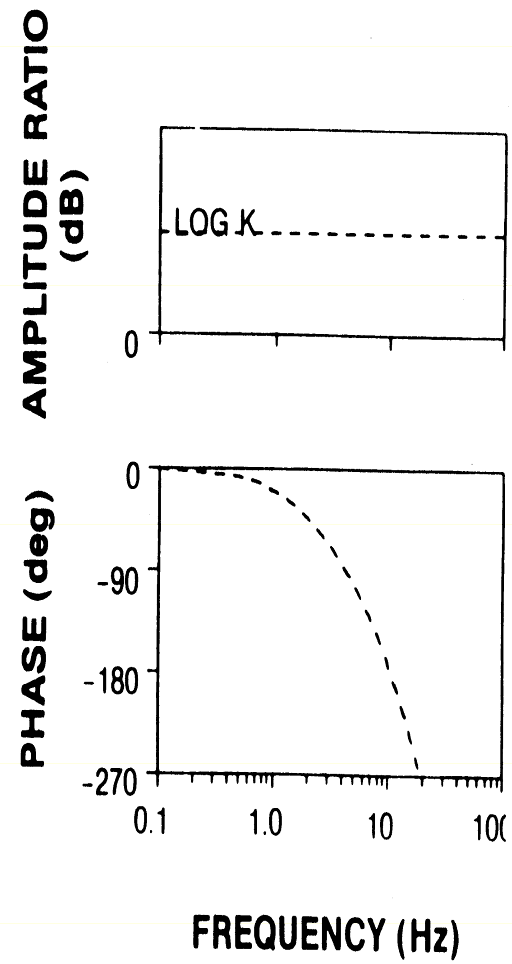
Time Domain Measurement



I----> ?

Frequency Domain Measurement

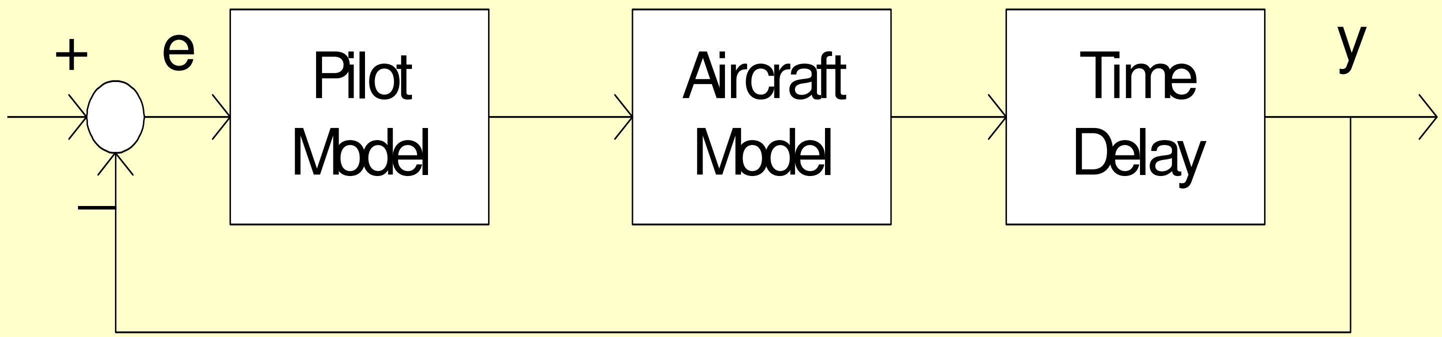




Measurement Domain

- Delays observed in the time domain will manifest a phase lag
- Some phase lags may not be a consequence of a pure delay.
    - EG numerical integration errors
    - System dynamics

Analyzing the Effects of Transport Delay



System Models

- **A/C model**
  - Air speed 430 Kts
  - Altitude 30000 Ft

$$\frac{\varphi(s)}{\delta_e(s)} = 5.57 \frac{\frac{s^2}{3.46} + \frac{0.48s}{1.86} + 1}{s(0.16s+1)\left(\frac{s^2}{3.53} + \frac{0.48s}{1.88} + 1\right)}$$

- **Pilot model**
  - Lateral control task
  - With rate controller
  - Lumped delay (neuromuscular & cognitive)

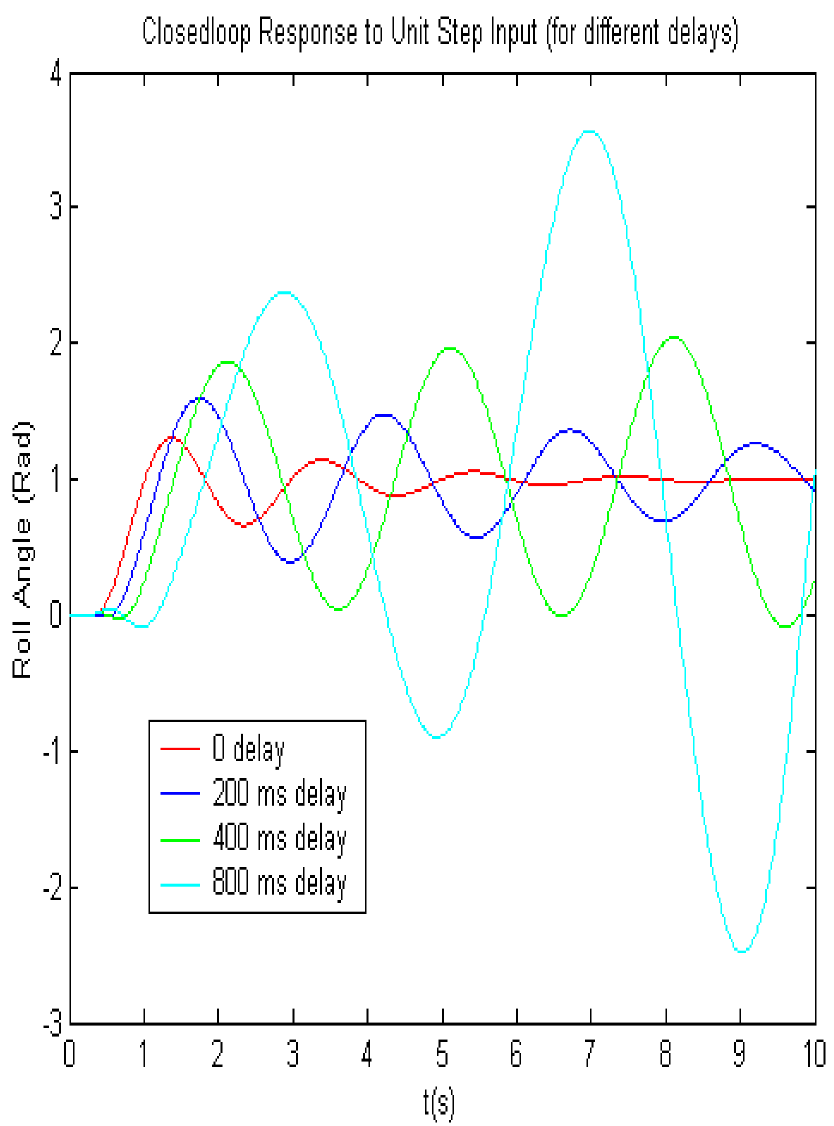
$$H_p(s) = \frac{18(s+1)e^{-0.3s}}{(s+3)(s+9)}$$

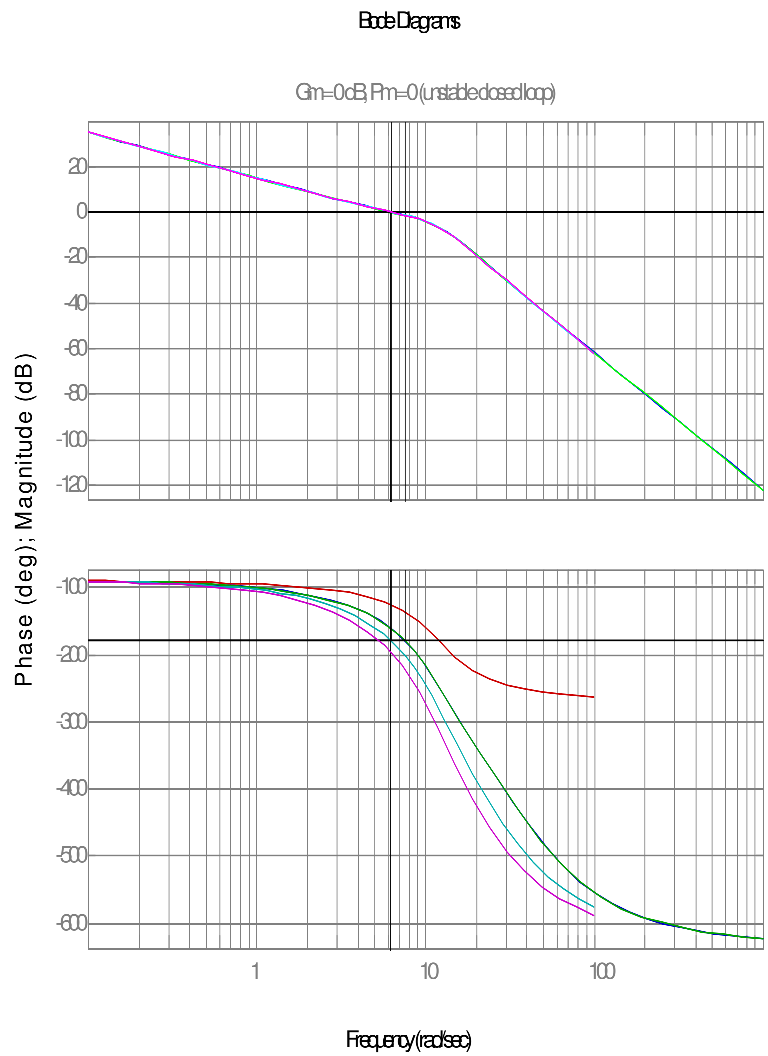
- **Transport delay**

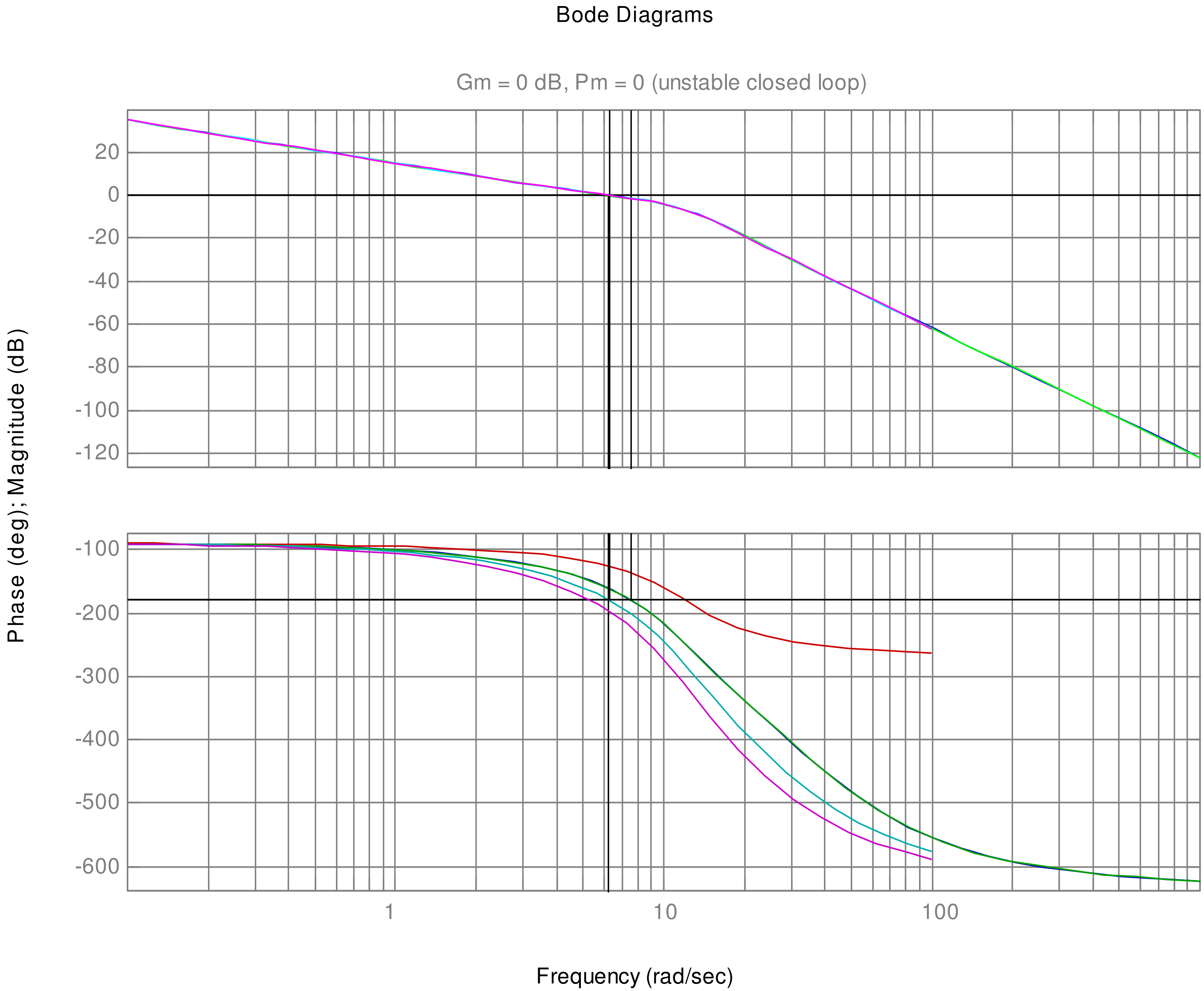
  Pade' Approximant

$$\frac{y_d}{y} = e^{-t_d s} = \frac{s^2 - \frac{6}{t_d}s + \frac{12}{t_d^2}}{s^2 + \frac{6}{t_d}s + \frac{12}{t_d^2}}$$

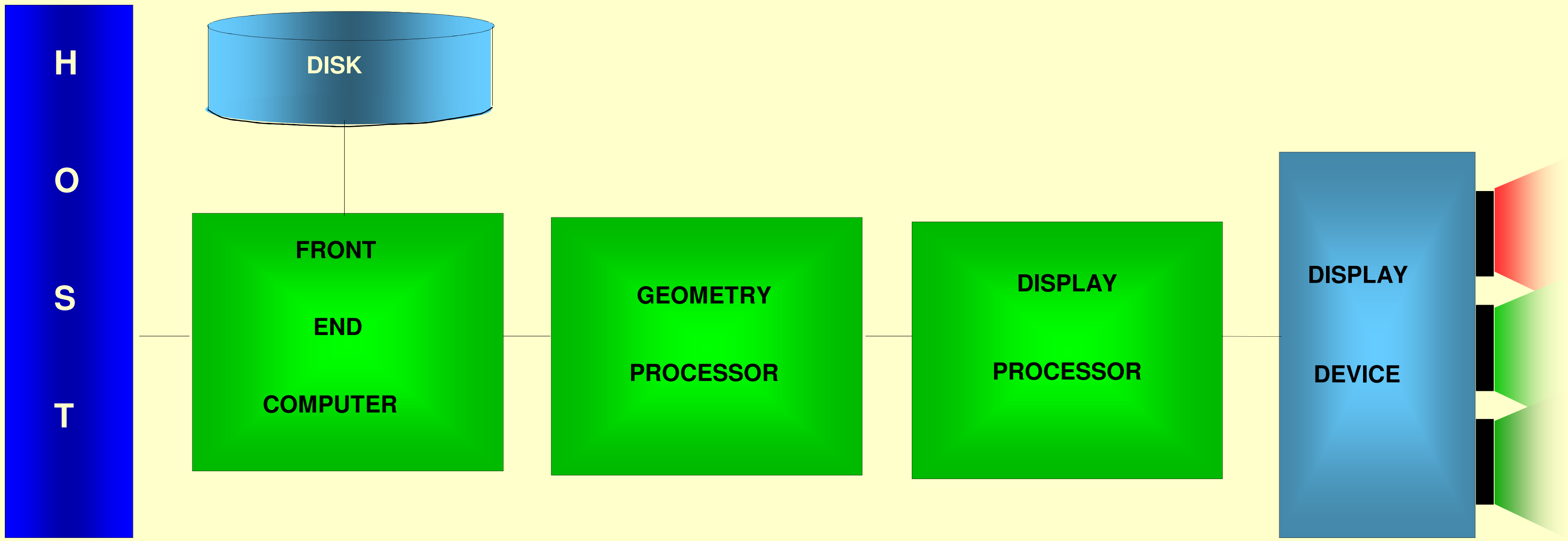
Time & Frequency Response for Different Delays



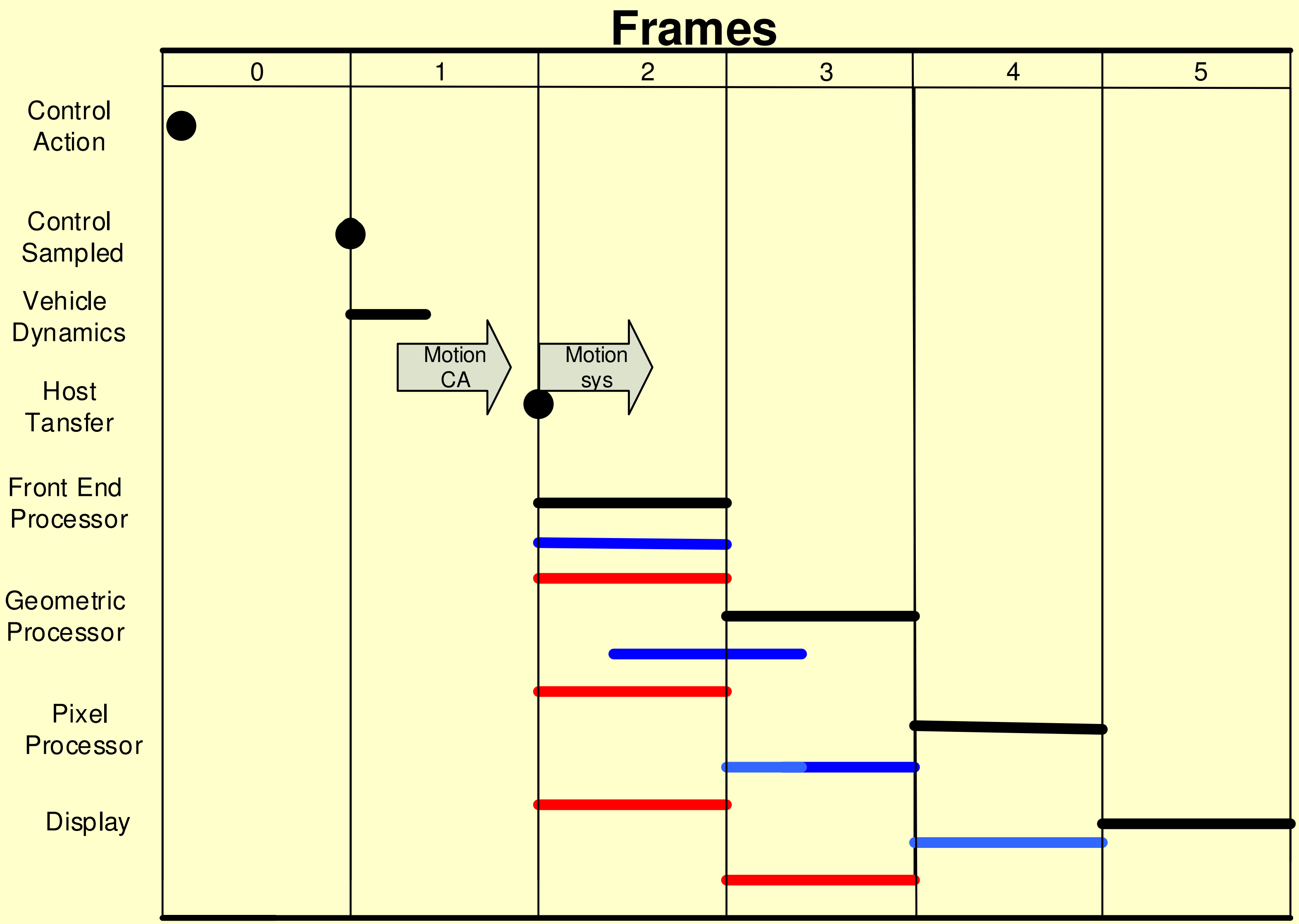



Bode Diagrams
Gm = 0 dB, Pm = 0 (unstable closed loop)
20
0
-20
-40
-60
-80
-100
-120
Phase (deg); Magnitude (dB)
-100
-200
-300
-400
-500
-600
1
10
100
Frequency (rad/sec)

Typical Visual System Architecture



Timing Diagram



Manifestations of Temporal Distortion

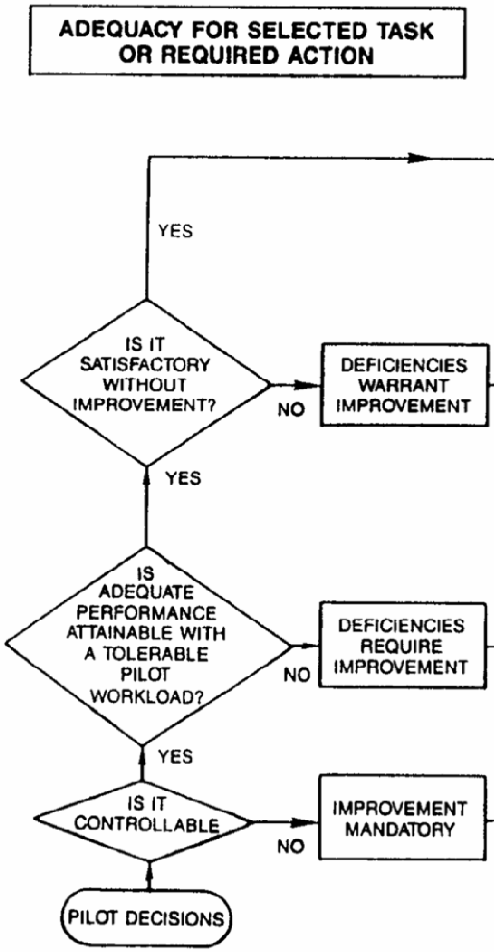
- Operator performance
- Workload
- Human-machine system instabilities
- Poor handling quality rating
- Cyber sickness

Results of Performance Studies

Effects on Operator

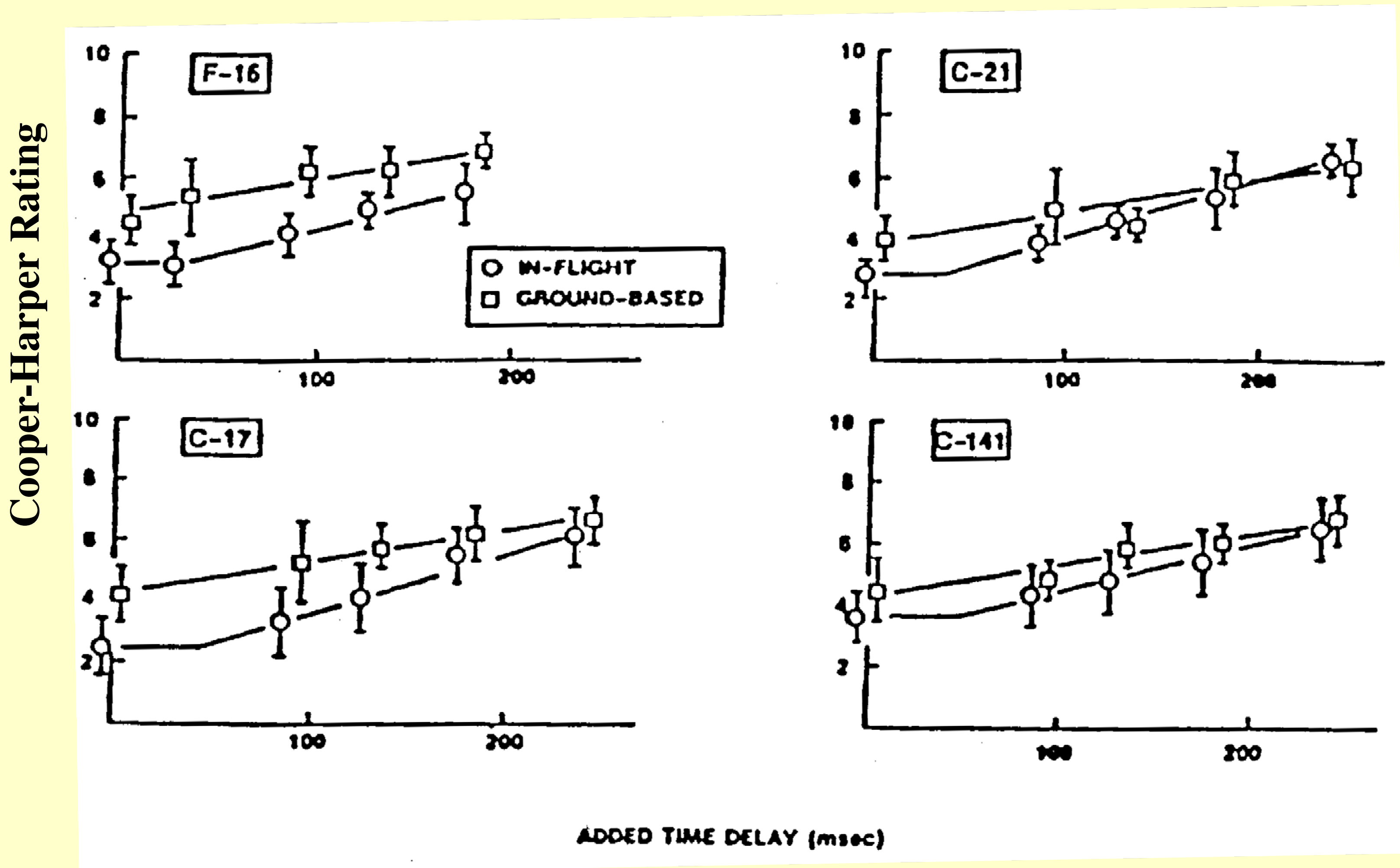
- Pilot Induced Oscillation
  - Decrease damping ratio;
  - Decrease phase margin;
  - Possible instability.
- Root Mean Square Error (RMSE) in compensatory tasks shows that the system performance is degraded
- Cooper-Harper Ratings show that operator's handling quality assessment is degraded.
- Control inceptor deflection and its PSD illustrate that the operator's workload is increased..
- Potential for simulator sickness

Cooper-Harper Rating System



AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION	PILOT RATING
EXCELLENT HIGHLY DESIRABLE	PILOT COMPENSATION NOT A FACTOR FOR DESIRED PERFORMANCE	1
GOOD NEGLIGIBLE DEFICIENCIES	PILOT COMPENSATION NOT A FACTOR FOR DESIRED PERFORMANCE	2
FAIR - SOME MILDLY UNPLEASANT DEFICIENCIES	MINIMAL PILOT COMPENSATION REQUIRED FOR DESIRED PERFORMANCE	3
MINOR BUT ANNOYING DEFICIENCIES	DESIRED PERFORMANCE REQUIRES MODERATE PILOT COMPENSATION	4
MODERATELY OBJECTIONABLE DEFICIENCIES	ADEQUATE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION	5
VERY OBJECTIONABLE BUT TOLERABLE DEFICIENCIES	ADEQUATE PERFORMANCE REQUIRES EXTENSIVE PILOT COMPENSATION	6
MAJOR DEFICIENCIES	ADEQUATE PERFORMANCE NOT ATTAINABLE WITH MAXIMUM TOLERABLE PILOT COMPENSATION. CONTROLLABILITY NOT IN QUESTION	7
MAJOR DEFICIENCIES	CONSIDERABLE PILOT COMPENSATION IS REQUIRED FOR CONTROL	8
MAJOR DEFICIENCIES	INTENSE PILOT COMPENSATION IS REQUIRED TO RETAIN CONTROL	9
MAJOR DEFICIENCIES	CONTROL WILL BE LOST DURING SOME PORTION OF REQUIRED OPERATION	10

Comparison of In-flight and Ground- based Delay Effects



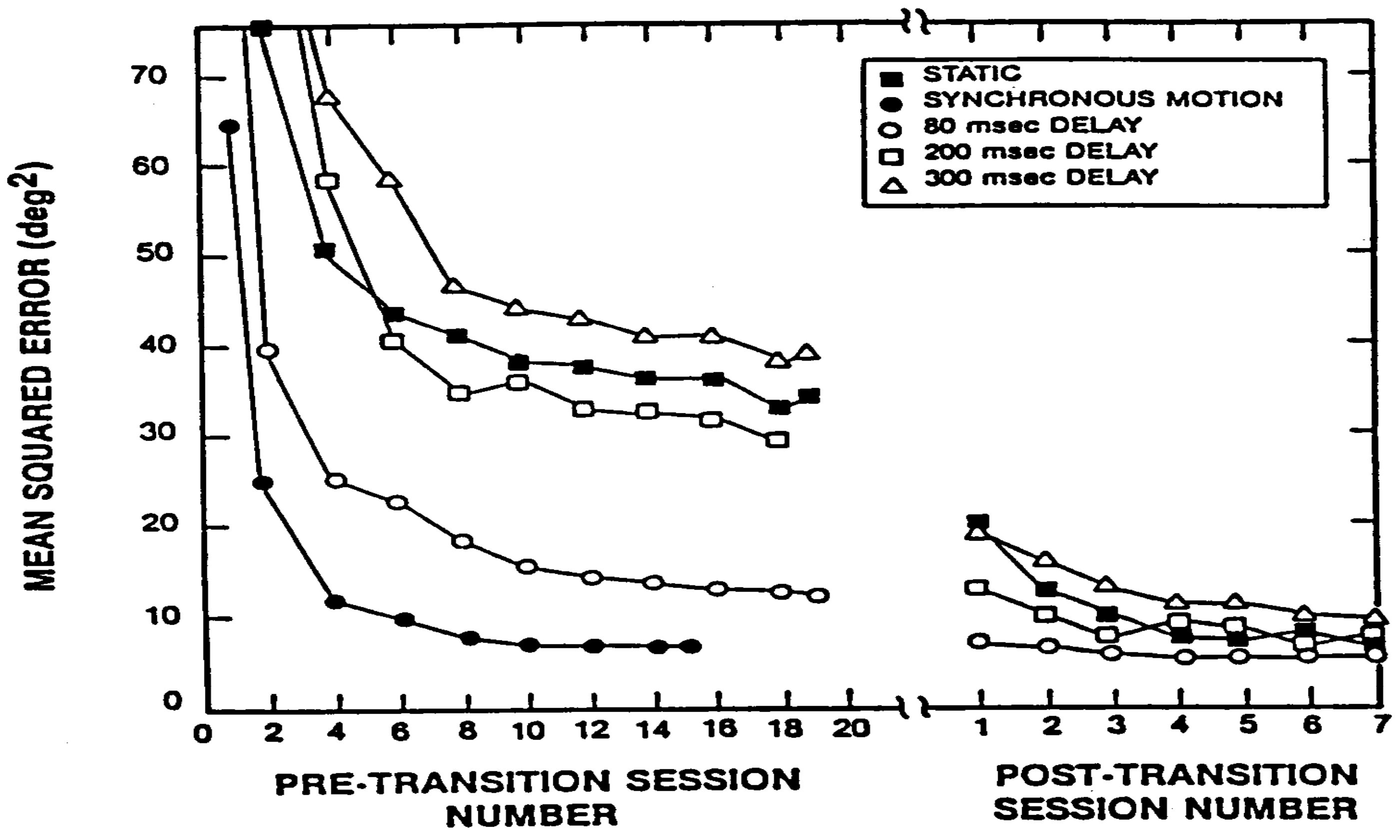
Motion Effects

- **Adding Synchronized Motion Increases Delay Tolerance**

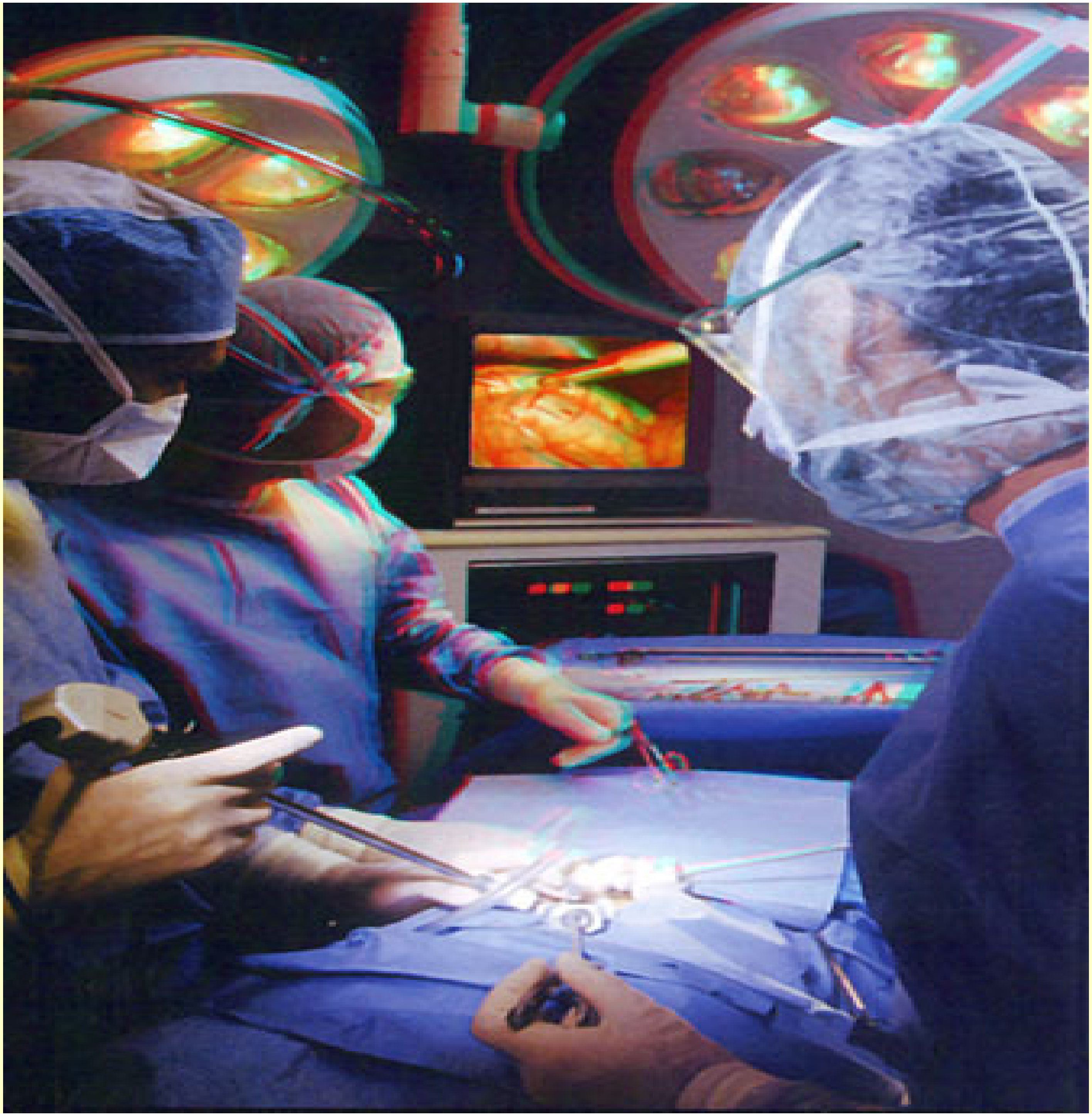
	Delay Tolerance: FIXED BASE	Delay Tolerance: MOVING BASE
Bad Airplane (6)	**<47 ms**	**<47 ms**
Basic Airplane (5)	**172 ms**	**297 ms**
Good Airplane (3)	**172 ms**	**422 ms**

(MILLER AND RILEY, 1976)

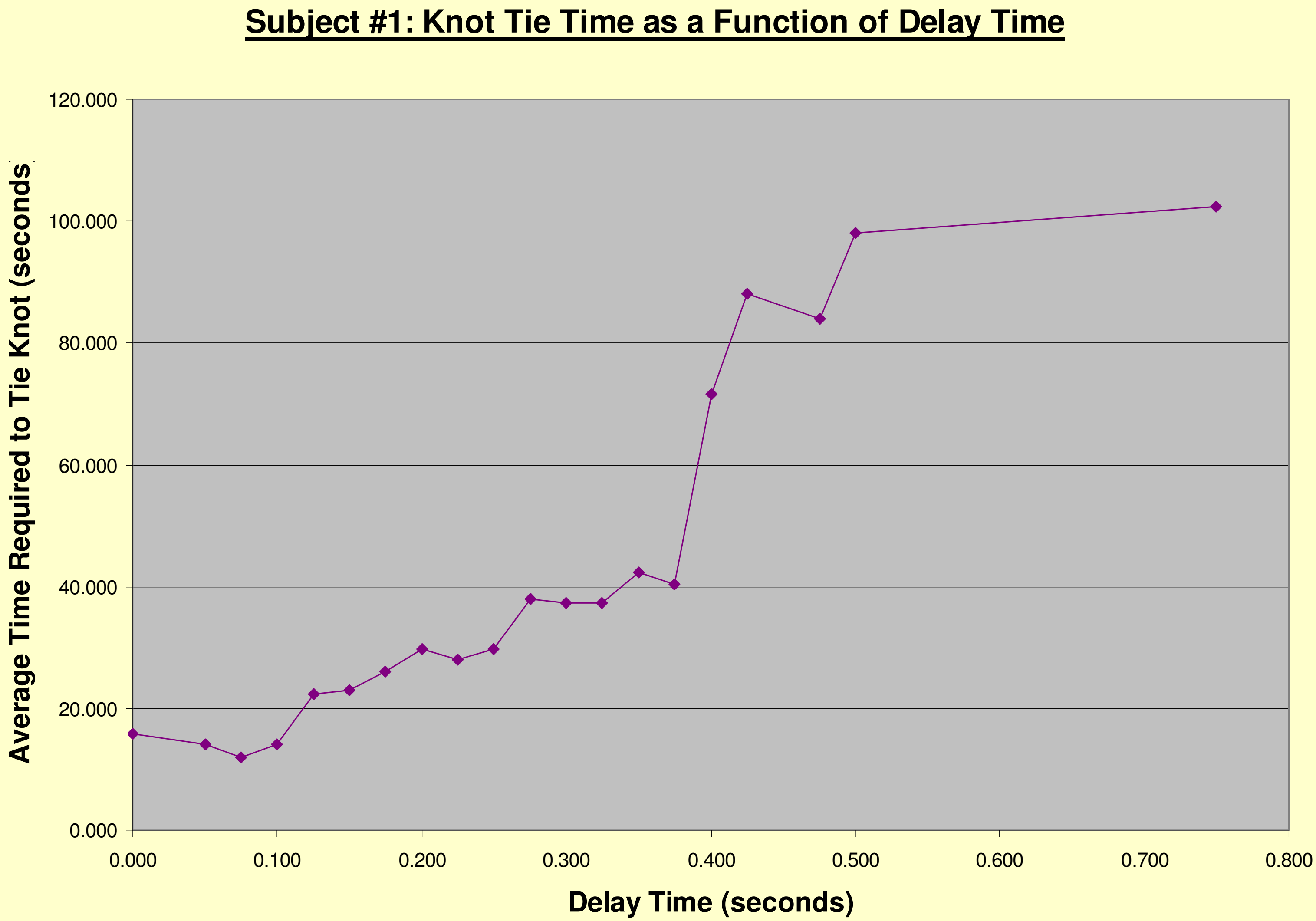
Effects of Delay on Performance and Training



EFFECTS OF DELAYED MOTION CUES ON LEARNING, PERFORMANCE, AND TRANSFER-OF-TRAINING. (From Levison, Lancraft, and Junker, 1979)



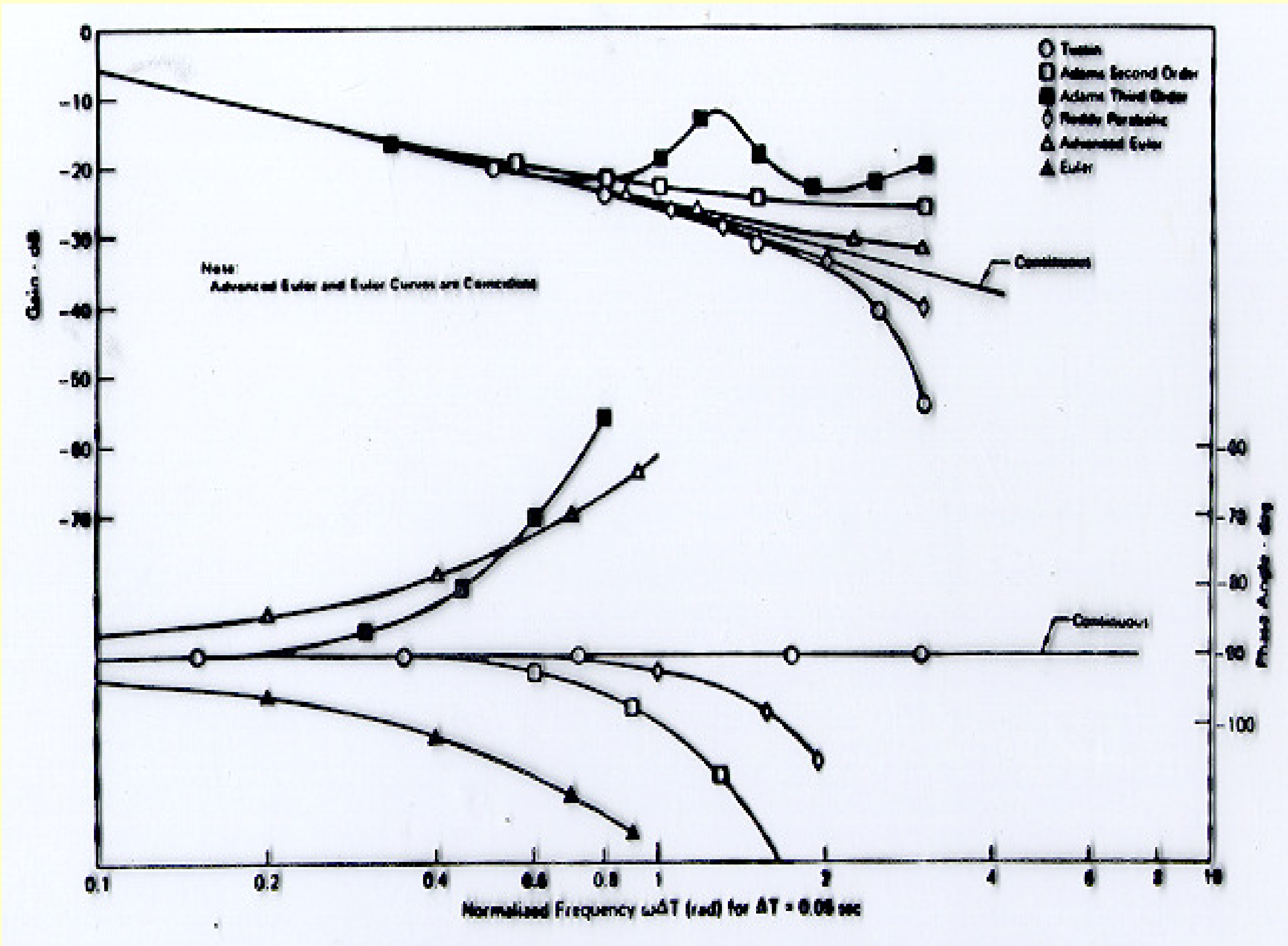
Surgeon Performance Data W/Delay



Compensation Techniques

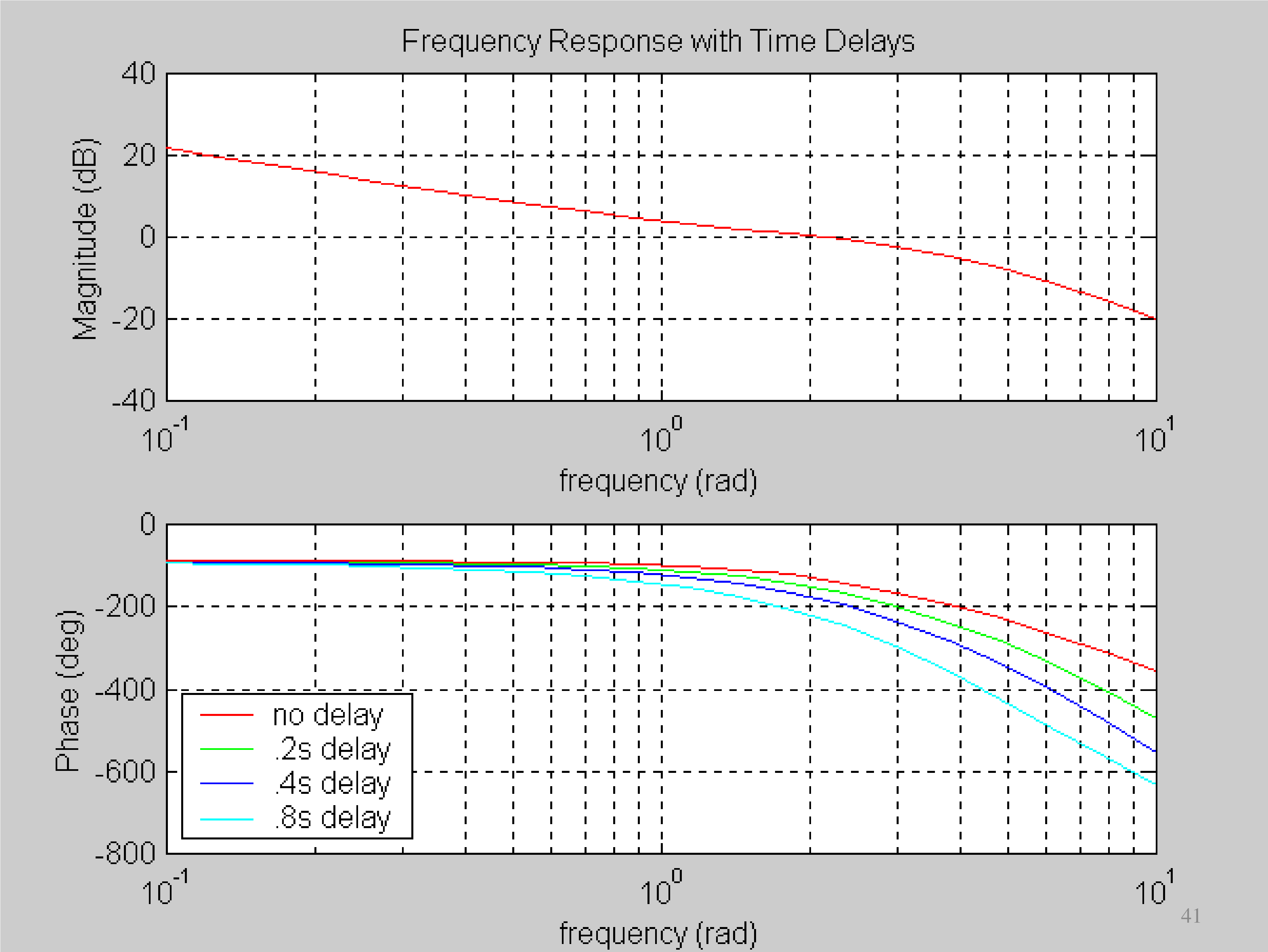
- Integration algorithms
- Synchronize host computer to visual
- Simple predictors (extrapolators)
- Various Lead/Lag algorithms
- McFarland Predictor
- Sobiski/Cardullo Predictor
- Adaptive Algorithm
- Advanced State Space Compensator

Frequency Domain Comparison of Various Integration Algorithms



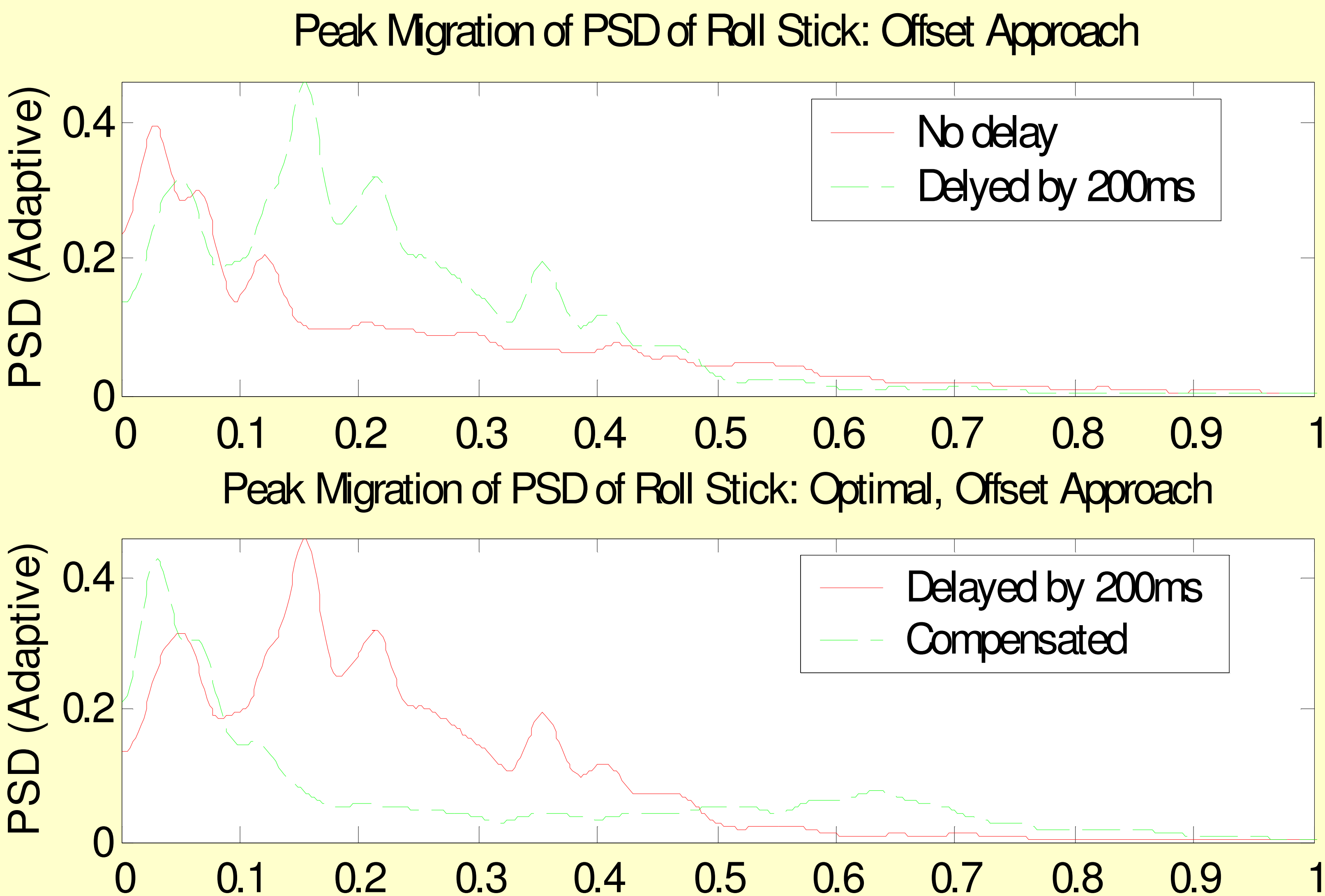
Metrics

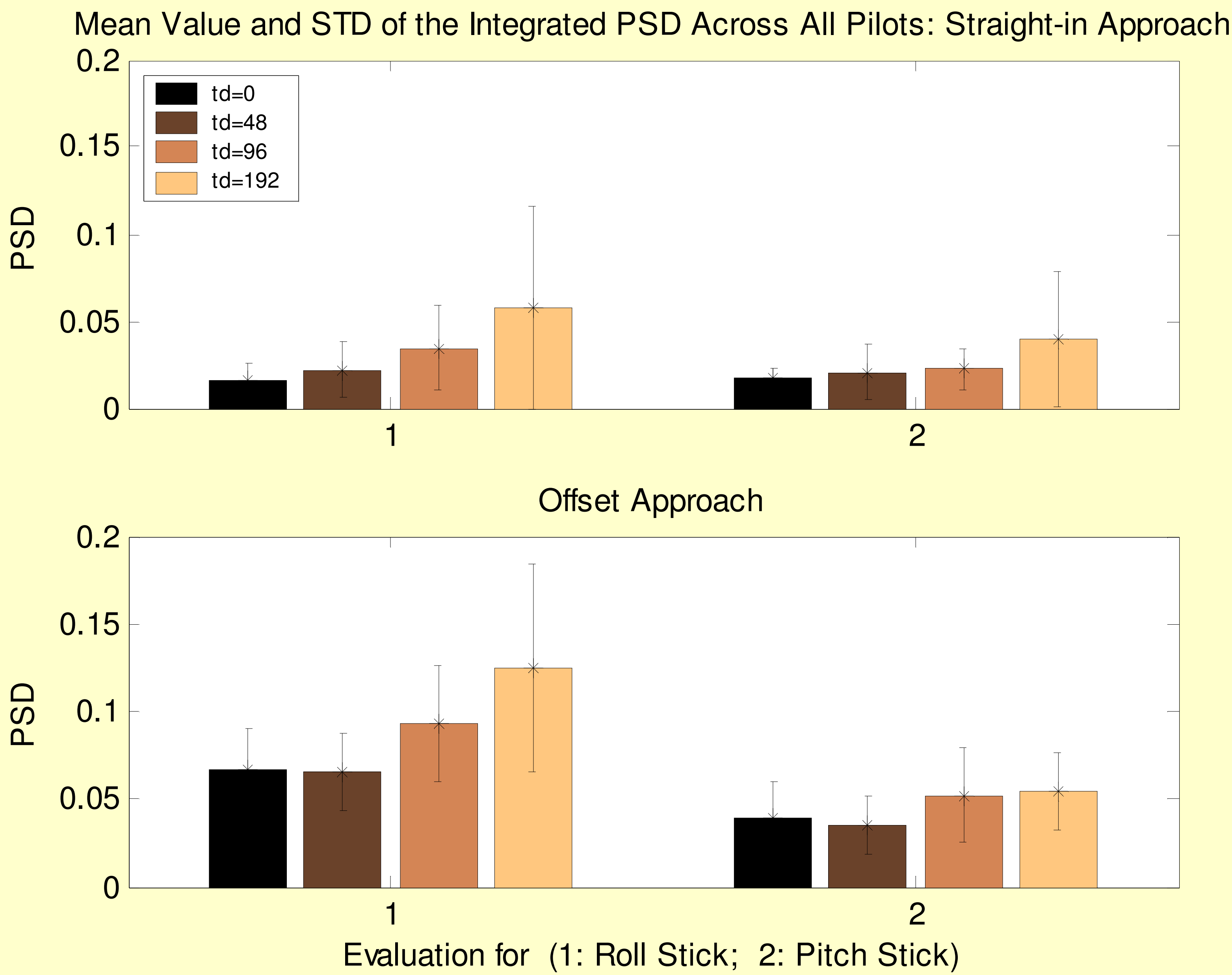
- **Analytical**
  - Time response
  - Frequency response
- **Human operator in-the-loop**
  - RMS Error
  - Power Spectral Density (PSD)
  - Integrated PSD
  - NASA TLX



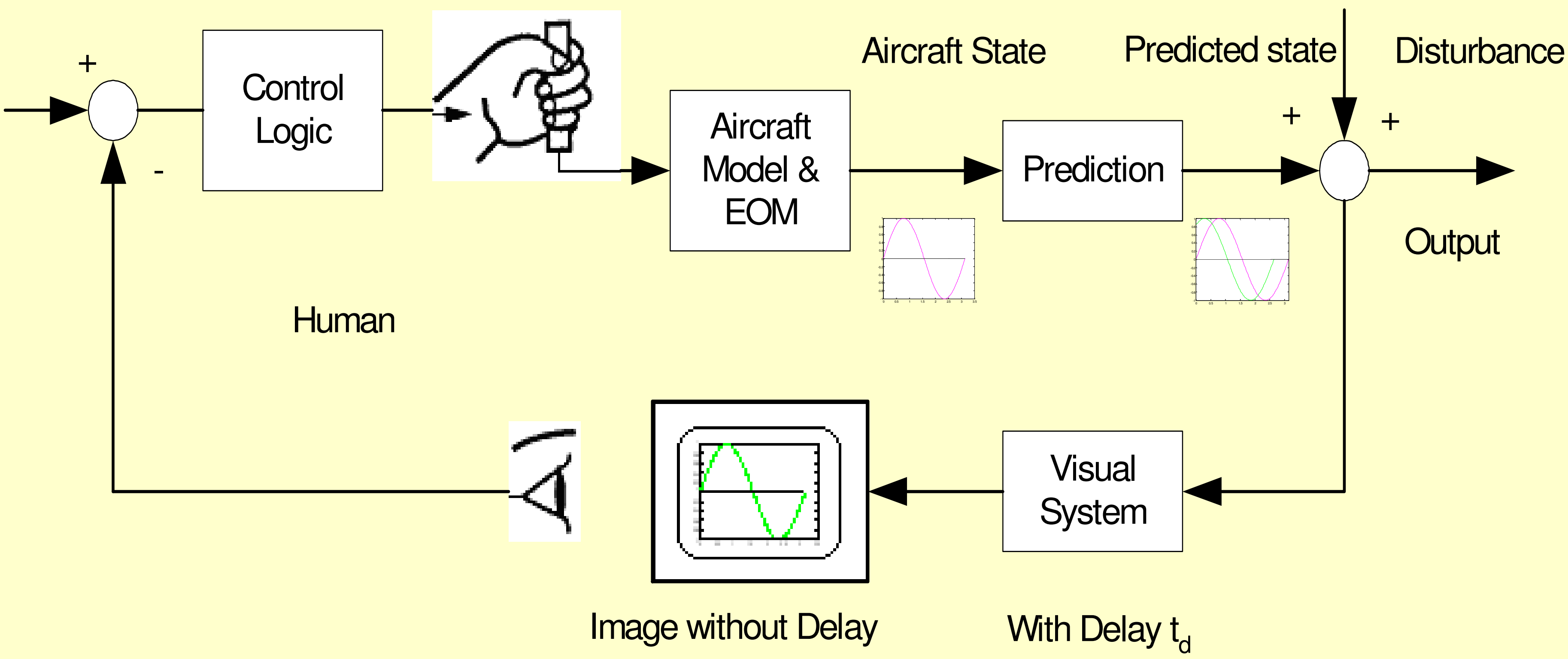
Frequency Response with Time Delays
Magnitude (dB)
40
20
0
-20
-40
10^{-1}
10^{0}
10^{1}
frequency (rad)
Phase (deg)
0
-200
-400
-600
-800
no delay
.2s delay
.4s delay
.8s delay
10^{-1}
10^{0}
10^{1}
frequency (rad)

Power Spectral Density (PSD) - Example




Mean Value and STD of the Integrated PSD Across All Pilots: Straight-in Approach
td=0
td=48
td=96
td=192
PSD
0.2
0.15
0.1
0.05
0
1
2
Offset Approach
Evaluation for (1: Roll Stick; 2: Pitch Stick)

Compensation via Predictor

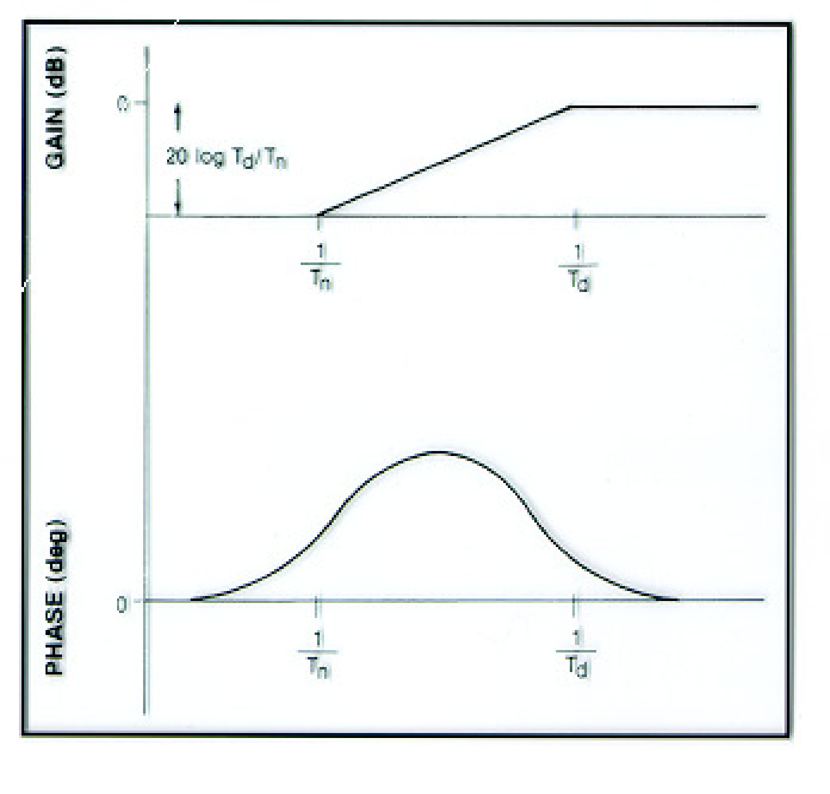


Lead/Lag Compensator

$$G(s) = \frac{s+\omega_n}{s+\omega_d}$$

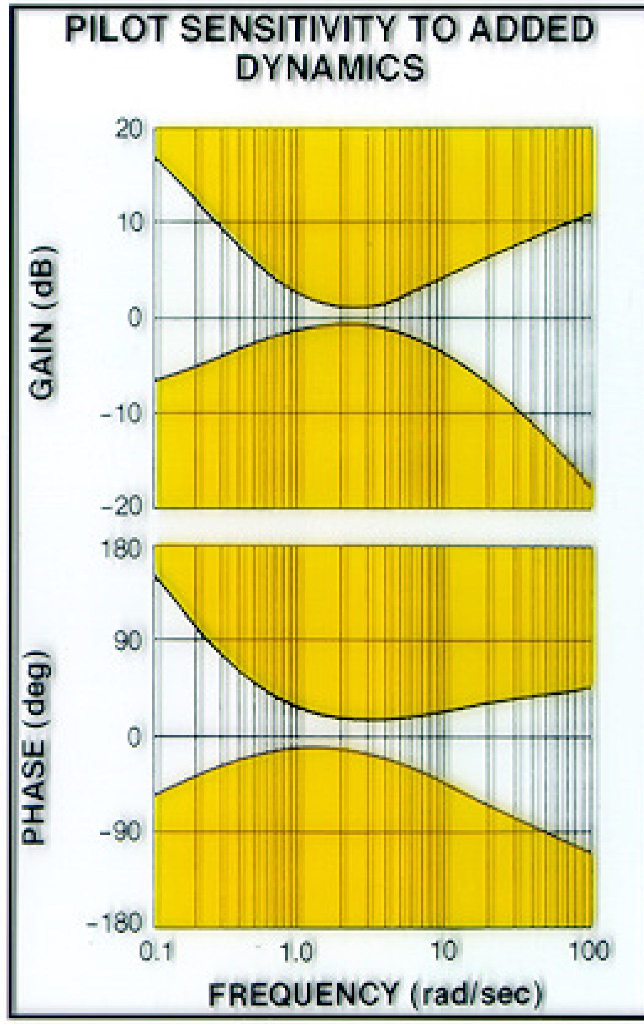
$$\omega_n = \frac{1}{\tau_n} \;\&\; \omega_d = \frac{1}{\tau_d}$$

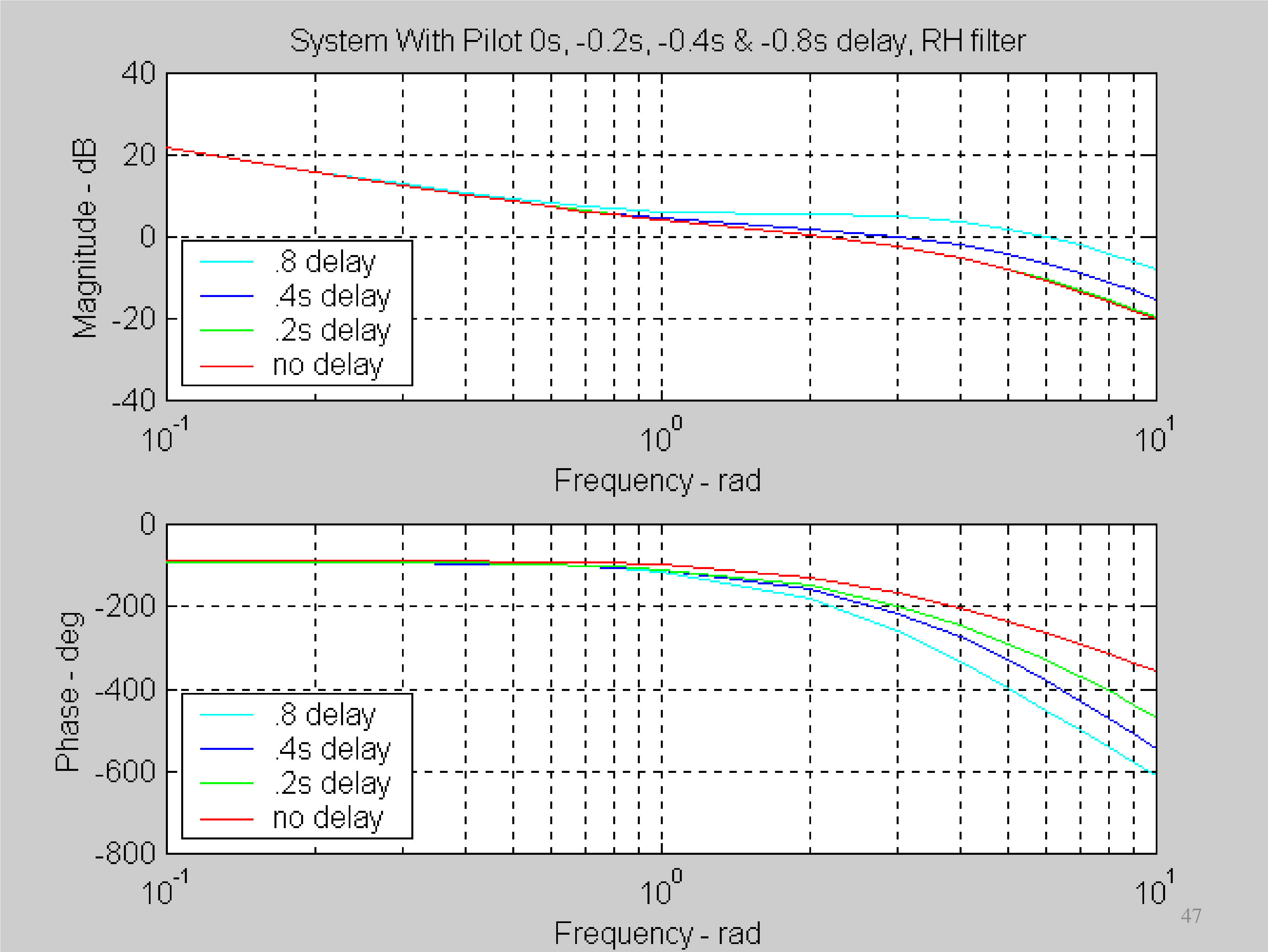
$$G(s) = \frac{s+\dfrac{1}{\tau_n}}{s+\dfrac{1}{\tau_d}} = \frac{\tau_d}{\tau_n}\left(\frac{\tau_n s+1}{\tau_d s+1}\right)$$



FIRST-ORDER LEAD/LAG FILTER

- $GF = \frac{K(T_N S+1)}{T_D S+1}$
- PARAMETER ADJUSTMENT
  - -RICHARD AND HARRIS (1980)
    - (1) SET T_N=DELAY
    - (2) ADJUST T_D FOR BEST PILOT PERFORMANCE
  - -CRANE (1983)
    - (1) MAXIMIZE PHASE CORRECTION AND MINIMIZE GAIN DISTORTION IN CROSSOVER REGION
    - (2) RESTORE SYSTEM PHASE MARGIN




System With Pilot 0s, -0.2s, -0.4s & -0.8s delay, RH filter
Magnitude - dB
40
20
0
-20
-40
.8 delay
.4s delay
.2s delay
no delay
10^{-1}
10^{0}
10^{1}
Frequency - rad
Phase - deg
0
-200
-400
-600
-800
.8 delay
.4s delay
.2s delay
no delay
10^{-1}
10^{0}
10^{1}
Frequency - rad

Phase and Gain Margin for Delayed Cases

Delay (s)	frequency (rad/sec)	Phase margin (deg)	frequency (rad/sec)	Gain margin (db)
0	2.1582	44.5706	3.3518	1.4881
.2	2.1582	19.6851	2.5531	1.1367
.4	2.1582	-5.1603	2.0717	0.9751
.8	2.1582	-53.8423	1.4831	0.8082

The McFarland Compensation Method

- The McFarland compensator, a special integrator, uses the previous two steps of velocity to extrapolate or predict the compensated displacement.

$$u_c(k) = u_d(k) + b_0 v_d(k) + b_1 v_d(k-1) + b_2 v_d(k-2)$$

- Where u is the displacement, v the velocity, subscript c the compensated and subscript d the delayed.
- Coefficients b_0-b_2 are determined by tuning the sinusoidal input signal.

McFarland Coefficients

- The coefficients are given by:

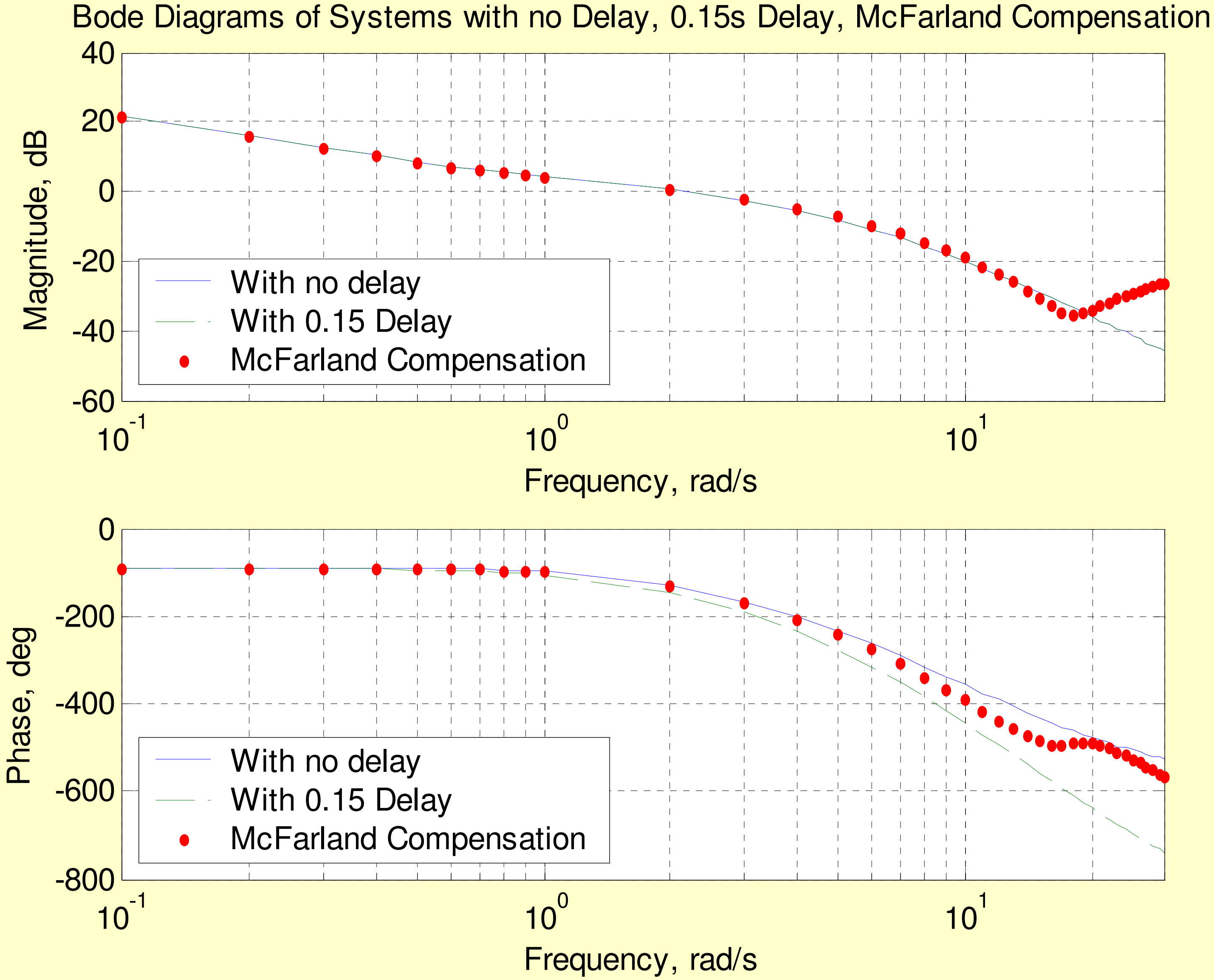
$$b_0 = \frac{\left[\psi_0 + \sin\psi_0\left(1-2\cos\theta_0\right)\right]\sin\theta_0 + \left[\tfrac{1}{2}\theta_0\sin\theta_0 - \cos\psi_0\left(1-\cos\theta_0\right)\right]\left(1+2\cos\theta_0\right)}{2\omega_0\sin\theta_0\left(1-\cos\theta_0\right)}$$

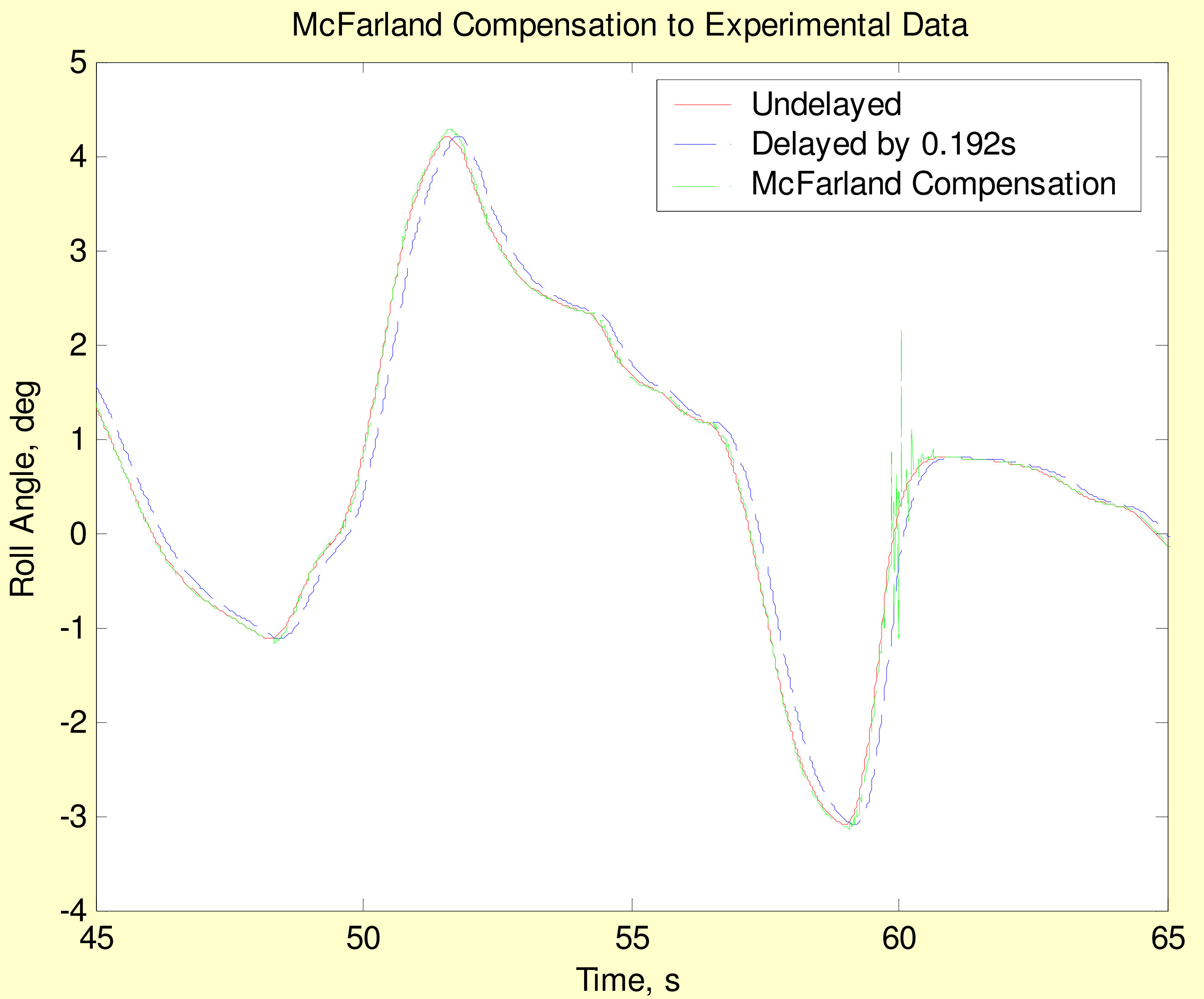
$$b_1 = \frac{2\sin\left(\theta_0+\psi_0\right) - 2\psi_0\cos\theta_0 - \theta_0\left(1+\cos\theta_0\right)}{2\omega_0\left(1-\cos\theta_0\right)}$$

$$b_2 = \frac{\left[\psi_0 - \sin\psi_0 + \tfrac{1}{2}\theta_0\right]\sin\theta_0 - \cos\psi_0\left(1-\cos\theta_0\right)}{2\omega_0\sin\theta_0\left(1-\cos\theta_0\right)}$$

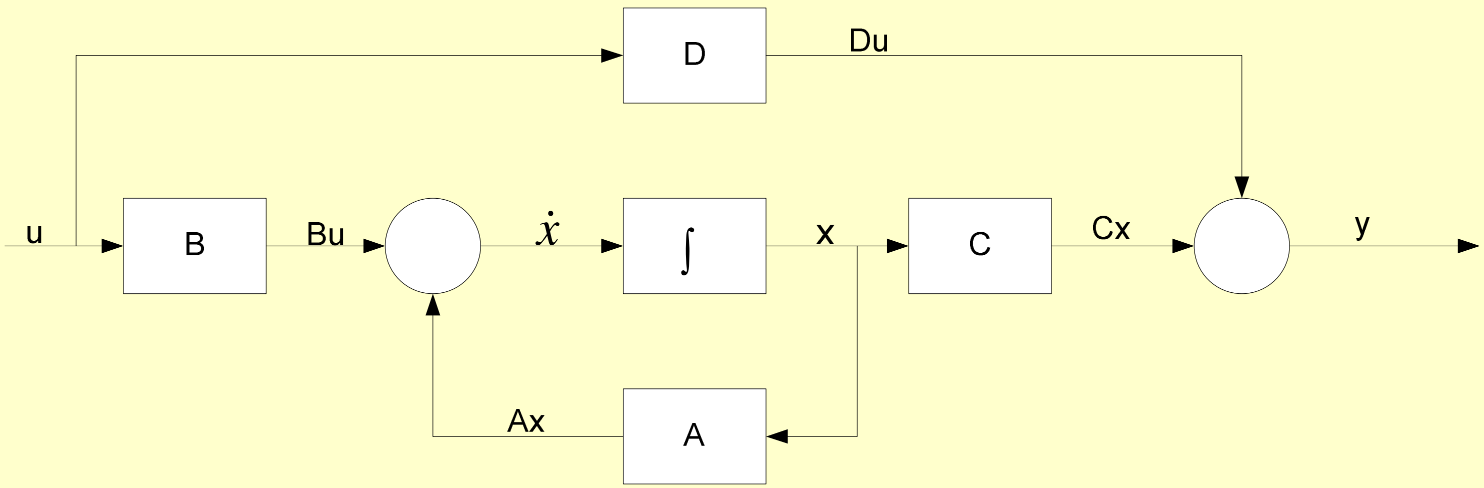
$$\theta_0 = \omega_0 T \qquad \psi_0 = \omega_0 t_d$$

- Where T is the sampling period, t_d time delay, and omega the upper limit of the pilot operational frequency, usually 3 Hz.


Bode Diagrams of Systems with no Delay, 0.15s Delay, McFarland Compensation
Magnitude, dB
Frequency, rad/s
With no delay
With 0.15 Delay
McFarland Compensation
Phase, deg
Frequency, rad/s
With no delay
With 0.15 Delay
McFarland Compensation


McFarland Compensation to Experimental Data
Undelayed
Delayed by 0.192s
McFarland Compensation
Roll Angle, deg
Time, s
5
4
3
2
1
0
-1
-2
-3
-4
45
50
55
60
65

State Space System Representation



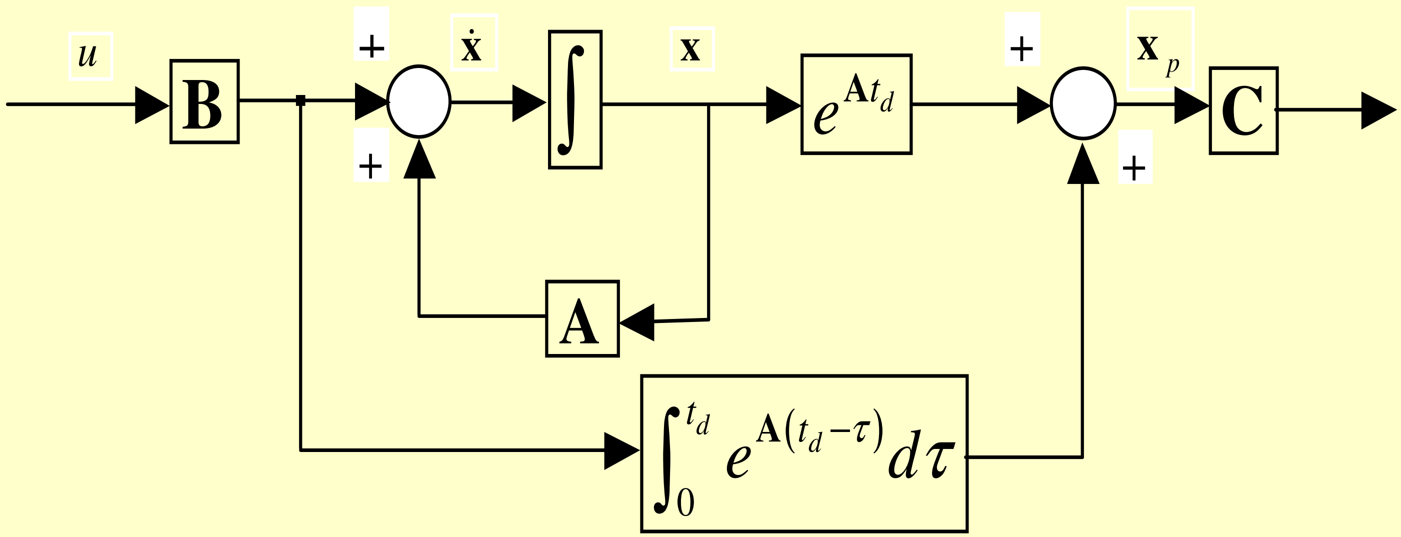
$$\dot{x} = Ax + Bu \quad y = Cx + Du$$

$A \equiv$ System Matrix; B $\equiv$ Input Matrix

C $\equiv$ Output Matrix; D $\equiv$ Feed Forward Matrix

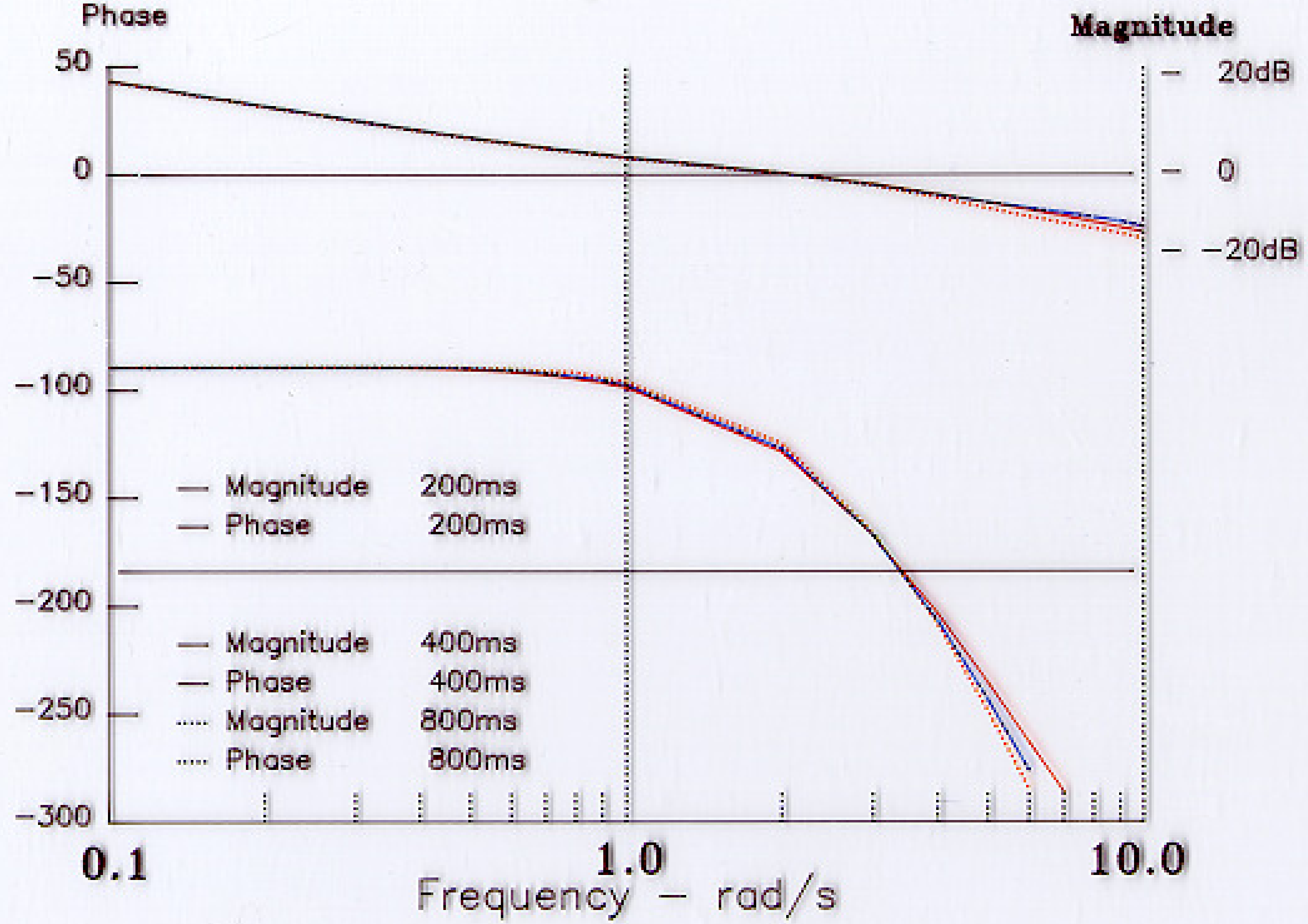
x $\equiv$ State Vector; y $\equiv$ Output Vector

Sobiski-Cardullo State Space Predictor



$$\mathbf{x}(t+t_d)=\left[e^{\mathbf{A}t_d}\right]\mathbf{x}(t)+\left[\int_0^{t_d} e^{\mathbf{A}(t_d-\tau)}d\tau\right]\mathbf{B}u(t)$$

- Constraints;
  - Only applies to LTI systems
  - Approximates the future input with the present
  - High computation burden due to matrix operations

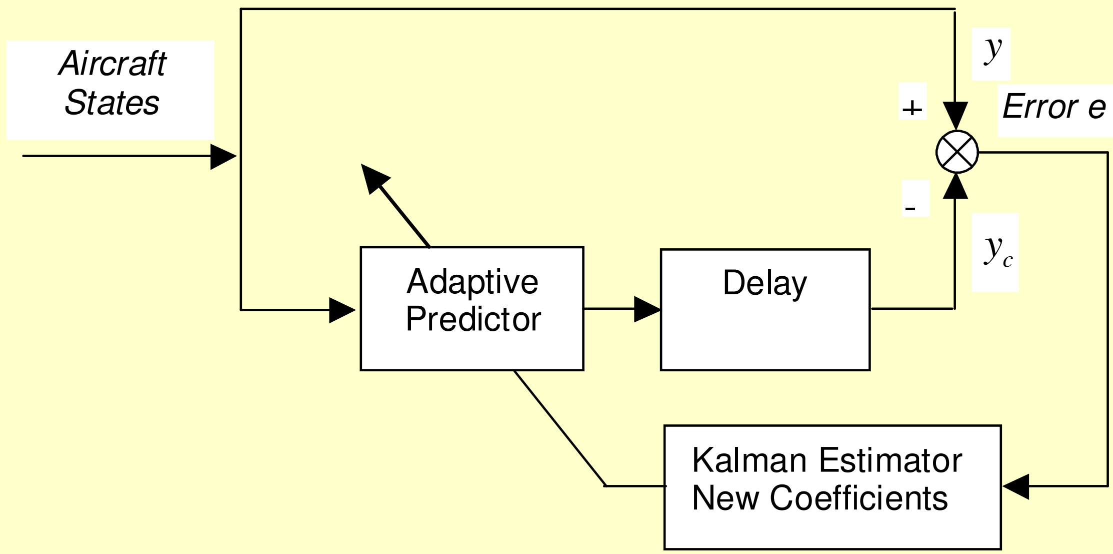


Full State Predictor Filter Frequency Analysis

Recent Developments in Delay Compensation

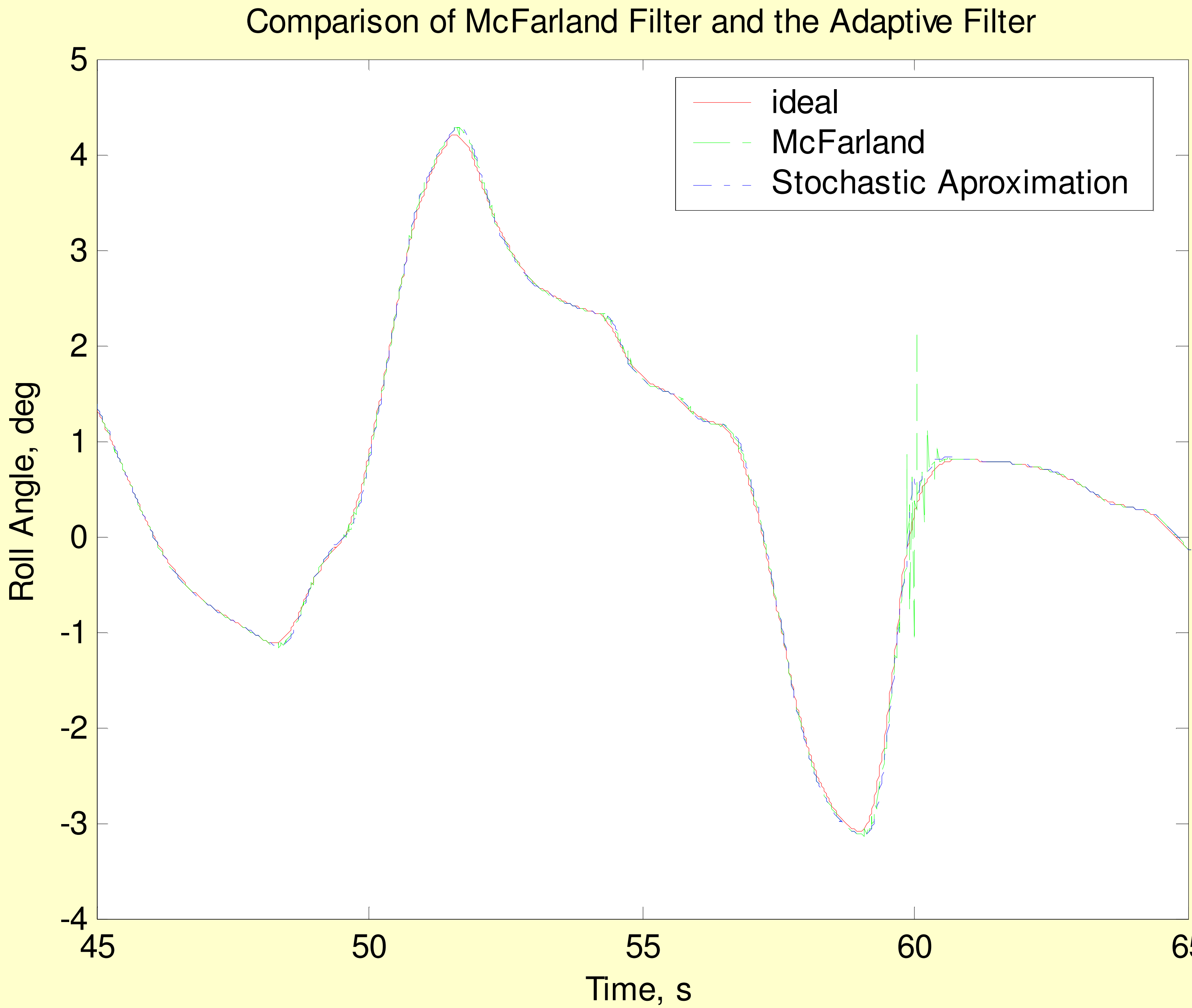
Ref. New Predictive Filters for Compensating the Transport Delay on a Flight Simulator. AIAA04-5441

The Adaptive Predictor

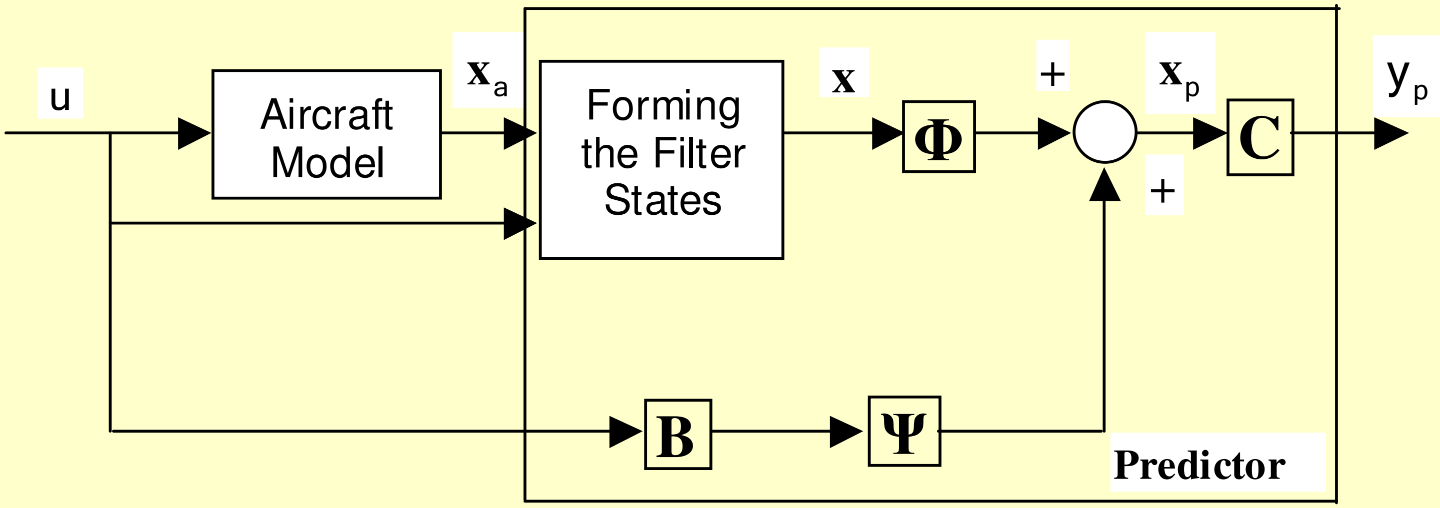


$$y_c = y_d + b_0 v + b_1 v_{-1} + b_2 v_{-2}$$

$$I = \frac{1}{2}\sum_{i=k_0}^{k}\left\{ y(i) - y_c(i) \right\}^2$$


Comparison of McFarland Filter and the Adaptive Filter
ideal
McFarland
Stochastic Aproximation
Roll Angle, deg
Time, s
5
4
3
2
1
0
-1
-2
-3
-4
45
50
55
60
65

A Practical State Space Compensator

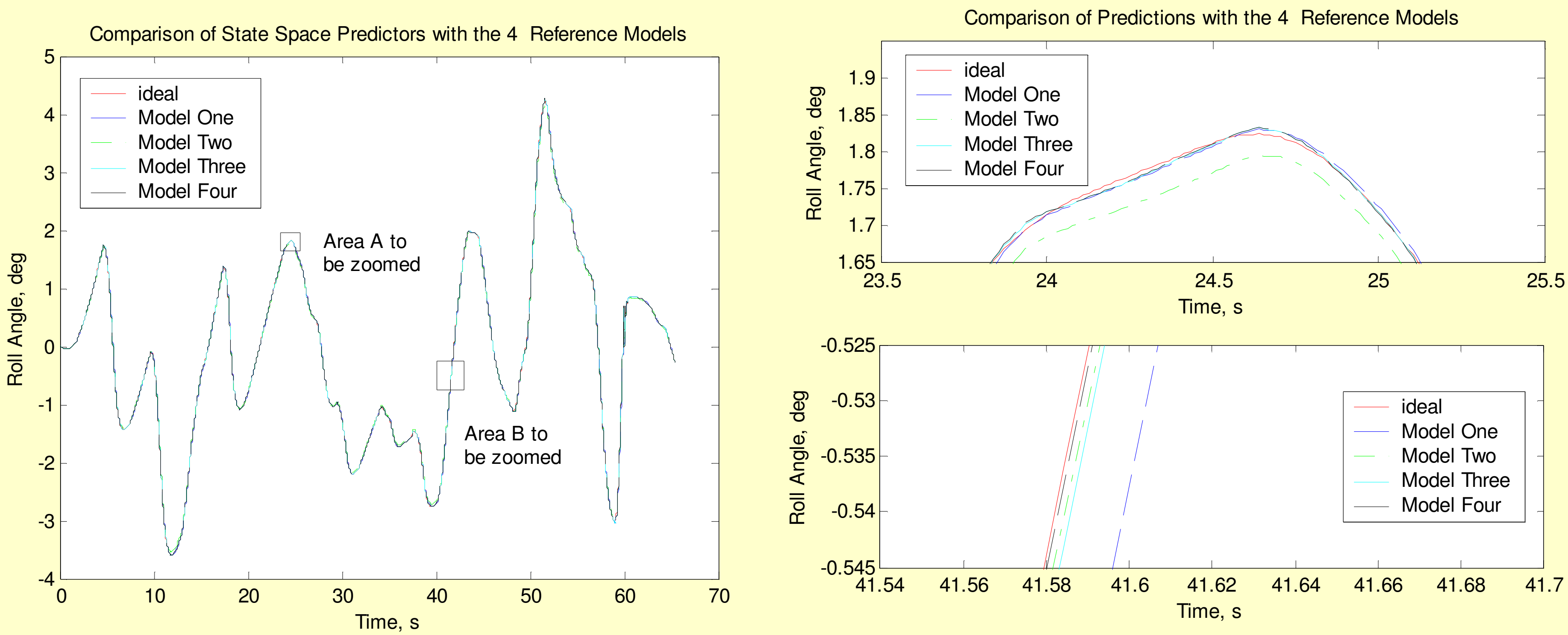


$$\mathbf{x}_p = \mathbf{\Phi x} + \mathbf{\Psi B u} \qquad \mathbf{\Phi} = e^{\mathbf{A}t_d} \qquad \mathbf{\Psi} = \int_0^{t_d} e^{\mathbf{A}(t_d-\tau)} d\tau$$

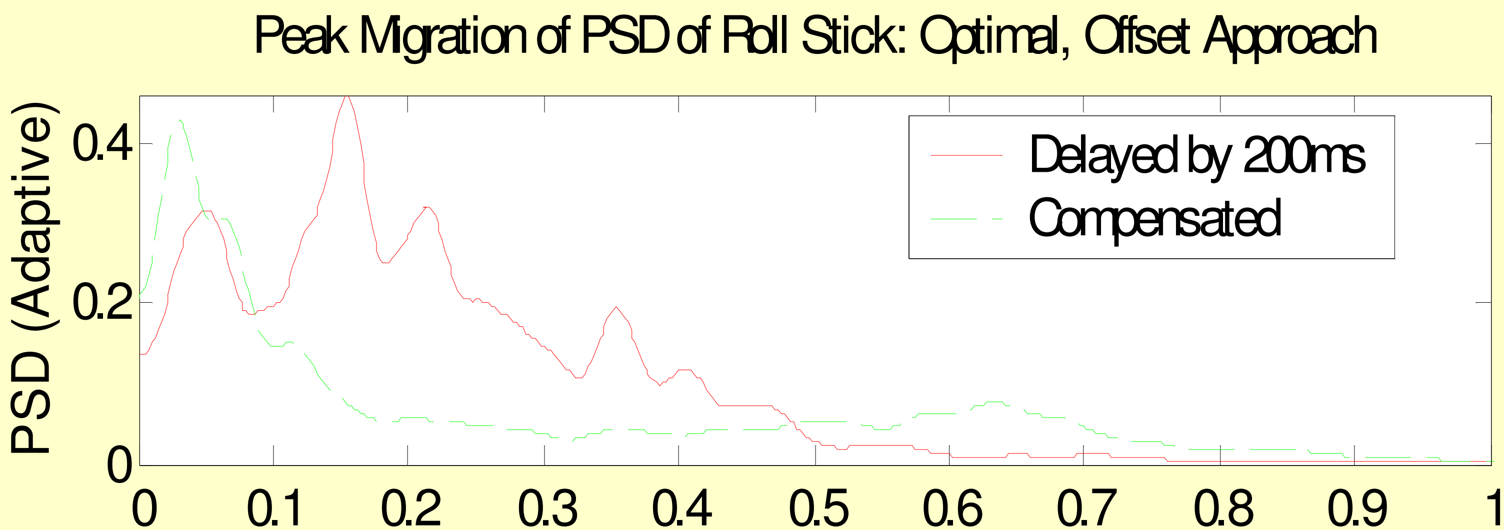
$$H_{AC}(s) = \frac{\beta_2 s^2 + \beta_1 s + \beta_0}{s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}$$

$$\mathbf{x}(t+t_d) = e^{\mathbf{A}t_d}\mathbf{x}(t) + \int_0^{t_d} e^{\mathbf{A}(t_d-\tau)}\mathbf{B}u(t+\tau)d\tau$$

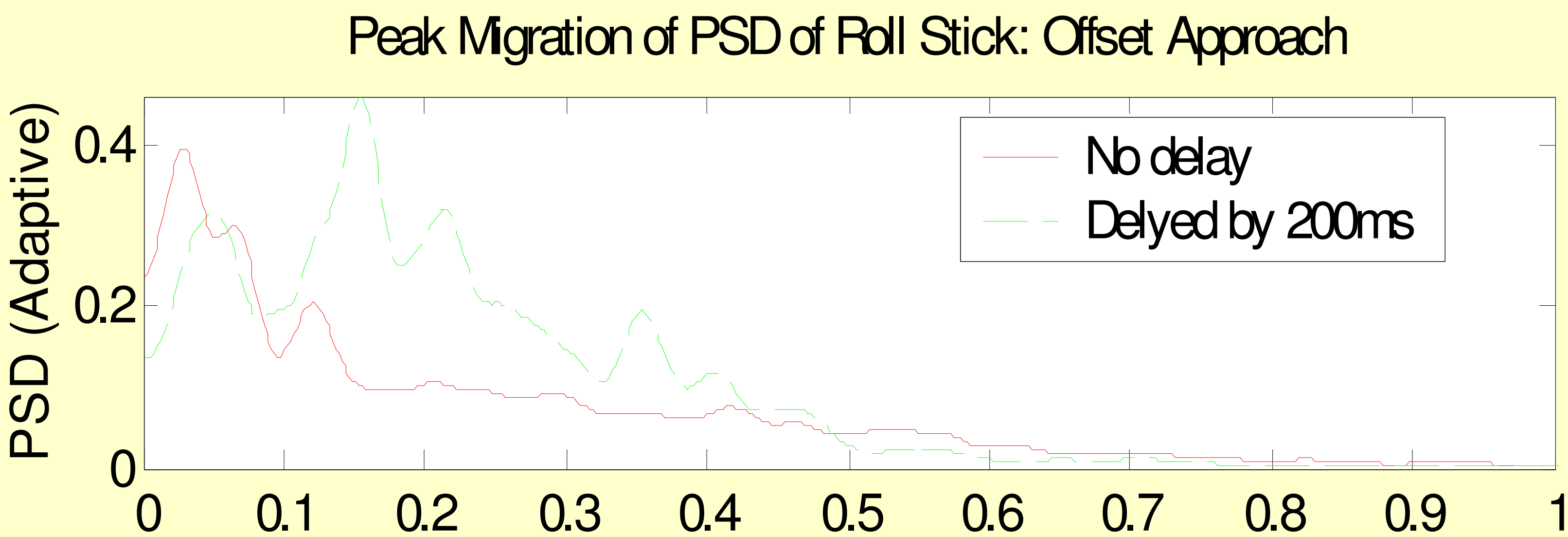
Results for the State Space Compensator

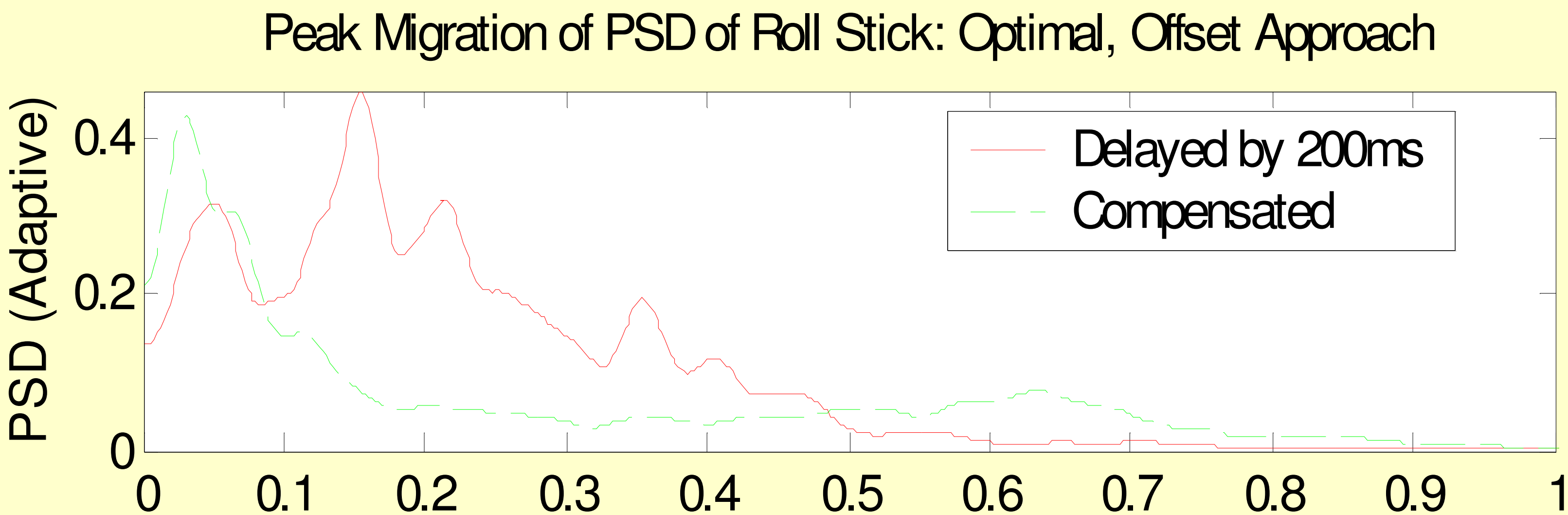


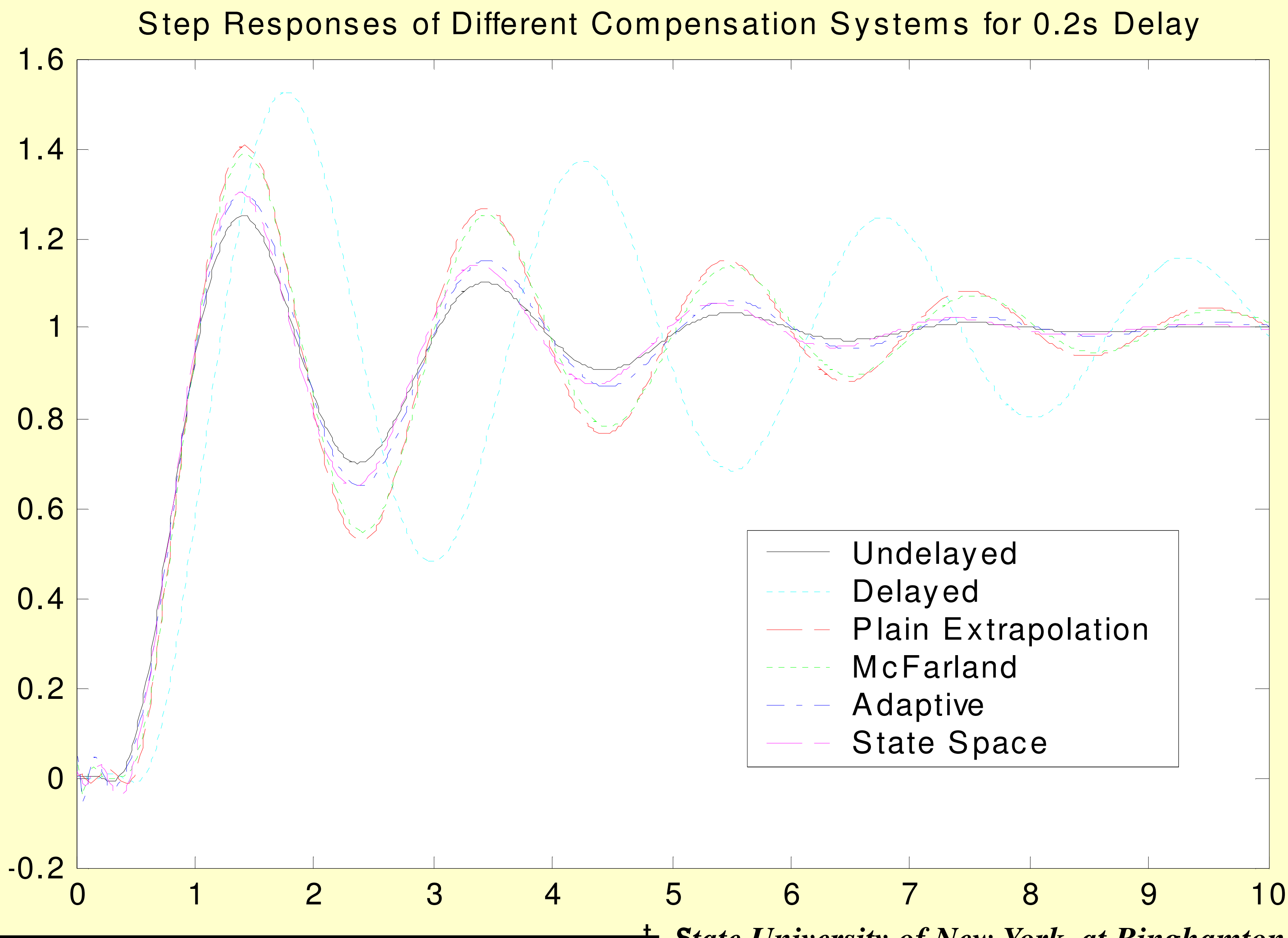
Compensated Results



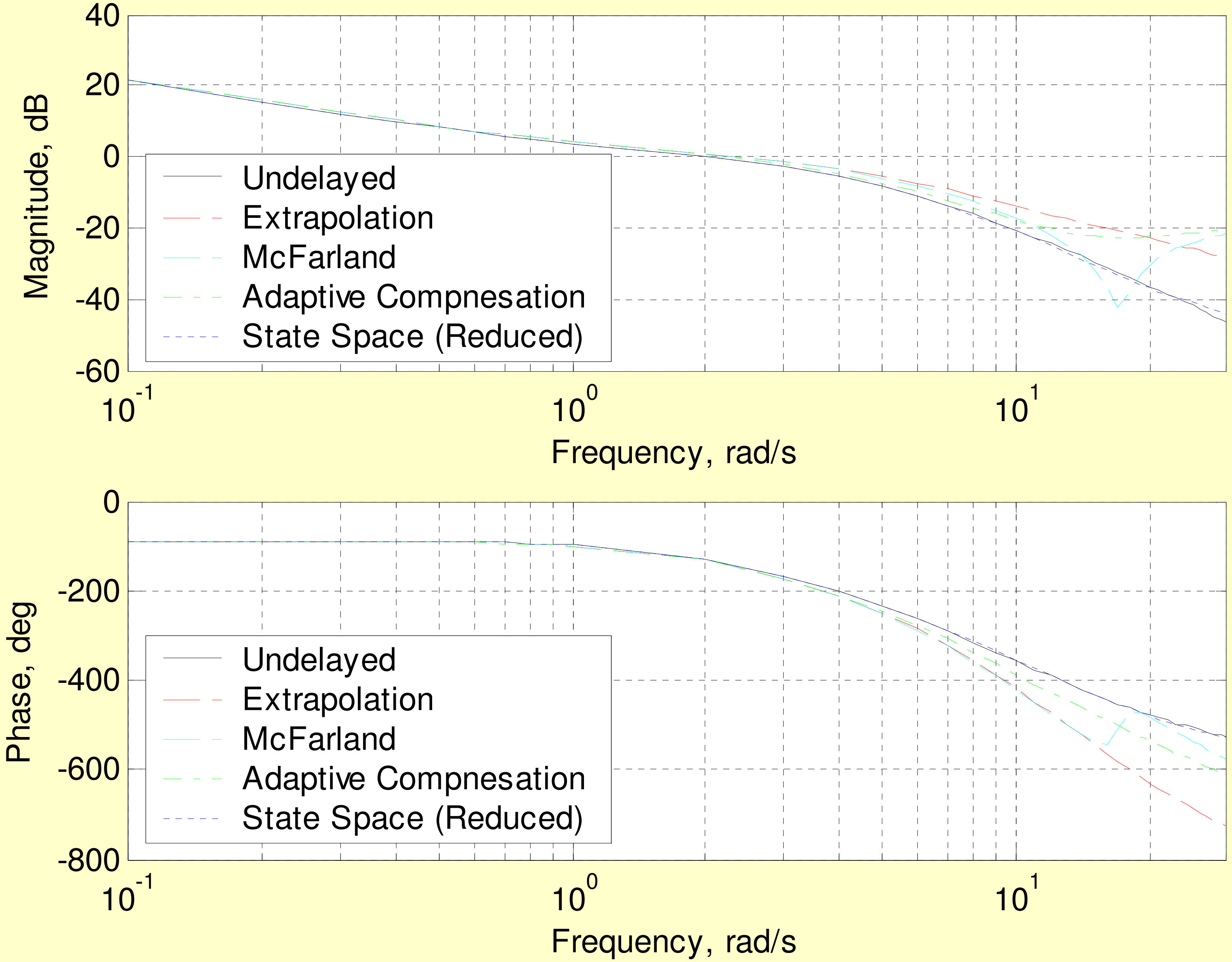
Power Spectral Density (PSD) - Example





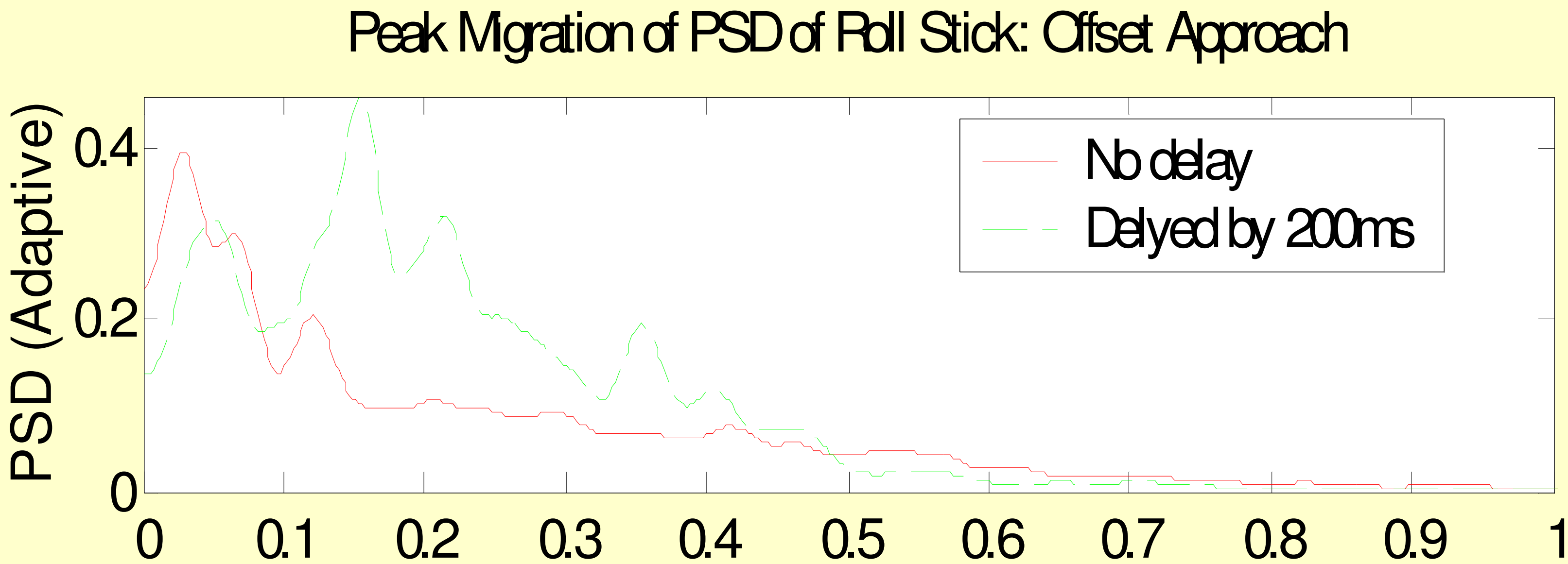

Step Responses of Different Compensation Systems for 0.2s Delay
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
1
2
3
4
5
6
7
8
9
10
t,
Undelayed
Delayed
Plain Extrapolation
McFarland
Adaptive
State Space

Frequency Response Comparison of Three Compensators for Compensating 0.2s Delay

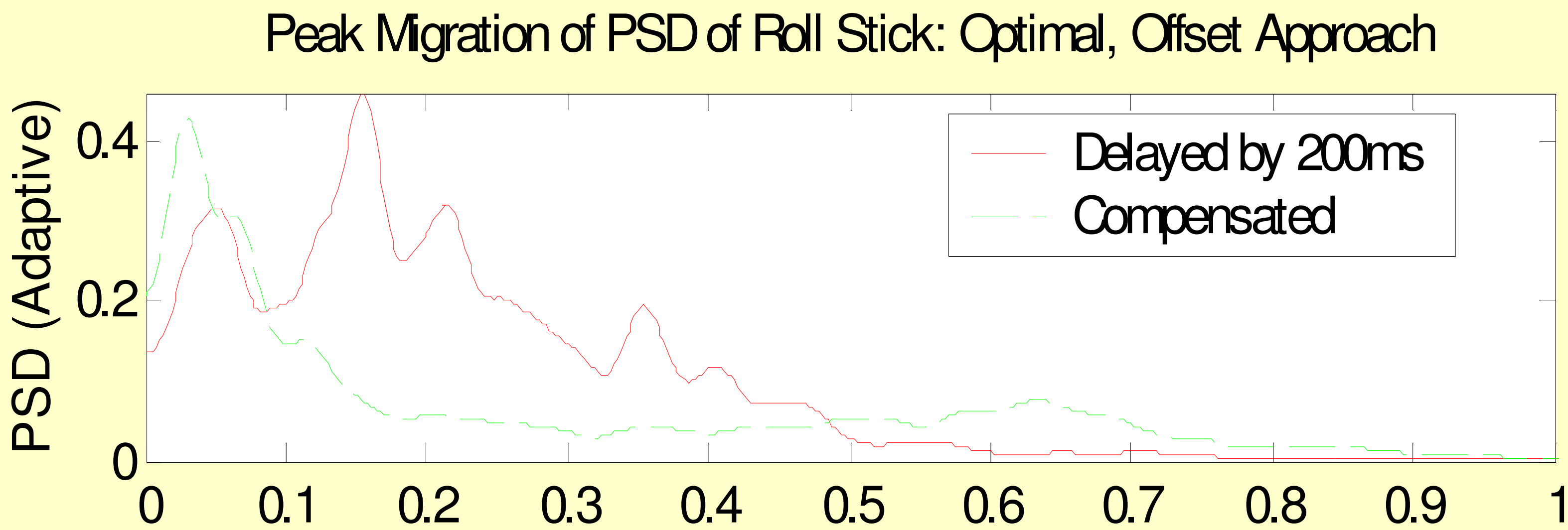


Error Measures for the Three Compensators

Compensators	td=0.1 s	td=0.2 s
McFarland filter	0.5973	12.051
Adaptive predictor	0.5819	7.3387
State space predictor	0.0649	1.9497

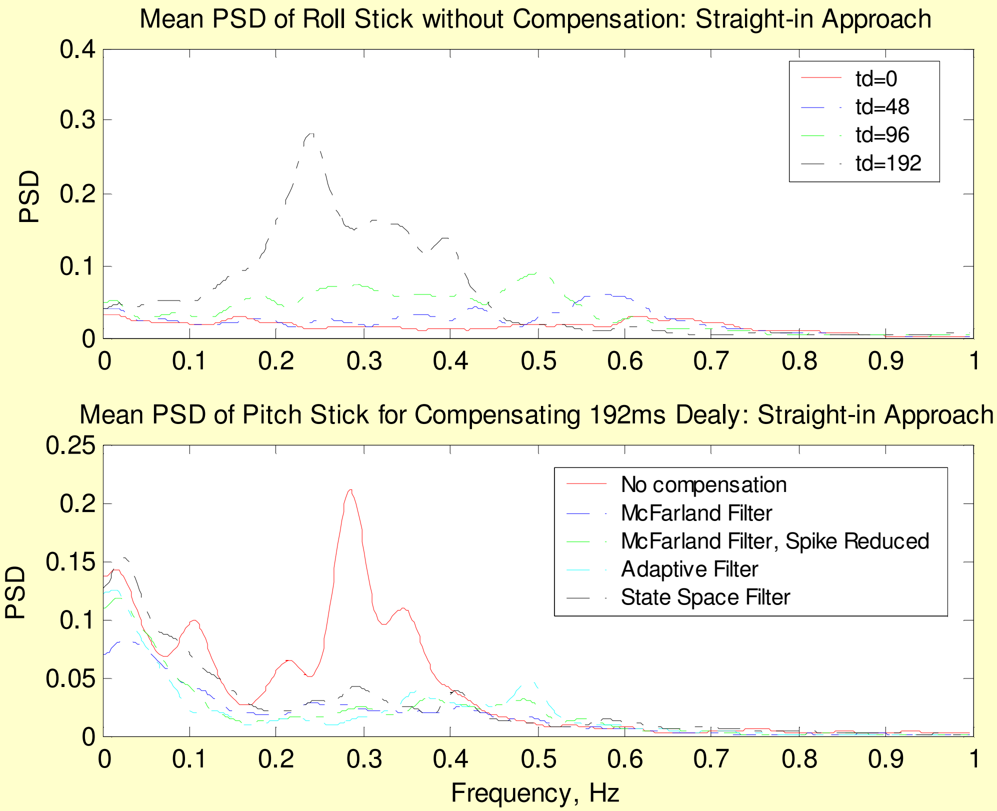


Peak Migration of PSD of Roll Stick: Offset Approach
PSD (Adaptive)
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
No delay
Delyed by 200ms



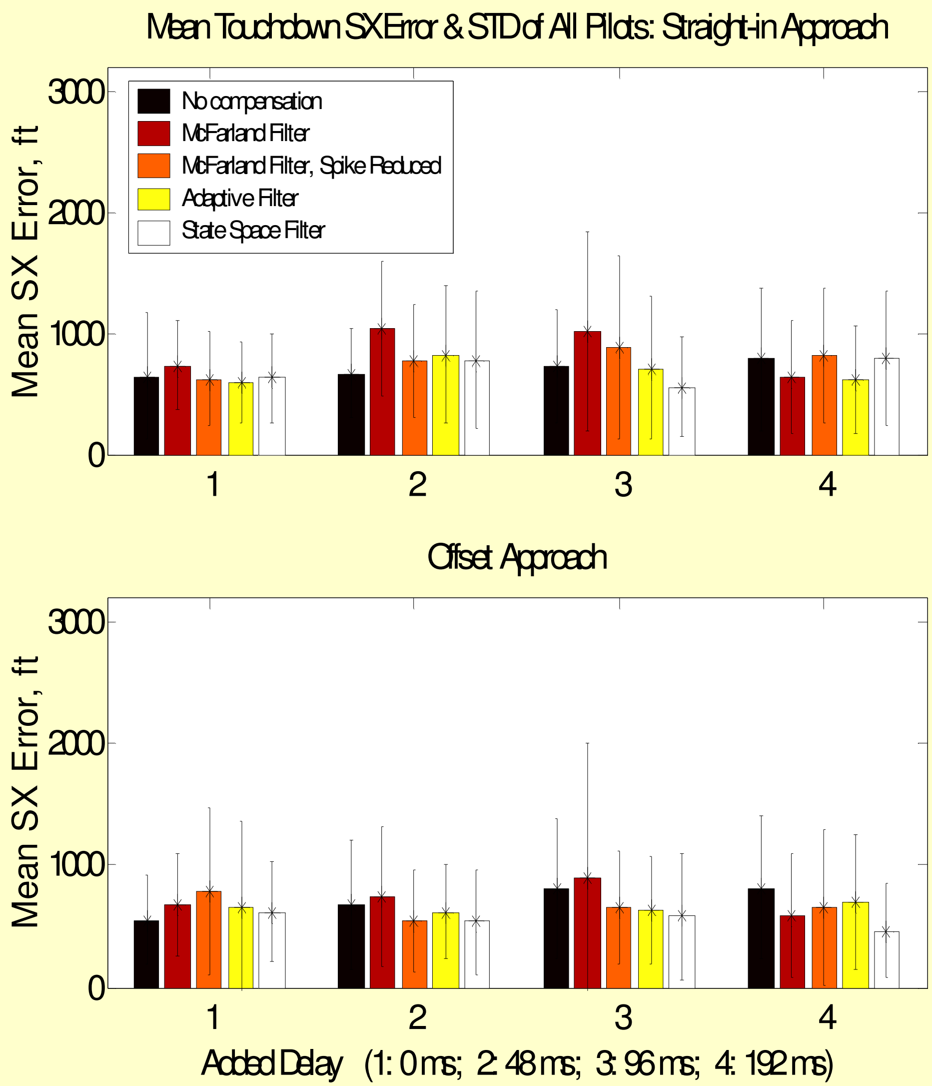
Peak Migration of PSD of Roll Stick: Optimal, Offset Approach
PSD (Adaptive)
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Delayed by 200ms
Compensated

PSD Change in Certain Intervals



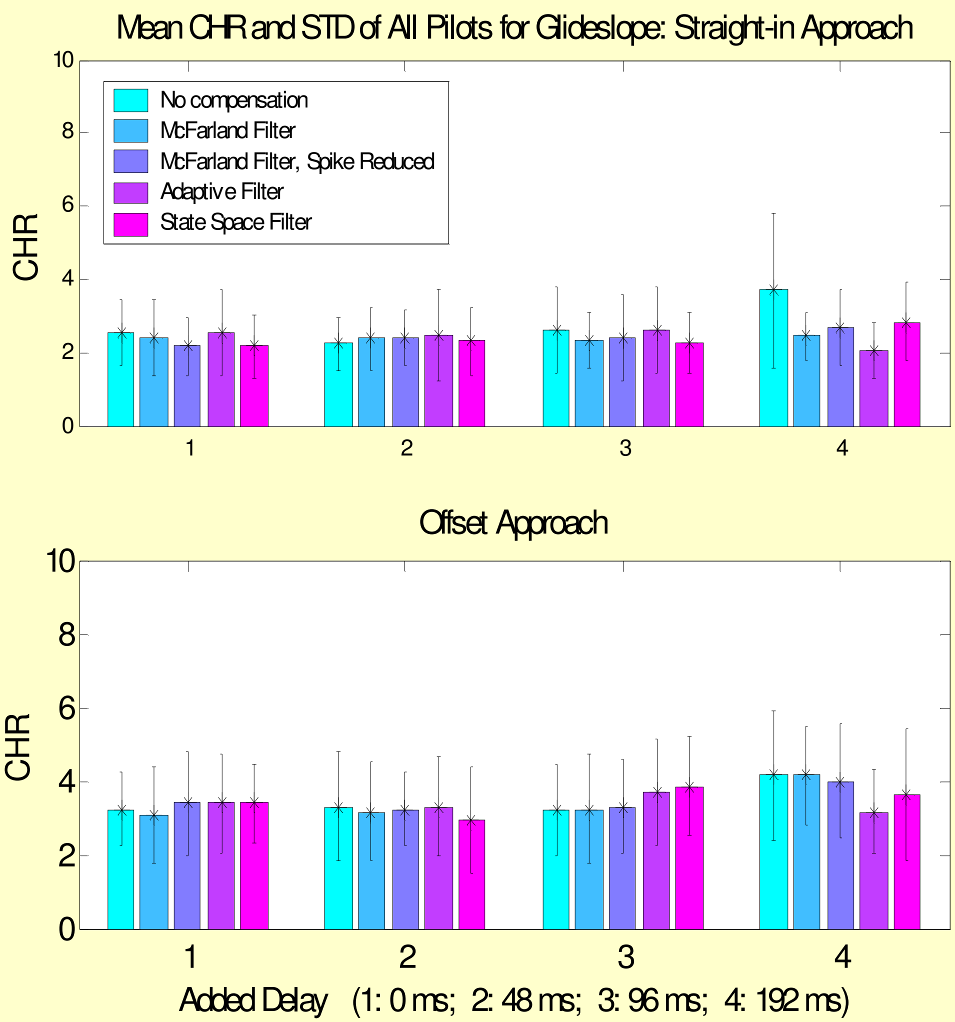
- 95% of PSD distributes in [0 1] Hz
- Delay & compensation affect some certain intervals narrower than [0 1] Hz
- Delay moves the highest PSD peak to higher frequencies, but compensation moves it back to lower frequencies.

Touchdown Error



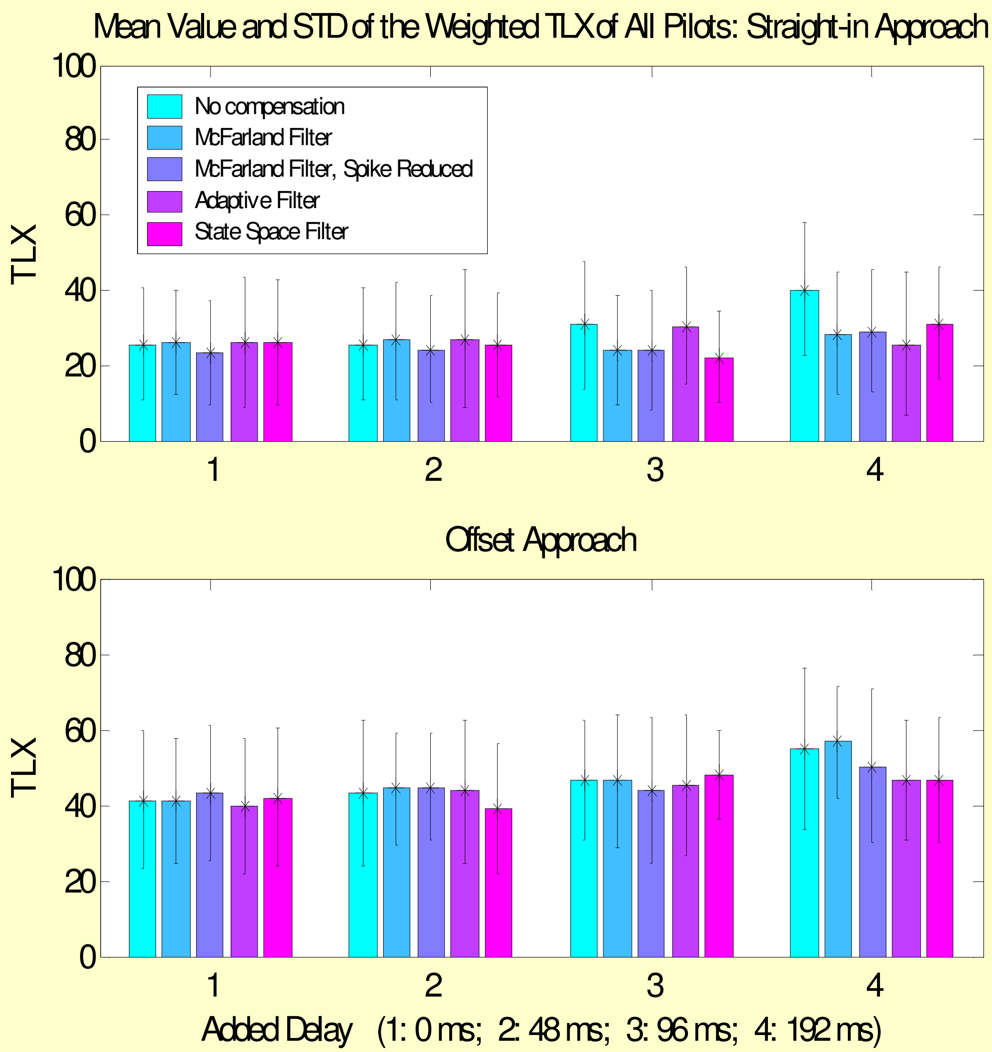
- MF shows decreased TDE only for 192 ms delay in both approaches
- AP: all except for 48 ms delay SA & 0 ms delay OA
- SS: all except for 48 & 192 ms delay SA, 0 ms OA
- Both AP and SS are better than MF
- MFR shows inconsistent difference from the MF

Handling Qualities (CHR)



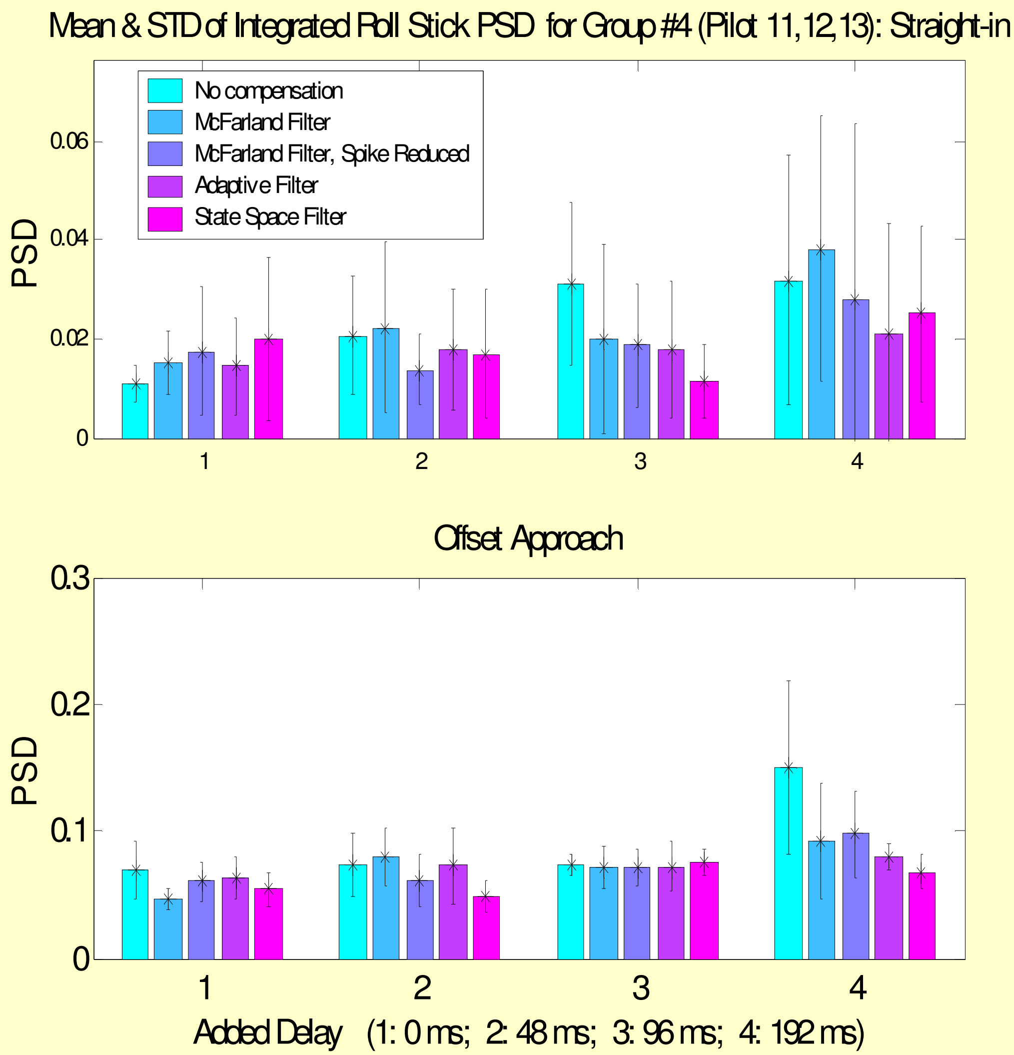
- CHR on GS& TD are close to each other
- MF shows decreased CHR for all except for 48 ms SA, 96 & 192 ms OA
- AP: only for 192 ms for both approaches
- SS: all except for 48 & 192 ms delay OA
- MF is better than AP, but worse than SS. However, Only MF showed full CHR
- MFR shows inconsistent difference from the MF

NASA Task Load Index (TLX)



- MF shows decreased TLX for 96 & 192 ms SA, 0 & 96 ms OA
- AP: for all except 192 ms SA, 0 & 48 ms OA
- SS: all except for 0 ms SA, 0 & 96 ms OA
- AP and SS are slightly better than MF
- MFR shows slight improvement over the MF

Integrated PSD of Control Sticks



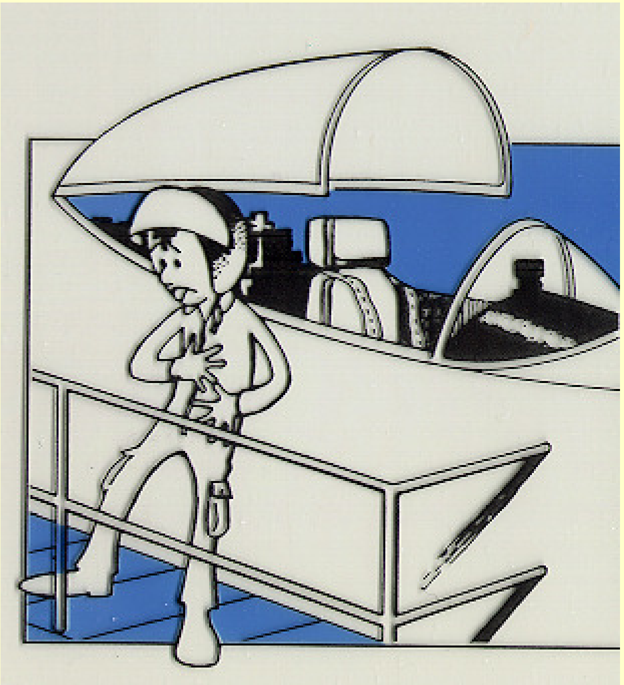
- MF shows decreased IPSD of roll stick for all except 0 & 48 ms SA, 48 ms OA
- AP: for all except 0 & 96 ms SA, 48 ms OA
- SS: all except for 0 ms SA
- AP & SS are better than MF, more significant decrease cases in IPSD of RS
- MFR shows inconsistent difference from the MF
- Results of PS IPSD is similar to the RS IPSD

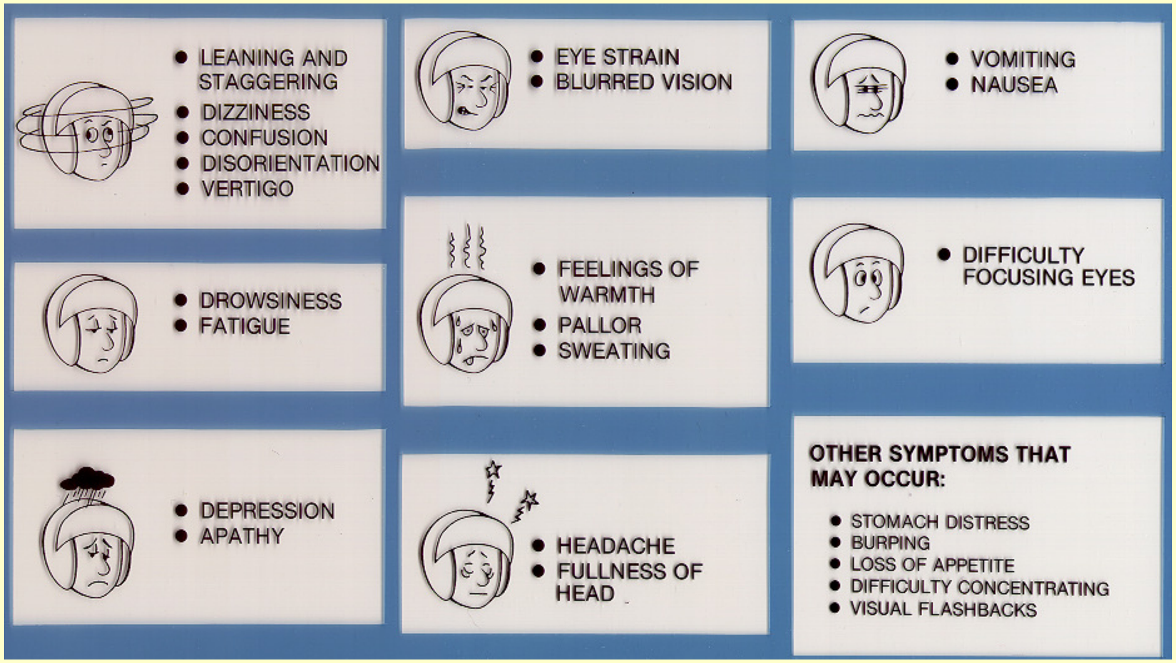
Delay Compensation Summary & Conclusions

- The Practical State Space Predictor gives the best results
- The adaptive filter is more robust than the McFarland
- References;
  - A comprehensive study of three delay compensation algorithms for flight simulators" " (with Liwen Guo, Jake Houck, Lon Kelly And Tom Wolters). AIAA paper no.AIAA 2005-5896, August, 2005
  - "New predictive filters for compensating the transport delay on a flight simulator" (with Liwen Guo, Jake Houck, Lon Kelly And Tom Wolters). AIAA Paper No. AIAA 04-5551, August 2004.
  - NASA/CR-2007-215095 & NASA/CR-2007 -2150956

Simulator Sickness

Simulator Sickness



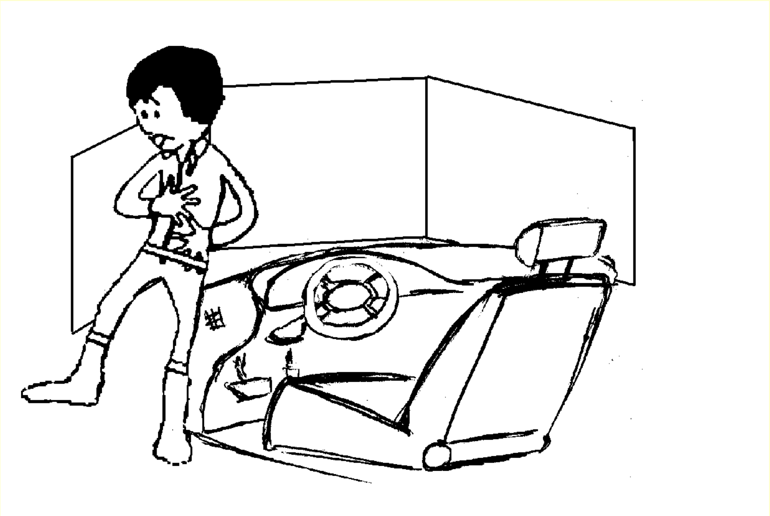


Sickness in simulator, but not in vehicle

Diverse set of symptoms

Some similar to motion sickness

Can occur during or after simulator sessions



What Seems to Induce the Most Sickness?

Types of Simulators

- Driving
- Helicopters
- Fighters
- Military Transports
- Civil Transports

Duration of Exposure

Maneuver Types

- High intensity dynamics
- proximity to the ground
- Large excursions
- High optical flow

Simulator Sickness Questionnaire

SSQ Symptom[a]	*Weight*		
	N	*O*	*D*
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		

source	simulator (Moving / Fixed base)	aircraft	incidents (%)	reference
Navy	2E7 (F)	F/A-18	31	Adapted from Lilienthal et.al.
	2F132 (F)	F/A-18	27	
	2F112 (?)	F-14	10	
	2F110 (M)	E-2C	47	
	2F64C (M)	SH-3	60	
	2F87F (M)	P-3C	39	
	2F117 (M)	CH-46	26	
	2F121 (M)	CH-53D	36	
	2F120 (F)	CH-53E	33	
		H53D	51	Kennedy
	2F120 (F)	CH-53E	62	Lilienthal&Merkle
	2E6 (F)	fighter	27 66 reported aftereffects	McGuiness et. al.
Army	2B33 (M)	AH-1	40	Gower
Coast Guard		HH-3F	47	Ungs
		HH-52		
		HH-65A		
		HU-25		

Percentage Reporting Simulator Sickness Symptoms

	Army				Navy			
Simulator:	2B33	2B38	2B40	2B42	2F64C	2F117	2F121	CH53E
Aircraft:	AH-1	UH-60	AH-64	TH-57C	SH3S	CH46E	CH53D	2F120
Asthenopia								
Eyestrain	37	35	24	27	37	26	21	23
Difficulty focus	9	19	6	7	24	6	6	10
Headache	14	22	14	7	31	12	9	17
Motion sickness								
Nausea	13	11	6	5	15	9	8	11
Dizzy, eyes open	2	3	1	4	9	3	1	6
Stomach awareness	10	16	5	1	14	7	2	4
Vertigo	1	3	1	3	10	3	1	4
Observations:	85	95	434	111	223	281	159	230

Authors	Barret & Nelson (1965)	Barret & Nelson (1966)	Barret & Nelson (1968)
Simulator Designation	Goodyear Aerospace I	Goodyear Aerospace II	Goodyear Aerospace I & II
% Incidence Sickness	64	72	
% Leaving Simulator	44	56	50
SYMPTOMS			
Queasiness			
Sweating	X	X	
Nausea	X	X	
Emesis	X		
Eyestrain		X	
Headache		X	
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			
Disorientation	X		
Visual Dysfunction			
Ataxia			
Dizziness	X	X	
Vertigo			

Iowa Driving Simulator

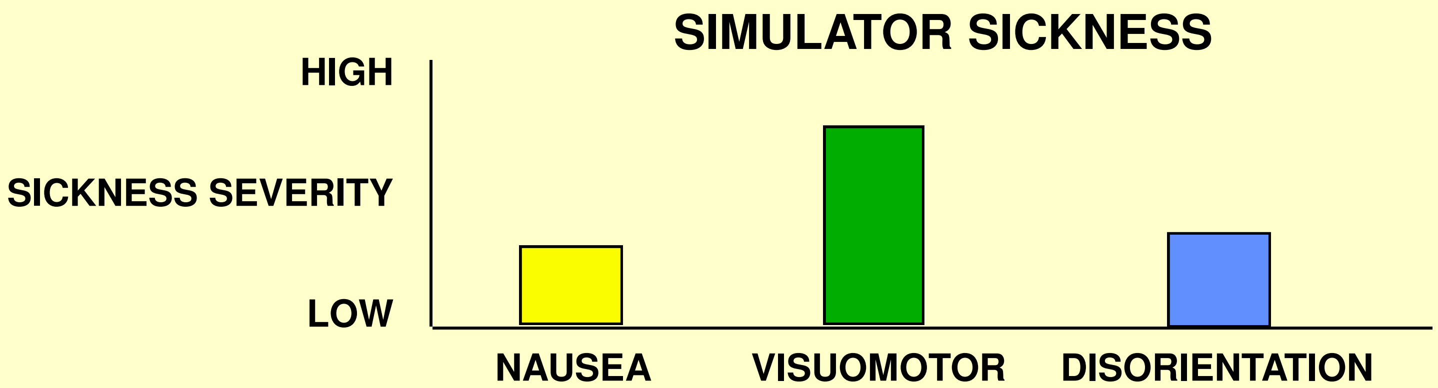
	Females				Males			
	Novice		Experienced		Novice		Experienced	
With motion	Finished	Quit	Finished	Quit	Finished	Quit	Finished	Quit
190^0 FOV	83%	17%	33%	67%	100%	0%	100%	0%
60^0 FOV	100%	0%	50%	50%	100%	0%	100%	0%
	92%	8%	42%	58%	100%	0%	100%	0%
Without motion	Finished	Quit	Finished	Quit	Finished	Quit	Finished	Quit
190^0 FOV	100%	0%	67%	33%	100%	0%	83%	17%
60^0 FOV	100%	0%	83%	17%	100%	0%	100%	0%
	100%	0%	75%	25%	100%	0%	92%	8%

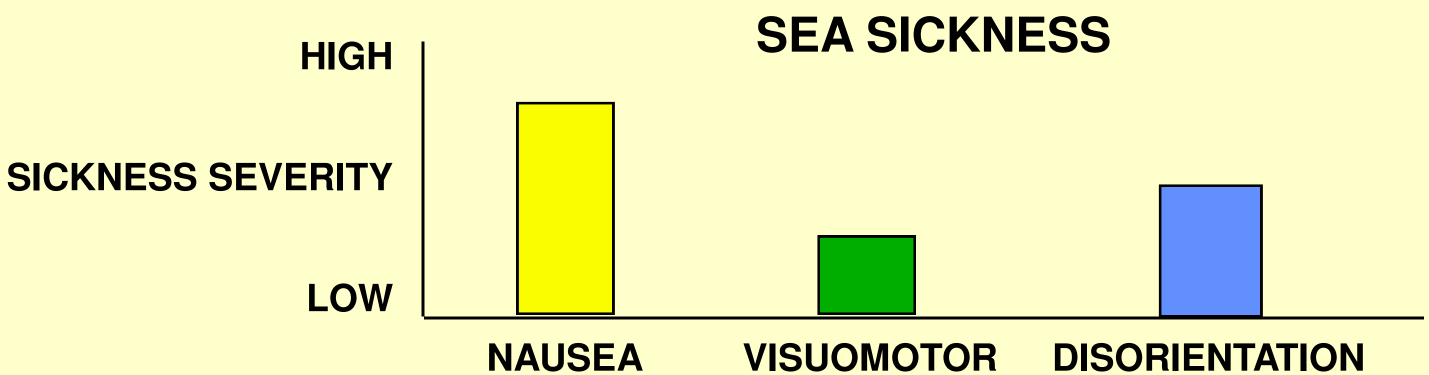
Iowa Driving Simulator (IDS)

SSQ Subscale Scores (mean values)

	Females	Males	Experienced	Novice
Nausea	35.97	21.86	47.70	10.34
Oculomotor	31.27	18.00	34.43	14.84
Disorientation	51.33	31.01	63.80	18.56

SIMULATOR SICKNESS SUBSCALES





Presumed Cause

Flight simulators present the pilot / driver with **different** relationships among visual, vestibular, and somatosensory stimuli.

Sensory Conflict Theory

- **These new relationships may produce sensory conflict**
  - Between or within sensory/perceptual modalities
  - Between what is expected and what is perceived (E.G. Perception of the local vertical).
- **Sensory systems respond to this conflict in a similar manner to poisoning**
- **The emphasis is on the sensory aspects of sickness**

Postural Instability Theory

- These new relationships make it difficult to maintain stable posture
- Prolonged postural instability leads to disruption of behavior and sickness
- The emphasis is on pilot simulator interaction

Advantages Of Postural Theory

- Immediate "Cause" Of Sickness Can Be Quantified
  - Postural Instability
- Accounts for Many Conflict Situations Which Are Not Provocative
- Suggests New Ways to Reduce Sickness
  - Passive Restraint

Potential Compromise Of Simulator Effectiveness

- **Training**
  - Retarded Learning Rates
  - Inappropriate Responses To Minimize Conflict
- **Decreased Usage And Confidence**
- **Altered Behavior**
- **Ground Safety**
  - Exiting Simulator
  - Driving
- **Flight Safety**
  - No Direct Evidence
  - Theory And Anecdotal Reports Suggest a Link

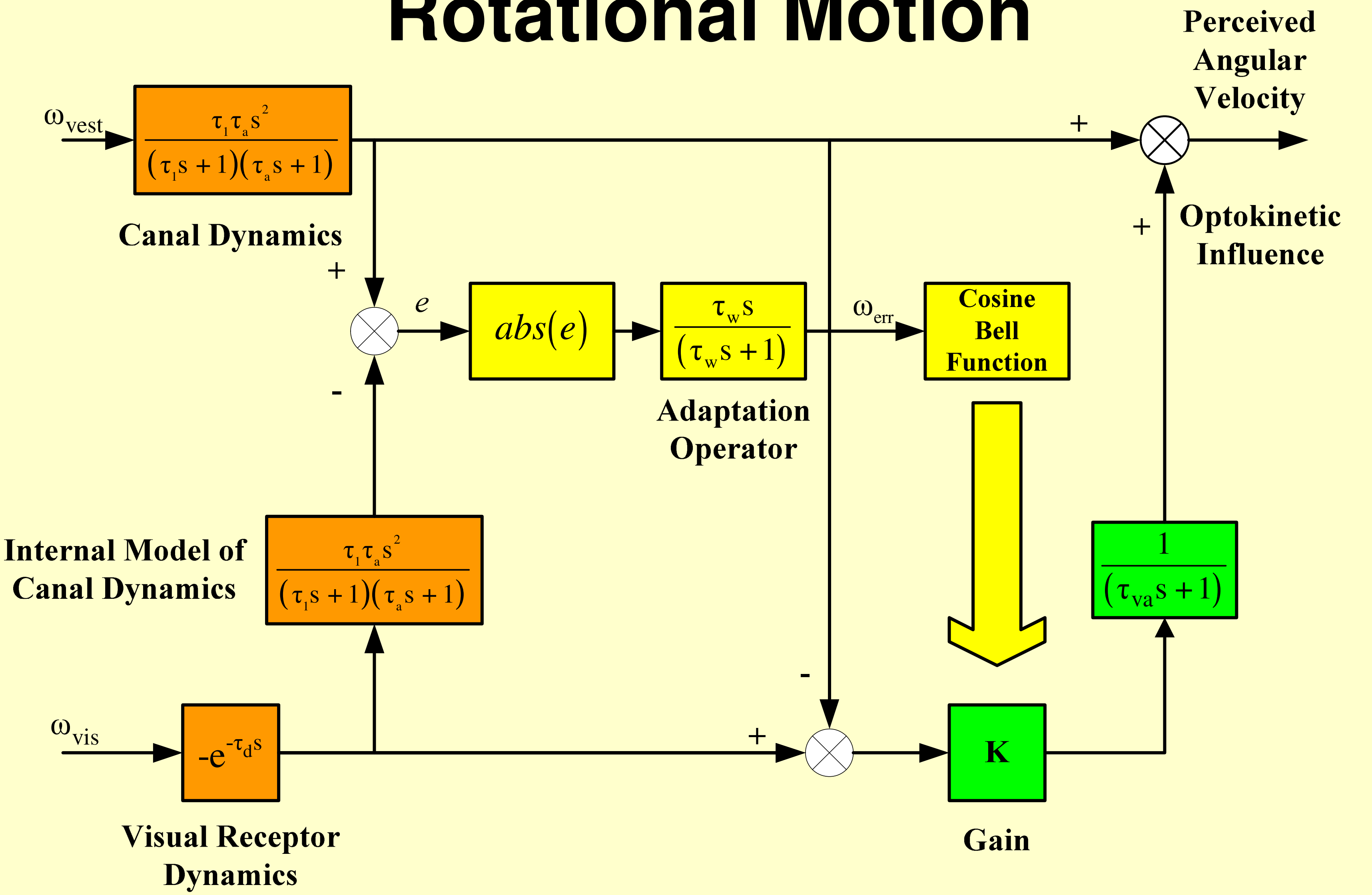
Measuring Simulator Sickness

- **Performance**. Does performance change with SS symptoms onset.
- **Workload**. Will workload increase with SS symptoms onset.
- **Simulator Sickness Questionnaire *(SSQ)*.** A set of 27 symptoms and a four-point Likert scale (none, slight, moderate, and severe).
- **Model operator behavior using PID methods**

Mitigation Techniques

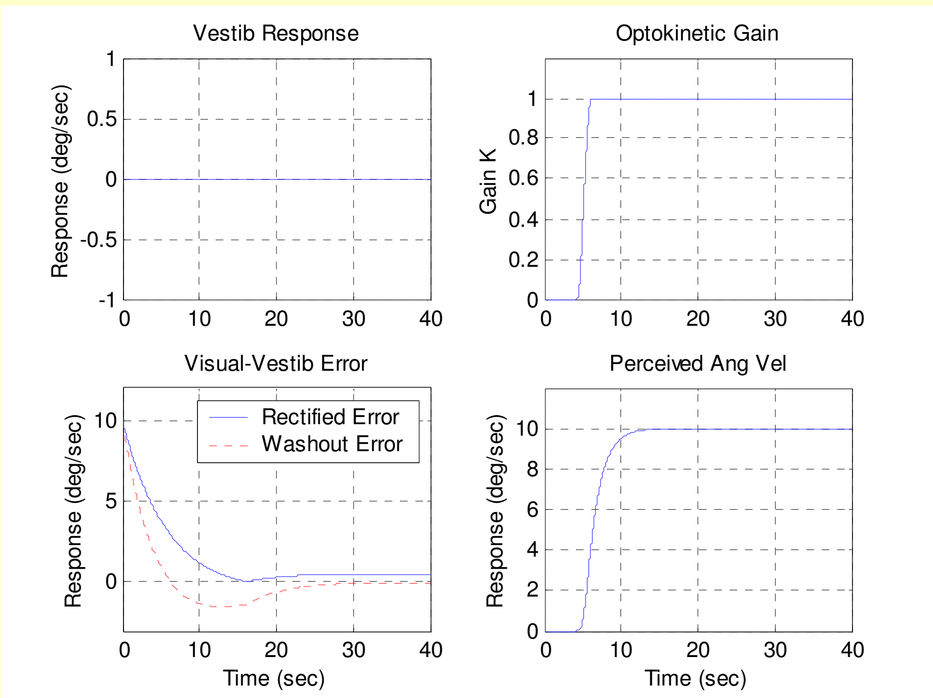
- Become knowledgeable of symptoms
- Use simulation freeze judiciously
- Use reset judiciously
- Avoid lengthy high intensity sessions
- Turn off visual system during entry or exit
- Avoid lengthy sessions of rapid maneuvering especially in close proximity to the ground
- Plan sessions with incrementally more intense maneuvers
- Avoid simulator use if subject has symptoms of illness
- Minimize aggressive head movements

Visual-Vestibular Model for Rotational Motion

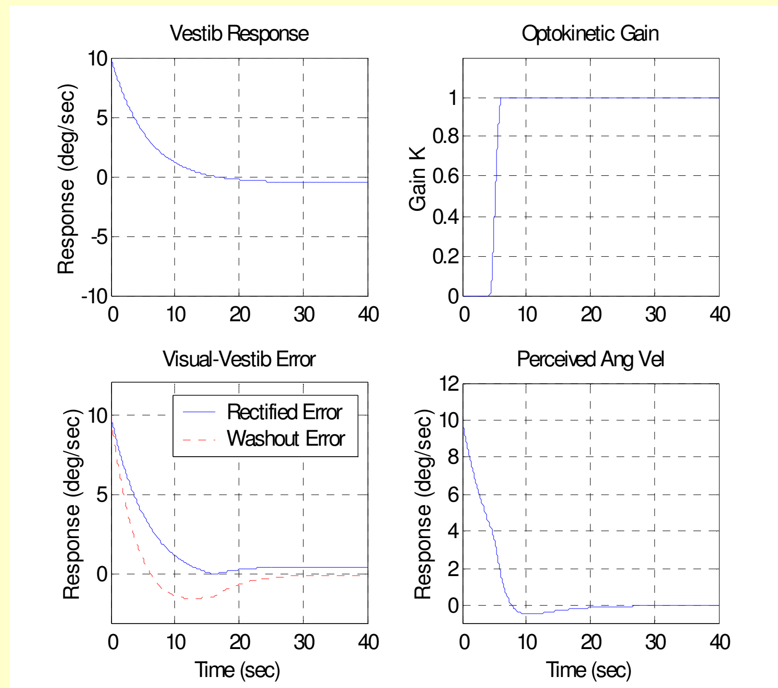


Rotational Perception Model Responses to Step Inputs

Visual Field Step Input

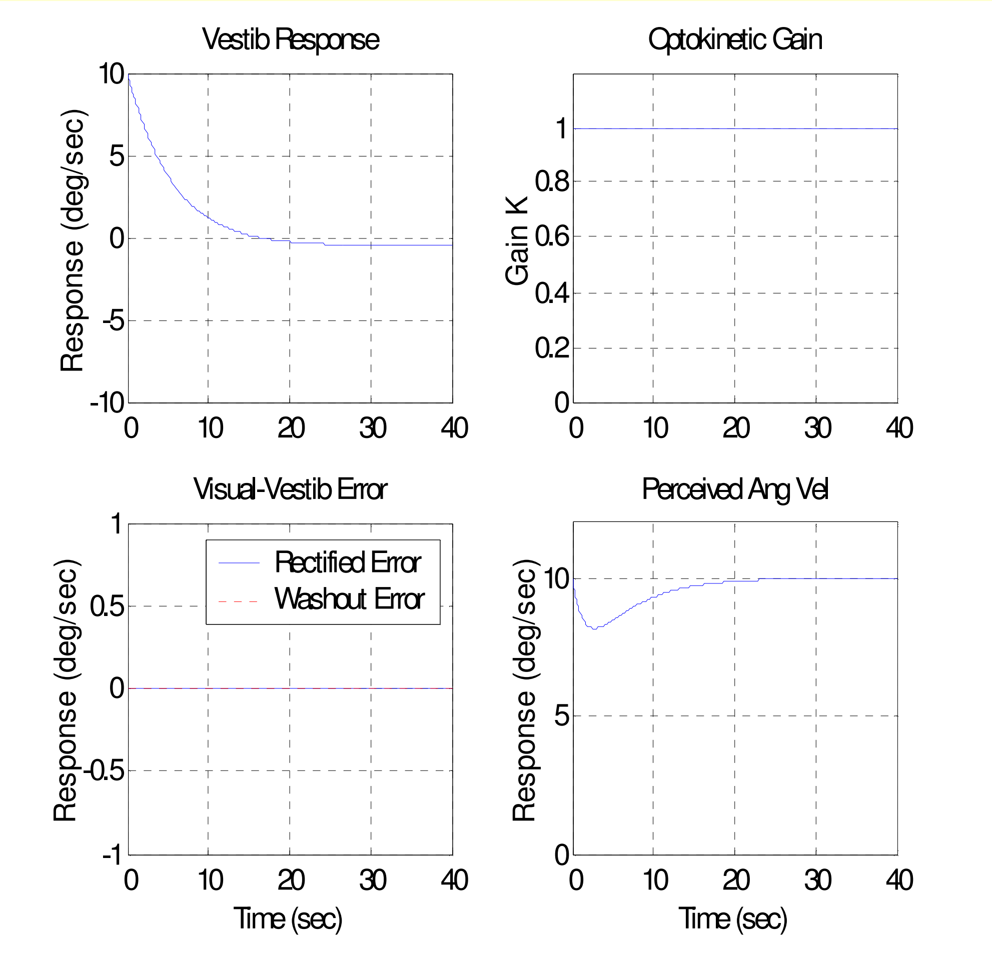


Vestibular Field Step Input

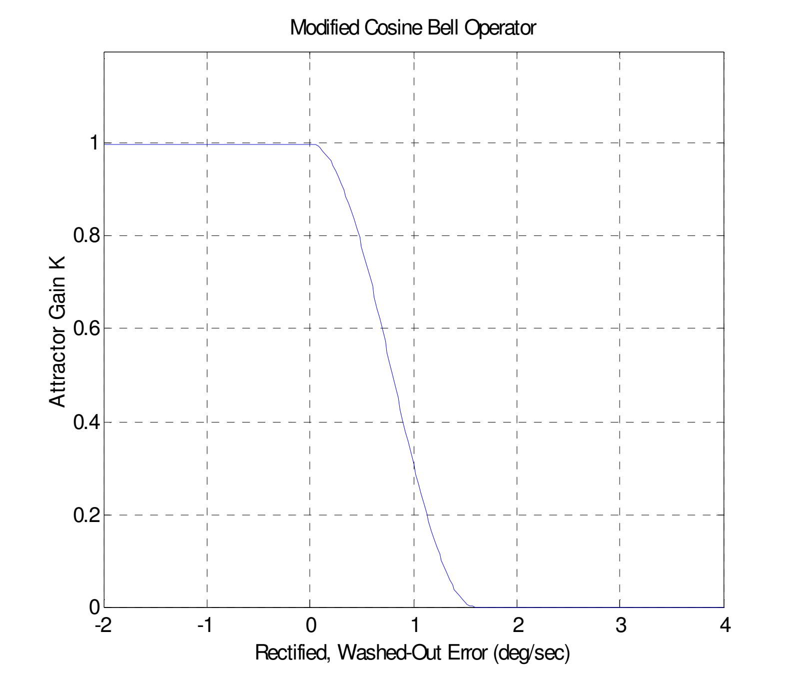


Rotational Perception Model Responses to Step Inputs

Confirming Visual and Vestibular Inputs

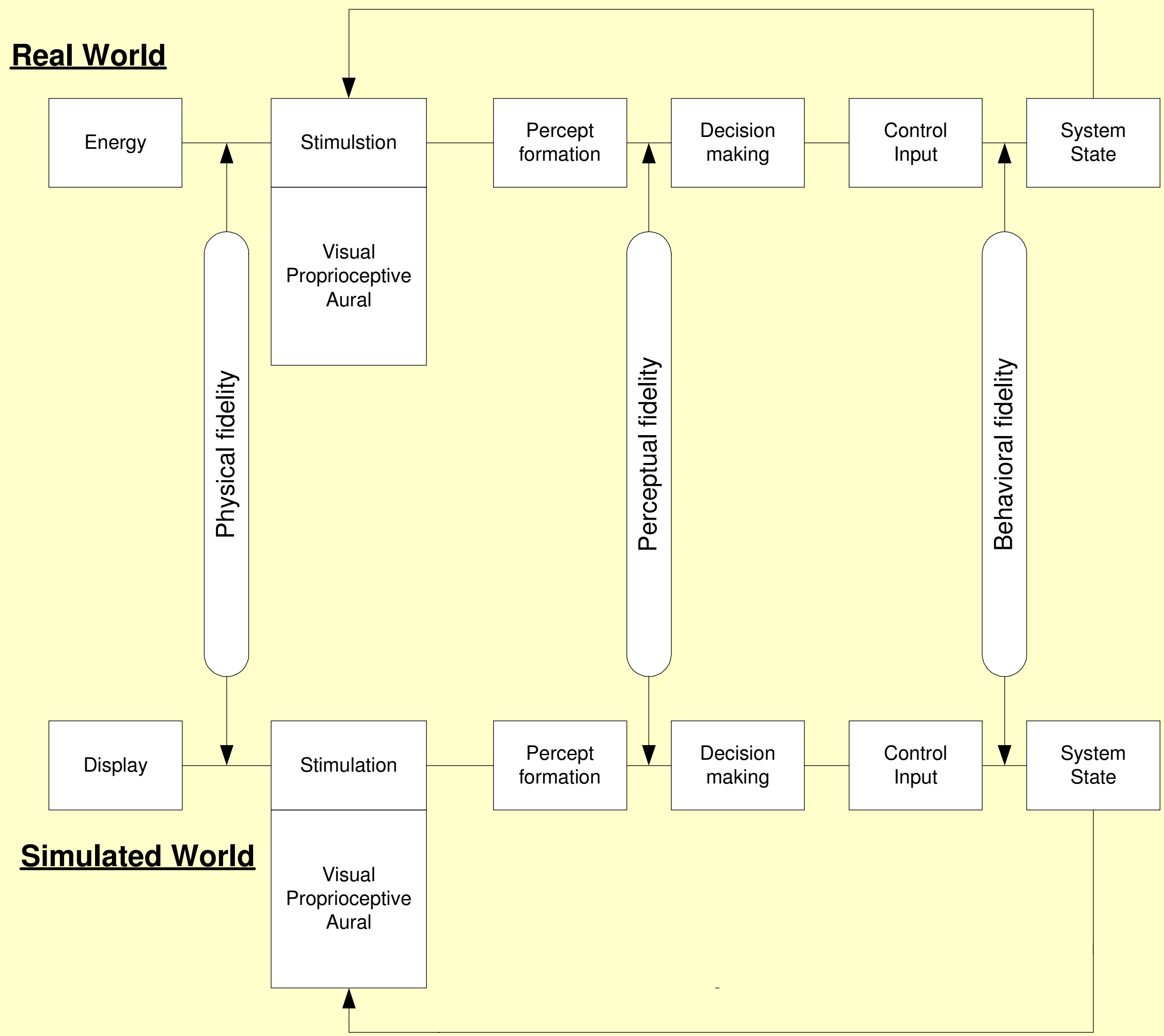


Modified Cosine Bell Operator



Evaluation of Human-in-the-Loop Systems

Simulation Fidelity Concept



Evaluation Methods

Subjective Methods

- Questionnaires
- Statistical Analysis

Quasi-quantitative Methods

- Cooper-Harper Rating
- NASA TLX
- Addition of Secondary Task

Quantitative Metrics

- Mean of error
- Standard deviation of error
- Correlation between control and state
- Total remnant energy
- Center frequency of remnant
- Standard deviation of remnant
- Center frequency of control
- Standard deviation of control
- Center frequency of error
- Standard deviation of error
- Physiological measures
  - Eye movements
  - Heart rate
  - Etc.

Advantages and Disadvantages

- Subjective:
  - Provides insight but lacks specificity
- Performance Measurement:
  - Quantitative, but results may be ambiguous because of expertise.
- Workload:
  - Quantitative or quasi-quantitative, but sensitivity of the metric may be an issue.

Evaluation Conclusions

- Behavior measurements are the most useful metrics.
- Quantitative metrics are preferred.
- Workload is a key indicator of behavior and is preferred.
- Many techniques are available for these analyses.

Integration Standards

- **Commercial airline simulator qualification**
  - 14CFR Part 60 App. A thru D (FAA)
  - ICAO
  - JAR FSTDA – Aeroplanes (Joint Aviation Reqirements)
  - JAR FSTDH - Helicopters
- Military standards vary but some use FAA
- AGARD Simulator testing
  - AR144 Motion
  - AR 159 Visual
  - CP408 Helicopter Visual and Motion

Minimizing Integration Errors

- No cookbooks or designers handbook available
- Thorough system design is necessary
  - Simulation Objectives
  - Task Analysis
  - Behavioral Objectives
  - Salient Cues Identification
  - Cue Implementation
- Engineering Data Compendium (Boff and Lincoln, 1988) Is a Key Resource

Conclusions

- Integration errors lead to problems such as
  - Poor operator performance & behavior
  - Simulator sickness
  - Reduced simulator effectiveness
  - Etc.
- Many integration errors may be remedied
  - By proper design practices
  - By compensation/mitigation techniques

Finito

Thanks for your attendance