DEVELOPMENT OF A HANDLING QUALITIES EVALUATION TOOLBOX ON THE BASIS OF GIBSON CRITERIA

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Abstract

Flight control system design is aimed at providing optimal handling qualities for all mission tasks of a particular aircraft over the entire flight envelope. Shaping the aircraft response such that precise task performance can be achieved with relative ease and low workload is not an easy task. There exist numerous design criteria that offer guidance in this process. A comprehensive set of criteria has been formulated by Gibson. In this paper, a handling qualities evaluation toolbox based on Gibson criteria was elaborated, which covers time domain represented by Dropback Criterion and frequency domain represented by Phase Rate Criterion and Gain Limit Criterion. The toolbox is capable of evaluating handling qualities of a fighter aircraft, by yielding some visual representations of the response characteristics. In addition, the toolbox is capable of improving the aircraft's handling qualities as well by using Gibson's methodology in which stick-to-surface feed forward gain and command path pre-filter are used as essential tools.

1 Introduction

1.1 Handling Qualities

Handling qualities is defined in Cooper and Harper [1] as 'those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform tasks required in support of an aircraft role'

Handling qualities relate directly to the ease with which a task can be performed. They describe the manner in which the aircraft responds both to the demands of the pilot and to the influence of turbulence, gusts, weapon release, airbrake, flap and undercarriage operation, reheat selection, engine failure, and other disturbances. Handling qualities depend not only upon aircraft characteristics but also upon the primary flight control, the visual and motion cues available, and the display of flight information in the cockpit. For most of aviation history, they have depended heavily on the basic aerodynamic stability and control, but in recent times they have become dominated by control augmentation effect in fly-by-wire control systems.

Handling qualities are difficult to specify because they inherently involve the quantification of pilot workload. A measure of handling qualities was made possible through the use of pilot opinion rating.

However, there is an overwhelming necessity for some sort of numerical description of handling qualities for use in engineering design and evaluation. It is very well established that the handling qualities of an aircraft are intimately dependent on the stability and control characteristics of the airframe including the flight control system when one is installed. Since stability and control parameters are readily quantified, these are usually used as indicators and measures of the likely handling qualities of the aircraft.

The key to the new framework was the definition of Levels of handling qualities. The definitions covered by levels of handling qualities are as follows,

Level 1: The handling qualities are completely adequate for the particular flight phase being considered.
Level 2: The handling qualities are adequate for the particular flight phase being considered, but there is either some loss in effectiveness of the mission, or there is a corresponding increase in the workload imposed upon the pilot to achieve the mission, or both.
Level 3: The handling qualities are such that the aircraft can be controlled, but either the effectiveness of the mission is gravely impaired, or the total workload imposed upon the pilot to accomplish the mission is so great that it approaches the limit of his capacity.

1.2 Pilot-Induced Oscillation

The introduction of fly-by-wire flight control systems has increased the potential of adverse interactions between pilot and the aircraft. This phenomenon was originally called *Pilot-Induced Oscillation (PIO)*. According to MIL-STD 1797 the meaning of PIO is stated as below,

PIOs are sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the aircraft.

Its origin is a misadaptation between the pilot and the aircraft during some task in which tight closed-loop control of the aircraft is required from the pilot, with the aircraft not responding to pilot commands as expected by the pilot himself. This term seems to blame the pilot as the cause of this phenomenon, which is actually not. A more rigorous analysis of the causes of PIO highlighted the fact that PIO are indeed caused by a poor design of flight control systems more than by pilot errors.

2 Gibson Handling Qualities Criteria

2.1 Time Response

Something happens to aircraft's dynamics as the pilot moves the stick. A time response history is an excellent graphical form to present and study aircraft's dynamics and handling information. A step is the simplest input in time domain response. The parameters which are usually evaluated in short period time responses are angle of attack (α), pitch acceleration ($\dot{q}$), pitch rate (q), pitch attitude (θ) and flight path angle (γ). The generic result of block type control input is shown in Figure 1.

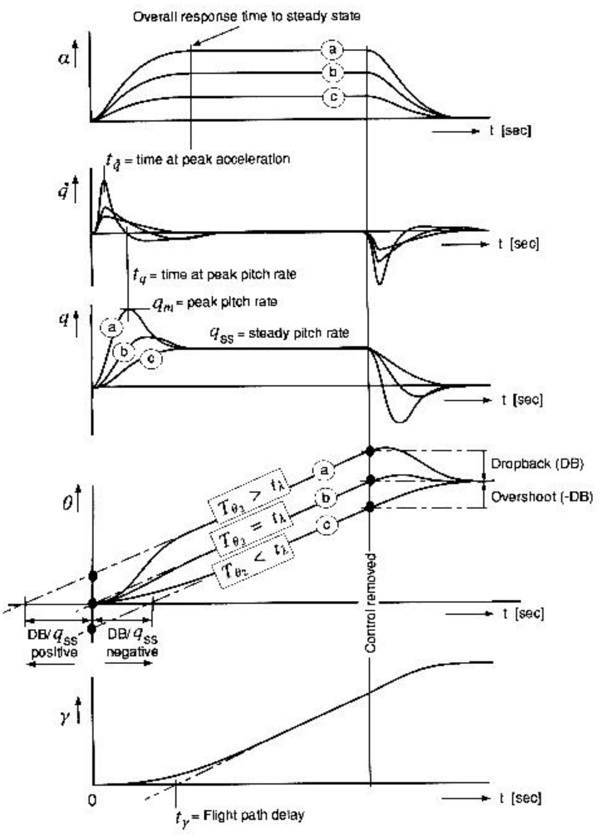

Figure 1: The generic result of block type control input (taken from [3])

In the time domain, Gibson has introduced two important criteria, i.e. Dropback Criterion and Flight Path Time Delay Criterion, which will be briefly explained here.

2.1.1 Dropback Criterion

The Dropback Criterion is defined in terms of limiting values on pitch rate overshoot ratio (q_m/q_{ss}) and the ratio of attitude dropback to steady state pitch rate (DB/q_{ss}). Those values indicate the quality of aircraft's response to the stick. Dropback is computed as the difference between the pitch attitude at the time the stick is released and the steady state pitch attitude after the stick is released. A positive value of this difference is referred to as dropback, while a negative value is called overshoot. Ideally, there should be no attitude dropback. When the attitude dropback is zero, the attitude time response tracks along the "K/s" line after the initial pitch rate is complete, hence it is said that the nose exactly follows the stick. Regions of typical pilot comments are defined in the criterion plane (q_m/q_{ss} versus DB/q_{ss}), which are shown in Figure 2.

Here, criterion mappings are related to qualitative descriptions of the response such as abruptness, sluggishness, and bobbling. Negative dropback is an indication of sluggishness, while large positive values of dropback indicate abrupt and bobbling tendencies.

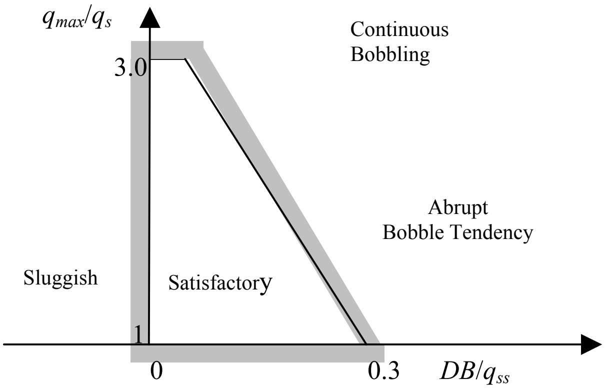

Figure 2: The boundaries of Dropback Criterion

Note that,

- if the pitch rate overshoot ratio $(q_m/q_{ss}) \leq 1$ then dropback is not possible and the lower part of “satisfactory” region cannot be attained.
- subsequent events have led Gibson to redefine the criterion such that zero dropback only is acceptable. The “satisfactory” region then collapses to (q_m/q_{ss}) axis and in the event this cannot be achieved precisely then it is better to err on the side of attitude dropback rather than overshoot.
- the acceptable values of pitch rate lies in the range of $1.0 \leq (q_m/q_{ss}) \leq 3.0$.

2.1.2 Flight Path Time Delay Criterion

The second time-domain criterion is flight path time delay. Flight path time delay (t_γ) is defined by the time delay of the second order short period motion oscillation. Flight path time delay, which is graphically defined as the intersection of the tangent of steady flight path angle to the time axis, can be determined from the flight path angle response to step input by taking the best fit tangent to the flight path angle response at around 4 seconds (See Figure 3).

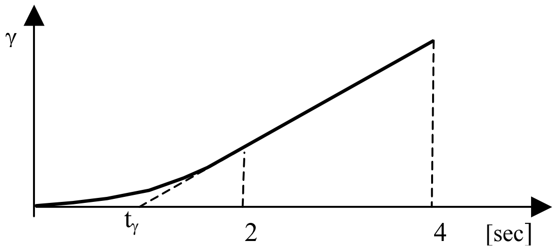

Figure 3: The Flight Path Time Delay Criterion

Basically, t_γ is a measure of the delay that is observed between stick input and a noticeable flight path response. Gibson in [2] suggests that for landing approach task, t_γ should not exceed 1.5 seconds generally and 1.0 second for precision control task.

2.2 Frequency Response

The Gibson's second approach was to determine boundaries of good handling based on the open loop attitude to stick force frequency responses of the research data.

2.2.1 Phase Rate Criterion

The phase rate criterion is concerned with the open loop attitude frequency response in the region around –180° attitude phase and is evaluated from a plot of the open loop attitude frequency response on the Nichols plot, as shown in Figure 4. Gibson found that attention should be focussed on the region around –180° attitude phase angle in order to investigate high order effects to handling qualities. The severity of the high order characteristics is related to the slope of the attitude response plot across the –180° phase angle line.

The frequency at –180° attitude phase angle, $\omega_{(-180°)}$, was also found to be significant because its possible role in triggering a landing PIO. It has also more general significance in indicating the physical possibility of large PIO amplitudes, as for a given pitch acceleration or control power the attitude response is inversely proportional to the square of frequency.

Gibson introduced a measure named the average phase rate. It is derived from the excess phase lag between the PIO frequency (the frequency at –180° phase angle) and twice of that frequency, as indicated in Figure 4.

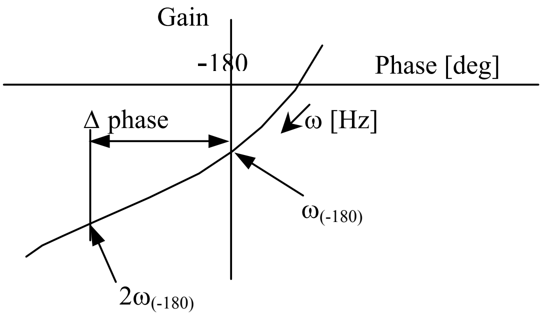

Figure 4: Definition of average phase rate

The definition of average phase rate is (See Figure 4):

$$Average phase rate = \frac{-\Delta phase angle}{\omega_{(-180)}} = \frac{-\left(\varphi_{2\omega_{(-180)}} + 180\right)}{\omega_{(-180)}} \text{ deg}/Hz \tag{1}$$

where $\omega_{(-180)}$ is expressed in Hz.

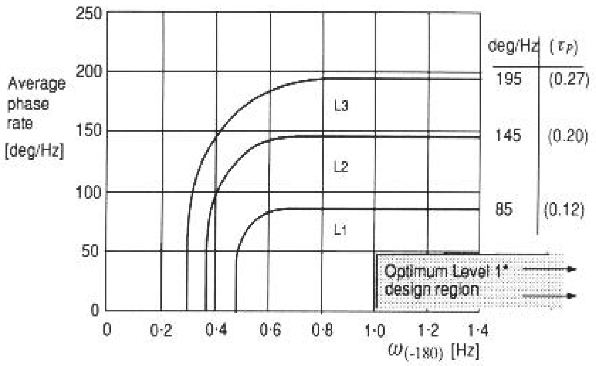

Figure 5: The boundaries of phase rate criterion (taken from [3])

The Phase Rate Criterion's boundaries dealing with PIO's level are illustrated in Figure 5.

2.2.2 Gain Limit Criterion

It was clear to Gibson that PIO occurred at a frequency very close to that at which the aircraft open loop attitude phase angle reached –180°, and the goal is to decrease the absolute gain of aircraft attitude response in this region.

In recent years Gibson used boundaries of Level 1, Level 2, and Level 3 on Nichols plot associated with PIO susceptibility. These Levels are basically determined by the absolute gain limits at the phase angle of –180°. The further outside the Level 1 limit boundaries that the response penetrates, the worse its PIO tendencies will be. The responses just within the Level 1 limits in all respects are unlikely to experience serious high order PIO. If a response falls within Level 2 region some PIO tendency might be encountered, but it is unlikely to be dangerous. For a response in Level 3, PIO susceptibility makes it dangerous. It was also noted in [2] that no PIO had been found where the attitude response gain at the PIO frequency was less than 0.1 deg/lb or –20 dB. Therefore he introduced the concept of an optimum design aim for handling qualities designated Level 1* (Level 1 star) which has the following limits:

- Maximum average phase rate of 50 deg/Hz, equal to phase delay of 0.07 seconds.
- Minimum attitude PIO frequency of 1.0 Hz.
- Maximum attitude to stick force gain of –20 dB or 0.1 deg/lb at the PIO frequency.
- Maximum attitude acceleration lag of 0.18 seconds in the time response.

Those boundaries compose "Gain Limit Criterion" as illustrated in Figure 6.

Some interpretation is necessary in the meaning of gain limits, as it can be the case that the response might be classed as Level 2 by its phase rate and frequency, but as Level 1 or Level 3 by the gain limit criterion. Gibson would interpret the effect as signifying better or worse PIO characteristics, so that any oscillations would be unlikely to diverge in the Level 1 gain example but would probably be divergent in the Level 3 gain example. The interpretation would be that the response should still be classed as Level 2 in the first case but must be downgraded to Level 3 in the second case.

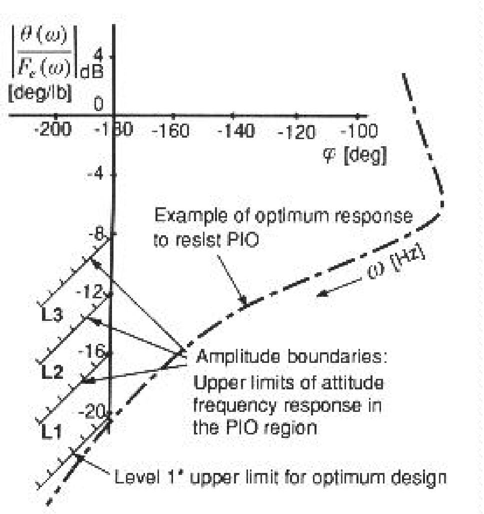

Figure 6: The gain limit criterion (taken from [3])

2.3 Sensitivity

Sensitivity in aircraft handling terms is a reference to a responsiveness of an aircraft relative to the inputs from the pilot. If the sensitivity is too high, the pilot will be unable to control with precision because the aircraft will over-react to the small inputs. On the other hand, if it is too low, the pilot must apply large physical motions or efforts to the stick to initiate a sufficiently rapid response and precision will again be diminished. With satisfactory sensitivity, the aircraft follows demands predictably and positively within a natural-seeming range of pilot effort.

The "Pitch Rate Sensitivity Criterion" by Sturmer [4] proposed upper and lower gain boundaries on pitch rate frequency response Nichols plots. Gibson, in [3], then extended this sensitivity criterion by the empirical observation that, at least for well damped highly augmented fly by wire response types, there is a reasonably good correspondence between the pitch rate gain at the bandwidth frequency and the gain of the initial peak of the pitch rate time response. The pitch rate sensitivity gain can readily be derived directly on the pitch attitude plot from the fact that, in simple harmonic motion, the peak rate equals the peak amplitude times frequency. Hence the addition of the frequency in radians per second (in dB) to the attitude gain point gives the pitch rate gain.

Pilot comments are consistent with proposed transient pitch rate sensitivity limits between 1.1 deg/sec/lb (or 0.83 dB) and 0.6 deg/sec/lb (or –4.44 dB) that stated in [3]. The upper gain limit marks the boundary of over sensitivity and the lower limit that of sluggishness.

Attaching pitch rate sensitivity boundaries to the frequency response Nichols plot makes it more integral to evaluate handling qualities of an aircraft.

2.4 Design for Good Pitch Handling

Gibson has developed methodology to the shaping of the time and frequency response dynamics to provide desired handling qualities. He used two essential tools for his method. The first tool is a direct stick-to-surface feed forward gain. The second one is a command path pre-filter.

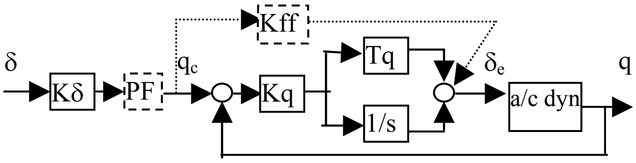

Figure 7: Pitch rate demand system with direct stick-to-surface feed forward gain and command pre-filter

2.4.1 Direct Feed Forward

What is meant by direct stick-to-surface feed forward here is a direct feed forward path from the pilot's inceptor to the control actuation. The augmentation of this feed forward path (See Figure 7) is aimed at giving the pilot direct connection with the aircraft response to maintain the feeling of positive control.

2.4.2 Command Path Pre-filter

The purpose of this command path pre-filter is to provide aircraft pitch attitude or flight path open loop responses that resemble the idealized *K/s*-like (zero dropback) dynamics as closely as possible, which cannot be provided directly by the basic feedback augmentation.

The basic form of pre-filter that should always be considered as the first option is a lead or lag pre-filter. A property of a step transient response is that the addition of a lag or lead filter to the input moves the intercept point of steady state response with the time axis by an amount equal to the added time constant, to the right for a lag and to the left for a lead. For zero dropback, the desired pre-filter time constants are taken as the flight path time delay in the basic unfiltered time response and the nominal $T_{\theta 2}$. Those time constants can be graphically obtained by intercepting from 2 and 4 seconds data points to the time axis. The choice of using these data points represents a time scale within which a settled response should be achieved and within a pilot's prediction capability.

The need for a lead or a lag filter is determined by whether the basic unfiltered response has attitude dropback or overshoot characteristics respectively.

3 Development of A Handling Qualities Evaluation Toolbox

Several handling qualities criteria, either in time domain or frequency domain, have been created by Gibson during the 1970s onwards, initially from studies of available flight research data, and then refined by direct experience in the development of several fighter aircraft projects. This chapter explains the development of a handling qualities evaluation toolbox on the basis of Gibson criteria. Since the toolbox is made based on Gibson criteria, it is named GATE, stands for Gibson Criteria-Applicated Toolbox for Evaluation.

3.1 Toolbox Functional Requirements

The handling qualities evaluation toolbox, GATE, are intended to cover time domain and frequency domain. The toolbox should be able to evaluate pitch handling qualities of a fighter aircraft, by yielding some visual representations of the response characteristics, given one of two types of aircraft model inputs, linear and nonlinear. In addition to evaluating the handling qualities of the aircraft, the toolbox should also be capable of improving the aircraft's handling qualities by using Gibson methodology, which uses stick-to-surface feed forward gain and command path pre-filter as essential tools.

3.2 Development of Algorithms for Criteria Application

The toolbox, which is made in MATLAB/Simulink environment, is basically divided into two parts, i.e. evaluation and design. Evaluation means evaluating the handling qualities of a given aircraft model based on Gibson criteria. Design means augmenting stick-to-surface feed forward gain and/or command path pre-filter in order to improve the handling qualities of a given aircraft model.

The aircraft model can be either linear or nonlinear model. The transfer function of pitch attitude with respect to elevator stick force is the input for linear model. The nonlinear model is a simulink model including trim data and linearisation routine. Linearisation is done for evaluating frequency-domain criterion, i.e. gain limit criterion and phase rate criterion.

The results of evaluation are time responses of pitch attitude, flight path, and pitch rate, and Gibson handling qualities criteria represented by dropback, gain limit, and phase rate criterion.

As explained before, Gibson methodology in designing a good pitch handling qualities uses feed forward gain and command path pre-filter as tools. The pre-filter used is a lead or lag pre-filter, $\frac{T_1 s+1}{T_2 s+1}$. This toolbox follows this methodology in improving handling qualities of an aircraft.

In this way, the toolbox allows the user to improve handling qualities of an aircraft simply by giving the input of three parameters. Those parameters are feed forward gain K_{ff}, pre-filter numerator time constant T_1, and pre-filter denominator time constant T_2. All responses of original aircraft and pre-filter and/or feed forward gain augmented aircraft are yielded in the same graphics to show improvement.

3.3 Development of Visualization Tools

This toolbox displays some windows, either for menus or graphics, as interface and visual representation to the user. The Graphical User Interface (GUI) is used for visualization of the toolbox.

3.4 Validation of the Toolbox

The toolbox is validated using Bjorkman configurations as linear model and HIRMplus model (a fighter aircraft model) as nonlinear model, where evaluation of both models using Gibson criteria have been reported in [5] and [6] respectively.

Table 1 shows the comparison of Average Phase Rate and PIO frequency (frequency at – 180° phase angle) of Bjorkman configurations resulted from the report [5] and from this toolbox. The results from this toolbox are shown in the shaded columns. It is obvious from Table 1 that the results from the toolbox are exactly the same as from the report.

Table 1: Validation of the toolbox using Bjorkman configurations as linear model

Conf.	Average Phase Rate [deg/s]	Frequency at 180 deg phase angle [rad/s]	Average Phase Rate [deg/s]	Frequency at 180 deg phase angle [rad/s]
2-1	39.38	6.17	39.38	6.17
2-5	169.08	2.33	169.08	2.33
2-8	138.36	3.54	138.36	3.54
3-1	42.74	10.19	42.74	10.19
3-12	228.49	2.23	228.49	2.23
3-13	200.97	2.89	200.96	2.89
5-1	38.00	5.05	38.00	5.05
5-9	187.02	2.47	187.02	2.47
5-10	258.28	2.10	258.28	2.10

▨ **results from the toolbox**

It is reported in [6] that the evaluation of the *HIRMplus* model with the following uncertainty parameters:

X_{cg} = -0.15 [m]
I_y = 0.05 [-]
Cm_α = 0.1 [1/rad]
$Cm_{\delta ts}$ = 0.04 [1/rad]
Cm_q = 0.1 [-]

results in **Level 1** handling qualities in terms of gain limit and phase rate criterion.

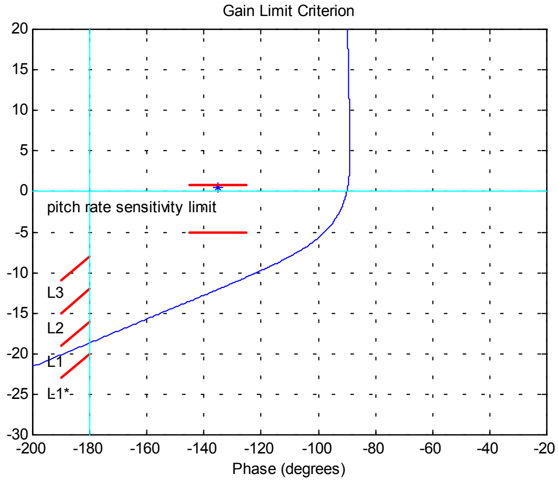

Figure 8: Gain limit criterion of HIRMplus nonlinear model

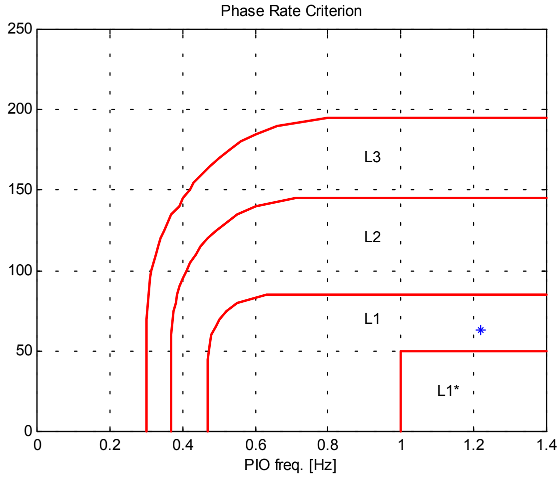

Figure 9: Phase rate criterion of HIRMplus nonlinear model

The result is used to validate this toolbox for nonlinear model. The evaluation of *HIRMplus* model, with the same uncertainty parameters, resulted from this toolbox are shown in Figure 8 and Figure 9 (indicated by star symbol). It can be clearly seen from these figures that the toolbox also predicts the *HIRMplus* model with the above uncertainty parameters as **Level 1** handling qualities in terms of gain limit and phase rate criterion.

4 Conclusion

A handling qualities toolbox, which is capable of evaluating and improving handling qualities of a given aircraft model, can be made on the basis of Gibson criteria. The toolbox was made in MATLAB/simulink environment. The given aircraft models, which are to be evaluated, may be linear model in the form of transfer function or nonlinear model in the form of block diagram in simulink model. Time responses of pitch attitude, flight path, and pitch rate are displayed as well as Gibson handling qualities criteria, i.e. Dropback, Gain Limit, and Phase Rate Criterion for evaluation of the handling qualities of an aircraft.

The handling qualities of an aircraft can be improved simply by augmenting stick-to-surface feed forward gain and command path pre-filter in the flight control system. A simple lag or lead filter can be used as command path pre-filter. In this way, three parameters, i.e. feed forward gain K_{ff}, pre-filter numerator time constant T_1, and pre-filter denominator time constant T_2 are sufficient for handling qualities improvement. Following this Gibson methodology, the toolbox allows the user to input these three parameters for improving an aircraft's handling qualities.

The toolbox has been validated using *Bjorkman configurations* as linear model, which had been evaluated using Gibson criteria and reported in [5]. For nonlinear model the toolbox has been validated using *HIRMplus* model, which had also been evaluated using Gibson criteria and reported in [6]. The same results given by the toolbox lead to a good validation.

References

[1] Cooper G.E. and Harper R.P. The use of pilot rating in the evaluation of aircraft handling qualities. *NASA TN D-5153*, 1969.

[2] Gibson J.C. Evaluation of Alternate Handling Qualities Criteria in Highly Augmented Unstable Aircrat. *AIAA-90-2844-CP*, 1990.

[3] Gibson J.C. *Development of a Methodology for Excellence in Handling Qualities Design for Fly By Wire Aircraft*, TU Delft, 1999.

[4] Sturmer S.R. Pitch Rate Sensitivity Criterion for Category C Flight Phases – Class IV Aircraft. *AIAA-86-2201*, 1986.

[5] McRuer D.T. Pilot_induced Oscillations and Human Dynamic Behavior. *NASA CR 4683*, 1995.

[6] Wilmes V.T. Clearance of HIRM+Ride Non-linear Augmented Aircraft Model: Standard Approach. *GARTEUR/TP-119-XX*, 2000.