

Lateral / Directional Feel System Characteristics Selection



International Collaborative Research in Handling Qualities for Requirements Definition and Validation

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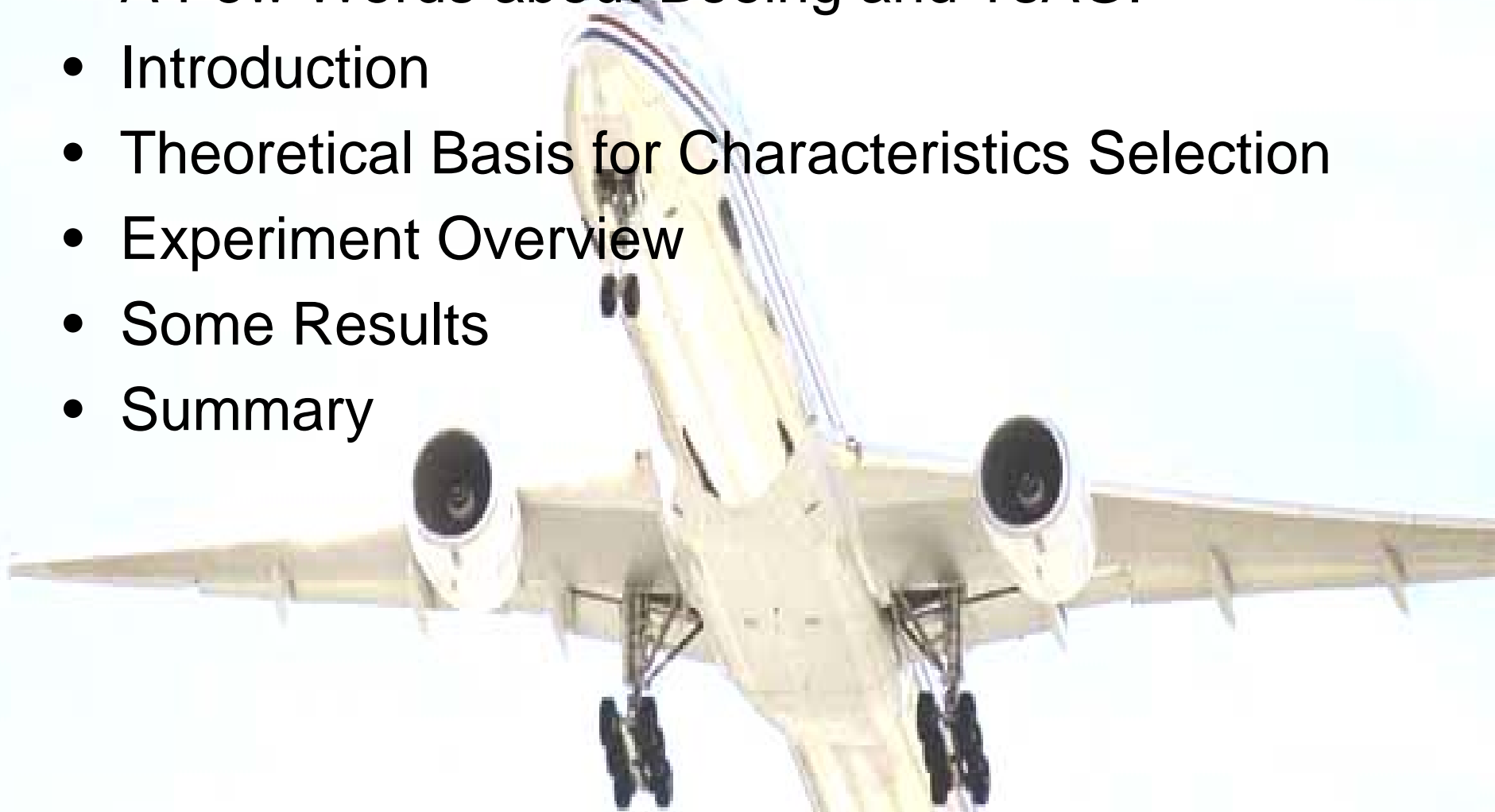
SAE Control & Guidance Systems Committee

Meeting 97, Lake Tahoe, NV

3 March, 2006

Agenda

- A Few Words about Boeing and TsAGI
- Introduction
- Theoretical Basis for Characteristics Selection
- Experiment Overview
- Some Results
- Summary



Boeing + TsAGI Collaboration

Why?

- **Technical Data:**
 - Can we learn anything from this relationship?
- **Collaboration Experiment:**
 - How could this kind of relationship work?
- **Cultural Exercise:**
 - Do we see technical problems and solutions in the same way?

Zhukovsky, Russia



Zhukovksy, Russia



SPAR
А НИЗКИЕ ЦЕНЫ!
ИВЕРСАМ 300 м

НАРКОМВОД
улица
↑ ГАГАРИНА
улица
КЕЛДЫША
улица →

↑ инко
8,5 км
ХЛАДОТЕРМИНАЛ
Нижневод. 22-й т. 777-12-21

Zhukovsky, Russia



TsAGI and Zhukovskiy



**One of the Russian
“Secret Cities”**



**Home of
Everything Aeronautical
in Russia**

TsAGI's Transport Simulations



FS-102

Formerly Buran Space Shuttle

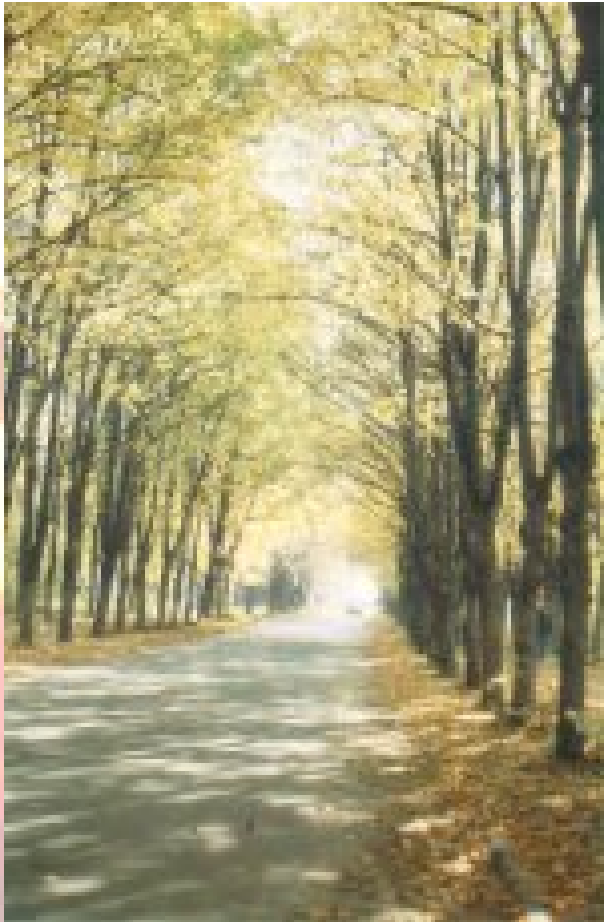
Gromov Flight Research Institute



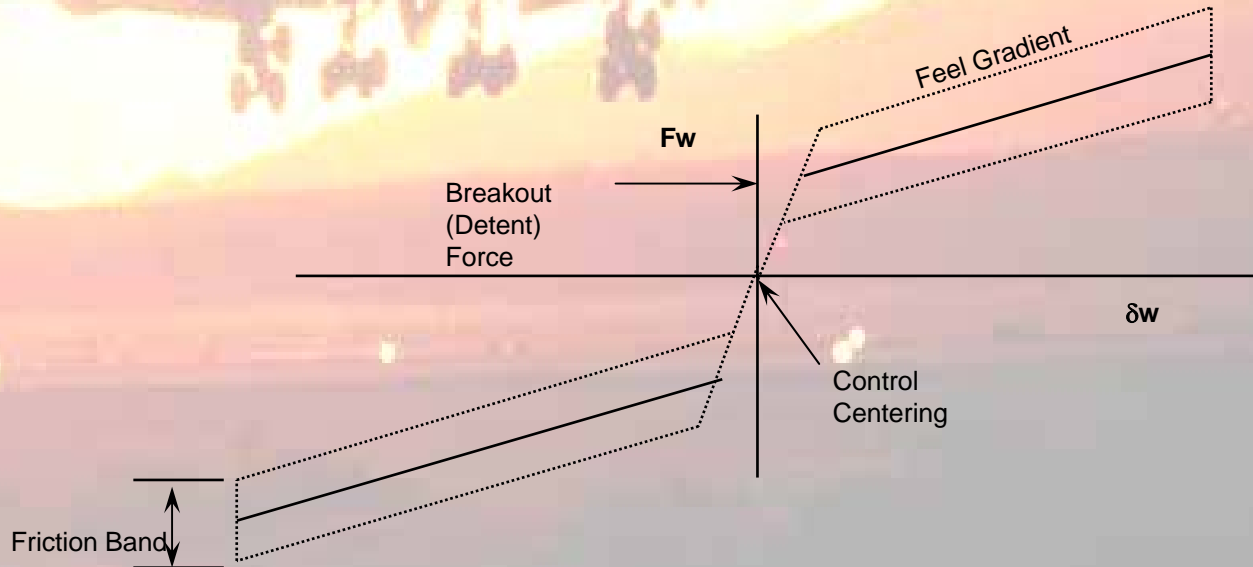
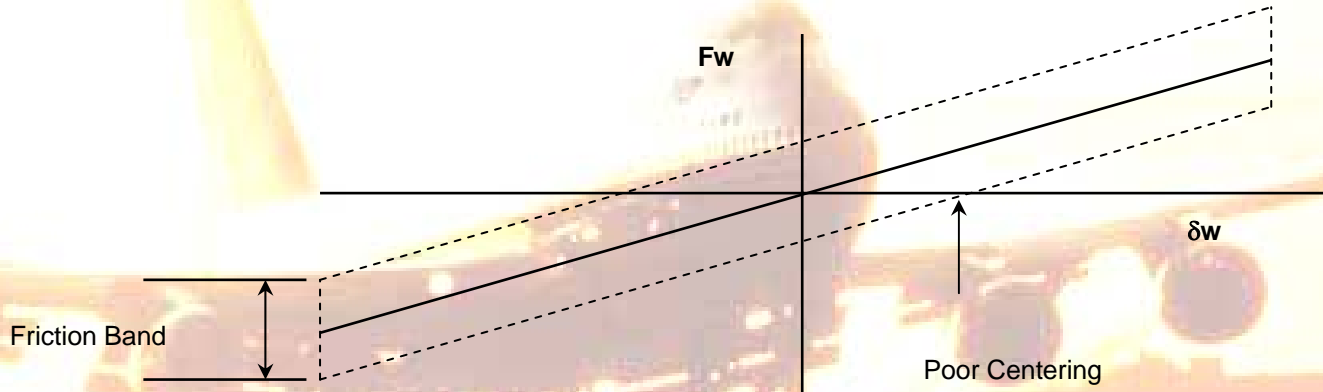
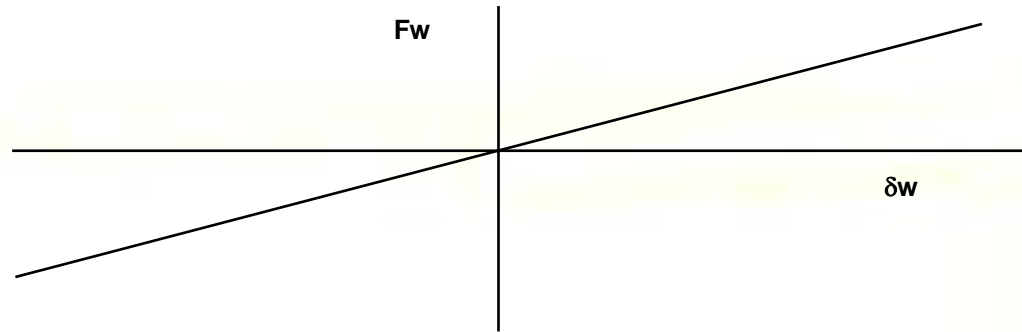
Main runway is
~18,000 Feet Long!



In-Flight Simulation



Some Definitions



Theoretical Approach to Feel System Characteristics

- Russian Philosophy
 - Should not conduct experiments until theoretical basis is established
 - Experiments then populate the theory with data
- For Feel System Characteristics

Forces/Displacements

- Function of Airplane dynamic response
- Function of control inceptor type

Dynamic Response Characteristics

- Independent of airplane dynamic response
- Independent of control inceptor type

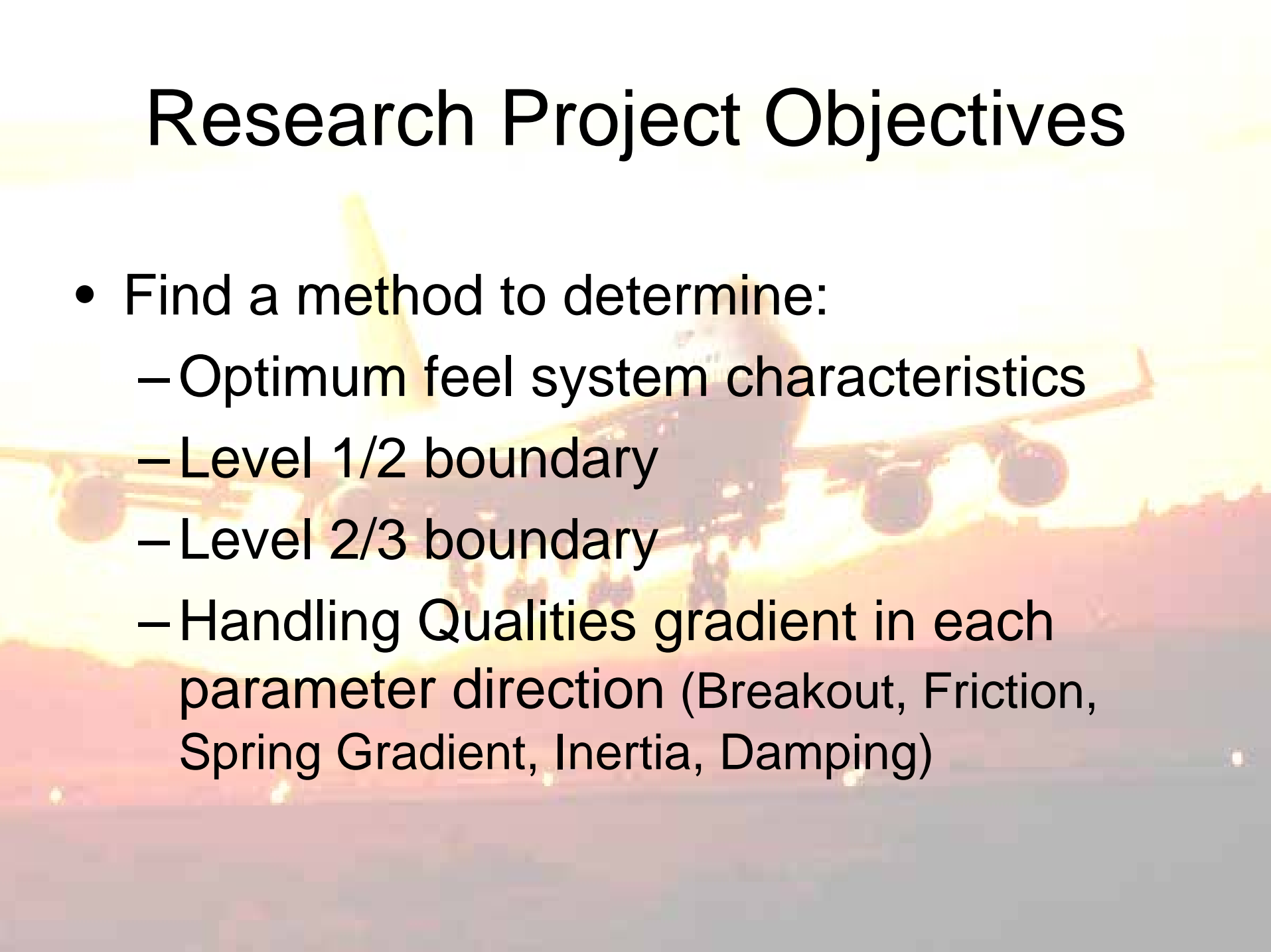
Wheel Systems



Standards for Wheel Feel System Characteristics

- FAR/JAR requirements for maximum total force
- MIL-HDBK gives only general guidance for static force characteristics
- No guidance on dynamic characteristics
- No guidance on relationship between spring gradient, breakout, friction, etc. in terms of handling qualities

Research Project Objectives

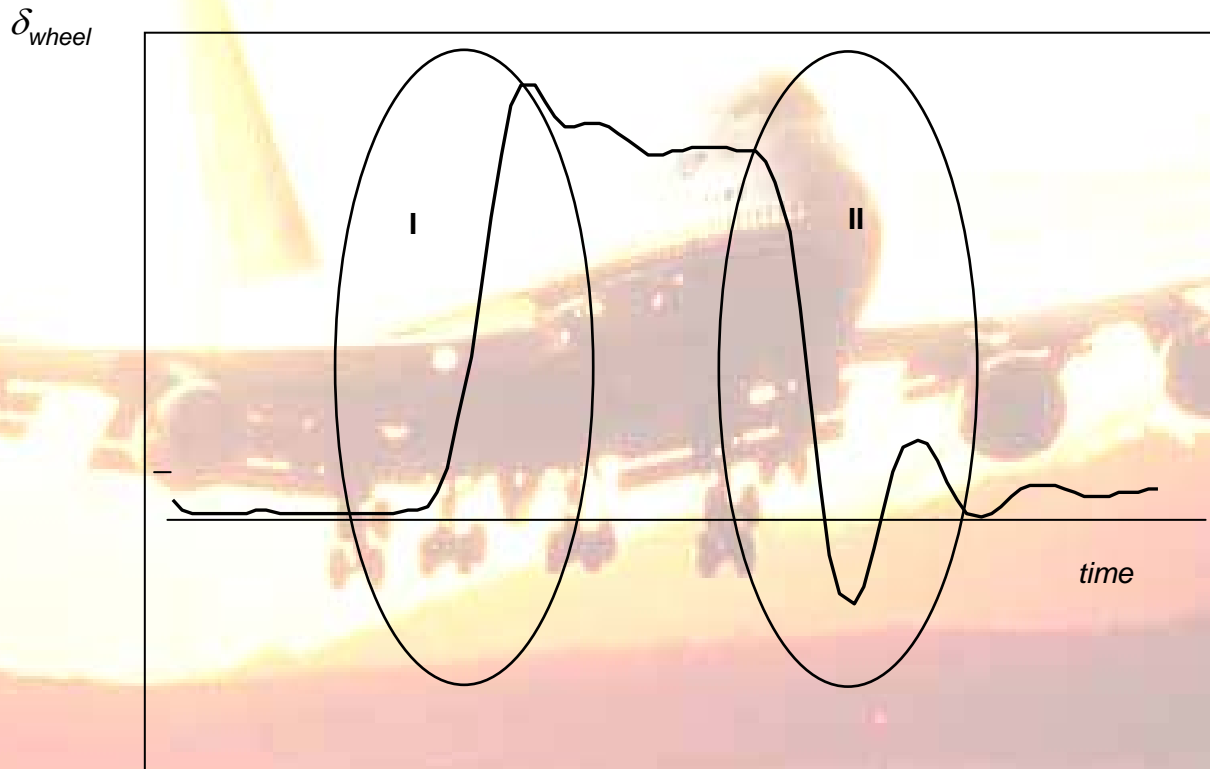


- Find a method to determine:
 - Optimum feel system characteristics
 - Level 1/2 boundary
 - Level 2/3 boundary
 - Handling Qualities gradient in each parameter direction (Breakout, Friction, Spring Gradient, Inertia, Damping)

Fundamental Principles of Theoretical Construct

- Effect of Feel System Characteristics on Handling Qualities depends on:
 - Applied Pilot Force Levels (F)
 - Wheel Displacements (δ)
 - Feel System Overshooting (Δ)
 - Control Inceptor Response Time (t_r)
- There is an optimum combination of these
- Aircraft state parameters (ϕ , p , etc.) are independent of control sensitivity, manipulator characteristics and aircraft dynamics
- When these parameters deviate from optimum, Handling Qualities degrade (approximately) according to Weber-Fechner Psychophysical laws

Careful Evaluation of Pilot Inputs to Understand Source of Comments



Region I – Important for pilot's impression of manipulator forces

Region II – Important for pilot's impression of manipulator dynamic characteristics

Mathematics of the Approach

- Optimum Feel System Characteristics

$$\min_{F_{\delta}, F_{br}, \dots} J(\bar{F} - F_*, \bar{\delta} - \delta_*, \bar{\Delta} - \Delta_*, \bar{t}_r - t_{r*})$$

- Handling Qualities Decrement

$$\Delta PR = k_F (\bar{F} - F_*)^2 + k_{\delta} (\bar{\delta} - \delta_*)^2 + k_{\Delta} (\bar{\Delta} - \Delta_*)^2 + k_{t_r} (\bar{t}_r - t_{r*})^2$$

- Applied Forces and Displacements

$$\bar{\delta} = \delta_p p_* \quad \bar{F} = F_{\delta} \bar{\delta} + F_{br} + F_{fr}$$

- Overshoot and Response Time

$$(m + m_{pilot}) \ddot{\delta} + F_{\dot{\delta}} \dot{\delta} + F_{\delta} + \cancel{F_{fr}}^0 \operatorname{sgn}(\dot{\delta}) + \cancel{F_{br}}^0 \operatorname{sgn}(\delta) = F_{pilot}$$

Accommodating Nonlinear Elements

$$(m + m_{pilot})\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta}\delta + F_{fr} \operatorname{sgn} \dot{\delta} + F_{br} \operatorname{sgn} \delta = 0$$

Recasting in terms of non-dimensional time and non-dimensional deflection

By setting:

$$\tau = \sqrt{\frac{F_{\delta}}{m + m_{pilot}}} \cdot t, \quad \tilde{\delta} = \frac{\delta}{\delta_0}$$

5 parameters + limb mass
vs.
3 parameters

Gives:

$$\tilde{\delta}'' + 2\zeta\tilde{\delta}' + \tilde{\delta} + \tilde{F}_{br} \operatorname{sgn} \tilde{\delta}' + \tilde{F}_{fr} \operatorname{sgn} \tilde{\delta} = 0$$

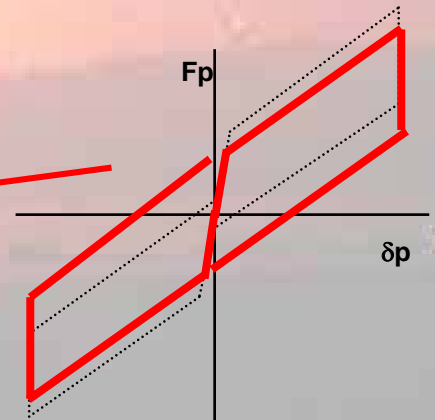
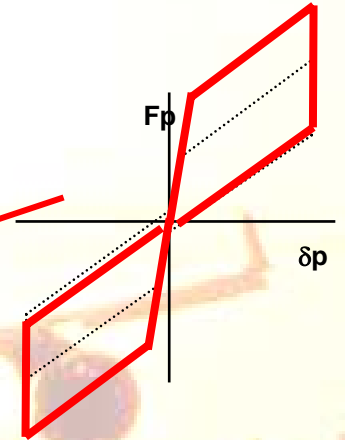
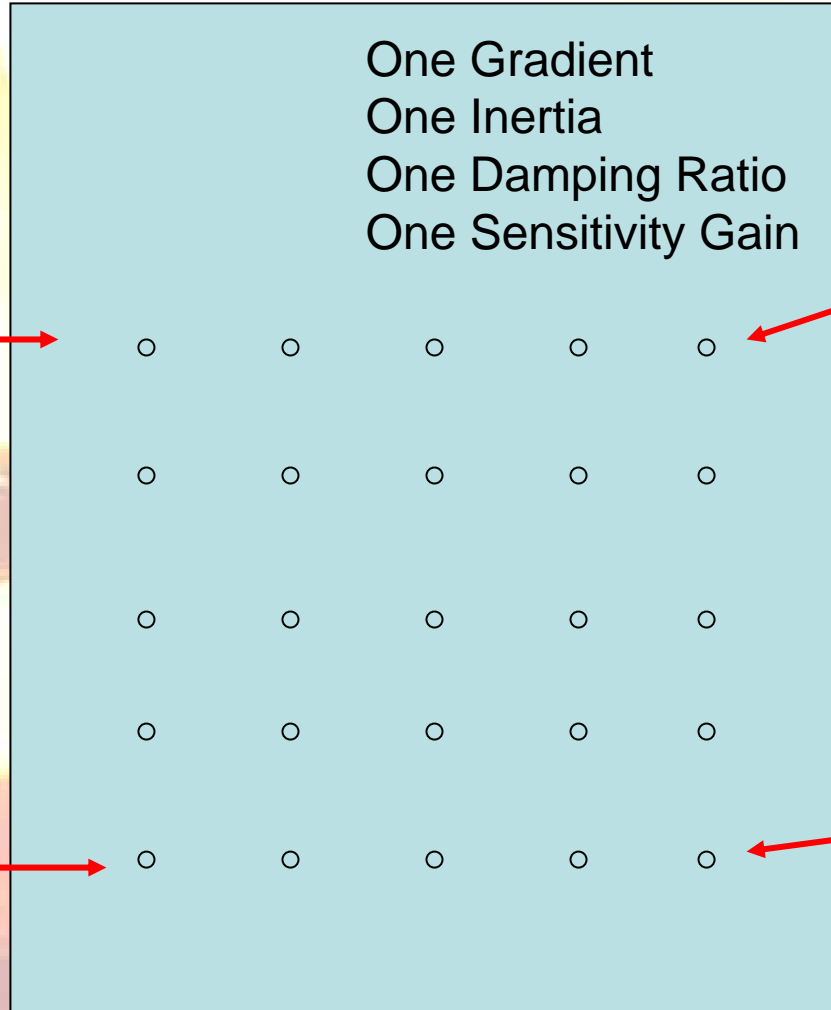
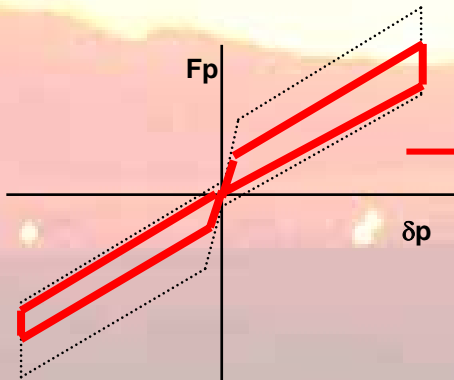
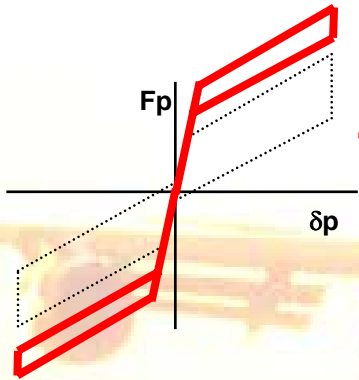
$$(\tilde{\delta}(0) = 1, \tilde{\delta}'(0) = 0)$$

where

$$\zeta = \frac{F_{\dot{\delta}}}{2\sqrt{F_{\delta}(m + m_{pilot})}}, \quad \tilde{F}_{br} = \frac{F_{br}}{F_{\delta}\delta_0}, \quad \tilde{F}_{fr} = \frac{F_{fr}}{F_{\delta}\delta_0}$$

Making sense of the map

F_{br}/F_*



F_{fr}/F_*

Wheel Centering

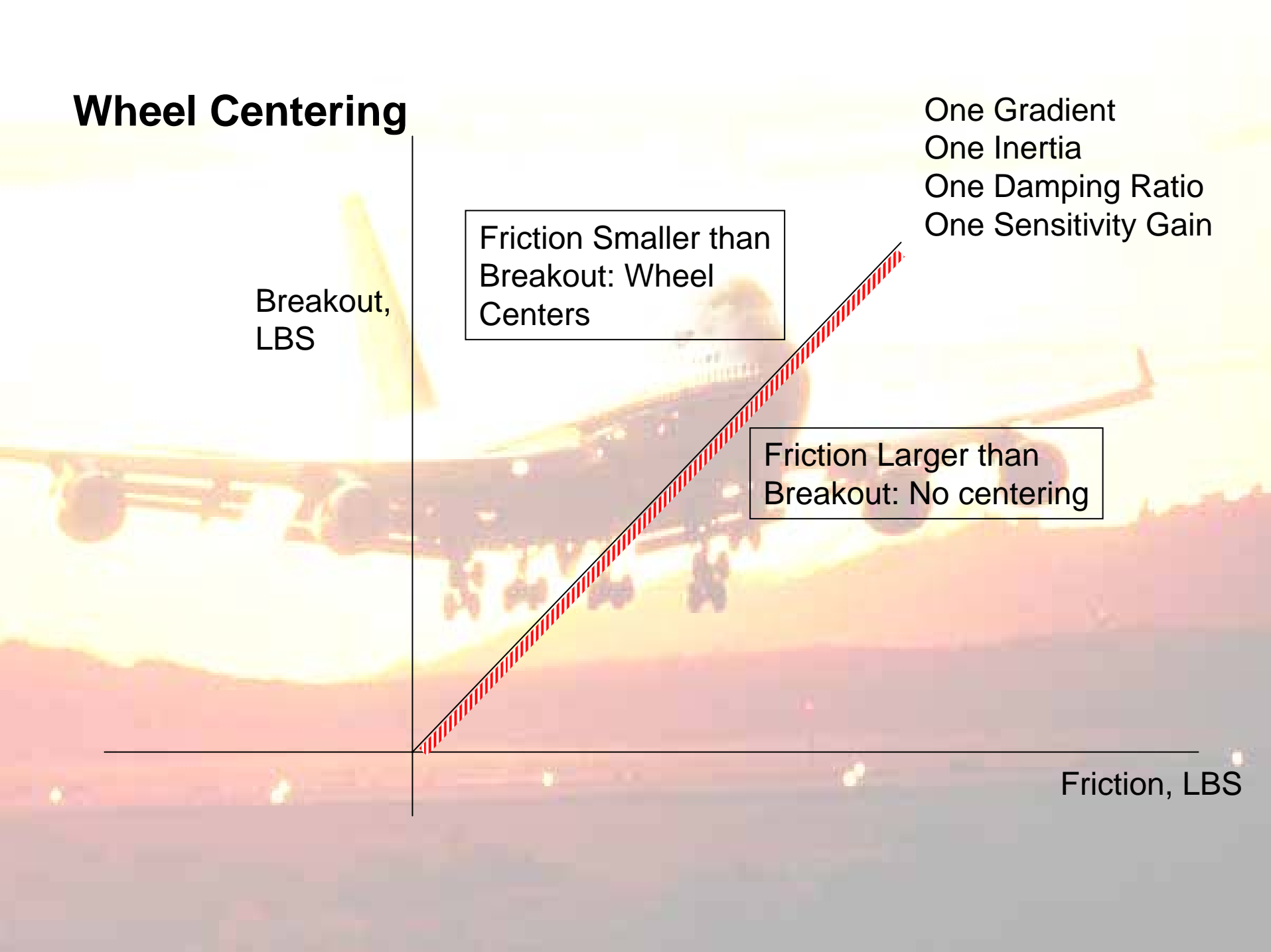
Breakout,
LBS

Friction Smaller than
Breakout: Wheel
Centers

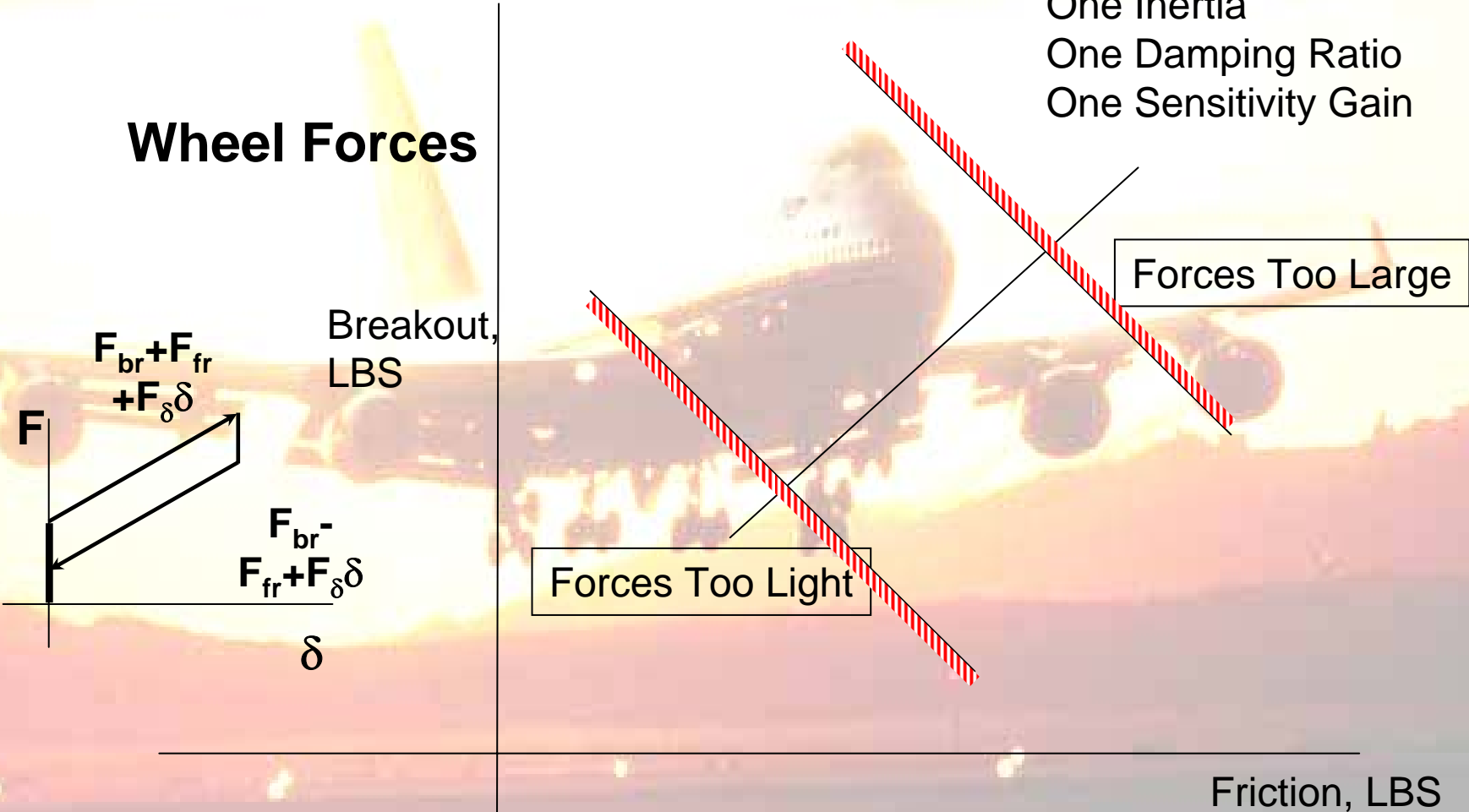
Friction Larger than
Breakout: No centering

One Gradient
One Inertia
One Damping Ratio
One Sensitivity Gain

Friction, LBS



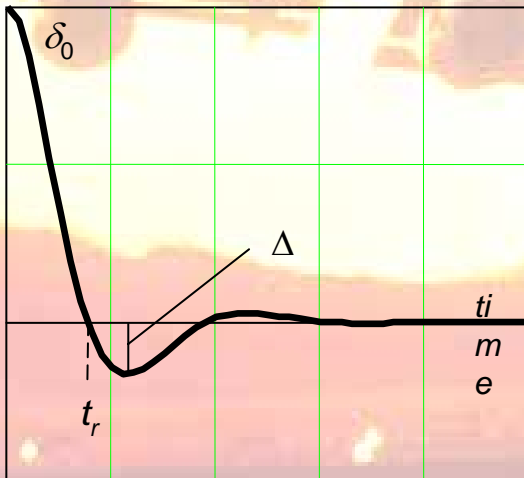
Wheel Forces



$$(m + m_{pilot})\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta} + F_{fr} \operatorname{sgn}(\dot{\delta}) + F_{br} \operatorname{sgn}(\delta) = F_{pilot}$$

Response Time

Breakout, LBS



Wheel Returns Too Quickly

One Gradient
One Inertia
One Damping Ratio
One Sensitivity Gain

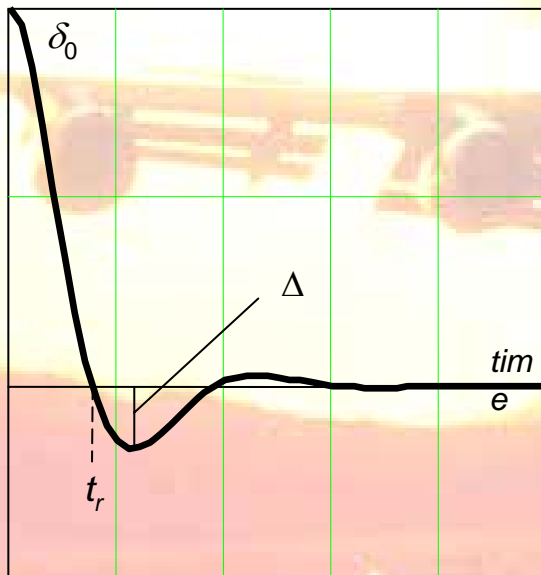
Wheel Does Not Return Quickly Enough

Friction, LBS

$$(m + m_{pilot})\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta} + F_{fr} \operatorname{sgn}(\dot{\delta}) + F_{br} \operatorname{sgn}(\delta) = F_{pilot}$$

Wheel Overshoot

Breakout,
LBS



Detent "Gets
In the way"
of
Flying

One Gradient
One Inertia
One Damping Ratio
One Sensitivity Gain

Cannot Feel
Detent

Friction, LBS

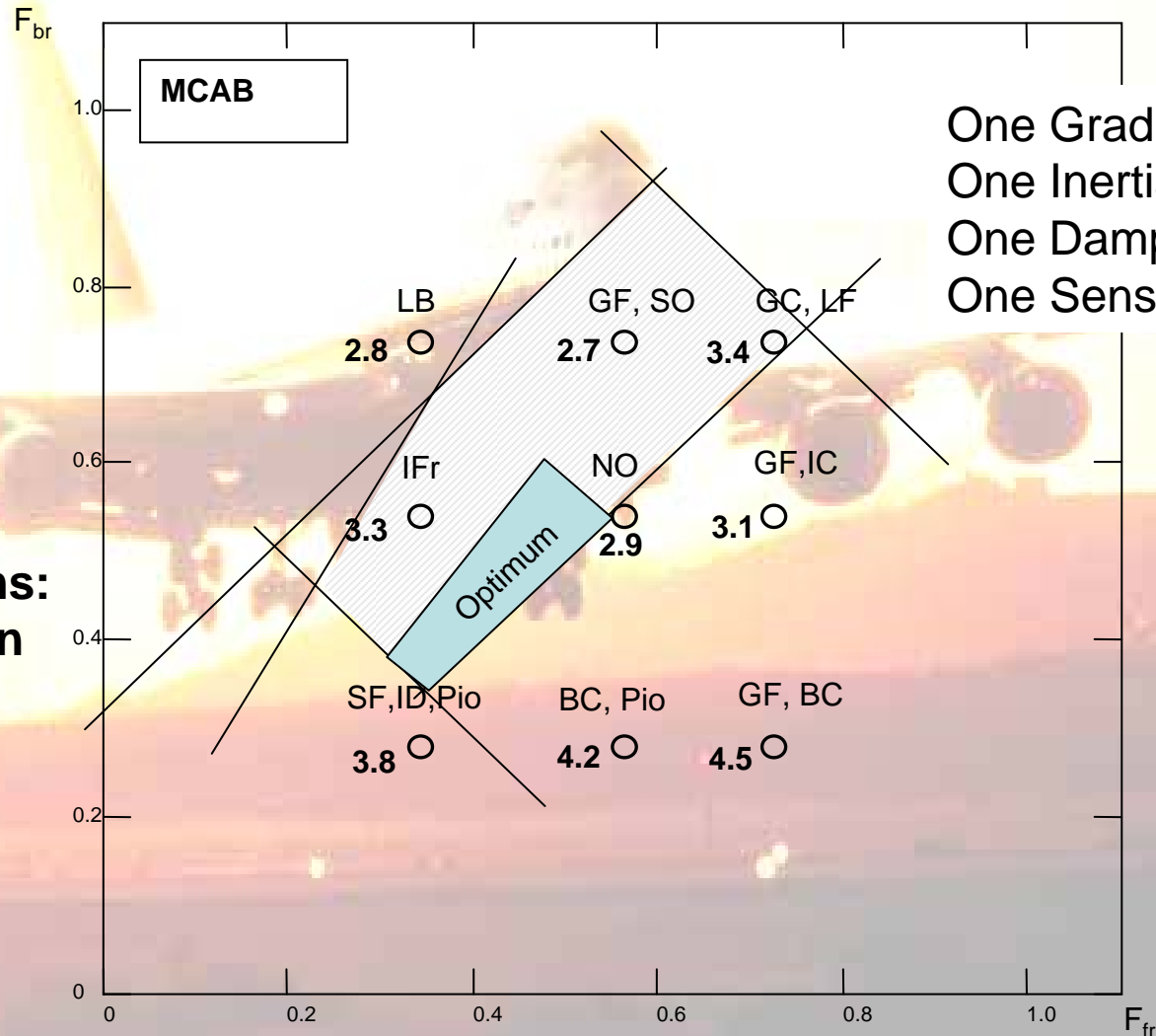
$$(m + m_{pilot})\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta} + F_{fr} \operatorname{sgn}(\dot{\delta}) + F_{br} \operatorname{sgn}(\delta) = F_{pilot}$$

Find “Optimum” and 1/2 Boundary

Compare with Measured Pilot Opinion

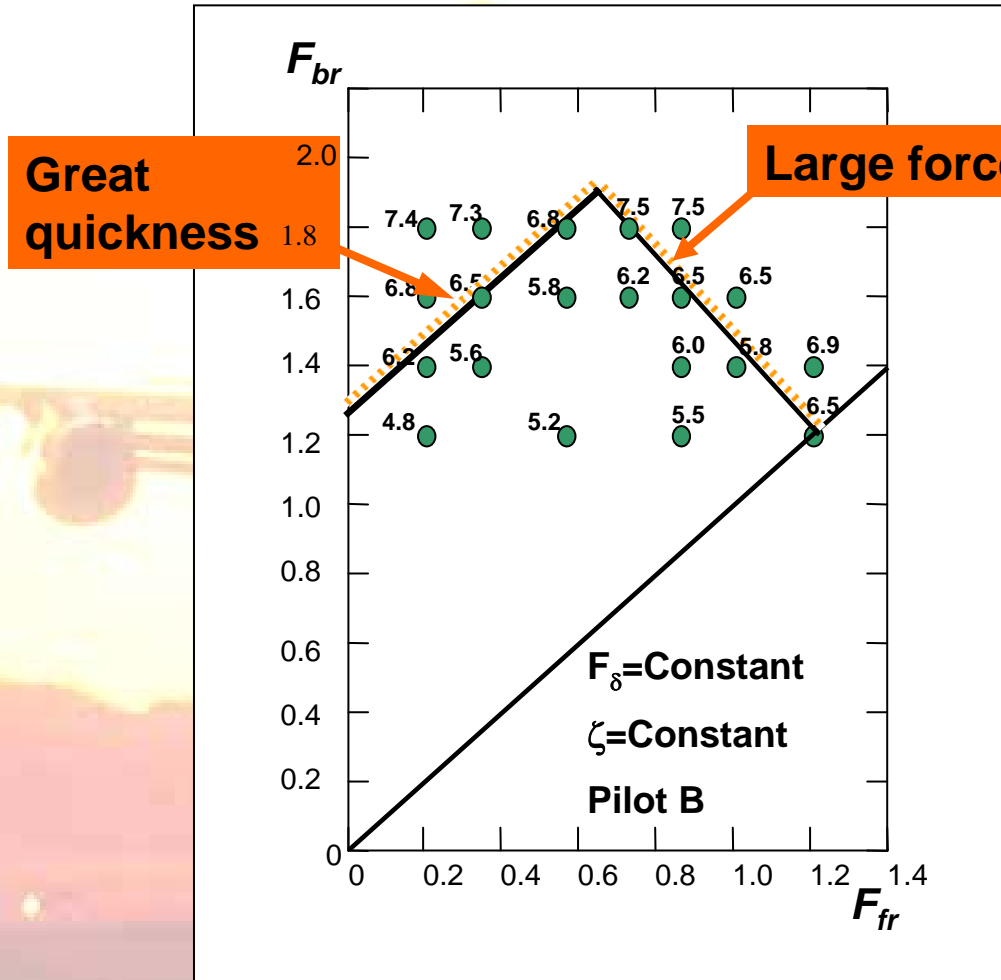
**For Linear Systems:
Compute Optimum
Directly**

One Gradient
One Inertia
One Damping Ratio
One Sensitivity Gain



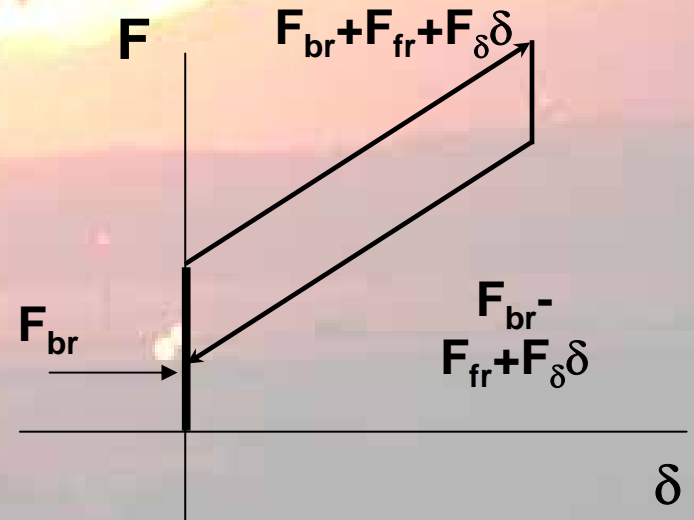
**For Nonlinear Systems:
Shape and Orientation
Of Lines is Constant,
Levels Set by Pilot
Comments**

Level 2/3 Boundary for Large Forces

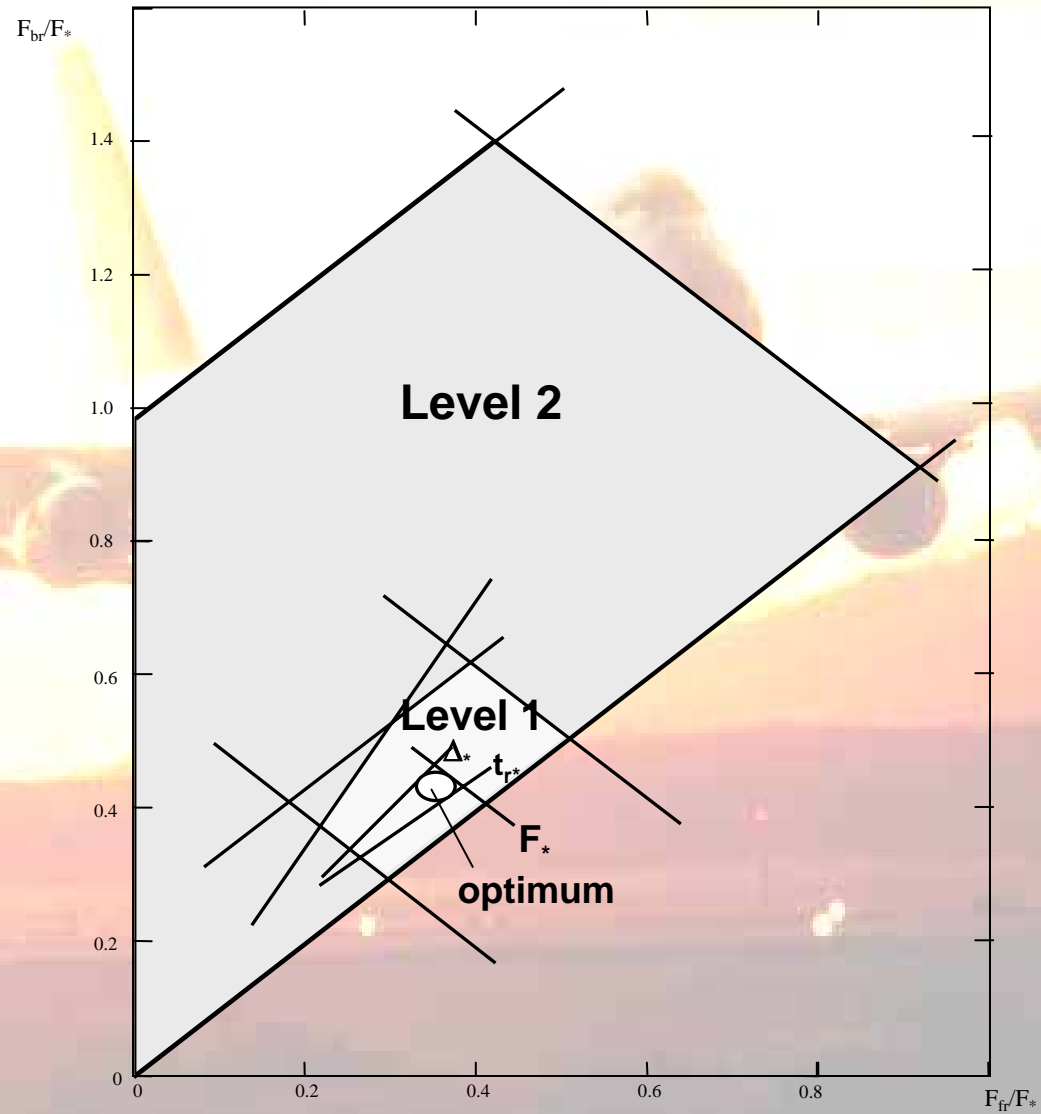


- Δ and t_r are NOT criteria for Level 2 boundaries

- “great quickness” boundary is determined as $F_{br} - F_{fr} + F_{\delta} \delta = F_{\text{permissible}}$



Simple method of feel system characteristics selection



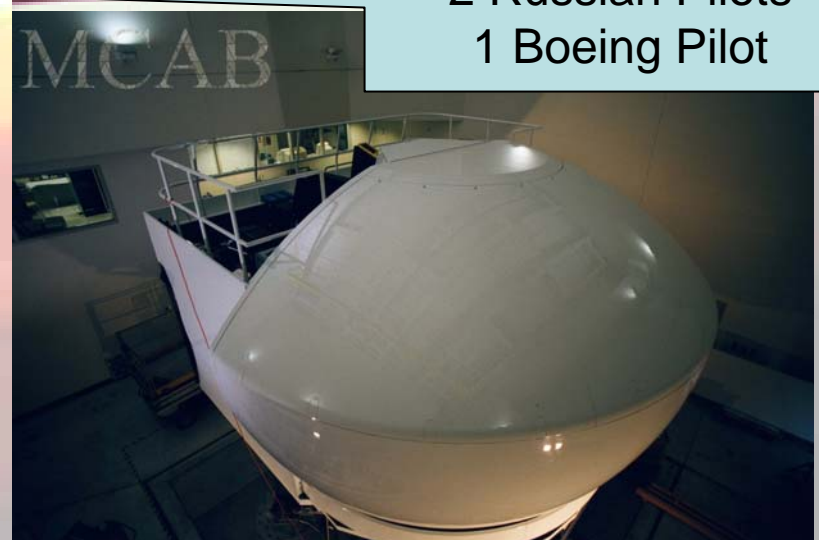
Wheel Experiments

- Experimental Parameters
 - Friction
 - Breakout
 - Damping
 - Spring Gradient
 - Inertia
 - Control Response Sensitivity
- 4 piloting tasks
- 3 pilots
- 2 different simulators
 - TsAGI: typical wide-body quad
 - Boeing: typical wide-body twin
- Total of 156 control system configurations

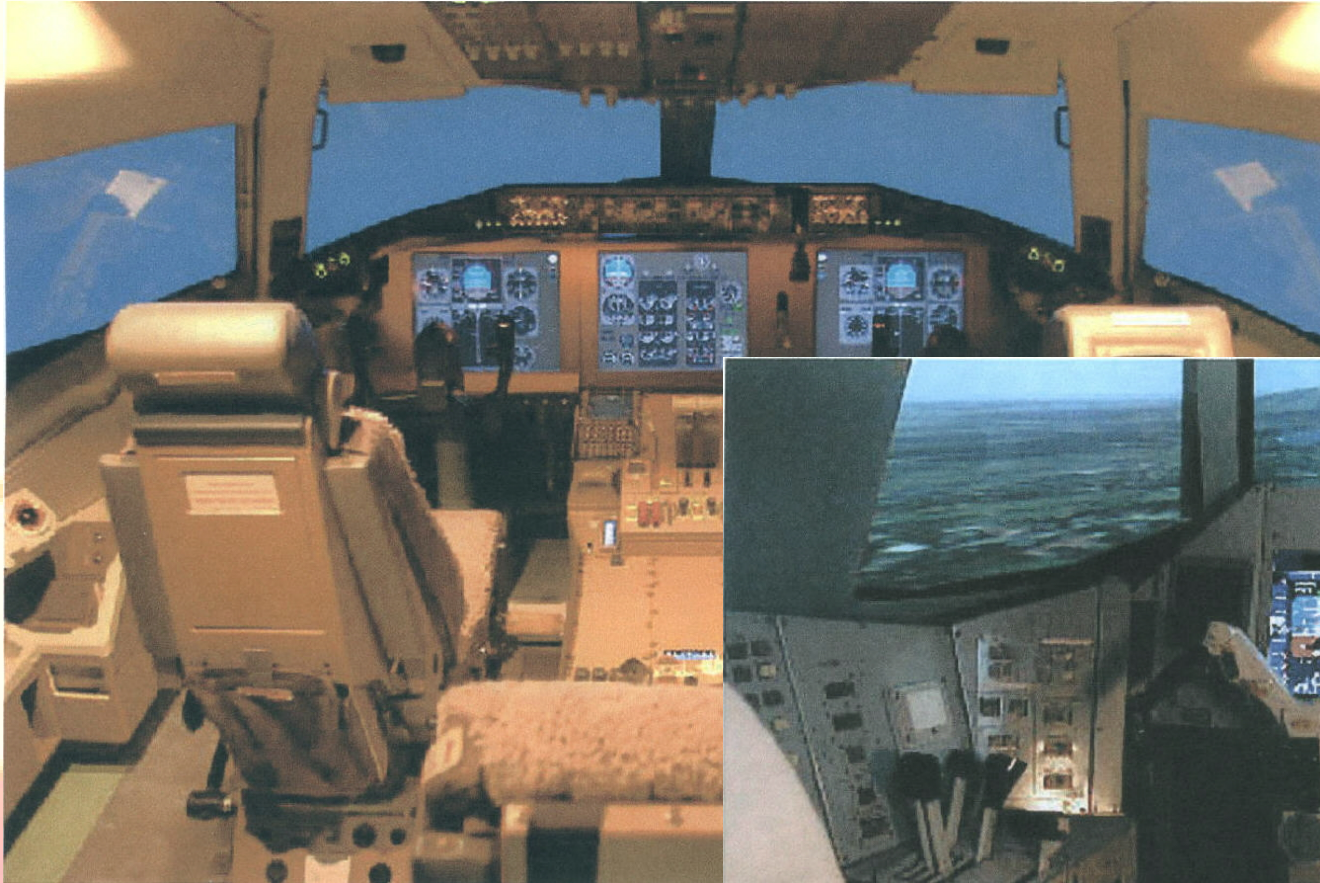


Normal Landing
“Gust” Landing
Offset Landing
Free Piloting Evaluation

2 Russian Pilots
1 Boeing Pilot



Simulator Environments



Mcab

FS-102

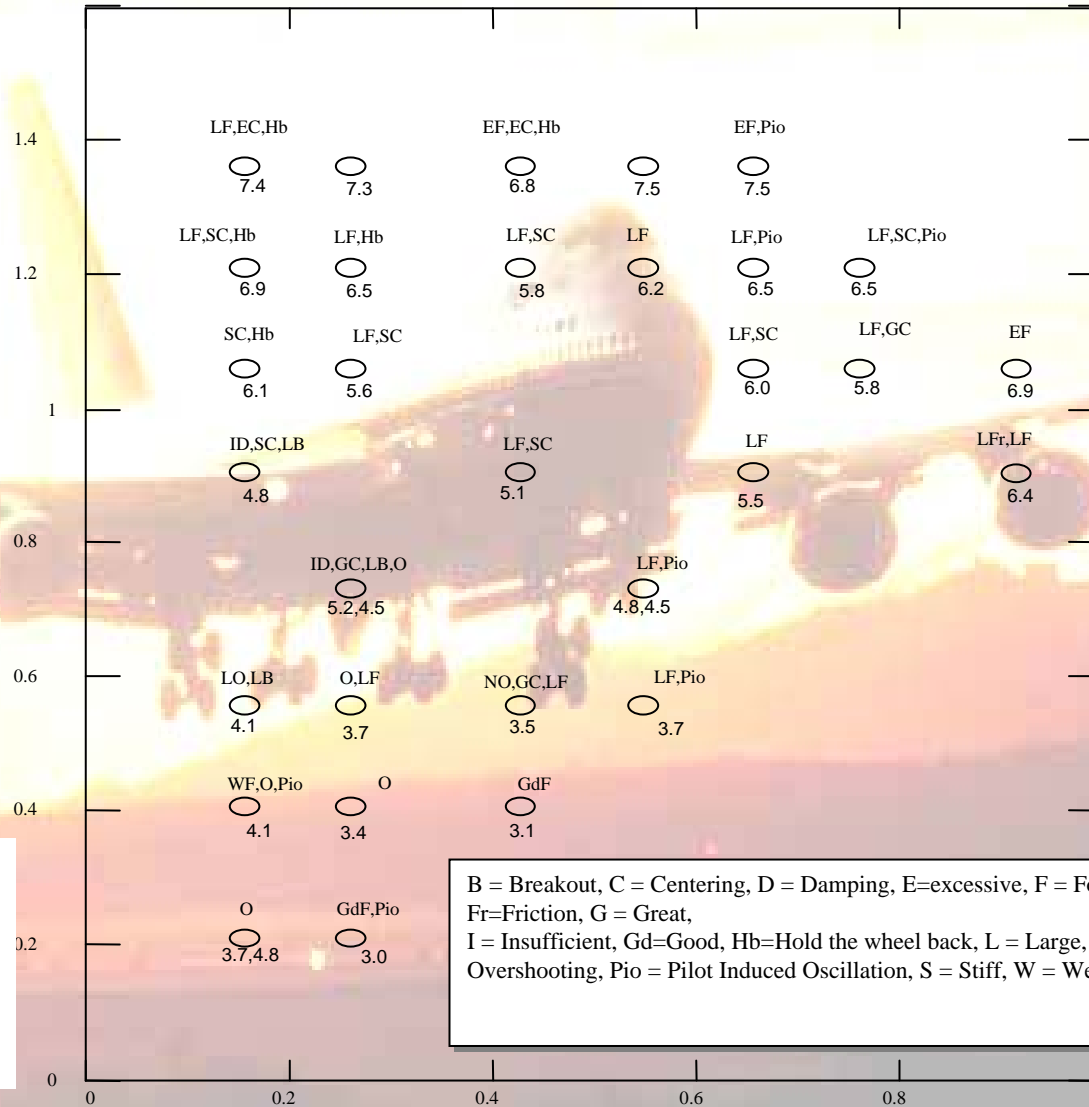


Some Cultural Observations to keep in mind when looking at data

- Russians tend to fly with both hands on wheel
- Russians do not decrab for crosswind landings
- Pilots have difficulty stepping across the Level 2/3 boundary
- Pilot Ratings have resolution of 0.1

Sample of the Data Obtained

breakout

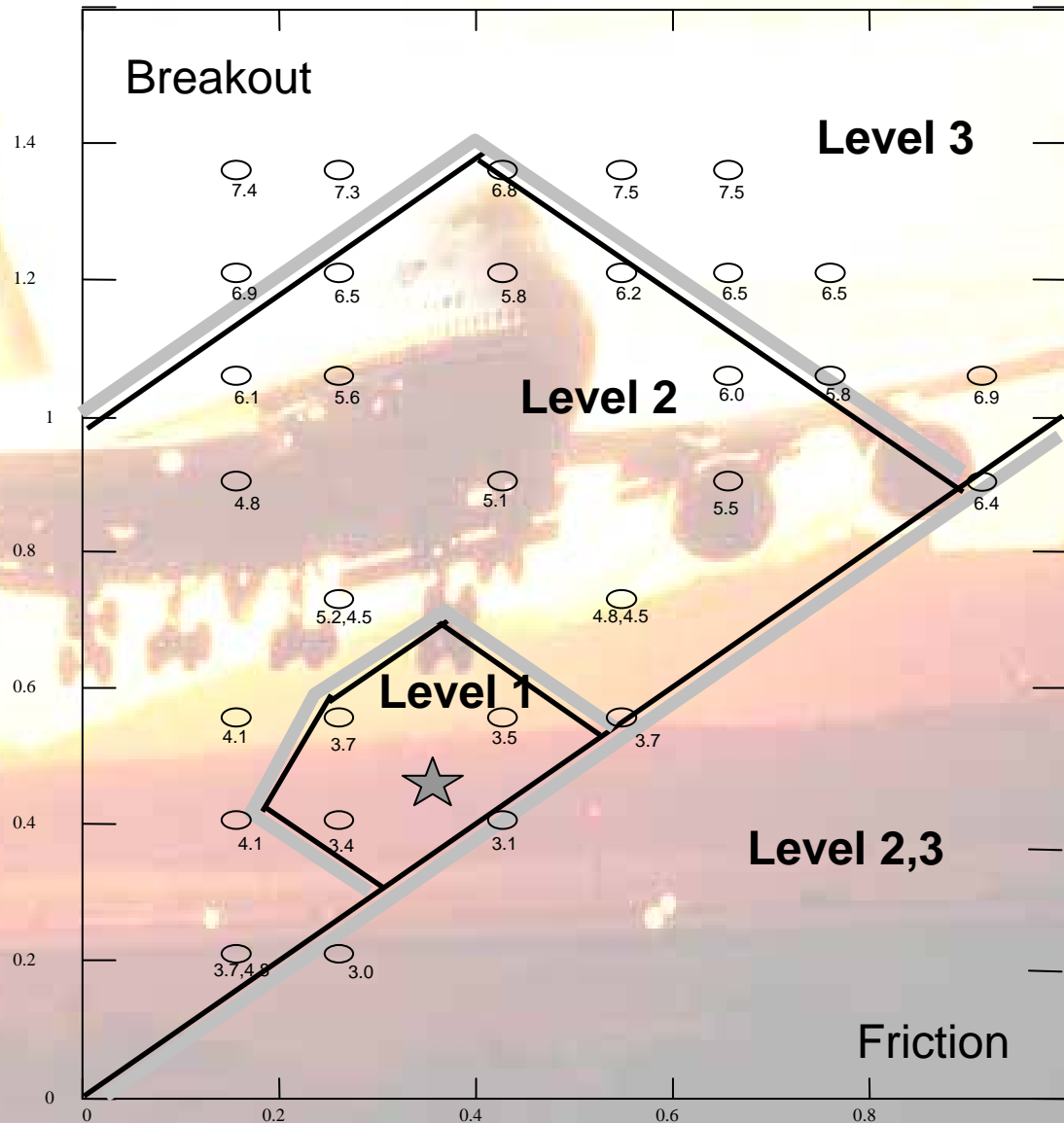


One Spring Gradient
 One Inertia
 One Damping Ratio
 One Sensitivity Gain

B = Breakout, C = Centering, D = Damping, E=excessive, F = Forces,
 Fr=Friction, G = Great,
 I = Insufficient, Gd=Good, Hb=Hold the wheel back, L = Large, N = No, O =
 Overshooting, Pio = Pilot Induced Oscillation, S = Stiff, W = Weak

friction

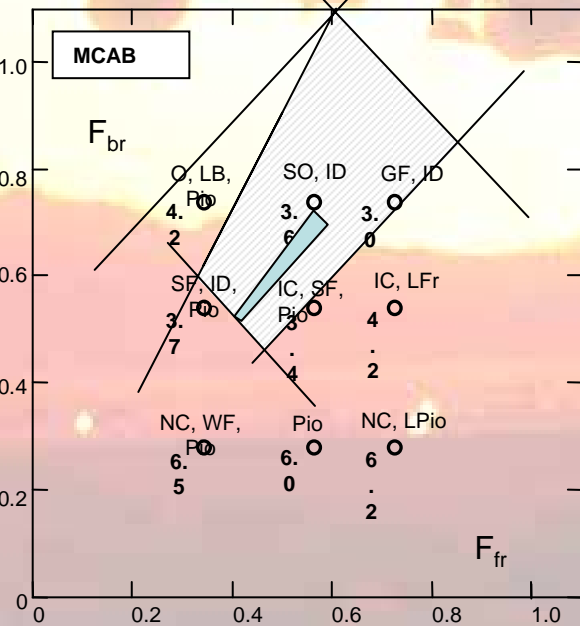
Sample Comparison with Theory



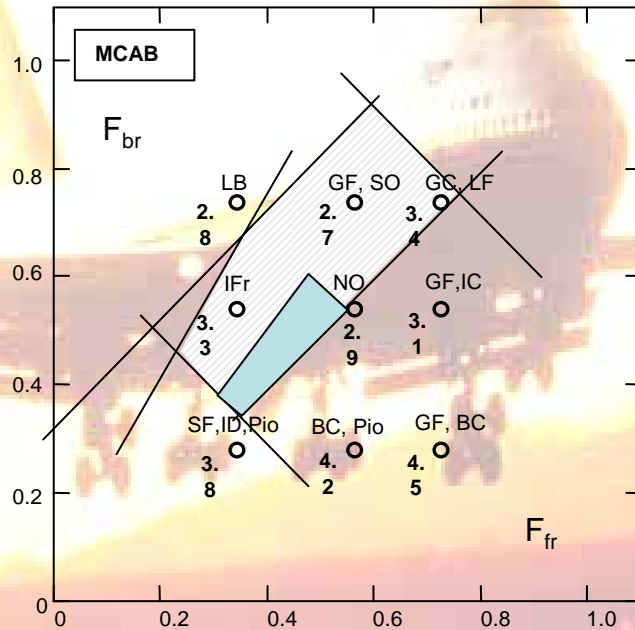
One Spring Gradient
One Inertia
One Damping Ratio
One Sensitivity Gain

Effect of Gradient on Optimum and Level 1 Boundaries

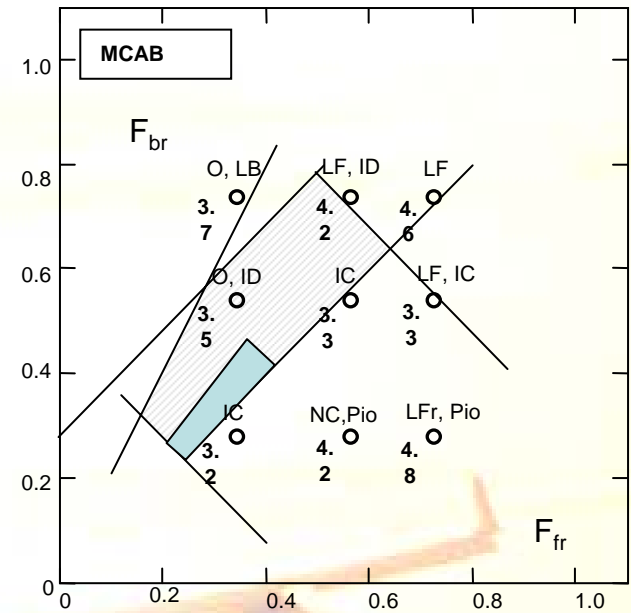
$F_{\delta} = \text{Weak Gradient}$



$F_{\delta} = \text{Medium Gradient}$

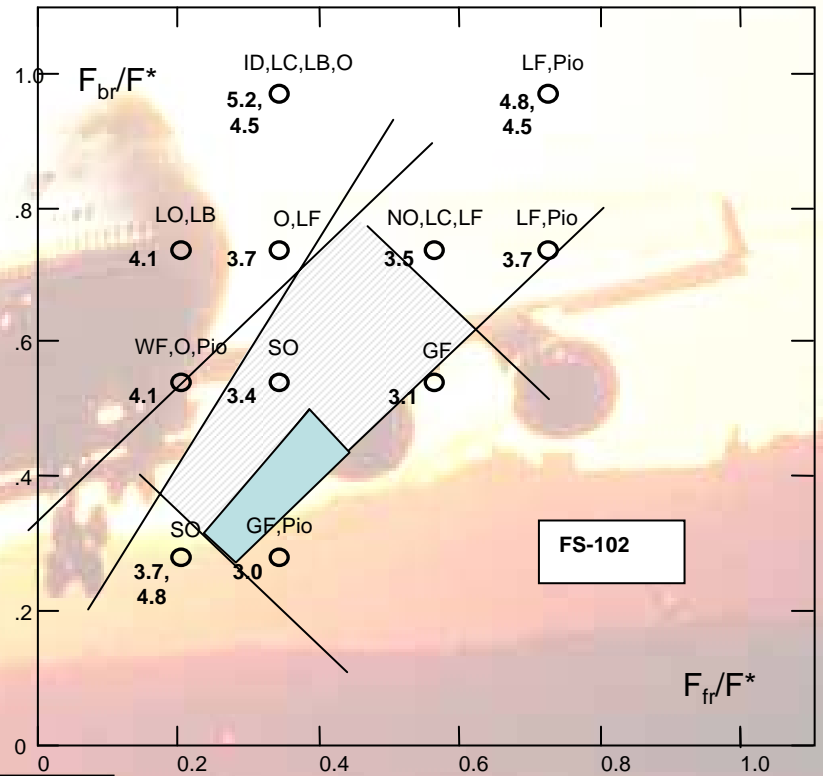
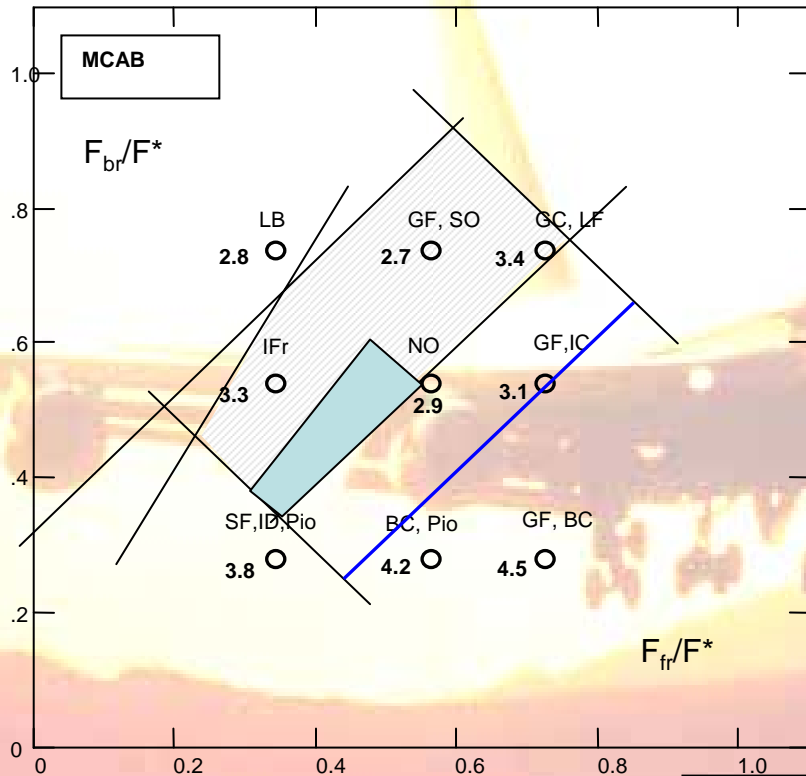


$F_{\delta} = \text{Stiff Gradient}$



One Inertia
One Damping Ratio
One Sensitivity Gain

Effect of Manipulator Type on Optimum and Level 1/2 Boundaries



MCab ~ Conventional Wheel

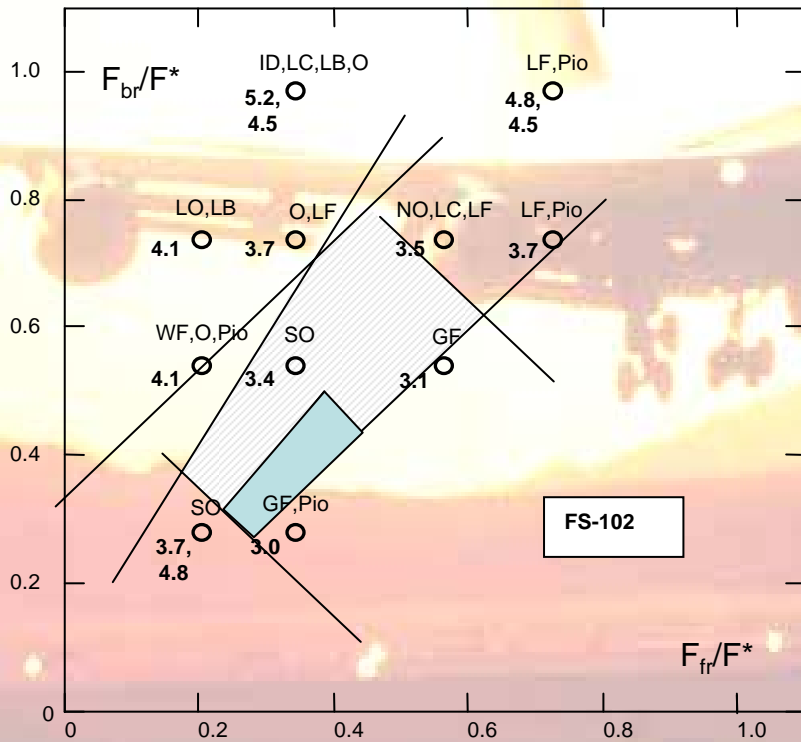
FS-102 ~ Tupulev Mini-Wheel

- One Gradient
- One Damping
- One Inertia
- One Sensitivity Gain

Effect of System Damping on Optimum and Level 1 Boundaries

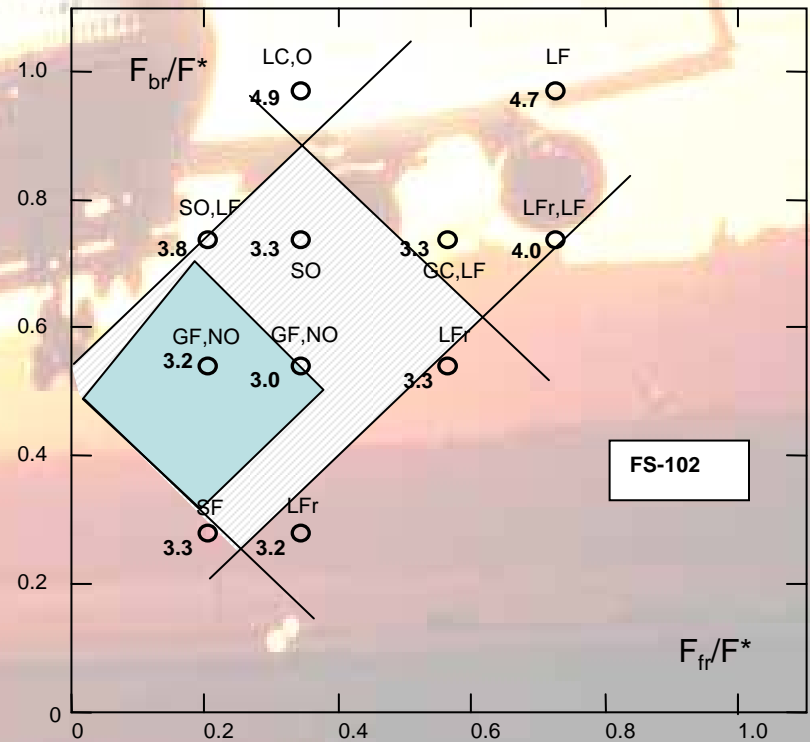
“I don’t know what you changed, but it feels smoother somehow.”

M. Carriker



Damping = 0.4

One Gradient
One Inertia
One Sensitivity Gain



Damping = 0.8

Wheel System Summary

- We now have the largest known database of feel system parameters in the world for a wheel/column controller
- Data were used to refine a generalized method of predicting handling qualities effects of feel system parameters
- A simplified graph-analytical method has been developed to estimate handling qualities levels boundaries

Pedal Systems



Standards for Pedal Feel System Characteristics

- FAR/CS requirements provide only for maximum total force and that the force should be proportional to deflection and sideslip
- MIL-HDBK gives only general guidance for static force characteristics
- No guidance on dynamic characteristics
- No guidance on relationships between spring gradient, breakout, friction, etc. in terms of handling qualities

Research Project Objectives

- For Rudder Pedals:

Find a method to determine:

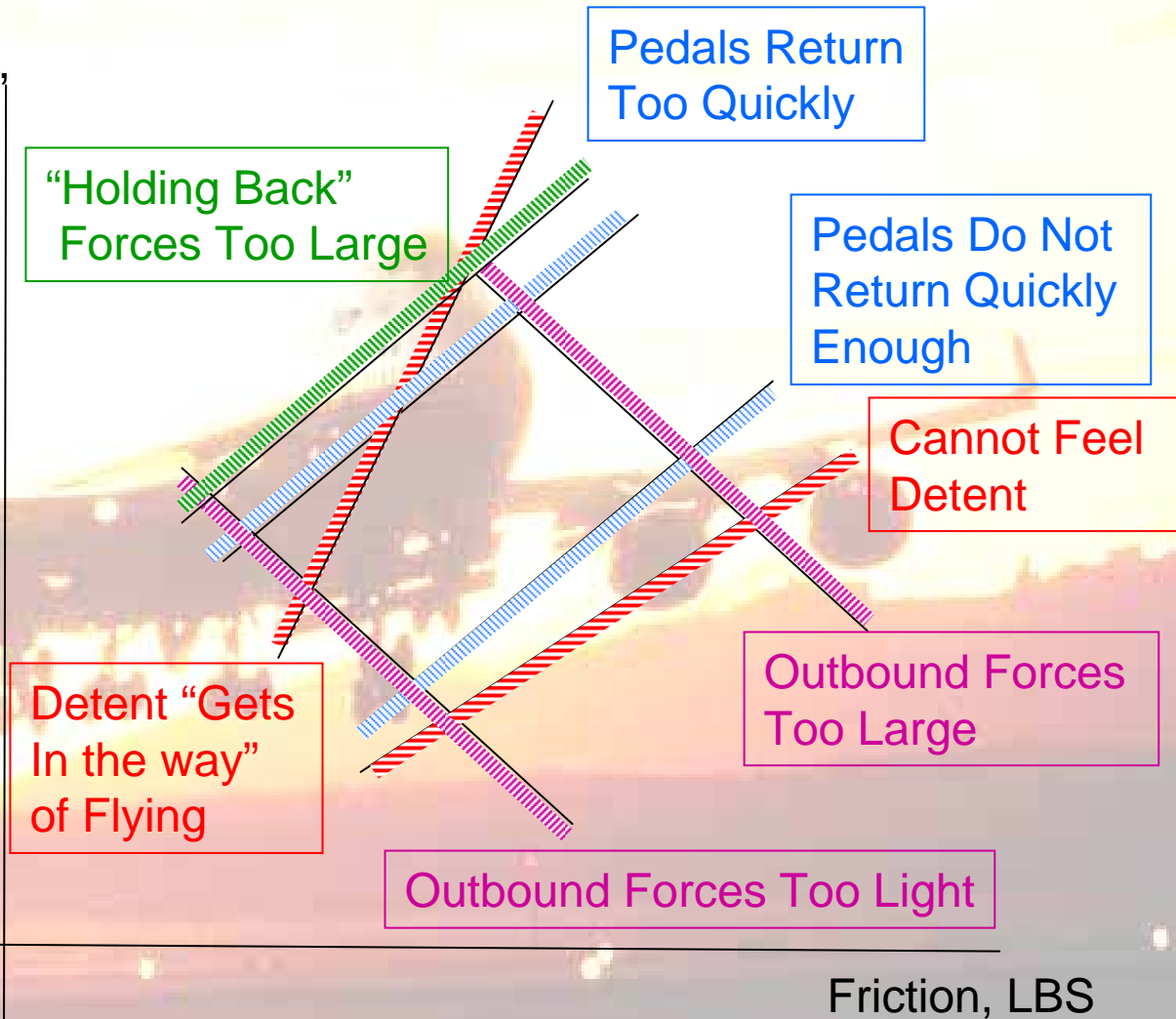
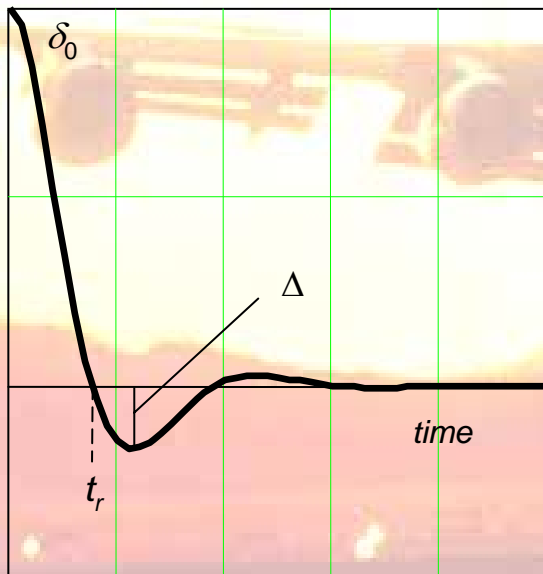
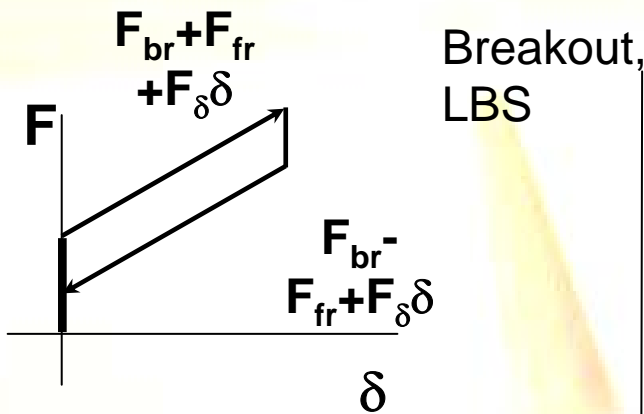
- Optimum feel system characteristics
- Level 1/2 boundary
- Level 2/3 boundary
- Handling Qualities gradient in each parameter direction (Breakout, Friction, Spring Gradient, Inertia, Damping)

Pedals are Different



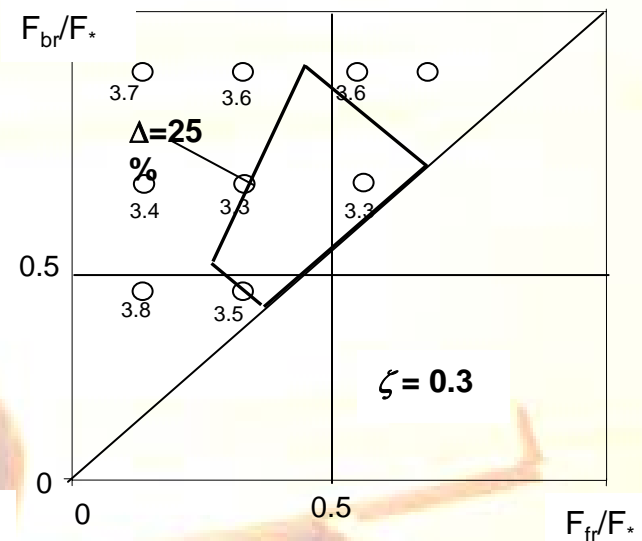
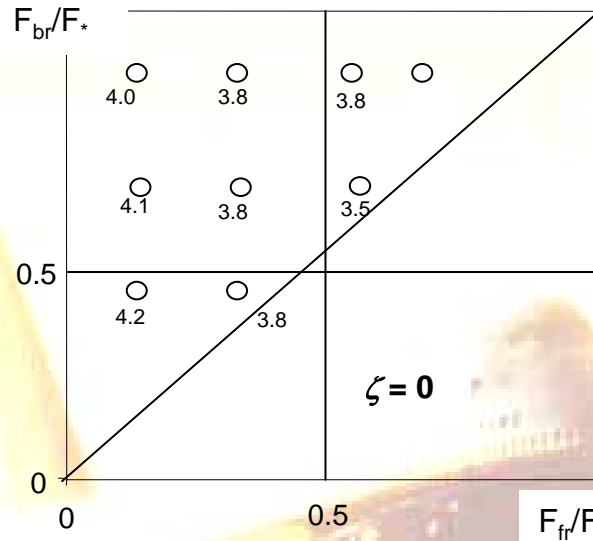
- Different man/machine interface
 - Only push; cannot grip and pull
- Different scale factors
 - Higher forces
 - Smaller displacements
- Pilots seem unaware of force gradient
 - Only aware of force under foot, not gradient
- No direct visual feedback of position
- Pilots use pedals differently
 - Sometimes relax force quickly
 - Sometimes deliberately relax the forces slowly

Friction/Breakout Boundary Build-up

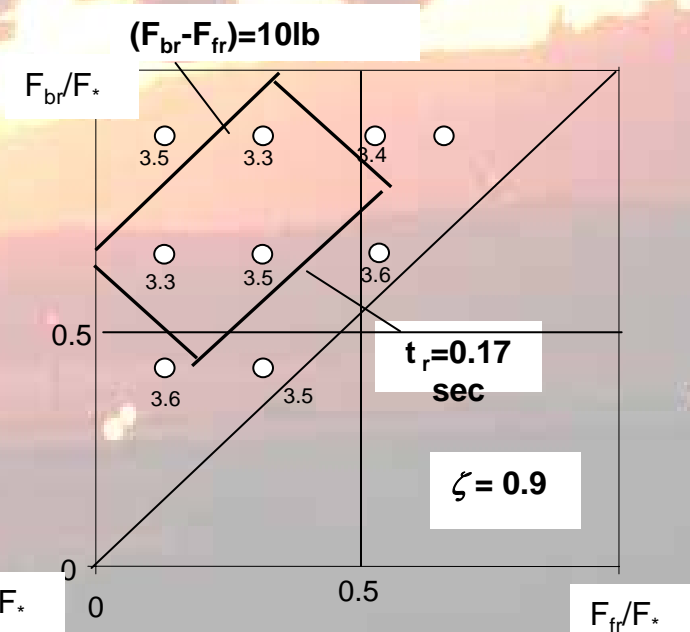
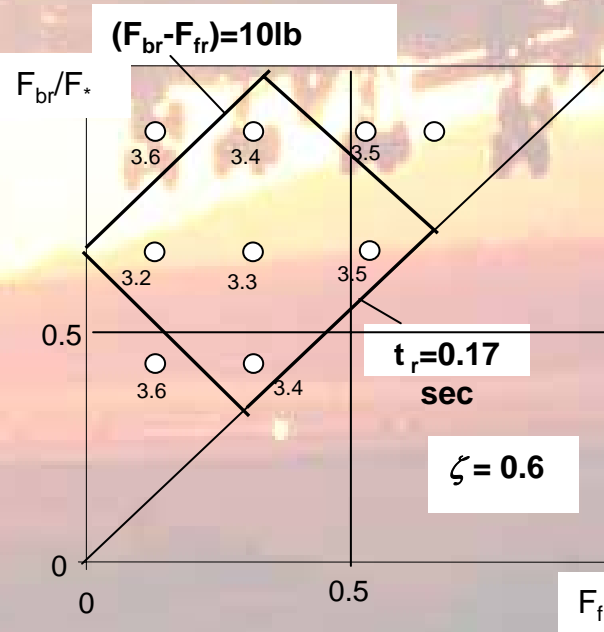


$$m\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta}\delta + F_{fr} \operatorname{sgn}(\dot{\delta}) + F_{br} \operatorname{sgn}(\delta) = F_{pilot}$$

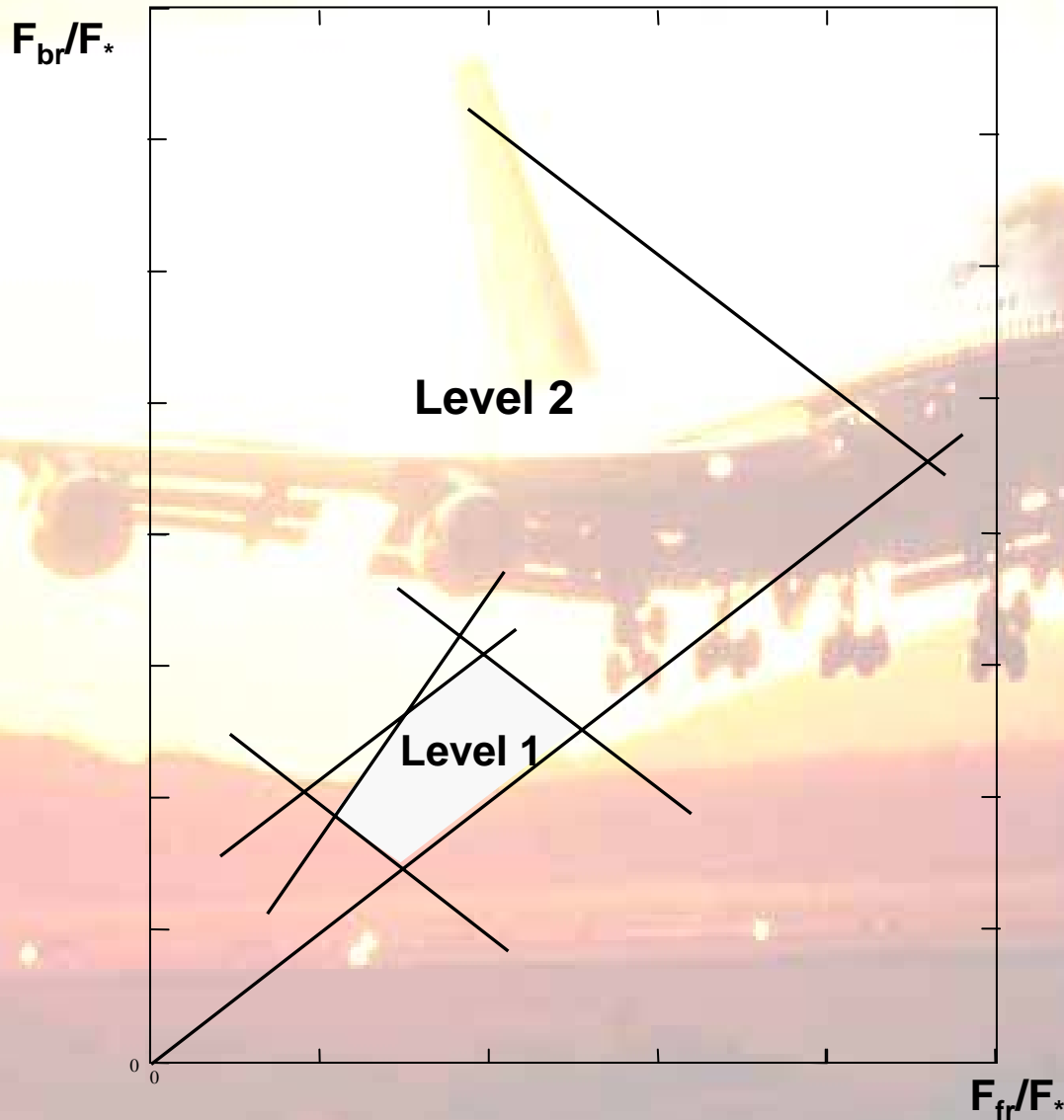
Feel System Dynamics Requirements



Dynamic Characteristics Parameters Boundaries are Functions of System Damping



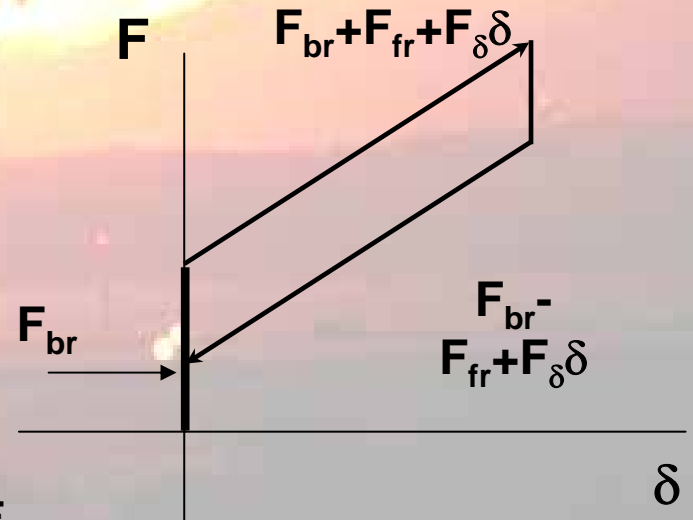
Level 2/3 Boundary for Large Forces



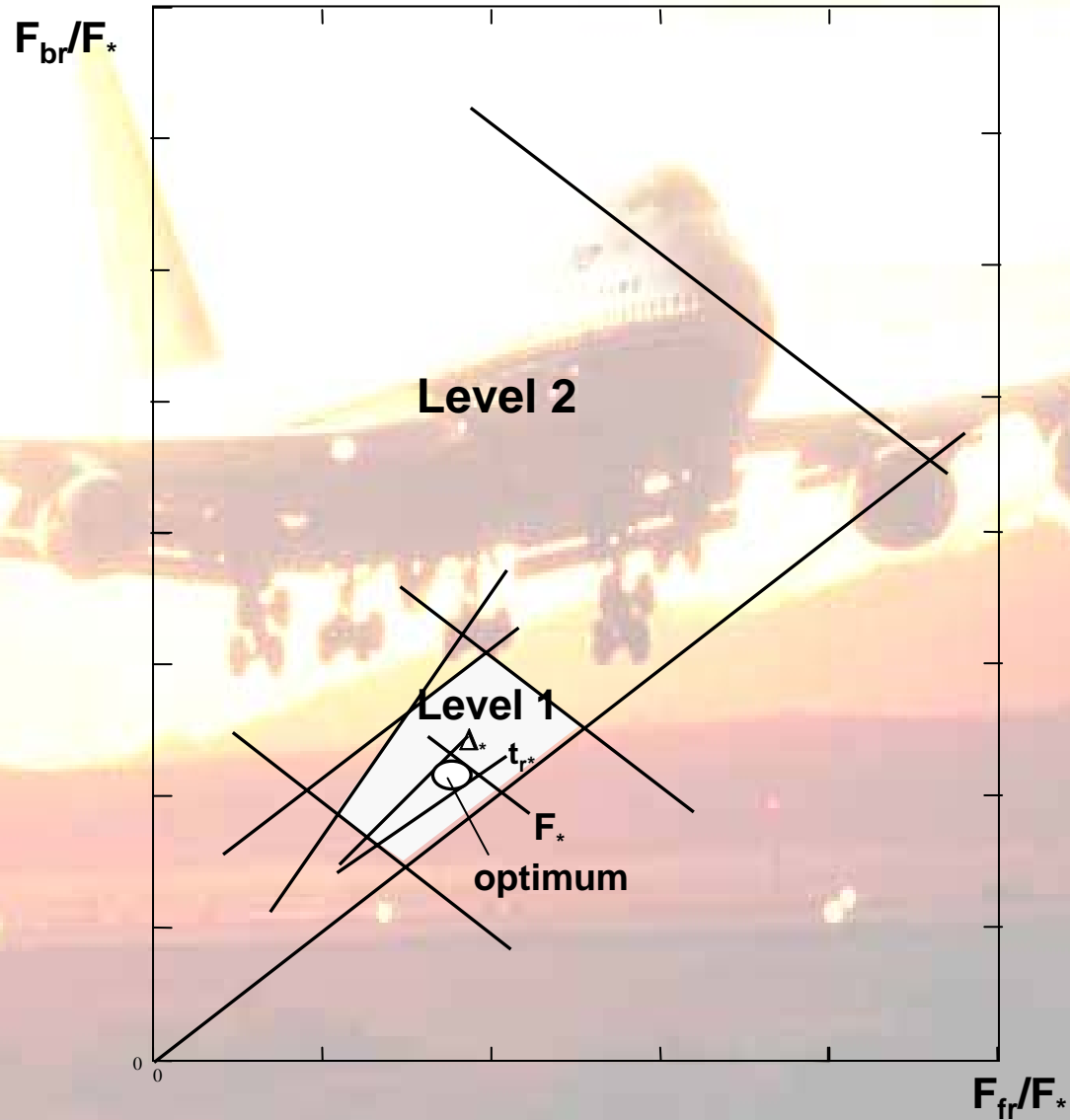
- Δ and t_r are NOT criteria for Level 2 boundaries

-Maximum Forces Boundary determined by

$$F_{br} + F_{fr} = F_{pilot}$$



Simple method of pedal feel system characteristics selection



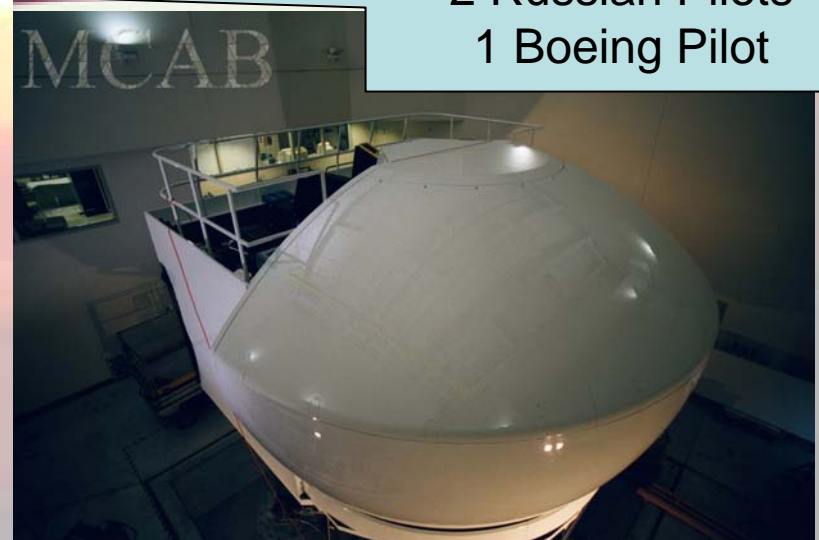
Pedal Experiments

- Experimental Parameters
 - Friction
 - Breakout
 - Damping
 - Spring Gradient
 - Inertia
 - Control Response Sensitivity
- 4 piloting tasks
- 3 pilots
- 2 different simulators
 - TsAGI: typical wide-body quad
 - Boeing: typical wide-body twin
- ~200 control system configurations

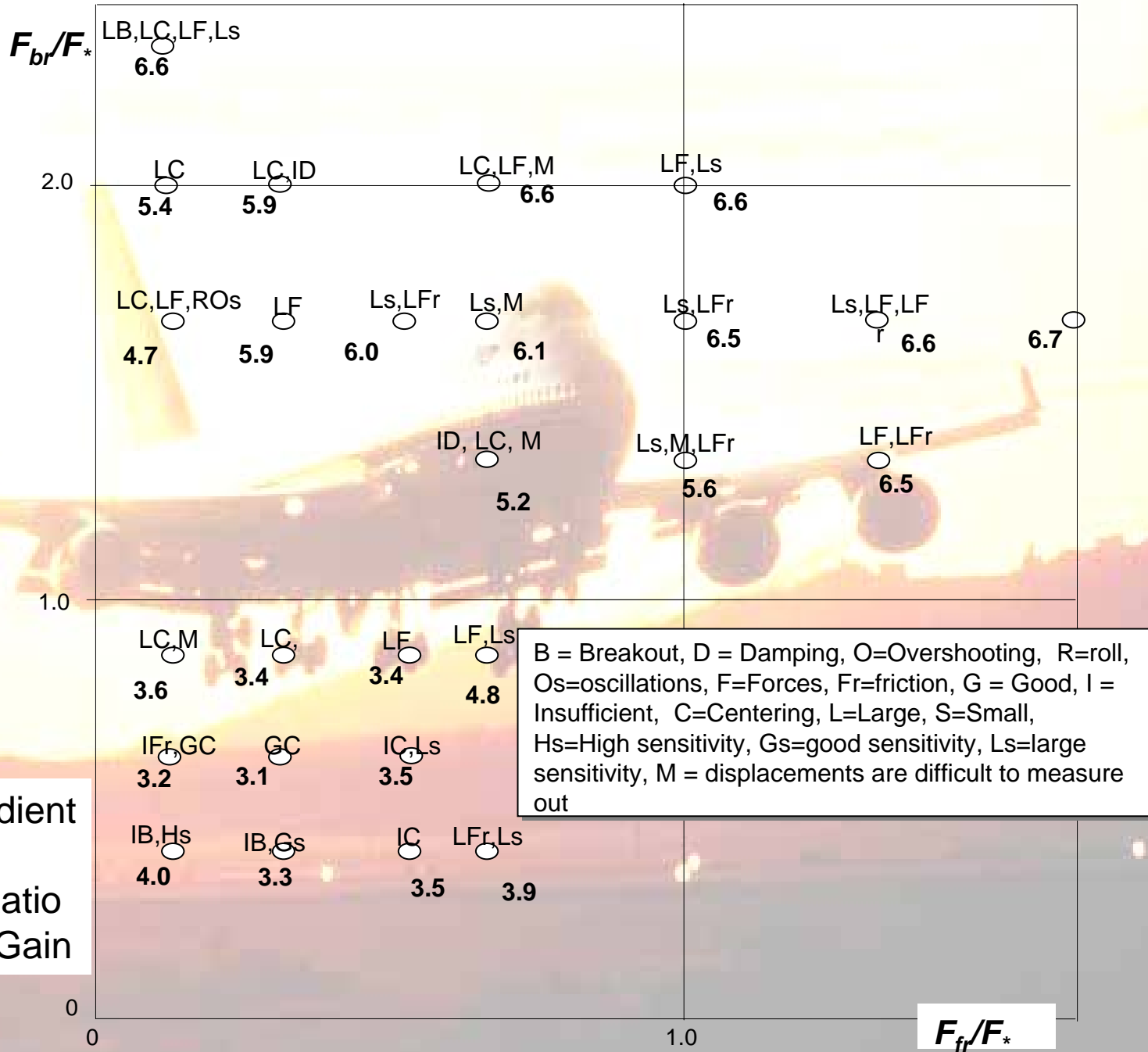


**Crosswind Landing
“Gust” Landing
“Jumping” Runway Tracking
Free Piloting Evaluation**

**2 Russian Pilots
1 Boeing Pilot**



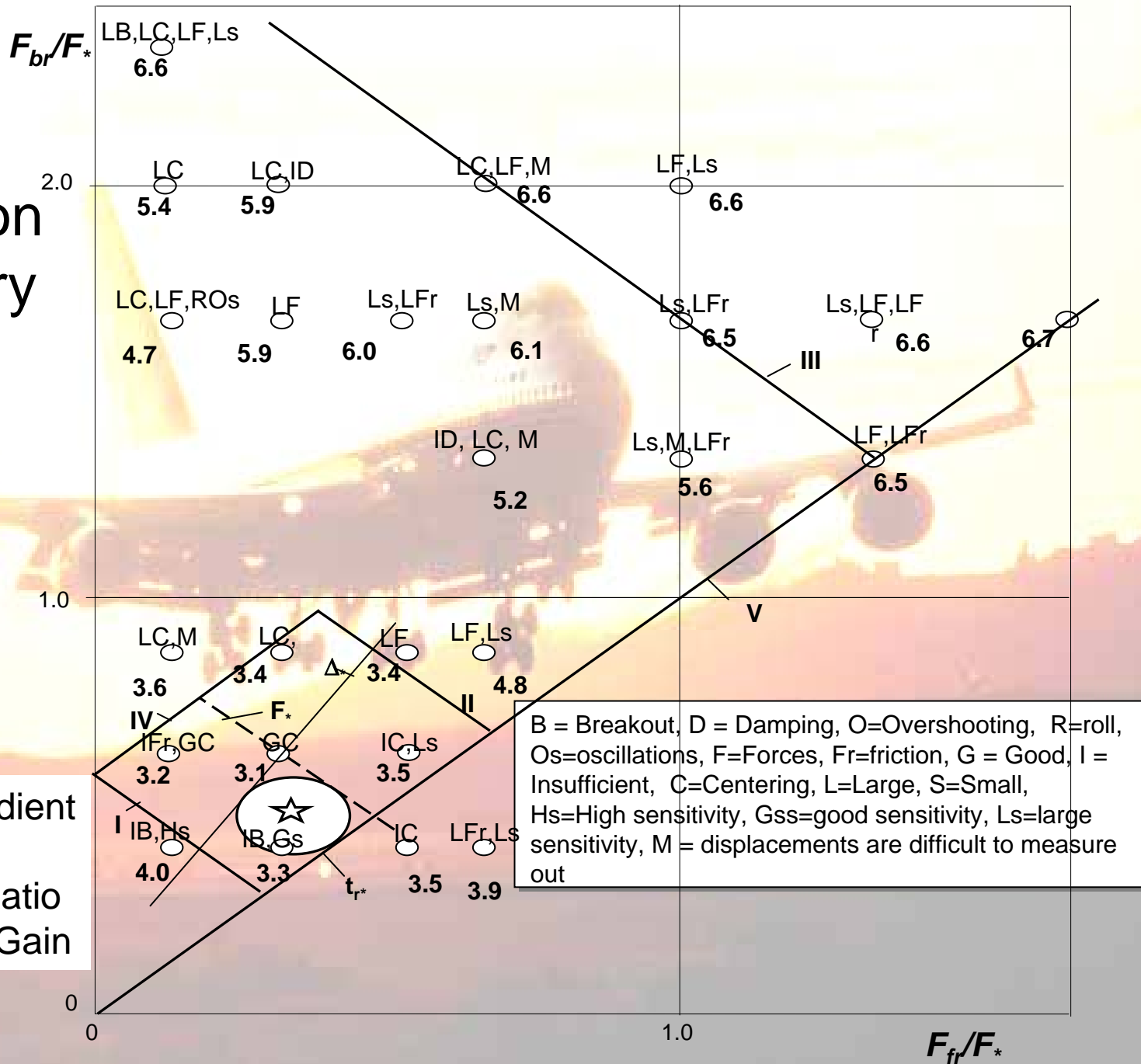
Sample of the Data Obtained



One Spring Gradient
 One Inertia
 One Damping Ratio
 One Sensitivity Gain

F_{fr}/F_*

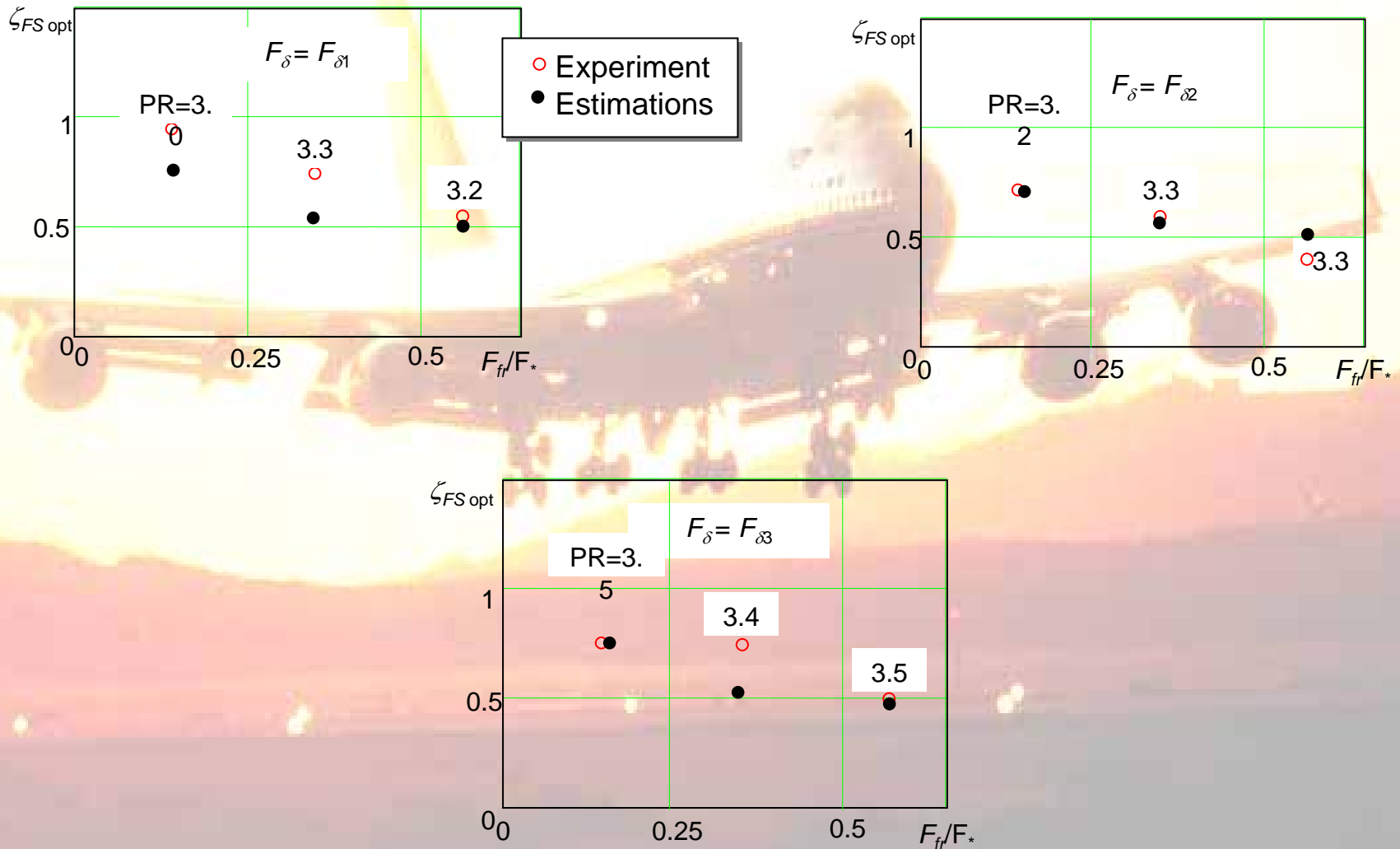
Sample Comparison with Theory



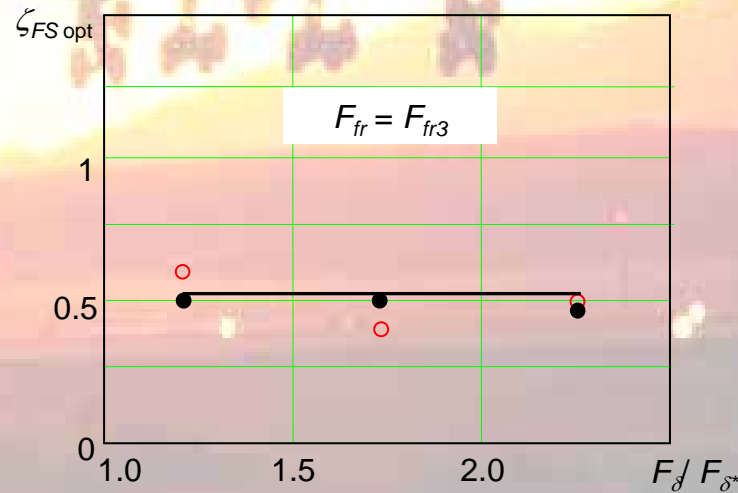
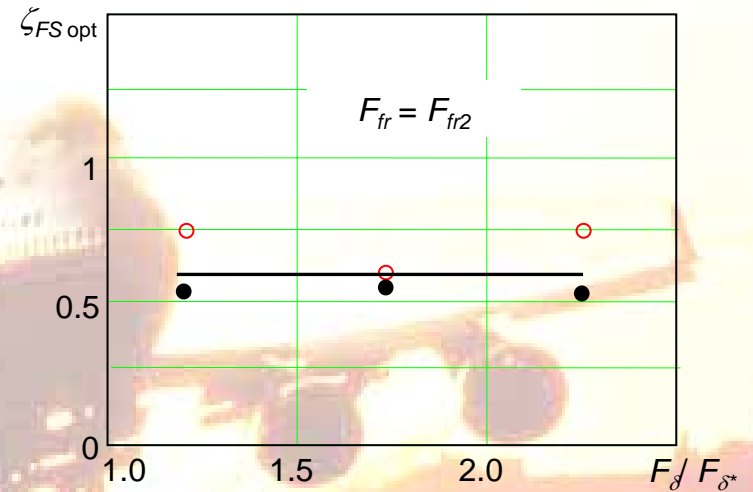
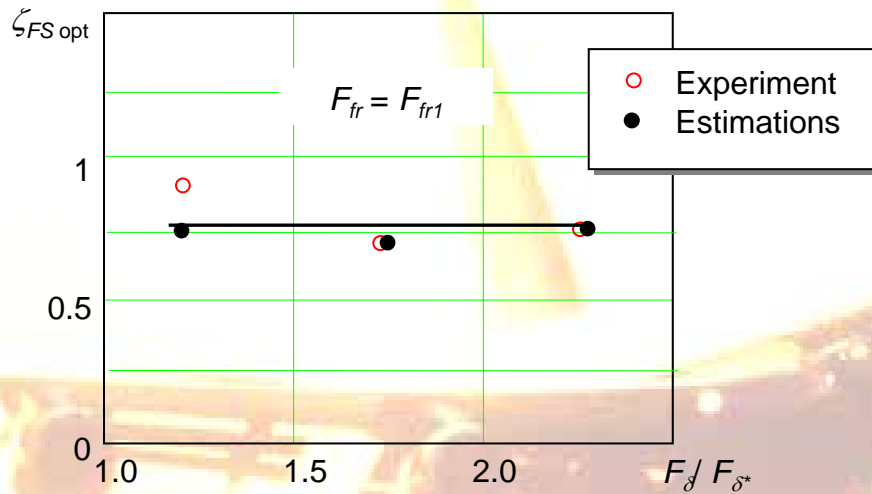
One Spring Gradient
 One Inertia
 One Damping Ratio
 One Sensitivity Gain

B = Breakout, D = Damping, O=Overshooting, R=roll, Os=oscillations, F=Forces, Fr=friction, G = Good, I = Insufficient, C=Centering, L=Large, S=Small, Hs=High sensitivity, Gss=good sensitivity, Ls=large sensitivity, M = displacements are difficult to measure out

Effect of Friction on Optimum System Damping



Effect of Spring Gradient on Optimum System Damping



Pedal System Summary

- Pedal feel characteristics significantly affect airplane handling qualities
- We now have a sizeable database of feel system parameters for rudder pedals on Transport Aircraft
- Data were used to produce a generalized method of predicting handling qualities effects of feel system parameters
- A simplified graph-analytical method has been developed to estimate handling qualities levels boundaries
- Analytical criterion agrees well with measured results