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The Effects of Stick Force Gradient on Pilot Mental Demand

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Abstract

During the flying task, the control feel of an airplane with a reversible mechanical flight control system enables the pilot to perceived small changes in airspeed with pitch control force changes. Current certification specifications for light airplanes are subjective, requiring only that there be perceptible stick force change with airspeed (or stick force gradient) and the final judgement is left to the test pilot. No minimum stick force gradient for desirable control feel is specified. Previous flight testing of selected airframes in the course of this program of research, showed that stick force gradients vary between aircraft makes/models and phase of flight. Flying tasks performed by twenty general aviation pilots using a simulated light airplane with configurable stick force gradient showed that as the stick force gradient is reduced to zero, simulating an airplane with neutral static stability, pilot mental demand increased significantly ($p < 0.05$). The results have implications for current airplane operations and future airplane design.

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Nomenclature

| | | |
|-----------------|---|-------------------------------------|
| AGL | | height above ground level (feet) |
| $\frac{dP}{dV}$ | | stick force gradient (lbf/kt) |
| h | = | altitude above mean sea level (ft) |
| F | = | pitch control force feedback (lbf) |
| F_c | = | commanded pitch control force (lbf) |
| F_e | = | pitch control force error (lbf) |
| H_o | = | The null hypothesis |
| H_1 | = | The alternate hypothesis |
| IMC | | Instrument Metrological Conditions |
| LoC-I | | In-flight Loss of Control |
| R/H | | right-hand |
| s | = | Pitch control displacement (in) |
| SEP | | Single Engine Piston |
| V | = | indicated airspeed (kt) |
| V_c | = | commanded indicated airspeed (kt) |
| V_e | = | indicated airspeed error (kt) |
| VMC | | Visual Metrological Conditions |
| θ | = | observed pitch attitude (deg) |
| θ_c | = | commanded pitch attitude (deg) |
| θ_e | = | pitch attitude error (deg) |

I. Introduction

In its simplest form, the task of maintaining a steady, desired airspeed in a given flight condition in VMC may be considered as a compensatory tracking task¹, the pilot representing one component of the closed loop system the others being the airplane itself and the external environment. The interaction between the pilot and the airplane controls or control feel for an airplane with reversible mechanical controls is directly associated with the pitch control forces applied by the pilot and the haptic feedback sensed by the pilot's hands. Whilst the pilot is

controlling the flightpath (the airplane altitude, heading & airspeed), peripheral visual and haptic cues are used to sense airspeed changes and the pilot makes small adjustments to maintain the flightpath and desired airspeed (push to go faster - pull to go slower). The pilot is continuously sampling and selecting available visual, aural, motion and haptic cues, applying perception, making decisions and manipulating the pitch control whilst in a closed-loop. The majority of general aviation pilots are taught that attitude controls airspeed and engine power controls the rate of climb or descent. Current, subjective certification specifications for light airplanes² require only that there be perceptible stick force change with airspeed (stick force gradient) and the final judgement is left to the test pilot. The importance of pitch control feel and how it may be used to sense airspeed, to reduce workload and to improve situational awareness is understated in current flight training curricula^{3,4}.

This research is limited to the pitch axis only and considers the variation of airspeed, altitude and angle of attack where in most flight mode, a nose-down pitch input will decrease angle of attack, reduce the rate of climb/increase the rate of descent and increase airspeed. Conversely, a nose-up pitch input will usually increase the angle of attack, increase the rate of climb/reduce the rate of descent and reduce airspeed. As the pilot is flying the airplane and attempting to maintain the desired airspeed (Figure 1) if the airplane is subject to an external disturbance (e.g. vertical gust) the pilot will perceive a discrepancy between desired and actual airspeed as evidenced by the airspeed indicator.

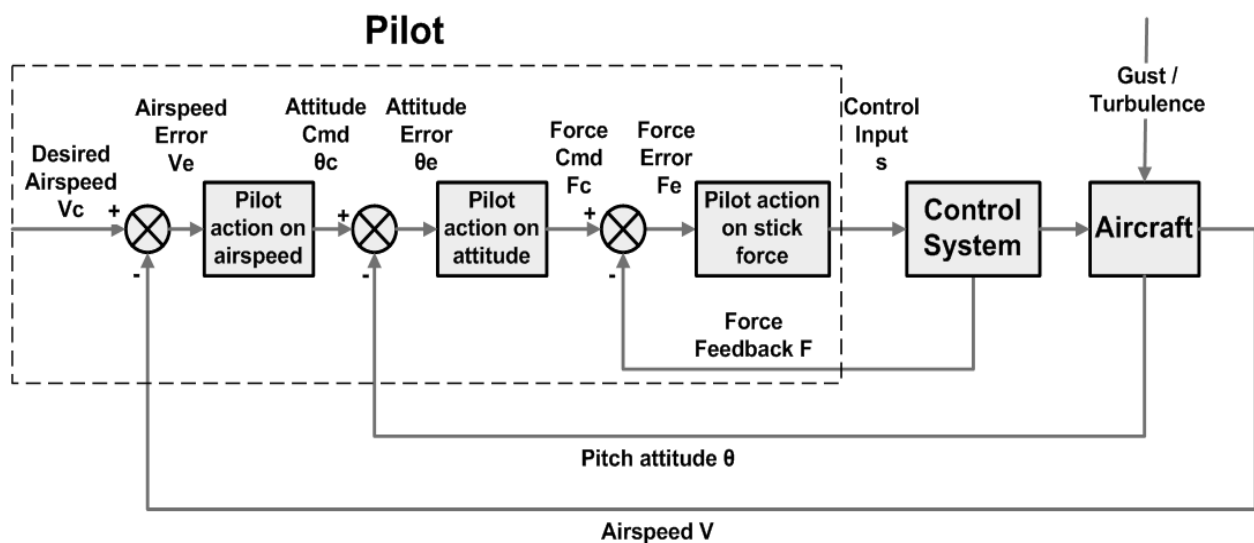


Figure 1. Pilot in the Loop during the Climb, adapted from Field & Harris⁵

The McRuer pilot in the loop model can be extended to include haptic cues and this may be represented as three nested loops:-

- an outer loop for the control of airspeed
- a middle loop for the control of pitch attitude
- an inner loop for the control of applied stick force.

Feedback is used continuously to track the desired airspeed but system time lags within the closed loop model mean that inner loop tactile stick force cues are sensed more quickly than either middle loop (external peripheral visual cues e.g. natural horizon) or outer loop (foveal visual cues e.g. cockpit airspeed instrument). The inner control loop (force) acts as a surrogate for pitch attitude and this in turn acts as a surrogate for airspeed management. The stick force gradient is used for precise and timely management of airspeed, essential for stall and LoC-I avoidance.

For the pilot of an airplane fitted with reversible mechanical controls, the response of the airplane to the pilot control inputs is directly dependent upon stability characteristics of the airplane⁶. The generally accepted relationship between stability and control suggests that pilot workload increases when stability is either too great or too small and that this corresponds with heavy or light control forces corresponding to high or low stick force gradients respectively (Figure 2).

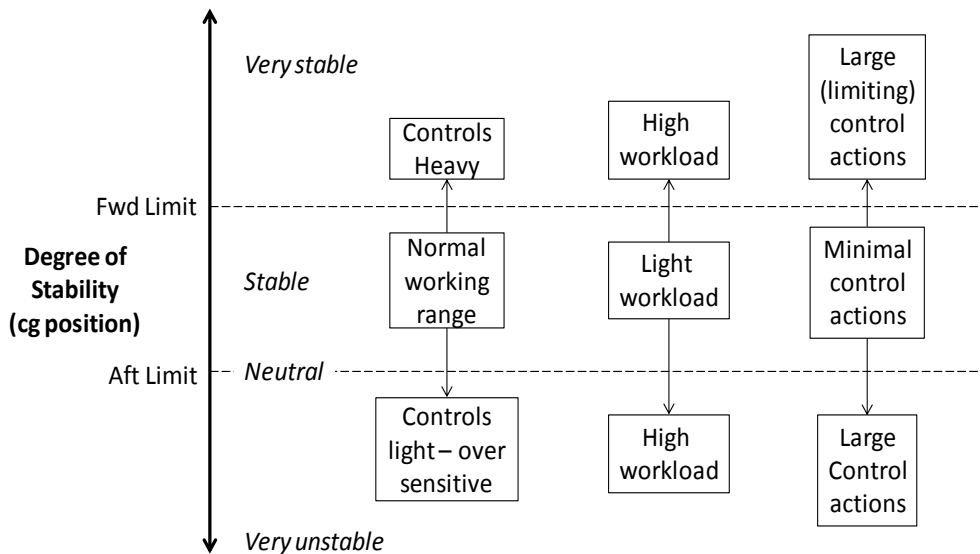


Figure 2. Stability & Control (Adapted from Cook⁶)

Previous, flight testing in light airplanes by experienced test pilots^{7,8} has shown that low stick force gradients can increase pilot workload (measured subjectively) and affect pilot performance and that this is most apparent in the landing condition when stick force gradients are lowest⁹. These previous studies utilising flight test in actual airplanes to evaluate handling qualities have been conducted by experienced test pilots. Test pilots possess exceptional piloting skills and experience and are dissimilar to the demographic group of General Aviation pilots. Previous studies have also been limited to small numbers of highly experience pilots with results of limited statistical significance. This use of flight simulation enables larger numbers of pilots, representative of the demographic group to safely participate in experiments and improving the likelihood of results of statistical significance though increased sample size. Although, previous simulation studies have been conducted¹⁰, these have not focussed specifically on the effects of stick force gradient on pilot workload in real-world scenarios.

II. Flight Simulation: The Effects of Stick Force Gradient on Pilot Workload

The lack of a targeted experimental program prompted the development a flight simulation experimental programme to evaluate the effects of stick force gradient on pilot workload.

Experimental Hypotheses

Two alternate hypotheses were proposed to gather additional research data with respect to the effects of stick force gradient on pilot workload:-

- The null hypothesis, H_o was that there is no change to the level of pilot workload as stick force gradient decreases;
- The alternate hypothesis, H_1 , was that pilot workload changes as stick force gradient decreases.

Experimental independent variables were stick force gradient and flying task and dependent variables were total pilot workload derived from associated sub-measures (mental demand, physical demand etc).

Participants

The hypotheses were evaluated using flight simulation tasks undertaken by a group of 20 volunteer GA pilots with a wide range of experience from PPL (88%) to CPL (8%) and ATPL (4%) and total hours ranged from 70 to 14,000+

with a median 222 hrs PIC. All pilots held a current medical certificate and most frequently flew single engine piston aeroplanes (96%) or 3-axis microlight (4%).

Experimental Apparatus

A fixed-base engineering flight simulator device was used to conduct all tests as this provided configurable control loading in pitch, roll and yaw using electrically driven torque motors. The external visual environment consisted of a 150° horizontal field of view by 40° vertical field of view, suitable for selected flying tasks based on the traffic pattern/circuit. The simulator used an approximate replica of an SEP cockpit with basic head down instrument panel, control stick, pedals, throttle, brakes, flaps and elevator trim. The system allowed stick force gradients to be software configured and dynamically calculated based upon control deflection generated by the flight model output. For this series of tests, the control loading software was configured to emulate a basic, linear stick force variation with elevator stick displacement and simulator data output was logged at a frequency of 5 Hz. A high-wing, low-tail aeroplane flight dynamics model based on the Cessna 172, was selected from library of available aeroplanes for all tests. Minor modifications were necessary to the basic instrument panel to provide indications of elevator trim position.

Method

The experimental method consisted of a pre-flight briefing for each pilot followed by execution of the individual simulation tasks and post-task workload assessment before moving onto the next test. Prior to commencing the tasks, all pilots received the same 10 minute pre-flight briefing containing information with regard aeroplane type, normal and emergency procedures, cockpit controls, instrumentation, radio telephony communication, airfield location and weather environment. All pilots were also briefed in the use of the basic, un-weighted NASA-TLX method¹¹ for the assessment of workload. NASA-TLX was selected for the assessment of GA pilot workload in preference to Cooper-Harper¹² since this method is more suited to trained test pilots and only provides subjective measurement of pilot compensation. NASA-TLX is straightforward to use, un-obtrusive and provides additional levels of assessment detail via drill down into sub-scale measurements where needed. The subjective ratings assessment enables total workload to be derived from the mean scores of the sub-scales (mental demand, physical demand, temporal demand, own performance, effort and frustration). NASA-TLX provided a means to measure compensation workload and task workload¹³ but since all of the tasks performed by the same pilots with each different stick force gradient were the same, the task workload can be considered 'constant' with variations in workload due to compensation differences alone. To avoid interference with the primary flying task and associated workload, basic, un-weighted NASA-TLX was used in a simple question and answer format after completion of each task using radio-telephony communication between test supervisor and the volunteer pilot situated in the cockpit environment. This enabled all post-task assessments to be completed within 2 minutes and minimal distraction from the primary flying task. Weighted NASA-TLX requires more time to complete and was therefore not utilised for this series of experiments for expediency.

Two contrasting stick force gradients were configured for the flight simulation tests, Gradient 1- representing a ‘zero’ stick force gradient and Gradient 2 – representing a moderate stick force gradient of 1 lbf per 6 kt, comparable with existing FAR Part 25.175 certification specifications for large aeroplanes¹⁴.

Table 1. Test Scenarios

| Task No. | Task | Description | Performance Targets / Pilot Decisions | Initial Trim Condition / Configuration | Phase of Flight |
|-----------------|--|--|--|---|--------------------------------|
| 1 | Traffic Pattern/ Circuit | Fly the airplane in the traffic pattern/circuit, executing turns, maintaining airspeed, heading and altitude as required. | Pilot to fly within ‘normal’ flying tolerance* | Circuit Runway 27 R/H, 1000’ AGL | Traffic Pattern/ Circuit |
| 2 | Normal Approach with Go-around request from ATC @50’ AGL | Fly the airplane in the approach, maintaining approach airspeed, runway heading and rate of descent. Execute go-around upon ATC request (no prior notice). | Pilot to fly within ‘normal’ flying tolerance* | Long finals, approach & FULL flap landing @65 kts, runway 27 2 nm 700’ AGL (with Go-around @ 50’ AGL) | Approach & Landing |
| 3 | Base to finals turn with sufficient fuel for 1 landing only (no go- around) | Fly the Airplane in the take-off and climb out, maintaining airspeed, heading and rate of descent. | Pilot to fly within ‘normal’ flying tolerance* | Mid-right base, base to finals turn w/landing runway 27 R/H 750’ AGL | Approach & Landing |

Notes:

*Normal, expected flying tolerance for the pilot of an SEP light airplane in the traffic pattern [15]

Each of the 20 pilot volunteers was required to complete 4 flying tasks using normal operating procedures and 2 different stick force gradients in alternate sequence so as to minimise experimental bias and minimise stick force gradient changes, a total of 160 simulator tasks were completed (Table 1). Post-task assessments for all sub-measures were completed in less than 2 minutes, scores being recorded manually by the test administrator and cockpit voice recordings were also used to confirm scores post-testing.

Statistical Analysis

Statistical analysis of the results was conducted using the statistical processing tool SPSS with a repeated-measures ANOVA¹⁶ and independent variables of stick force gradient and flying task. To avoid Type I error (rejecting the null hypothesis H_0 , when it is true) significance testing was performed at $p < 0.05$ level using a Bonferroni

correction, conversely to avoid Type II errors (retaining the null hypothesis H_0 , when it is incorrect), tests were conducted with all 20 participants. The two-tailed tests were used to determine if stick force gradient and task (independent variables) had a direct and significant effect on the dependent variables of total workload, mental demand, physical demand, temporal demand, own performance, effort and frustration.

III. Experimental Results

The statistical analysis of the experimental results was conducted using a repeated-measures ANOVA with dependent variables of total workload (and sub-measures) versus the independent variables of stick force gradient (x2) and flying task (x3). The summary of significance tests (Table 2, $p < 0.05$) shows that the nature of the flying task had a significant effect on total workload, this being derived from the mean scores of the sub-scales (mental demand, physical demand, temporal demand, own performance, effort and frustration).

Table 2. Summary of Significance Tests ($p < 0.05$)

| | Stick Force Gradient | Task | Stick Force Gradient x Task Interaction |
|------------------------|-----------------------------|-------------|--|
| Total Workload# | 0.657 | 0.000* | 0.893 |
| Mental Demand | 0.037* | 0.012* | 0.892 |
| Physical Demand | 0.672 | 0.004* | 0.077 |
| Temporal Demand | 0.460 | 0.000* | 0.304 |
| Own Performance | 0.802 | 0.000* | 0.802 |
| Effort | 0.925 | 0.001* | 0.169 |
| Frustration | 0.521 | 0.000* | 0.893 |

Notes:

- # Determined from the mean scores of all sub-scale measures
- * Significant at the level of $p < 0.05$

Of all workload sub-measures, only mental demand was significantly affected ($p = 0.037$) by changes in stick force gradient, increasing significantly as stick force gradient decreased from a moderate gradient (≈ 1 lbf /6 kt) to 'zero'. The combination or interaction of stick force gradient and flying task had no significant effect ($p < 0.05$) on total workload or sub-measures.

Plotting the mean mental demand versus stick force gradient and flying task (Figure 3) for each stick force gradient shows that relative differences in mental demand for each flying task were similar, with the go-around rating lowest, followed by the standard traffic pattern/circuit and the base to finals turn (sufficient fuel for one landing and no go-around possible) rating the highest. It can also be seen that the mental demand ratings for all flying tasks are significantly ($p < 0.05$) higher for a stick force gradient of 'zero' when compared to the moderate gradient.

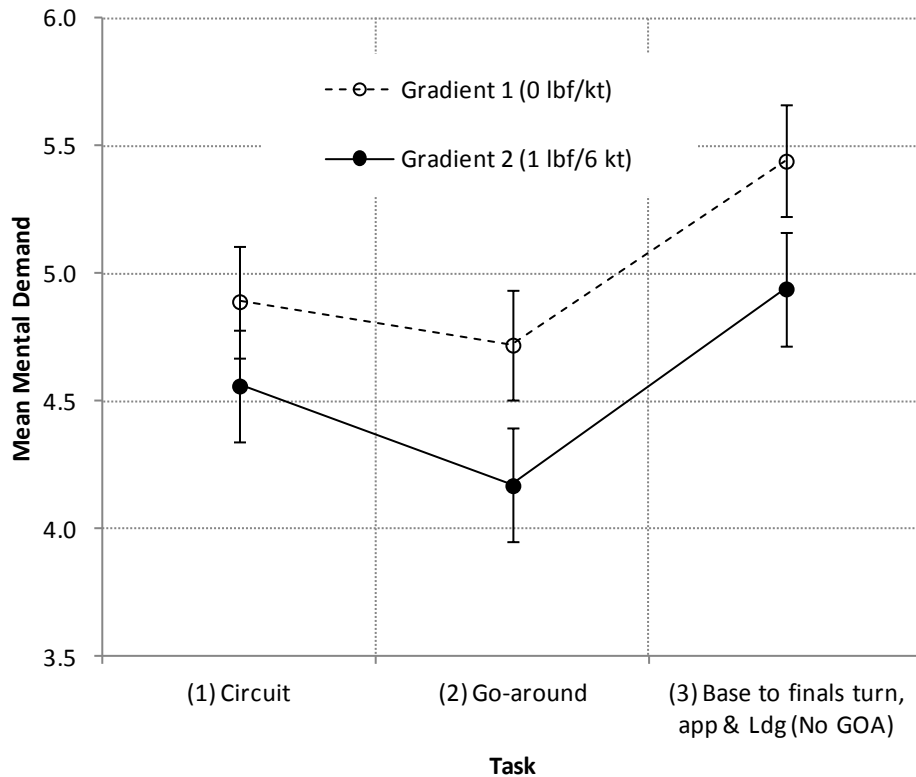


Figure 3. Effect of Stick Force Gradient & Task on Mean Mental Demand ($p < 0.05$, Standard Error Bars)

This demonstrates that of all sub-measures for the limited range of stick force gradients tested, mental demand is most influenced by changes in stick force gradient, especially when the gradient tends towards zero (all sub-measures were treated equal and no weightings applied).

IV. Discussion of Results

The results show that for a representative sample size of GA pilots ($n=20$) conducting simulated flying tasks in the circuit/pattern, mental demand increases significantly as stick force gradient diminishes to 'zero'.

The results are consistent with the intuitive relationship as expressed by Cook⁶ (Figure 2) who suggested that pilot workload increases as controls become light and oversensitive. Revisiting Cooks' illustration in the light of the results obtained during this research program suggests that pilot mental demand may be minimised for a given flight condition when stick force gradient is a non-zero, optimum value (Figure 4).

The increase in pilot mental demand is believed to be primarily due to the pilot being required to adapt control gain (force input > airspeed output) to compensate for the reduced stick force gradient. Referring to the pilot in the loop airspeed management task (Figure 1), as the stick force gradient approaches zero and control force cues diminish, the pilot is required to use alternative slower, middle-loop external visual cues (airplane nose in relation to the horizon) and even slower outer-loop internal visual cues (cockpit airspeed instrument with instrument lag).

The use of un-weighted NASA-TLX for expediency resulted in all sub-measures (including mental demand) being treated with equal weighting. Given the significant effect of mental workload, it is recommended that weighted NASA-TLX be used in future experimentation requiring the subject to rank the contribution of each sub-measure to workload for a specific task using pair-wise comparisons.

It is recognised that GA pilots of typical levels of experience are unlikely to possess exceptional piloting skills and that they are therefore likely to adopt this basic compensatory model for airspeed tracking. Highly experienced pilots may adopt a pre-cognitive approach.

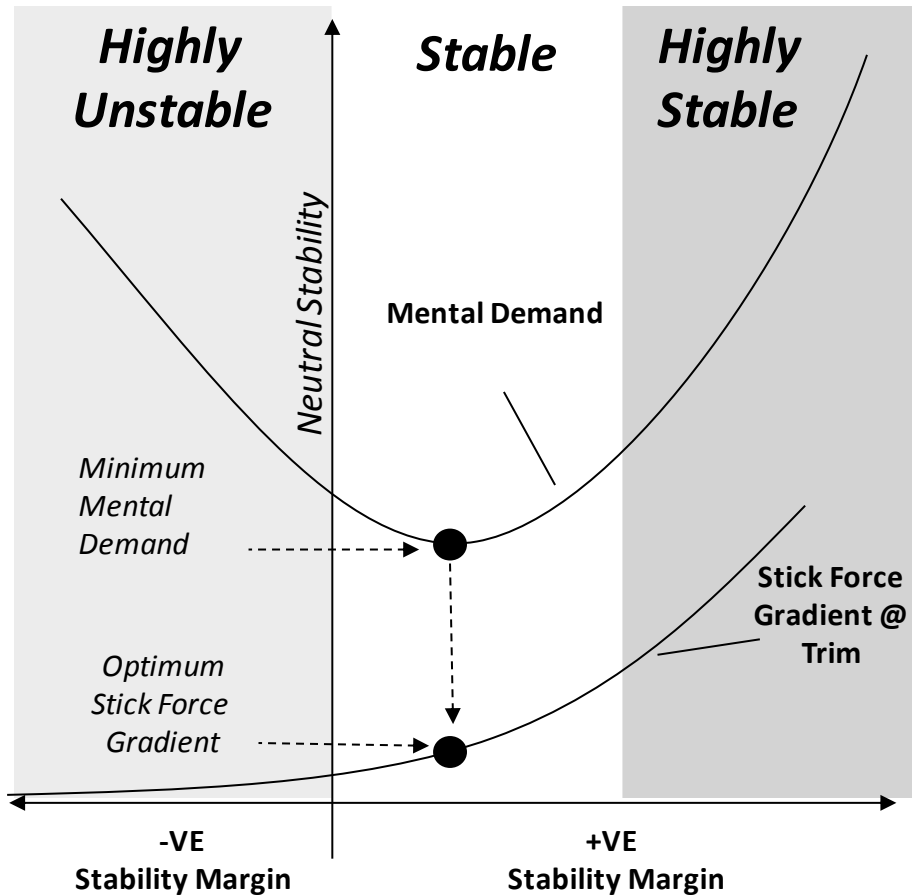


Figure 4. Effect of Stability Margin & Stick Force Gradient on Pilot Workload

For a light airplane with reversible mechanical controls, stick force gradient (and control feel) vary between airplane makes/models, with flight condition (flap, power & trim setting) and with CG margin. The apparent increase in pilot mental demand with decrease in stick force gradient under these conditions has safety implications for current airplane operations and future airplane design. Due consideration should be given to differences and/or familiarisation training for pilots converting from one airplane make/model to another where there are substantial gradient changes. With respect to pilot education and flying training, the transition between flight conditions and gradient changes may also give rise to increase in pilot mental demand, the go-around/balked landing being an extreme case). With respect to flight performance and planning, mass and balance conditions in the region of the aft CG limit may give rise to increased mental demand in the landing condition.

V. Conclusions

For the pilot of an airplane with reversible mechanical pitch control systems, haptic cues generated by positive, non-zero stick force gradients reduce mental demand and improve situational awareness by providing additional cues for the management of airspeed. Some optimum value of stick force gradient is desirable for such airplanes flown by pilots without exceptional piloting, skill, alertness or physical strength for all flight conditions normally encountered in service.

References

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- ¹ McRuer, D.T., "The Development of Pilot in the Loop Analysis," *AIAA Journal of Aircraft*, vol. 10, no. 9, pp 515-524, September 1973
 - ² Federal Aviation Administration, "Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes," FAR-23.171 & FAR-23.173, Electronic Code of Federal Regulations, July 2, 2013, <http://www.ecfr.gov>, [retrieved 5 July 2013].
 - ³ Federal Aviation Administration, "Feel of the Aeroplane," *Airplane Flying Handbook*, FAA-H-8083-3A, 2004, pp. 3.2-3.3.
 - ⁴ Campbell, P., "European JAR-FCL Syllabus," JAR-FCL, Private Pilots Licence – Aeroplanes, 3rd Edition, AOPA-Pooleys Flight Equipment Ltd., Cranfield, UK, 2002.
 - ⁵ Field, E., & Harris, D., "Handling Qualities and Flight Deck Design", *Human Factors for Civil Flight Deck Design*, Ashgate Publishing Company, Aldershot, UK, 2004, pp. 162-178.
 - ⁶ Cook, M.V., "Stability," *Flight Dynamics*, 3rd ed., Elsevier, London, 2012, pp. 226.
 - ⁷ Barber, M.R., Jones, C.K. Sisk, T.R., & Haise, F.W., "Evaluation of Handling Qualities of Seven General-Aviation Aircraft," NASA TN D-3726, November, 1966.
 - ⁸ Anderson, S.B., "Historical Overview of Stall/Spin Characteristics of General Aviation Airplane," *AIAA Journal of Aircraft*, Vol 16, No7, July 1979.
 - ⁹ Bromfield, M.A. & Gratton, G.B., (2012), "Factors Affecting the Apparent Longitudinal Stick-free Static Stability of a Typical High-wing Light Airplane," *Aeronautical Journal*, Volume 116, Number 1179, May, 2012.
 - ¹⁰ Mooij, H.A. & van Gool, M.F.C., "Handling Qualities of Transports with Advanced Flight Control Systems," NLR Technical Report NLR-MP-82009-U, National Aerospace Laboratory, Amsterdam, Netherlands, 1982.
 - ¹¹ NASA, "NASA-TLX – Task Load Index V2.0," NASA Ames Research Center, Moffett Field CA 94035, December 19, 2003.
 - ¹² Cooper, G.E. & Harper R.P., "The Use of Pilot Rating in the Evaluation of Aeroplane Handling Qualities," AGARD-R-567, 1969 & NASA, Report TN-D-5153, 1969.
 - ¹³ Heiligers, M.M., Van Holten, T & Mulder, M., "Predicting Pilot Task Demand Load During Final Approach," *The International Journal of Aviation Psychology*, 2009, 19:4, pp. 391-416
 - ¹⁴ Federal Aviation Administration, "Airworthiness Standards: Transport Category Airplanes," FAR-25.173, Electronic Code of Federal Regulations, July 2, 2013, <http://www.ecfr.gov>, [retrieved 5 July 2013].

¹⁵ Federal Aviation Administration, “ Private Pilot Practical Test Standards for Airplane (SEL, MEL, SES, MES),” FAA-S-8081-14 , Amendments 1~5, November, 2011.

¹⁶ Field, A., “Repeated-Measures Designs,” *Discovering Statistics Using SPSS*, 2nd ed., Sage Publications, London, 2005., pp. 427-482.