Flight Test 101

Today: Flying Qualities and PIO

F-22 PIO (Pilot Induced Oscillations)

- Initial testing of F-22
- Testing new flight controls
- Gear up
- Publicity pictures

- Why did this happen??

Big planes too

Civilian planes too…

Goals for this week:

1. Learn something about how to test airplanes
2. Connect fundamental a/c dynamics to how a/c handles
3. "Build the case" for handling qualities
4. Talk about engineering solutions in the real world
5. Have fun!

Overview

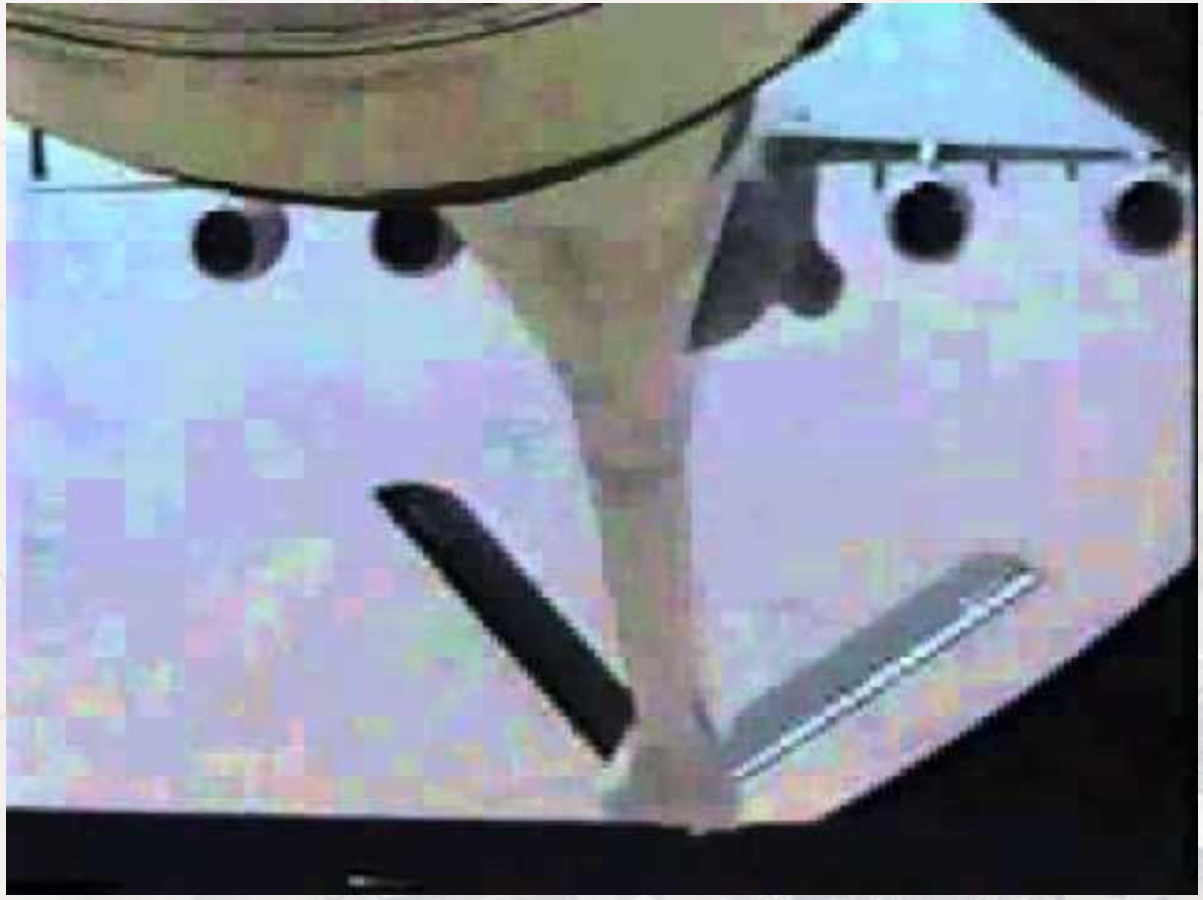
- Day 1:
  - Testing airplanes
  - Big picture
  - Flying Qualities**
  - PIO**
- Day 2:
  - Handling Qualities**
  - Operational Evaluation**
  - So what?
  - Recap

**With demonstration

Background: Cougar Boyer

- Family: Meredith (>21), Rory (4), Bogey (7)
- School: USAFA (2012), MIT (2014), TPS (2022)
- Current PhD Student here at CU
- Background:
  - F-35A + T-38A/C primary aircraft
  - Test Pilot School (2021-22)
  - TPS Instructor 2023-24
- Experience “highlights”:
  - 1x CENTCOM deployment F-35 (2019)
  - Flown F-35A/C (~800 hours)
  - Aircraft flown: T-38C, C-12C, C-12J, F-16, F-15E, F-15EX, F-18F, A-10, P-51, UH-1, UH-72, Extra-300, KC-135, LJ25, HU-16, T-6 (old/new), T-33, DC-3, R-44, MQ-9, 4x gliders, L-39, C172, Piper Warrior

More PIO examples



ROE

- <u>Ask questions!</u>
  - Guarantee someone else is thinking it
  - No dumb questions…
- Test questions?
- If you want to know more, let's chat after!

What is “Test”?

- “Spec Verification”
  - Does it do what the contractor says it does?
- Requirements validation
  - Does it meet the requirement we said we needed?

- My definition: does it reduce the risk to the operator?
  - **Safety**
  - **Capability**

Types of Military Flight Test

- Performance
  - How fast? How high? How much fuel? How much runway? Etc.
- Handling Qualities
  - Is it stable? Can it do the task I need it to do?

- Systems
  - Do the systems work? Can it do the mission?
- Weapons
  - Can it safely deliver the weapon? Hit the target?
- First Flight
  - Can I takeoff and land safely? How do I go from drawing board to combat?

Handling Qualities

Poll: Which has better handling qualities?

A

B

C

D

Trick question!

- Handling qualities: Can the aircraft *perform the intended task* with *minimal pilot compensation*?

How do you measure the handling qualities of an aircraft?

1. Is it stable?
2. Is it responsive?
3. Is it possible to PIO (aka undesired oscillations)?
4. Can it do basic tasks?
5. Can it do the mission?

The Big Picture of Handling Qualities

"Building the case"

Flying Qualities — "Bare airframe"

PIO Susceptibility — "Pilot in the Loop"

Handling Qualities — "Can it do the task?"

Mission Capability — "Can it do the mission?"

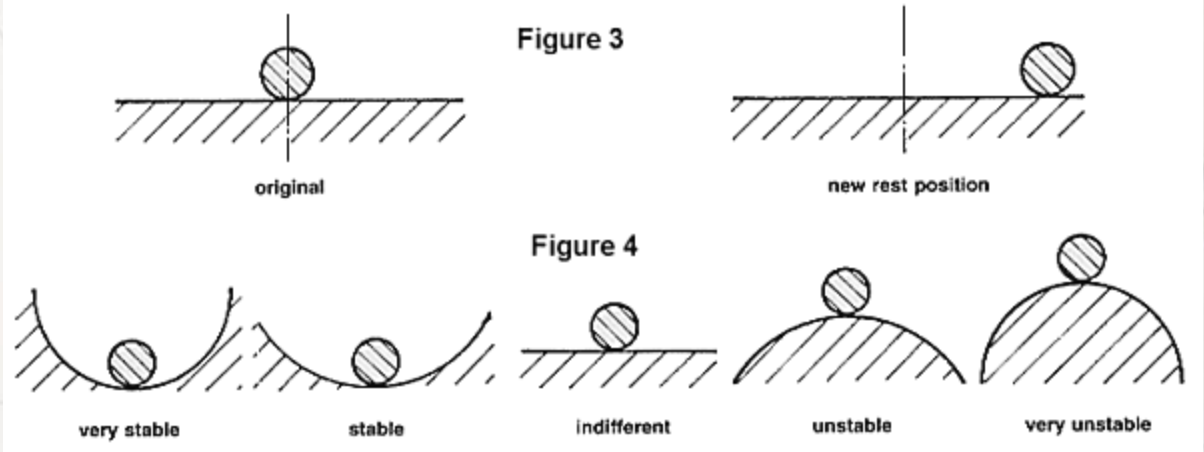
Flying Qualities → PIO → Handling Qualities → Mission Capability

Theory + Test

Stability

- If moved from a stable point, what will happen?

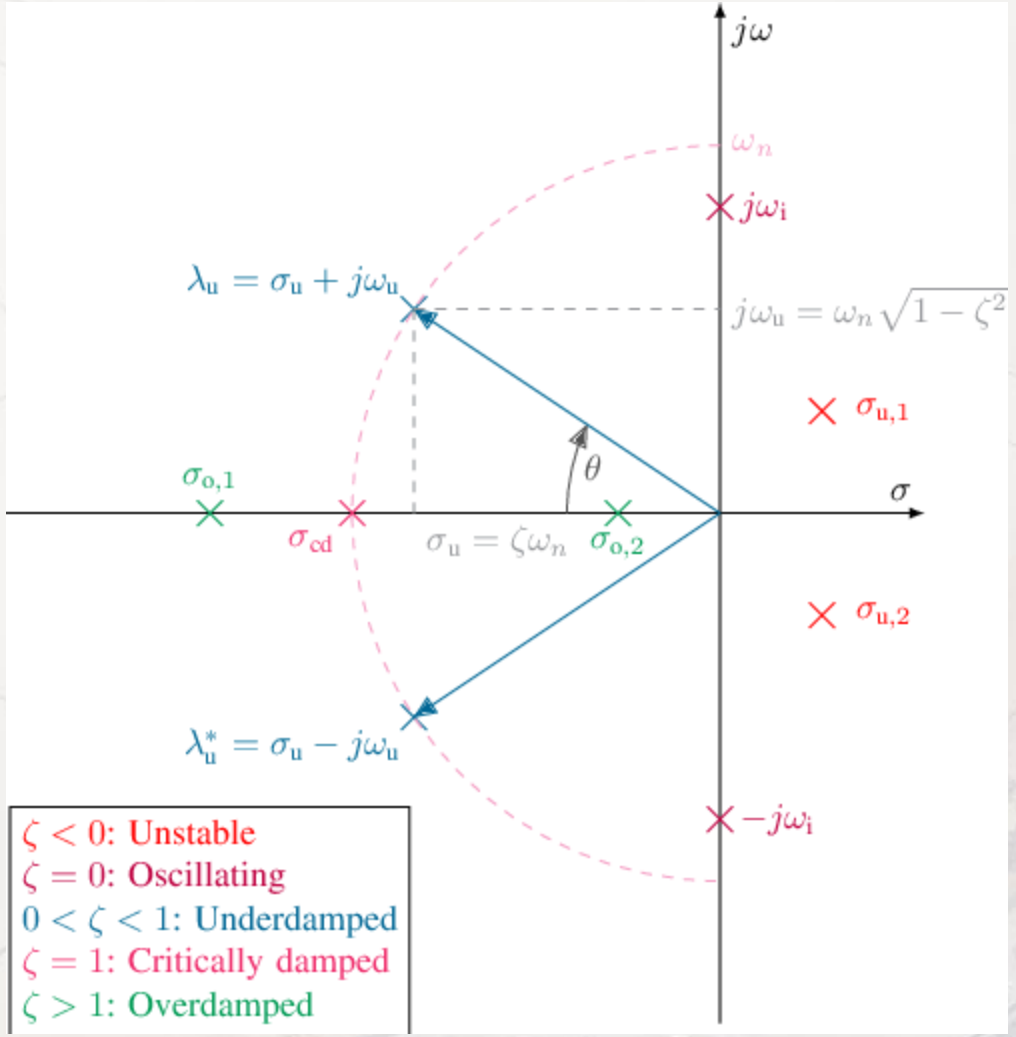
- Positive
- Neutral
- Negative



Demo: Golf ball in bowl + water

Stability

- How does damping change the response?



Demo: Golf ball in bowl + water

1. Flying Qualities – "Bare airframe"

- **Bare airframe**
- Stability
  - Static – *Initial* move back to equilibrium
  - Dynamic – Motion *over time*
- Responsiveness
  - How much response do I get for a certain amount of input?

Someone explain to me longitudinal aircraft dynamics (big picture)

Model

- Coefficients:
  - C_m_alpha
  - C_m_q
  - C_m_u
  - ….

$$\omega_n \approx \sqrt{\frac{-C_{m_\alpha}}{I_y} \cdot \frac{qSc}{U}}$$

PREDICTS

UPDATES

Reality

- Response
  - ω_d = damped natural frequency
  - ζ = damping ratio
  - ω_n = natural frequency
  - τ = time constant (ex: time delay)
  - p, q, r _max = a/c response rates
  - ….

- Assumptions?
- Utility?

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- Utility?

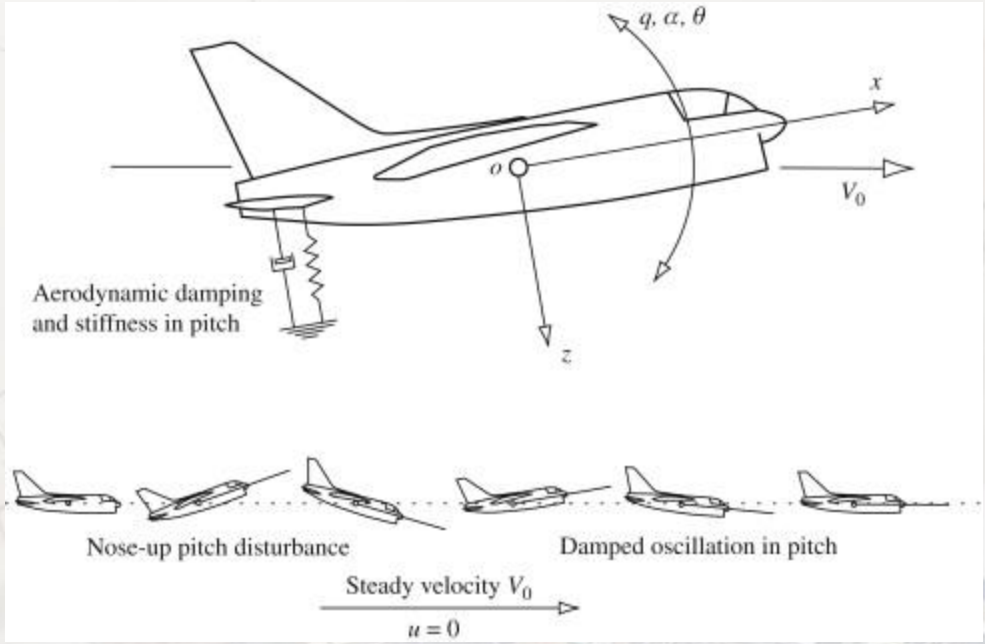
So what are the “qualities” of a bare airframe?

<u>How the airplane actually responds:</u>

- Damping ratio
- Natural frequency
- Delays
- Response rates

<u>How the airplane is modeled:</u>

- Coefficients
  - Restoring forces (ex: C_{m_α})
  - Damping forces (ex: C_{m_q})



1. Flying Qualities Test

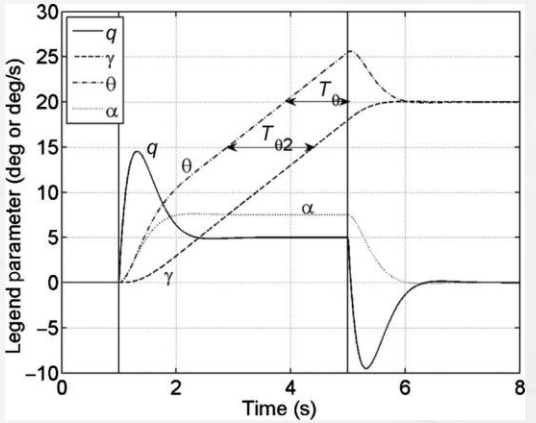
- Stability
  - Trim *really* well
  - Some disturbance from trim
  - Record aircraft response
  - FTTs: Raps, steps, doublets
- Responsiveness
  - Start at specific condition
  - Apply exact control input
  - Record response
  - FTTs: Rolls, steps

1. FQ Flight Test Technique Examples

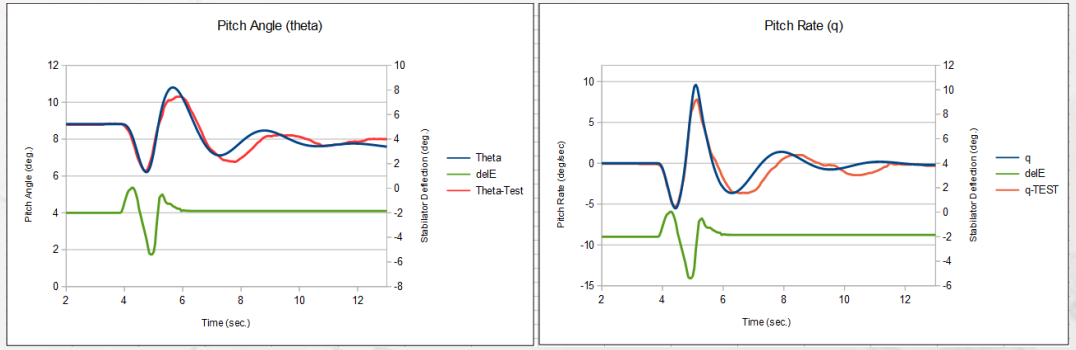
- Pitch investigation (i.e. longitudinal axis)

Desired Flying Quality	Flight Test Technique
Time delay (initial)	Rap
Time to steady state rate	Step
Damping ratio	Doublet
Natural frequency	Doublet
Elevator power	Step
Crossover frequency	Sweep
And more…	

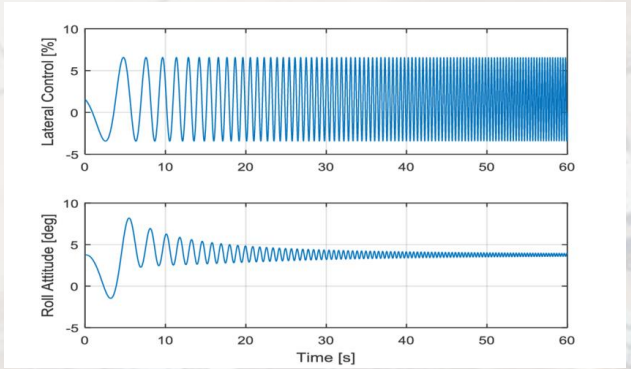
Ex: Step + Hold

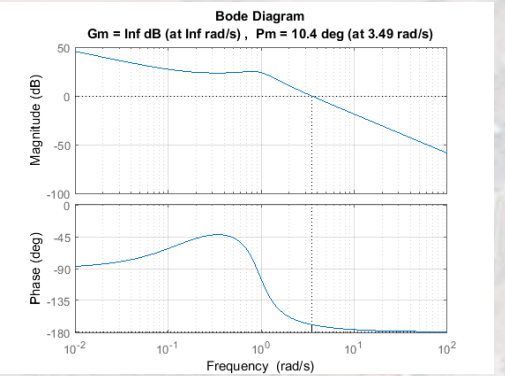


Ex: Doublet



Ex: Freq Sweep -> Bode Plot





1. Flying Qualities – Levels of stability/responsiveness

Flying Qualities | PIO | Handling Qualities | Mission Capability

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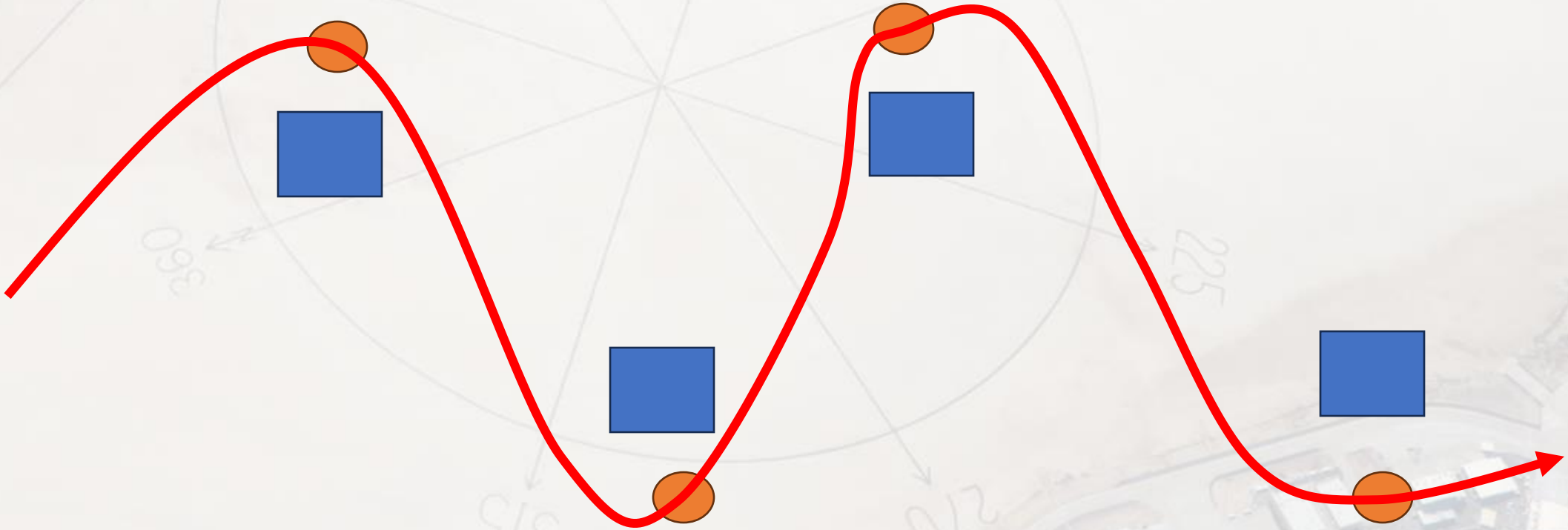
KS-3000

- Must be able to pop 4 balloons on obstacle course within 10”



1. Flying Qualities Test – Demo 1

- *Scooter shall be able to pop balloons on obstacle course.*

- Delays?
- Damping?
- Oscillations?
- Non-linear response?
- Fast or slow response?

2. Pilot Induced Oscillation (PIO) Susceptibility: "Pilot in the loop"

- Which is easier to drive through at 70mph? Why?
  - Same car, same size lane, same speed

2. PIO Susceptibility

- Now pilot is “in the loop”
- We want to artificially increase the “stress” on the pilot to see if it might oscillate
- How?
  - Workload buildup
  - Switch-induced Simulated PIO

2. PIO Susceptibility

- Fundamentally: PIO occurs when pilot inputs are *out of phase* with response of aircraft
- Culprits:
  - **Delays in system**
  - Rate limiting
  - Non-linear response
  - Deadband
  - More...

2. PIO Susceptibility

Note the tails

2. PIO Susceptibility – Demo 2

- Does it oscillate with a disturbance?
- Is the oscillation divergent?
- Is the frequency high or low?
- Is the magnitude of deviations high or low?

- Workload buildup
- SISPIO

	Too low	Operating range	Too high
Large response			
Small response			

Day 1 Recap

- Handling qualities: Can I do the task with minimal compensation?
- 1) Bare airframe:
  - Model vs. Testing
  - Delays? Stability? Responsiveness?

- 2) Will it oscillate?
  - Pilot in the loop
  - Stressed
  - Frequency + magnitude

Next time: Can I do the job??

Day 2: Handling Qualities

What is “compensation”?

Handling Qualities Day 2

- ROE: Ask questions and (hopefully) learn something!

- Recap:
  - Bare airframe (“Flying qualities”)
    - Stability vs. Responsiveness
    - Model vs. Reality -> Predict…test…validate
  - Pilot in the loop
    - Undesirable/uncontrollable oscillations
    - Gain + frequency
  - KS-3000 testing complete
    - No delays, linear response, possible oscillation

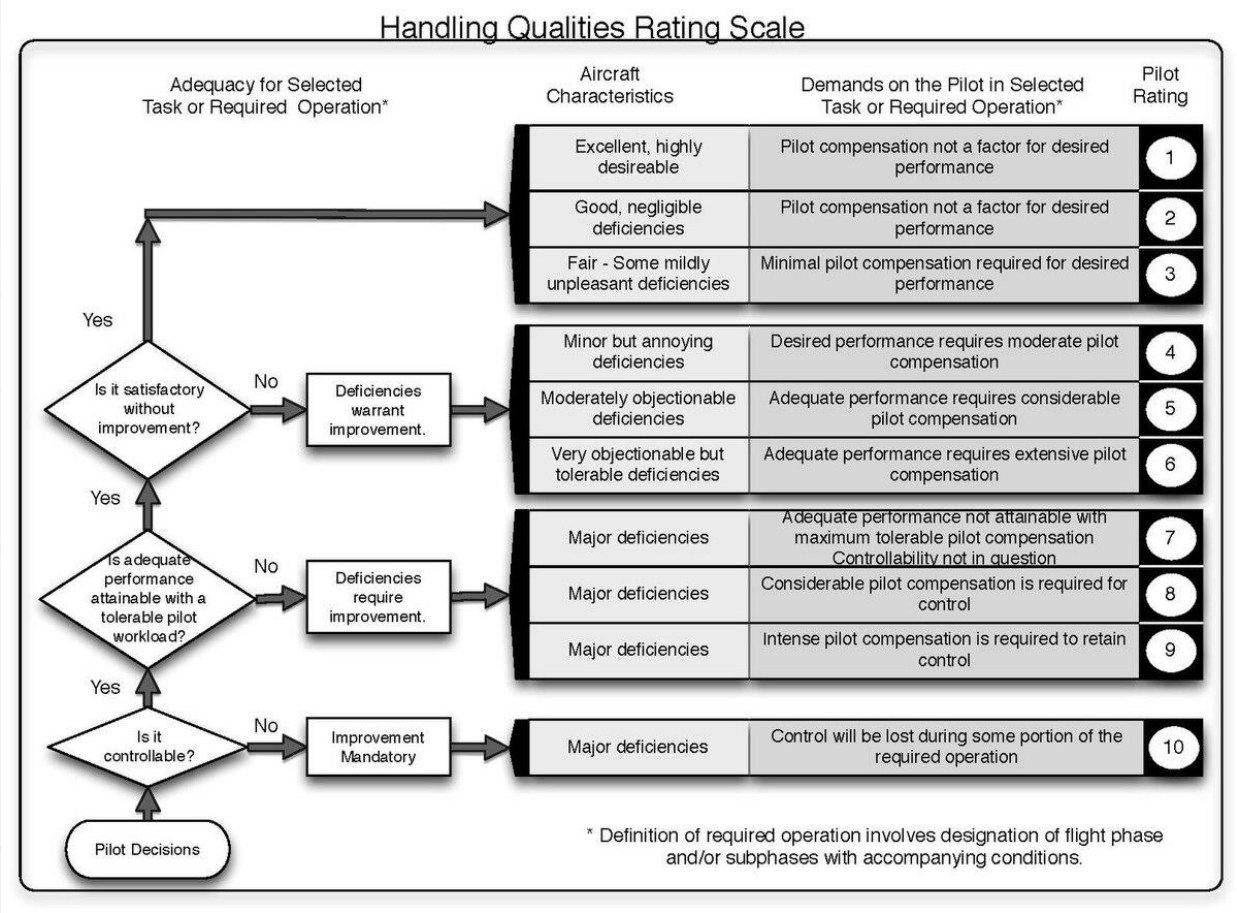
3. Handling Qualities – "Can it do *a task?*"

- Can it do basic tasks that build up to real thing?
- Cooper-Harper Rating Method

- Build-up approach
  - Start small + safe
  - Simplified tasks to mimic real tasks
  - Get more aggressive + dangerous once safely done
  - Predict…verify…progress

3. Handling Qualities

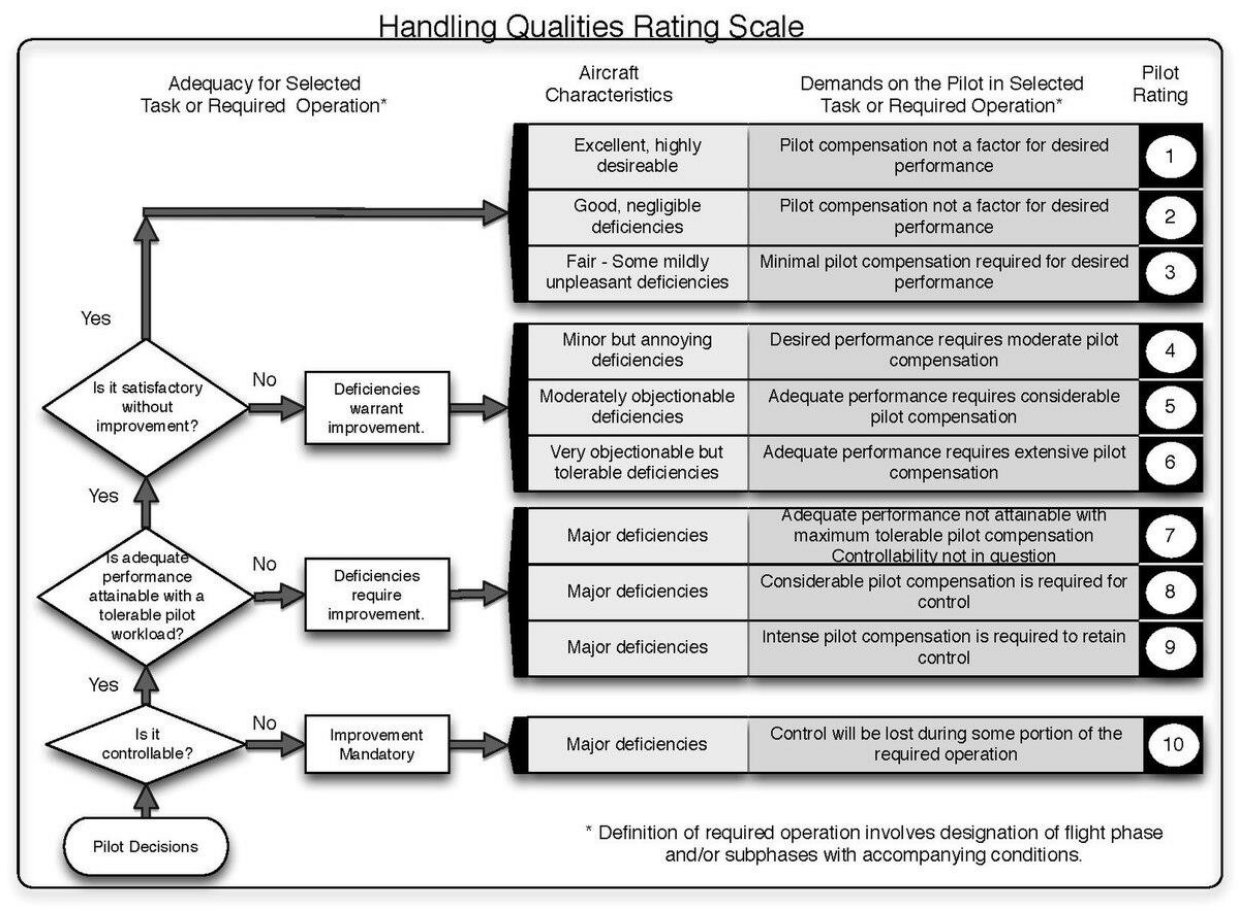
- Example:
  - Start in a 3* nose low flight path configured for landing
  - Then capture a level reference point within ½ second
  - Hold for 3 seconds
- “Grading” criteria
  - Adequate vs. Desired



Flying Qualities | PIO | Handling Qualities | Mission Capability

3. Cooper-Harper Rating Scale

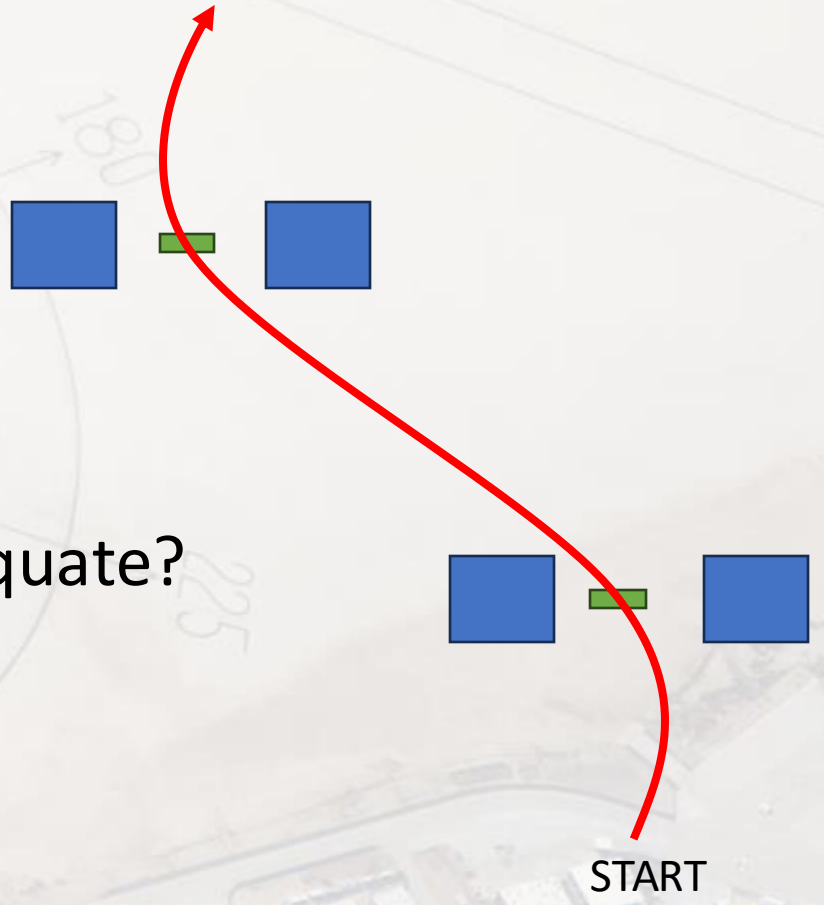
- Do the task
- “Grading” criteria
  - Adequate vs. Desired
- Run scale ASAP
- Level 1, 2, 3
  - 1: Desired Performance
  - 2: Adequate Performance
  - 3: Controllable



Flying Qualities | PIO | Handling Qualities | Mission Capability

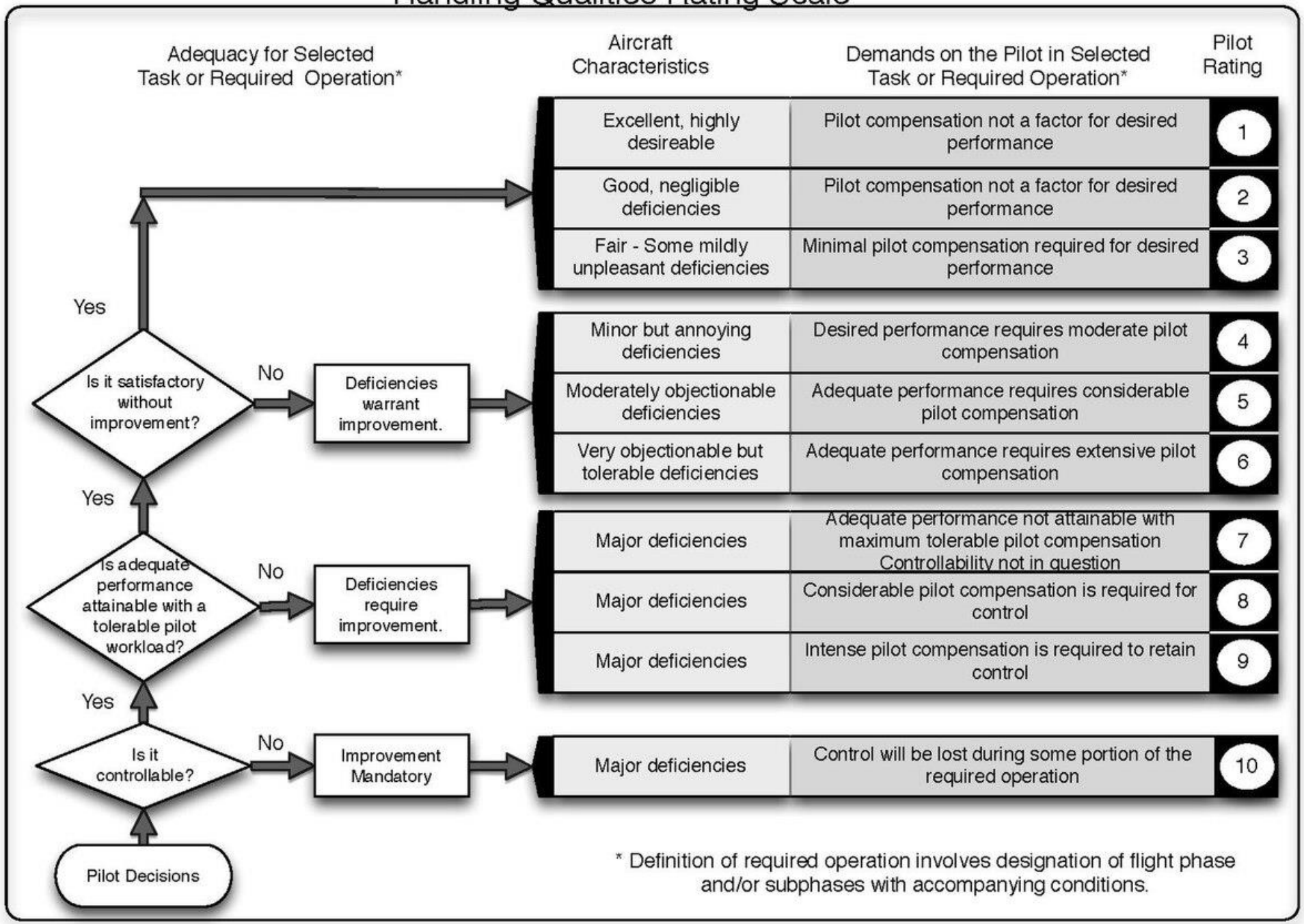
3. Handling Qualities – Demo 3

- Go around 2 cones in under 5”
- Adequate: Do not hit cones
- Desired: Nose wheel within designated area



- Can you achieve desired performance? Adequate?
- Did you have to compensate?
- How hard did you have to work?
- Learning? Repeatability?

Handling Qualities Rating Scale



4. Mission Capability

- Do the actual job
- Operational test vs. Developmental Test
- Ensure the capability/aircraft
  - Meets specification
  - Meets the warfighter's needs

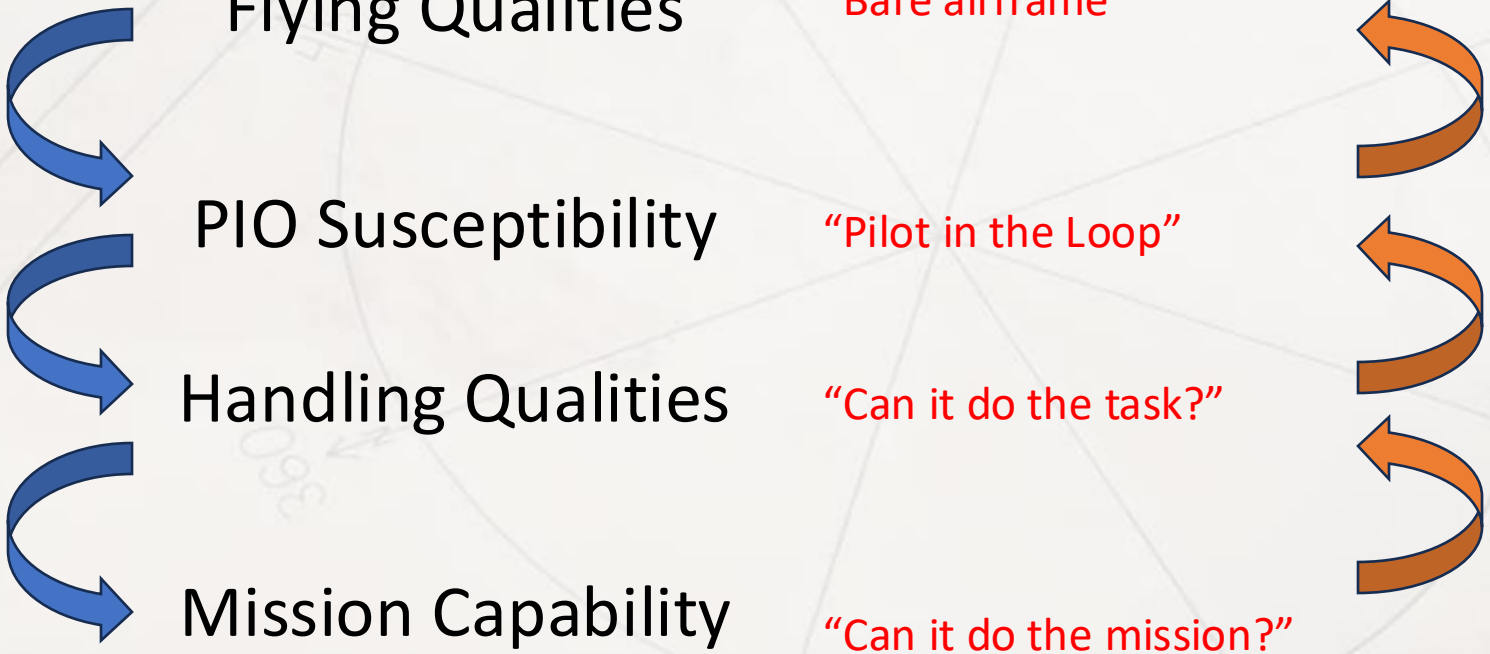
4. Mission Capability

- Case study 1:
  - Extremely high control forces required
  - Unstable in certain regimes
  - Very difficult to fly precisely
  - Requires assistance of chase airplane to land
  - Does not meet several criteria for adequate flying qualities

4. Mission Capability

- Case study 2:
  - State of the art stability and control system
  - Stable in entire flight regime
  - Pilots highly rate handling qualities
  - Well-tuned control forces
  - Meets almost every objective FQ/HQ criteria in the book

Putting it all together!

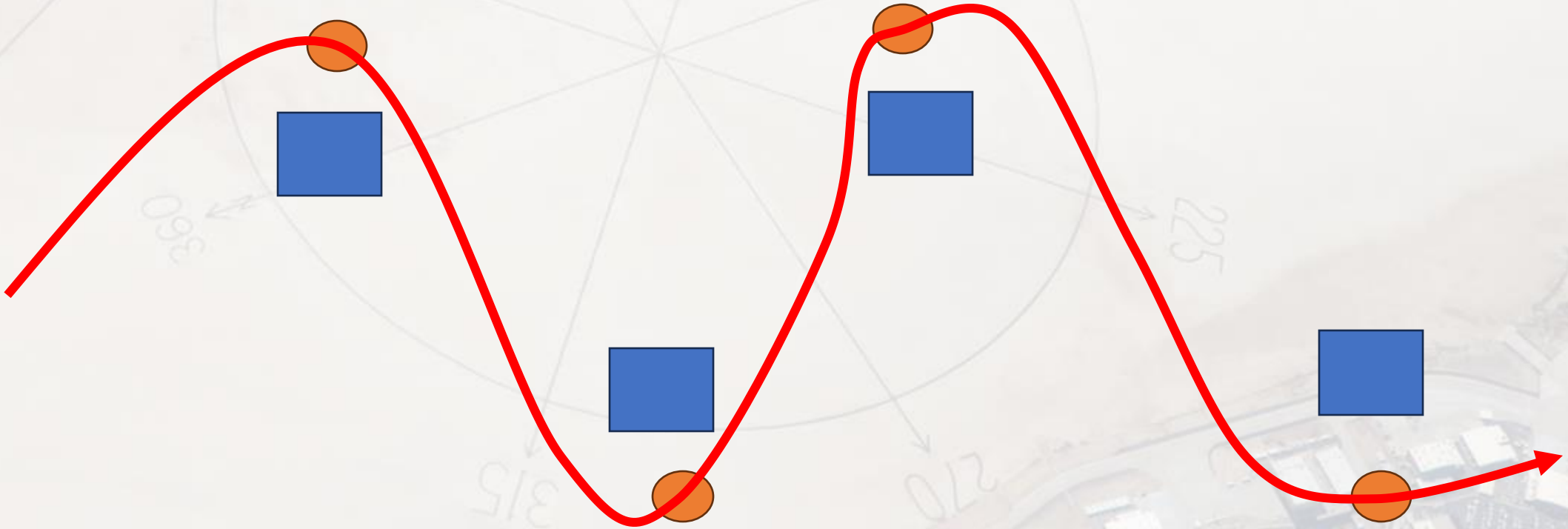


- Delays and light pitch damping
- Small oscillations on fine pitch tracking exercises
- Some deficiencies in pitch tracking
  - Level 2 Handling Qualities
- F-35A strafe not effective

Flying Qualities → PIO → Handling Qualities → Mission Capability

4. Mission Capability – Demo 4

- Can you do the job?
- Must be able to pop 4 balloons on obstacle course within 10”



Flying Qualities → PIO → Handling Qualities → Mission Capability

You found a deficiency – now what??

When you have bad handling qualities…

1. Fix the airplane
   - Time and $$$$$
   - Band-aid or redesign??
2. Limit the airplane
   - *Thou shalt not do…*
   - See “Limitations” section in flight manual
3. Train the pilots
   - Compensation for defects
   - $$$$$$$$$$$$$$$$
   - May never get to desired performance

Why should you care?

- Understand why limitations in place
  - “Every limitation is written in blood…”
- Cessna 172 to F-22 to 787…
  - Same methodology!
- Buildup approach
  - Start basic
  - Expand complexity/risk
  - Analyze performance along the way
  - Validate performance

Story time?

1. F-35B/C Aerial refueling
2. T-38 Nosewheel steering
3. F-35 AoA for landing

Questions?