Flying and Handling Qualities

Prof. Leo Torres

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Section 1

Flying Qualities Overview

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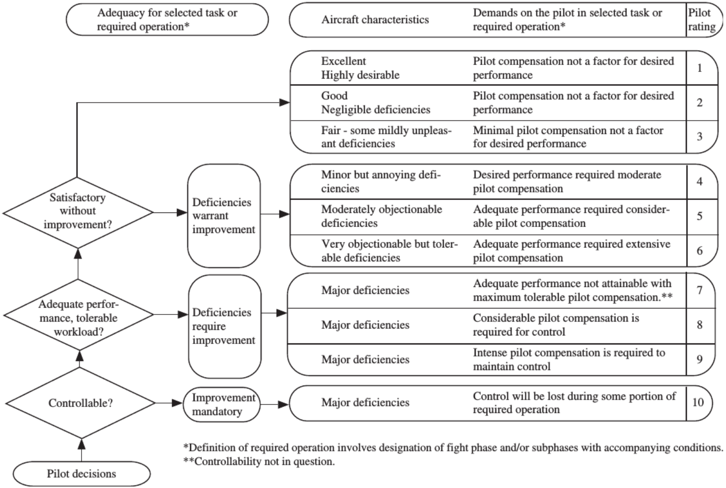
How to translate Pilot's Opinions to Engineering Requirements?

The Cooper-Harper Scale I

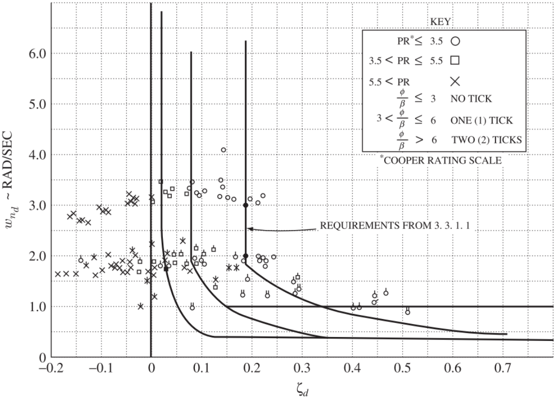
- It is also known as Handling Qualities Rating (HQR) ou Pilot Rating (PR).
- Scores ranging from 1 to 10:
  - **1**: pilot compensation not a factor.
  - **2 – 4**: moderate compensation for satisfactory performance.
  - **5 – 7**: from "considerable compensation" to "maximum tolerable compensation".
  - **8 – 10**: aircraft controllability is questionable.

The Cooper-Harper Scale II



The Cooper-Harper Scale III

- Statistical analysis: various pilots, same aircraft, same mission and flight phase.
  Example: Dutch-roll damping ratio and natural frequency.



The Cooper-Harper Scale IV

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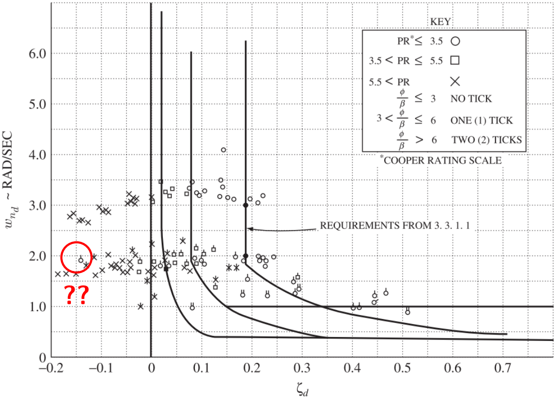


The Cooper-Harper Scale V

- It is possible to establish a relation between the HQR and the **Flying Qualities Levels** defined in the military norm MIL-F-8785C:
  - **FQ Level 1:** HQR from 1 to 3.5: adequate for the flight phase in a given mission.
  - **FQ Level 2:** HQR from 3.5 to 6.5: good, but increased pilot's workload and degradation in mission effectiveness for the given flight phase.
  - **FQ Level 3:** HQR from 6.5 to 10: the aicraft can be safely piloted, but with excessive pilot's workload and/or degraded mission effectiveness. Category A flight phases can be safely ended, and Categories B and C phases can be completed.

  The continuous lines in the previous figure are boundaries to areas dividing the chart in different Flying Qualities Levels.

Section 2

Specifications and Standards: MIL-F-8785C and MIL-STD-1797A

The norm MIL-F-8785C I

- The military North American norm **MIL-F-8785C** is the most well-known document where quantitative performance criteria for piloted aircraft can be found.
- Quantitative Handling Qualities specifications are based on the decomposition of the aircraft movement in Longitduinal and Lateral-directional dynamics, and modal approximations for the corresponding Transfer Functions.
  - Longitudinal:
    1. Phugoid mode.
    2. Short-period mode.
  - Lateral-directional:
    1. Dutch roll mode.
    2. Roll subsidence mode.
    3. Spiral mode.

The norm MIL-F-8785C II

- The norm has objective and subjective requirements:
  - **Objective**: using reduced order models for the Aircraft local linear dynamics via dynamic modes elimination, specific parameters are defined that correspond to Poles and Zeros of Transfer Functions.
  - **Subjective**: used when the objective ones would be too variable in practice, and to precisely quantify them would make the requirements unduly restrictive.
    Examples found in the norm:
    - "Objectionable flight characteristics"
    - "Realistic time delay"
    - "Excessive loss of altitude or buildup of speed"
    - "Normal pilot technique"

The Standard MIL-STD-1797A

- The norm MIL-F-8785C frequently leads to conflicting design parameters. It is usual in such situations to adopt the Standard MIL-STD-1797A instead.
- In the standard one can find many instances where "shall" was replaced by "should", and this relaxation is very important for Aircraft manufacturers that are pursuing a new development contract.

MIL-F-8785C: Basic Concepts and Definitions I

1. There are 4 Aircraft classes:
   - **Class I**: Small, light airplanes.
   - **Class II**: Medium weight, low-to-medium maneuverability airplanes.
   - **Class III**: Large, heavy, low-to-medium maneuverability airplanes.
   - **Class IV**: High-maneuverability airplanes.

   In addition, letters L or C are also added to indicate if the airplane is Land-based or Carrier-based. Ex.: II-L, II-C, etc.

MIL-F-8785C: Basic Concepts and Definitions II

2. There are 3 categories for Flight Phases:
   - **Category A**:
     - Nonterminal.
     - Require rapid maneuvering, precision tracking, or precise flight-path control.
     - Exemplos: Air-to-air combat (CO), Ground attack (GA), In-flight refueling (receiver) (RR), Formation Flying (FF).
   - **Category B**:
     - Nonterminal.
     - Normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required.
     - Exemplos: Climb (CL), Cruise (CR), Descent (D).

MIL-F-8785C: Basic Concepts and Definitions III

- **Category C**:
  - Terminal.
  - Normally accomplished using gradual maneuvers and usually require accurate flight-path control
  - Exemplos: Take-off (TO), Catapult Takeoff (CT), Approach (PA), Wave-off/Go-around (WO), Landing (L).

MIL-F-8785C: Logintudinal Dynamics Criteria I

- Longitudinal Static Stability
  - Levels 1 and 2: no divergence with fixed or free controls.
  - Level 3: if unstable, time to double the amplitude due to a perturbation $T_2 > 6\,\mathrm{s}$.
- Phugoid mode:
  - Level 1: $\zeta_{\mathrm{ph}} > 0.04$.
  - Level 2: $\zeta_{\mathrm{ph}} > 0$.
  - Level 3: $T_2 > 55\,\mathrm{s}$.
- Short-period Mode (damping ratio ζ_{SP}):

	Category A & C Flight Phase		Category B Flight Phase	
Level	Minimum	Maximum	Minimum	Maximum
1	0.35	1.30	0.30	2.00
2	0.25	2.00	0.20	2.00
3	0.15	–	0.15	–

MIL-F-8785C: Logintudinal Dynamics Criteria II

- Flight Path Stability: During the PA flight phase, considering that the speed is controlled by the flight path angle γ (by changing θ, without changing the thrust command), the slope of the curve $\gamma \times V_\mathrm{T}$ shall be negative, or smaller than
  - Level 1: < 0.06 [deg/knot].
  - Level 2: < 0.15 [deg/knot].
  - Level 3: < 0.25 [deg/knot].

MIL-F-8785C: Logintudinal Dynamics Criteria III

- Short-period Mode Natural Frequency $\omega_{n\mathrm{sp}}$: The equivalent short-period undamped natural frequency shall be within the limits shown in charts of $\omega_{n\mathrm{sp}} \times \left(\frac{n}{\alpha}\right)$ for each flight phase category, where n is the Load Factor:

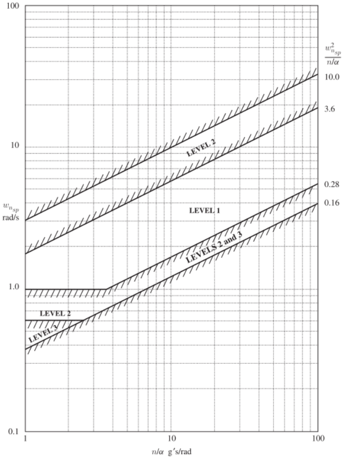
$$n = \frac{L}{W}$$

with L the lift force, and W the weight force, such that

$$\frac{n}{\alpha} \approx \frac{\partial n}{\partial \alpha} = n_\alpha = \frac{1}{W}\frac{\partial L}{\partial \alpha} = \frac{C_{L\alpha}}{W}.$$

The reason for using n/α is its correspondence with an expected **Zero in the transfer function $Q(S)/\Delta_{\mathbf{e}}(s)$ (pitch rate from elevator deflection)**, using a short-period approximation, that correlates well with Pilots opinions.

MIL-F-8785C: Logintudinal Dynamics Criteria IV



Example for Cat. A flight phases.

Short-period approximation:

$$\frac{Q(S)}{\Delta_e(s)} \approx \frac{G_{dc}\left(s - n_\alpha \frac{g_0}{V_T^*}\right)}{s^2 + 2\zeta_{sp}\omega_{nsp}s + \omega_{nsp}^2}$$

$$n_\alpha \approx \frac{n}{\alpha}$$

The Zero in this transfer function can change significantly the Percent Overshoot for step responses.

MIL-F-8785C: Lateral-directional Criteria I

- Dutch-roll damping ratio ζ_d and natural frequency $\omega_{\mathrm{n}d}$:

Level	Flight Phase category	Class	Min $\zeta_d{}^a$	Min $\zeta_d \omega_{n_d}{}^a$ rad/s	Min ω_{n_d} rad/s
	A (CO and GA)	IV	0.4	–	1.0
	A	I, IV	0.19	0.35	1.0
		II, III	0.19	0.35	0.4^b
1	B	All	0.08	0.15	0.4^b
	C	I, II-C, IV	0.08	0.15	1.0
		II-L, III	0.08	0.10	0.4^b
2	All	All	0.02	0.05	0.4^b
3	All	All	0	0	0.4^b

[a]The governing damping requirement is that yielding the larger value of ζ_d, except that ζ_d of 0.7 is the maximum required for Class III.
[b]Class III airplanes may be excepted from the minimum ω_{n_d} requirement, subject to approval by the procuring activity, if the requirements of *3.3.2* through *3.3.2.4.1*, *3.3.5*, and *3.3.9.4* are met. When $\omega_{n_d}|\phi/\beta|_d$ is greater than 20 (rad/s)^2, the minimum $\zeta_d\omega_{n_d}$ shall be increased above the $\zeta_d\omega_{n_d}$ minimums listed above by:

Level 1 – $\Delta\zeta_d\omega_{n_d} = 0.014(\omega_{n_d}|\phi/\beta|_d - 20)$
Level 2 – $\Delta\zeta_d\omega_{n_d} = 0.009(\omega_{n_d}|\phi/\beta|_d - 20)$
Level 3 – $\Delta\zeta_d\omega_{n_d} = 0.004(\omega_{n_d}|\phi/\beta|_d - 20)$
with ω_{n_d} in rad/s.

MIL-F-8785C: Lateral-directional Criteria II

- Roll subsidence mode time constant τ_{rs}, in seconds:

Flight Phase category	Class	Level		
		1	2	3
A	I, IV	1.0	1.4	
	II, III	1.4	3.0	
B	All	1.4	3.0	10
C	I, II-C, IV	1.0	1.4	
	II-L, III	1.4	3.0	

MIL-F-8785C: Lateral-directional Criteria III

- Spiral mode: minimum time to double the amplitude, in seconds, following an initial perturbation of up to 20 degrees in bank:

Flight Phase category	Level 1	Level 2	Level 3
A and C	12	8	4
B	20	4	4

MIL-F-8785C: Lateral-directional Criteria IV

- Roll-Spiral coupled oscillation: sometimes, instead of two real eigenvalues, the Local Linear Model will exhibit a pair of complex conjugate poles that represents a mode of response combining the roll subsidence and spiral modes.
  In flight phases demanding more aggressive maneuvers, such as CO and GA, there shall not be this oscillatory mode of response.
  However, for Cat. B and C flight phases (gradual maneuvers), this is allowed as long as the product $\zeta_{\mathrm{rss}}\omega_{\mathrm{n\,rss}}$ is below the indicated limits:

Level	$\zeta_{\mathrm{rss}}\omega_{\mathrm{n\,rss}}$ upper limit
1	0.5
2	0.3
3	0.15

MIL-F-8785C: Lateral-directional Criteria V

- Roll-control effectiveness: time taken to reach a certain desired bank angle after a step input in the roll command.
  Below an example for Classes I and II aircraft. There are other tables for other classes and specific flight phases that define the required roll performance:

Time to achieve the following bank angle change (seconds)							
		Category A		Category B		Category C	
Class	Level	60	45	60	45	30	25
	1	1.3		1.7		1.3	
I	2	1.7		2.5		1.8	
	3	2.6		3.4		2.6	
	1		1.4		1.9	1.8	
II-L	2		1.9		2.8	2.5	
	3		2.8		3.8	3.6	
	1		1.4		1.9		1.0
II-C	2		1.9		2.8		1.5
	3		2.8		3.8		2.0

Section 3

Other Criteria

Additional Criteria

- In this Section we will briefly comment on other parameters that have been considered relevant to extract quantitative criteria for piloted Aircraft whose satisfaction can potentially lead to good Pilot Ratings (PR/HQR).
- More details can be found on [3, Section 4.3].

Poles e Zeros

- Short-period Poles:

$$0.4 < \zeta_{\mathrm{sp}} < 1.0; \qquad 2.4\,\mathrm{rad/s} < \omega_{\mathrm{sp}} < 3.8\,\mathrm{rad/s}.$$

- Dutch-roll almost Zero/Pole cancellation:

$$\frac{\omega_\phi}{\omega_{\mathrm{dr}}} \approx 1, \qquad \frac{\omega_\phi}{\omega_{\mathrm{dr}}} > 1,$$

where ω_ϕ is the natural frequency for the pair of complex conjugate Zeros (numerator polynomial), and ω_{dr} is the Dutch-Roll Poles natural frequency (denominator polynomial).

Frequency Response Specifications I

- **Target Closed-loop Frequency Response:** For example, the Local Linear Model response from changes in the stick force $f_{\mathrm{s}}(t)$ in [lbf] to pitch rate $q(t)$ in [rad/s]:

$$\frac{Q(s)}{F_{\mathrm{s}}(s)} \approx \frac{K(s+1/T_{\theta_1})(s+1/T_{\theta_2})e^{-\tau s}}{(s^2+2\zeta_{\mathrm{ph}}\omega_{\mathrm{ph}}s+\omega_{\mathrm{ph}}^2)(s^2+2\zeta_{\mathrm{sp}}\omega_{\mathrm{sp}}s+\omega_{\mathrm{sp}}^2)},$$

with specified parameters, such that $\tau < 10\,\mathrm{ms}$ for Flying Quality Level 1.

Frequency Response Specifications II

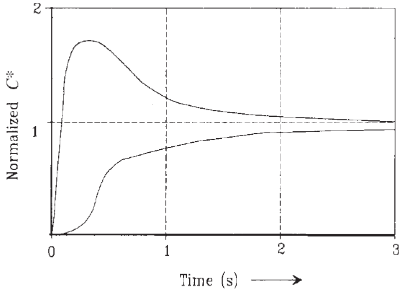
- Minimum **Gain and Phase Margins**: 6 dB and 30°, respectively, according to MIL-F-9490 – "General Specification for Flight Control Systems: Design, Installation, and Test of Piloted Aircraft".
  - Gain Margin: how much the system gain could be increased without destabilizing the system.
  - Phase Margin: how much additional delay can be introduced in the control-loop without destabilizing the system or deteriorating the transient response.

Time Response Specification

- **C-Star** ou $\mathbf{C}^*$: a special purpose output signal that can be used to evaluate Aircraft Flying Qualities:

$$C^*(t) = 12.4q(t) + a_z(t),$$

where q is the pitch rate in [rad/s] and a_z is the Normal Acceleration (in z-axis direction of the body-fixed reference frame) in [g]. For a step input in the elevator deflection, the response should be inside the following envelope, considering the **nonlinear model**:



Human Operator Models I

- For piloted aircraft an interesting idea in evaluating Flying Qualities is to introduce some mathematical representation of the pilot's behavior in the loop: Pilot in the Loop approach.
- This is quite important since it is known that in different occasions the pilot behavior can induce unstable dynamics: the so-called **Pilot Induced Oscillations** – PIO.

Human Operator Models II

A model that can be used to approximate human's behavior is the one relating the force felt by the pilot on the command stick:

$$\frac{F_\mathrm{s}(s)}{\Theta_\mathrm{e}(s)} = \frac{k_\mathrm{p}(\tau_l s + 1)e^{-T_\mathrm{delay} s}}{(\tau_\mathrm{i} s + 1)(\tau_\mathrm{m} s + 1)},$$

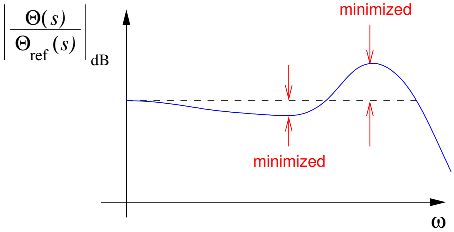
where

- $\Theta_\mathrm{e}(s)$ represents the error in the pitch angle;
- $F_\mathrm{s}(s)$ is the force applied by the pilot on the stick/column;
- $T_\mathrm{delay} \approx 0.3\,\mathrm{s}$ is the pilot's response delay time;
- τ_m is the muscles and limbs time constant (often neglected);
- k_p, τ_l and τ_i are **adaptive parameters** that a human being utilizes to adjust his/her performance[1].

[1] Interestingly, this corresponds to a well-known controller structure called Lead-Lag compensator

Human Operator Models: Neal-Smith Method

- In the Neal-Smith method one considers that the adaptive parameters of the mathematical representation for the human pilot will be adjusted such that the droop and the peak in the Transfer Function representing the closed-loop relation from the pitch reference $\theta_{\mathrm{ref}}(t)$ to the pitch angle $\theta(t)$ will be minimized:



- The "optimal" parameters k_{p}, τ_{l} and τ_{i} are then used to estimated what would be the HQR (Cooper-Harper) score.

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