CRITERIA FOR ACCEPTABLE STICK FORCE GRADIENTS OF A LIGHT AEROPLANE

A thesis submitted for the degree Doctor of Philosophy

by

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ABSTRACT

During the period 1980 to 2008 there were 359 fatal accidents involving UK registered light aeroplanes of which 36% occurred in visual meteorological conditions. In all, 216 lives were lost with accidents being attributed to the pilot 'failing to maintain proper control resulting in a stall or spin'. Dissimilar fatal stall-related accident rates are evident for aeroplane makes & models of similar design. During the course of this programme of research, flight testing of two similar aeroplane models using a case study method showed marked differences in the variation of stick force with airspeed or stick force gradient in all flight conditions. This suggested that 'control feel' was a contributory factor towards the pilot's failure to maintain proper control.

Current certification standards for light aeroplanes rely upon the subjective assessment of stick force gradients by test pilots, requiring that substantial changes in airspeed are accompanied by clearly perceptible changes in stick force with no specified minimum gradient.

This programme of research has been carried out to determine acceptable criteria for stick force gradients of a light aeroplane in all flight conditions. Criteria has been determined from flight tests of aeroplanes with different in-service safety records and subjective pilot workload assessment using simulated flying tasks with different stick force gradients performed by twenty GA pilots. Simulation tests indicated that pilot mental demand increased significantly ($p > 0.05$) when stick force gradient was reduced to 'zero', representing an aeroplane with neutral longitudinal static stability.

A predictive model has been developed to estimate stick force gradients for a light aeroplane in any flight condition under quasi-static, longitudinal, non-manoeuvring flight and 1-g loading conditions. The model builds upon previous published work limited to cruising flight, and enables the estimation of stick forces and gradients due to high lift devices in the climb and landing condition by consideration of the

combined effects of wing loading, CG, elevator gearing, flaps and elevator trim setting. Implemented using MATLAB, the model has been validated by comparing with flight test results for the case study aeroplanes and showed mean differences of ±0.025 daN/kt.

The predictive model should be used in preliminary aeroplane design to assess tendencies towards neutral stability in high workload, safety critical flight conditions such as the take-off and landing. In addition, the model should be used to analyse existing aeroplanes with comparatively low or neutral stick force gradients in safety critical flight phases and to predict the effects of changing CG and/or flap limits to increase stick force gradient and improve control feel.

The combined results of these studies suggest that a minimum acceptable stick force gradient for a non-aerobatic light aeroplane in all flight conditions should be non-zero and between 0.10~0.13 daN/kt. A stable and predictable stick force variation with airspeed will ensure that any substantial deviation from trimmed airspeed is accompanied by a stick force change clearly perceptible to the pilot and also provide additional warning of the proximity to the stall. The use of specific criteria to complement qualitative test pilot opinion, will assist in confirming compliance and provide consistency with current standards for sailplanes/powered sailplanes and large commercial aeroplanes, both of which already have defined minimum acceptable gradients.

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Nomenclature

a	lift curve slope (/rad)
a'	lift curve slope, elevator free (/rad)
a_e	elevator effectiveness or change of tail-plane lift coefficient with elevator deflection (/rad)
A	coefficient 'A', speed dependent term in stick force estimation
AAIB	Air Accident Investigation Branch
ANOVA	analysis of variance
AOPA	Aircraft Owners and Pilots Association
ASI	airspeed indicator
ATC	Air Traffic Control
ATPL	Airline transport pilots licence
BCAR	British Civil Airworthiness Requirements
BFSL	Brunel Flight Safety Laboratory
BEW	basic empty weight (lbf)
b_0	change of elevator hinge moment coefficient with tail-plane setting (/rad)
b_1	change of elevator hinge moment coefficient with angle of attack (/rad)
b_2	change of elevator hinge moment coefficient with elevator deflection (/rad)
b_3	change of elevator hinge moment coefficient with elevator trim tab deflection (/rad)
BHP	brake horse power
BO+F	combined breakout force (BO) and friction (F) within the control system
C	coefficient 'C', speed independent term in stick force estimation
CAA	United Kingdom Civil Aviation Authority
CAS	calibrated airspeed (kts)
$\bar{c}$	mean aerodynamic chord of the wing (ft)
$\bar{c}_e$	mean chord of the elevator (ft)
CFD	computational fluid dynamics
CG	centre of gravity, aft of datum (in)

CH	Cooper Harper (Handling Qualities Rating)
C_{he}	elevator hinge moment coefficient
C_L	lift coefficient for the aeroplane
C_{L_α}	lift coefficient for the aeroplane due to angle of attack
$C_{L_{\delta_e}}$	lift coefficient for the aeroplane due to elevator deflection
$C_{L_{trim}}$	lift coefficient for the aeroplane in the trimmed flight condition
$C_{L_{wb}}$	lift coefficient for the wing-body combination
CS	Certification Specification
C_{m_0}	pitching moment coefficient for the wing
CofA	certificate of airworthiness
COTS	commercial ‘off the shelf’ technology solutions
CPL	commercial pilots licence
CVR	cockpit voice recorder
det	matrix determinant, $det = C_{L_\alpha}\left[C_{L_{\delta_e}}\left(h_n - h_{n_{wb}}\right) - a_e\bar{V}_H\right]$
EAS	equivalent airspeed (kts)
EASA	European Aviation Safety Agency
ETPS	Empire Test Pilot School
FAA	Federal Aviation Administration
FAR	Federal Airworthiness Requirements
FdN	Fiche de Navigabilitie
FDR	flight data recorder
FI	flight instructor
FTE	flight test engineer
G	elevator gearing (rad/ft)
GA	General Aviation
GASCo	General Aviation Safety Council
h	location of the centre of gravity (%MAC)

H_e	elevator hinge moment (lbf.ft/rad)
h_H	horizontal tailplane height above the wing-chord plane (in)
h_n	stick-fixed neutral point, wing-only (%MAC)
H_n	stick-fixed CG margin (%MAC)
h'_n	stick-free neutral point (%MAC)
H'_n	stick-free CG margin (%MAC)
$h_{n_{wb}}$	stick-fixed neutral point, wing/body combination (%MAC)
H_o	null hypothesis
H_1	alternate hypothesis
HQR	Cooper-Harper handling qualities rating
IAS	indicated airspeed (kt)
i_h	horizontal tail incidence angle, relative to wing-body zero lift line(rad)
IMC	instrument meteorological conditions
ISA	international standard atmosphere
K_n	stick-fixed static margin (%MAC)
K'_n	stick-free static margin (%MAC)
KIAS	indicated airspeed (kt)
LoC	loss of control
LMS	longitudinal manoeuvring stability
LSS	longitudinal static stability
l_t	distance from centre of gravity to horizontal tail aerodynamic centre (ft)
MAC	mean aerodynamic chord
MATLAB	MATrix LABoratory, a numerical computing environment and 4th generation computer programming language
MIAS	indicated airspeed (mph)
MTOW	maximum take-off weight (lbf)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics & Space Administration

NASA-TLX	NASA Task Load indeX Rating
NTSB	National Transportation Safety Bureau
p	p-value or observed significance level is the calculated probability of an observed (or more extreme) result arising by chance
P	elevator stick force applied by the pilot, pull positive (daN)
PEC	pressure error correction
PFtS	elevator pull force to stall (daN)
PiC	pilot in command
PLF	power for level flight
POB	persons on board
PPL	private pilots licence
$\frac{dP}{dV_E}$	stick force gradient (daN/kt)
s	elevator stick displacement, positive rearwards (in)
S	wing area (ft^2)
S_e	elevator area (ft^2)
S_t	horizontal tailplane area (ft^2)
sHp	standard pressure altitude using altimeter reading with 1013.25 hPa set on subscale (ft)
T_a	ambient temperature (°K)
T_0	temperature at ISA sea level conditions (°K)
TAS	true airspeed (kt)
TCDS	Type Certificate Data Sheet
TPDF	Tail Damping Power Factor
V	true airspeed (ft/s)
V_E	equivalent airspeed (kt)
V_G	ground speed (kt)
$\bar{V}_H$	tailplane volume coefficient, $\bar{V}_H = \frac{l_t S_t}{\bar{c} S}$
VLA	Very Light Aircraft

V_{minD}	minimum drag speed (kt)
V_S	stall speed (kt)
V_{SO}	stall speed in the landing condition (kt)
V_T	true airspeed (kt)
V_{Trim}	equivalent airspeed at the trim condition (kt)
V_W	wind speed (kt)
V_Y	best rate of climb airspeed (kt)
w	wing loading - equivalent to *W/S* (lbf/ft^2)
W	weight (lbf)
α	angle of attack (rad)
α_{crit}	critical angle of attack (rad)
$\alpha_{T_{trim}}$	effective angle of attack of the horizontal tailplane at the trim condition (rad)
α_{wb}	angle of attack of the wing-body combination from the zero lift line (rad)
α/α_{crit}	non-dimensionalised angle of attack
δ_e	elevator deflection, positive trailing edge down (rad)
$\delta_{e_{max}}$	maximum elevator deflection, positive trailing edge down (rad)
$\delta_{e_{trim}}$	elevator deflection at the trim condition (rad)
$\delta_e/\delta_{e_{max}}$	maximum elevator deflection, positive trailing edge down (rad)
δ	relative pressure ratio
δ_f	flap deflection, positive trailing edge down (rad)
δ_t	elevator trim tab deflection, positive trailing edge up (rad)
$\delta_{t_{trim}}$	elevator trim tab deflection at the trim condition (rad)
ε	tail downwash angle, positive downwards (rad)
$\dfrac{dC_M}{d\alpha}$	pitching moment derivative or $C_{M_\propto}$ (/rad)
$\dfrac{d\varepsilon}{d\alpha}$	downwash derivative

$\emptyset_{AC}$	aircraft heading (rad)
$\emptyset_{W}$	wind direction (rad)
ρ	local air density (slug/ft^3)
ρ_o	air density at ISA sea level conditions (slug/ft^3)
σ	relative air density ratio
θ	relative temperature ratio

Note – use of units

This thesis refers to airspeed in knots, aircraft weights in lbf and control forces in both lbf and daN since these units are standard in the majority of operating documents for the aircraft under consideration. 1 kt = 0.515 m/s and 1 lbf = 4.448 N or 0.4448 daN (1 daN = 10 N). The units of deca-Newtons (daN) are commonly used in current EASA Certification standards [1].

1 An Introduction to Stick Force Gradients and the Relevance to Flight Safety

During the period 1980 to 2008 there were 359 fatal accidents involving UK registered light aeroplanes with a maximum gross weight of 5,700 kg or less [2]. A review of all fatal accidents showed that 36% occurred in VMC and were attributed to the pilot failing to maintain proper control, resulting in a stall or a spin claiming 216 lives. The accidents occurred in varied situations, including loss of control during forced landing, mishandling in the circuit or go-around, intentional low flying, beat-ups and aerobatics in close proximity to the ground. Dissimilar accident rates (the number of fatal stall-related accidents per 100,000 flying hours) were evident for similar aeroplane makes & models.

One case in point as identified by GASCo [3] is that of the Cessna 152 and Cessna 150 with fatal stall-related accident rates of 0.04 and 0.71 respectively. At the request of the GASCo Stall/Spin Working Group, it was decided to conduct a safety review, design review and flight tests for Cessna 152 and Cessna C150L and C150M aeroplane groups to obtain additional research data and to identify possible contributory factors [4][5]. Cessna models C150L and C150M were selected since they accounted for 10 out of the 11 fatal accidents involving Cessna 150s. The design review showed that for 25 sampled airframes, the mean BEW for the Cessna 152 was greater (+4.4%) and further forward (+4% MAC) than the Cessna 150. Cessna 152 elevator gearing was higher than the Cessna 150 (+8%), together with available maximum engine power (+8~10%). Preliminary flight test results showed marked differences in the apparent (as felt by the pilot) longitudinal stick-free stability, the Cessna 152 exhibiting greater stick force gradients than the Cessna 150 in all flight conditions, especially the landing. The results suggested that ‘control feel’ is a contributory factor worthy of further investigation, and that this partially accounts for the apparent differences in accident rates. This view is also held by Abzug & Larrabee [6], who considered it highly plausible that good flying qualities have the potential to reduce training and operational accidents in the approach and landing, but stress that so far, it has not been feasible to perform statistically significant experiments.

1.1 The ‘Pilot in the Loop’ and the Importance of Control Feel

The ‘control feel’ of an aeroplane is directly associated with the stick and rudder forces felt by the pilot’s hands and feet, and the response of the aeroplane to those control inputs. However, the importance of control feel and how it is used to sense flight conditions is briefly described in FAA flight training documentation [7] and omitted from pilot training syllabi [8]. Whilst the pilot is controlling flightpath and airspeed, stick force and position provide essential cues with respect to airspeed changes and proximity to stall (providing the aeroplane is not re-trimmed). The pilot continuously samples available visual, aural, acceleration, balance, touch and feel sensory cues, applying perception, making decisions and manipulating stick and rudder whilst receiving feedback in a closed-loop. Time delays and the quality of perception of the sensory cues have a significant influence on pilot decisions, actions and feedback. The apparent (as felt by the pilot) stick-free LSS or stick force gradient is also a measure of the aeroplane’s stability and its natural tendency to return to a trim condition in flight as the airspeed is changed and the elevator is free to float whilst the pilot is ‘hands-off’. Control sensitivity or gain influences pilot performance and workload and this is especially true during safety-critical phases of flight [9][10]. The task of maintaining a steady airspeed in cruising flight for a light aeroplane in VMC may be considered in its simplest form as a compensatory tracking task with the pilot acting as one element in the closed loop system (Figure 1).

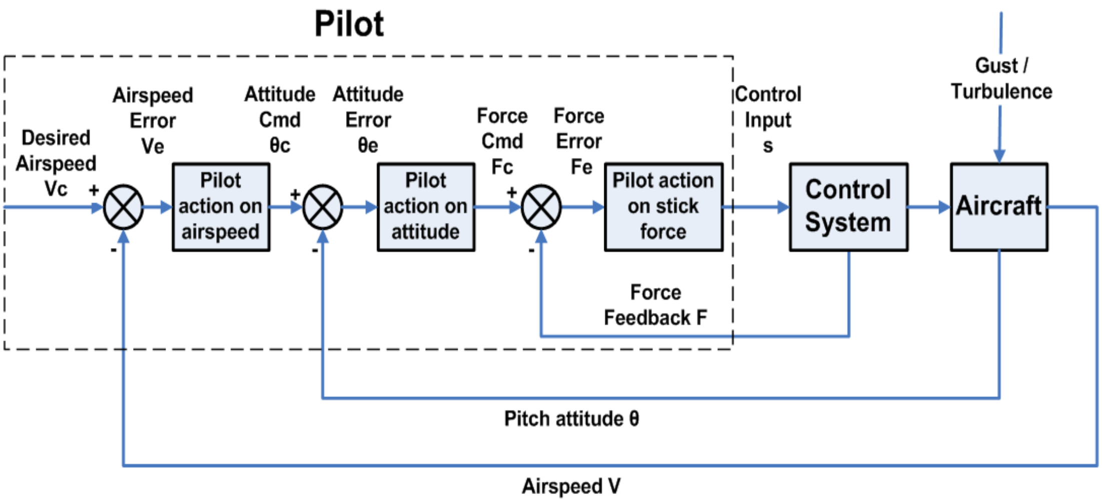


Figure 1, ‘Pilot in the Loop’, Airspeed Management in VMC Adapted from Field & Harris [11]

The pilot in the loop model consists of three nested loops: an inner stick force feedback loop, a middle pitch attitude control loop and an outer airspeed control loop, all used in a continuous closed-loop manner to track the desired or commanded airspeed. Whilst maintaining the desired airspeed, if the aeroplane is subject to external disturbances (e.g. wind gusts or turbulence), the pilot perceives an error between the desired airspeed and the actual airspeed as indicated by visual cues from the cockpit airspeed instrument. The pilot uses pitch attitude control within the middle loop to manage the airspeed, and raises or lowers the nose using external peripheral visual cues (e.g. natural horizon) to estimate the required changes. The raising or lowering of the nose is achieved by using the inner force feedback loop to apply the desired level of stick force to the control system and control surfaces via the system gearing, and uses tactile cues to estimate the force to apply. Inherent time lags within the closed loop model mean that inner loop tactile stick force cues are sensed more quickly than middle loop external peripheral visual cues (natural horizon) or outer foveal visual cues (cockpit airspeed instrument). The inner force feedback loop therefore acts as a surrogate for airspeed and pitch attitude management and is represented by the change in stick force with airspeed or stick force gradient.

This combination of the human pilot, control system, aeroplane dynamics and configuration state, determine the overall aeroplane flying qualities with a given environment performing a specific flying task. Any configuration change, such as deployment of flaps for the approach and landing phase, alter the aeroplane dynamics and may have a significant effect on the aeroplane flying qualities. The human pilot model can be considered as a combination of pilot gain, pilot reaction time delay and the pilot equalisation characteristics, used to form an adaptive control strategy. The pilot critically reviews feedback and consciously decides whether or not to lead or lag an aeroplane with control inputs during selected flight conditions [12]. Aeroplane design considers the complete pilot in the loop model and this is supported and guided by certification specifications for stability and control feel.

1.2 Stability and Control Certification Specifications for Light Aeroplanes

Adequate stability and 'control feel' is also a basic certification requirement for the safe operation of a light aeroplane in the range of flight conditions normally encountered in service [13]. For larger, transport category aeroplanes (jets with 10+ seats or MTOW >5,670 kg or propeller-driven aeroplanes with > 19 seats or an MTOW > 8,618 kg), quantitative control feel requirements are specified and all aeroplanes must demonstrate a minimum stick force gradient of 0.074 daN/kt (1 lbf per 6 kt) in all phases of flight [1]. However, standards for light aeroplanes have no specified minimum, relying upon subjective test pilot opinion (manufacturer and the certifying authorities). Standards for light aeroplanes also allow stick force gradient reversal; however, the evidence suggests that the human pilot responds more favourably to linear, predictable variations in quantity and/or rate. When stick forces are perceived to either rapidly increase or decrease in a non-linear manner, the pilots ability to adapt his/her compensation model deteriorates and may result in an unpredictable pilot response [14]. Since stick force gradient has a major influence on handling qualities, it is therefore desirable to specify quantitative criteria for acceptable stick force gradients in any flight condition (as is the case for large aeroplanes) to complement subjective test pilot opinion and not replace it.

1.3 The Research Aims and Objectives

The aims of this research were to investigate how control feel assists the pilot in the management of airspeed, avoidance of the stall and likely flight safety implications. The specific objectives of this research were:-

- To establish criteria for minimum acceptable pitch stick force gradients for a non-aerobatic, light aeroplane in any steady flight condition. The lack of specific certification requirements for light aeroplanes was the key driver for this primary objective. The availability of specific guidelines would enable objective assessment of stick force gradients and compliment subjective test pilot opinion. This approach would then be consistent with other specifications e.g. sailplanes/powered sailplanes and large transport category aeroplanes.

- To develop a model to estimate stick force gradients for a light aeroplane in any flight condition. The ability to predict stick force gradients in ANY flight condition and tendencies towards 'zero' stick gradients would prove useful in the preliminary design of a light aeroplane.

1.4 The Structure of the Thesis

In this Chapter, the background and key drivers to this research have been described, as have the important role that control feel plays in the assessment of an aeroplane's flying qualities. The research aims and objectives have also been stated.

Chapter 2 reviews previous work in the field of stability and control from both the engineer's and pilot's perspectives and the developments up to today The emphasis in this study is with regard to the pilot's perspective and defining criteria for acceptable stick force gradients (apparent stick-free LSS) for safe operation. The effects of stability on pilot workload are described together with current certifications requirements for stick force gradients of light aeroplanes. The limitations of previous knowledge and the 'gaps' within current light aeroplane certification specifications are highlighted and addressed.

Chapter 3 presents a predictive model for the estimation of stick force gradients that should be used in preliminary design to assess potentially hazardous tendencies towards neutral stability [15]. This extension to previous published work considers the effect of flaps in the take-off & climb-out and approach & landing, phases of flight where the majority of fatal accidents occur. The method was implemented using MATLAB [16] and parametric analysis was conducted for a typical light aeroplane (Cessna 150M) to determine contributory factors towards neutral stability.

Chapter 4 presents the results obtained using flight testing, flight simulation and modelling using the predictive method, to establish acceptable stick force gradient criteria for a light aeroplane in any flight condition.

Experimental and theoretical results are discussed in Chapter 5 and related to previous work in the field and the original research objectives. The implications for future flight safety and preliminary design are explored.

Chapter 6 presents specific criteria for acceptable stick force gradients and the scope of application of the predictive method.

2. Previous Work in the Field and Current Stick Force Gradient Criteria

Adequate stability and control feel is a basic certification requirement for the safe operation of light aeroplanes [13] in the range of flight conditions normally encountered in service (as outlined in Chapter 1). Stability and 'control feel' may be considered as two complimentary, integrated requirements of light aeroplane design [17]. From the design engineer's perspective (aerodynamic) longitudinal static stability is concerned with the balancing of moments about the CG, and the aeroplane is statically stable if it exhibits a tendency to return to the trim condition in flight following a disturbance. From the pilot's perspective, 'control feel' is the (apparent) longitudinal static stability as felt by the pilot with hands and feet on the controls, and is achieved by the proper design of control inceptors and reversible flight control systems to provide good quality and predictable inceptor force and position cues to enable safe control. Apparent longitudinal static stability is traditionally assessed by flight test measurement of the variation of stick force (stick-free LSS) and stick displacement (stick-fixed LSS) with airspeed [18].

The development of the engineer's and pilot's perspective with respect to stability and control are described in the following sections. The emphasis in this study is with regard to the pilot's perspective and defining criteria for acceptable stick force gradients (apparent stick-free LSS) for safe operation. The effects of stability on pilot workload are described together with current certifications requirements for stick force gradients of light aeroplanes. The limitations of previous knowledge and gaps within current light aeroplane certification specifications are highlighted and these issues are addressed.

2.1 The Engineer's Perspective - Longitudinal Stability & Control

This section reviews the engineer's perspective with respect to longitudinal aeroplane stability and control. The requirement for longitudinal static stability was first documented in 1907 by Lanchester [19] who noted that a negative, restoring pitching moment, increasing with angle of attack was necessary for positive longitudinal static stability. An unstable aeroplane exhibiting negative LSS is characterised by a positive variation of pitching moment with an increase in angle of attack. Neutral LSS is characterised by no change in pitching moment with angle of attack. Thus, the guiding equation for longitudinal static stability was developed and is valid for non-augmented, reversible control systems typically found in a light aeroplane, namely:-

$$\frac{dC_M}{dC_L} < 0 \qquad \textbf{Eqn 1}$$

The degree of longitudinal static stability (or 'pitch stiffness') from the engineer's perspective is defined mathematically and used to compare aeroplanes of different categories and makes/models (Figure 2). Levels of stability are associated with the aeroplane's specific role (or mission / task). For example, heavy transport aeroplanes possess high levels of stability $\left(C_{M_\alpha} > 1\right)$ but limited manoeuvrability, whereas fighter aeroplanes possess low levels of stability $\left(C_{M_\alpha} < 0.2\right)$ and high manoeuvrability. Light aeroplanes sit between these two broad categories.

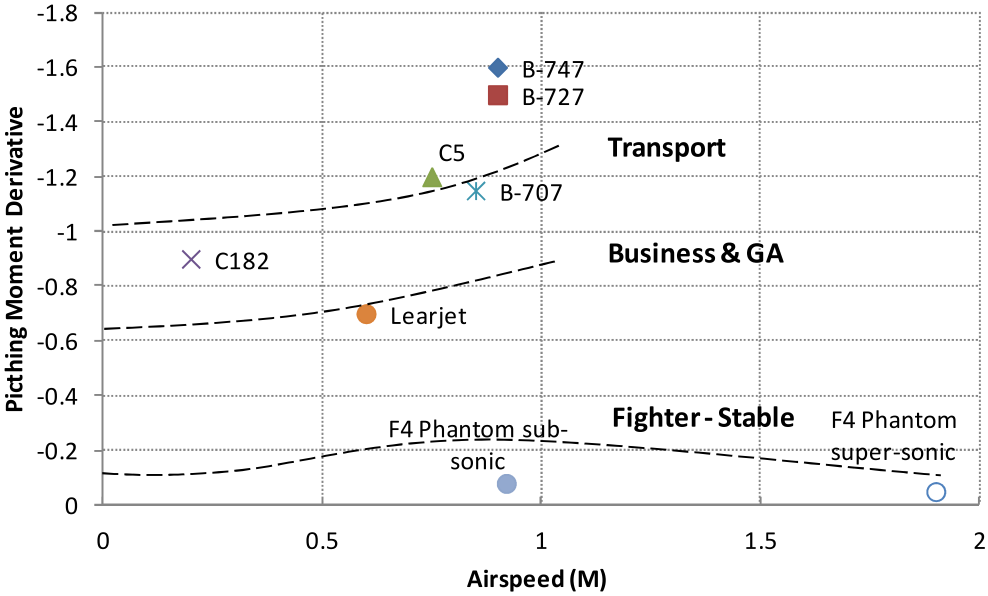


Figure 2, Typical Pitching Moment Derivatives for Different Aeroplane Categories, adapted from Raymer [20]

An alternative method of assessing the degree of longitudinal stability was devised in 1934 by Jones [21] who develop the concept of 'metacentric ratio', commonly known today as the static margin, the difference between the actual CG and the neutral point (CG where neutral longitudinal static stability occurs). At around the same time, Gates [22] noted that aeroplane trim and control forces gave clear indications of the degree of static stability and that stick forces felt by the pilot were dependent upon the CG and the neutral point. With regard to manoeuvring stability, he is also reputed to be the first to have specified manoeuvre margins and stick force per g criterion [23].

In 1949 Perkins and Hage produced a concise treatment of aeroplane stability & control [24] and further explored the importance of margins with regard to stick-free LSS for an aeroplane in flight with power on/off and in/out of ground effect. Their analysis of CG ranges and in particular aft CG limits, proposed that zero stick force gradients were undesirable and that all aeroplanes should possess at least a (negative) stable gradient even at the aft CG location (Figure 3). US military certification specifications at the time (1949) specified only that the aft CG limit should be ahead of the stick-free neutral point. Perkins and Hage acknowledged that designing for a negative, stable gradient at aft CG was a difficult requirement to satisfy since many high-speed aeroplanes of the period (post-World War II fighters and large transport aeroplanes) were required to have a wide CG range to accommodate varied mission/task driven payloads. They suggested the use of artificial devices such bob-weights, downsprings and elevator trim tabs to overcome basic design issues. They stopped short of defining a desirable minimum gradient but did specify the close relationship to flying controls mechanical characteristics and that due consideration be given during design.

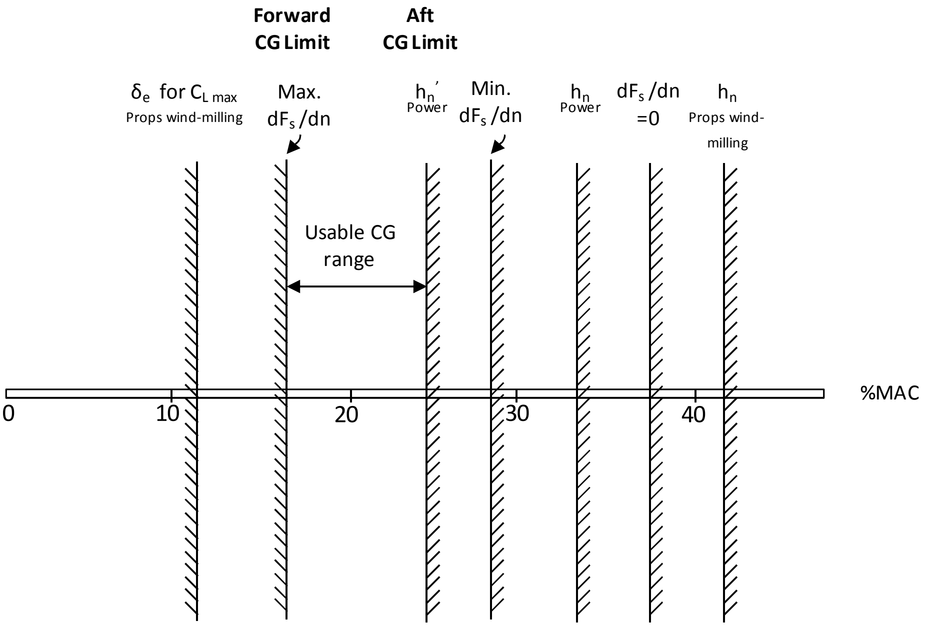


Figure 3, Summary of Stability & Control Limits, Adapted from Perkins & Hage [25]

The forward CG limit is governed by $C_{L_{max}}$in ground effect during landing and the aft CG limit is governed by the position of the stick-free neutral point with power ON (Figure 3). Perkins & Hage also referred to the importance of large stick force gradients and how these enable pilots to trim more easily the aeroplane, and do not require a high degree of pilot attention to maintain a given airspeed. The implication of this statement is that low stick force gradients have the opposite effect and that they increase pilot attention.

There are many classical derivations of stick-fixed (K_n) and stick-free static margin (K'_n) [20],[22],[26],[27],[28] and all are based upon the total pitching moment equation in the trimmed flight condition considering all moments acting upon the aeroplane in the longitudinal axis (Figure 4).

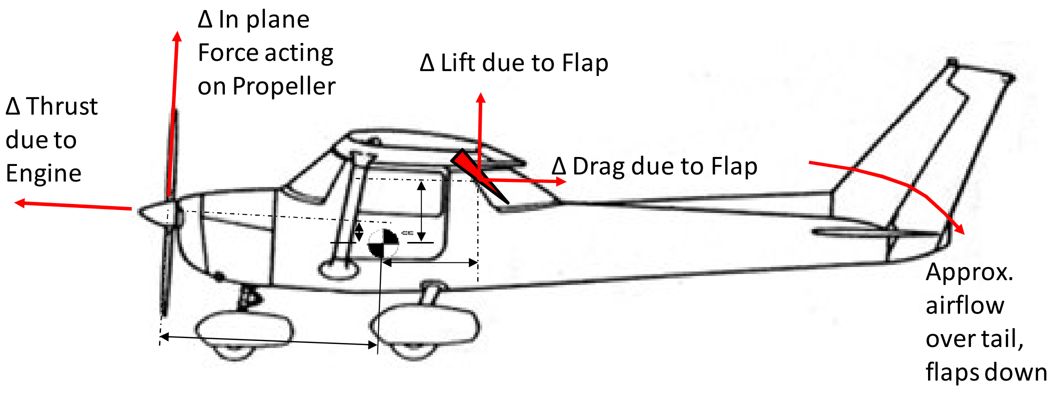


Figure 4, Effects of Wing Flap Deflection and Engine Thrust Changes on Longitudinal Moments and Airflow at the Tail

Multiple factors affect longitudinal static stability and these include wing, tail, fuselage and propulsive system contributions [20]. There is an additional contribution to pitching moment due to flap deflection and this generates increments in both lift and drag, in combination with increased downwash at the tail (Figure 4). With regard to tail contribution, the drag moment of the tail is typically small and ignored; however, a negative lifting tail (due to CG forward of the wing aerodynamic centre) requires a positive pitch moment to counteract the pitching moment due to the wing. The propulsive system contributes directly and indirectly to the pitching moment. Direct effects on the pitching moment are due to thrust line and the vertical distance from the CG and also due to the in-plane (normal force) acting on the propeller disk. Indirect effects on the pitching moment are due to the interaction of the propeller slipstream with the wing, flaps and tail.

The aeroplane structure is generally assumed rigid with no flexing of the tail boom and the effects of aeroelasticity are therefore ignored so that $K_n = H_n$ [29]. Therefore the stick-fixed static margin (K_n) for an aeroplane with CG forward of the aerodynamic centre of the wing is given by [26]:

$$K_n = H_n = h_n - h$$ **Eqn 2**

And the corresponding stick-free static margin (K_n') is given by [30]:

$$K_n' = H_n' = h_n' - h$$ **Eqn 3**

Thus, both stick-fixed and stick-free static margins are reduced by aft movement of the CG and/or forward movement of the neutral point.

Typical values of stick-fixed static margin in the cruise presented by Brandt [28] demonstrate the variations between categories of aeroplane (Table 1). Generally, high speed and manoeuvrable fighter aeroplanes (e.g. F-16) have low or even negative static stability due to low or negative static margins. Modern fighters, with relaxed static stability, require computerised flight control systems to provide artificial stability [20]. Older high speed transport aeroplanes such as the Boeing B747-100 have limited manoeuvrability but are highly stable requiring powered controls for adequate pilot handling qualities. Modern high speed transport aeroplanes such as the Airbus A330/A340 and Boeing 777 have relaxed static stability to improve aerodynamic efficiency of the tail and require augmented powered controls to provide artificial stability. Non-aerobatic light aeroplanes tend to sit between these broad categories and stick-fixed static margins of not less than 5 %MAC in all flight conditions are suggested by McCormick [31] and 2~5 %MAC by Stinton [22]. A typical light aeroplane such as the Cessna 172 or PA28 has stick-fixed static margins of 19 %MAC and 25 %MAC respectively, in the cruise. Aerobatic light aeroplanes, requiring high manoeuvrability, have significantly lower stick-fixed static margins and some are even 0% MAC.

Table 1: Stick-fixed Static Margins for Different Aeroplane Categories in the Cruise [28][32]

Aeroplane Type	Category	Static Margin (%MAC)
Boeing 747	Transport	27
Piper PA28	General Aviation	25
Cessna 172	General Aviation	19
Learjet 35	Business	13
Convair F-106	Fighter	7
North American P-51 Mustang	Fighter	5
General Dynamics F-16C	Fighter	1
Airbus A330	Transport	0
Airbus A340	Transport	0
General Dynamics F-16A (early)	Fighter	-2

Before considering the pilot perspective for the assessment of aeroplane longitudinal static stability and control feel it is worth reviewing the inherent association between static and dynamic stability.

2.2 The Link between Longitudinal Static and Dynamic Stability

Longitudinal static and dynamic stability are intrinsically linked by characteristics such as pitch stiffness and pitch damping. The short period pitching oscillation mode is the most important dynamic mode in the longitudinal axis and is characterised by heavily damped, high frequency oscillation [33]. The mode is excited by disturbance from the trimmed flight condition e.g. due to external wind gust or intentional/un-intentional pilot control input. The mode is characterised by a pitch oscillation with variations in pitch rate and angle of attack with typical frequencies in the order of 0.5 to 2 Hz, well within the control capability and natural frequency of the human pilot. Light aeroplanes (e.g. Cessna 150/152) are typically completely deadbeat (well damped, no overshoots) and therefore the SPO does not present handling problems [4].

The phugoid or long period oscillation mode is characterised by lightly damped low frequency oscillations in airspeed and height. Disturbance from the trimmed flight condition results in sinusoidal oscillations in pitch attitude and height but predominantly constant angle of attack. Light aeroplanes (e.g. Cessna 150/152) typically have a period in the region of 25~30 seconds and this low frequency can be easily controlled by the pilot when adequately damped [4].

2.3 The Pilots' Perspective (Flying Qualities)

This section considers the pilot perspective for the assessment of aeroplane stability and control feel commonly referred to as 'flying qualities' [34]. Although the term 'flying qualities' was not universally used until late 1930s/early 1940s, much work was undertaken in the preceding decades to assess aeroplane flying qualities qualitatively through pilot opinion and quantitatively through measurement. Before describing these in detail it is worth recalling the generally accepted definition of flying qualities as given by Vincenti [35]:

"Those qualities or characteristics of an aeroplane that govern the ease and precision with which a pilot is able to perform the task of controlling the vehicle"

The context of this definition is important and requires further qualification to consider safety, type of operations and flight conditions normally encountered during service. For example, in comparing a low-speed basic training aeroplane with a high-speed aerobatic aeroplane, their different roles demand a different balance of stability and manoeuvrability and hence their respective flying qualities will be different.

Both quantitative and qualitative methods are used to assess flying qualities; quantitative methods used during flight testing include the measurement of apparent stick-free and stick-fixed LSS, and predictive methods have been developed. Qualitative methods used in flight testing include the use of subjective pilot opinion ratings and pilot workload assessment.

Quantitative Assessment of Flying Qualities - Apparent Stick-Free LSS

In the early 1920s the first attempts to quantitatively analyse stability and control were undertaken by Warner & Horton [36]; prior to this, aeroplane stability had been assessed using qualitative pilot opinion only [37]. Using typical aeroplanes of the period, Warner & Horton measured elevator deflection and stick force required to hold a range of airspeeds with different throttle settings (Figure 5).

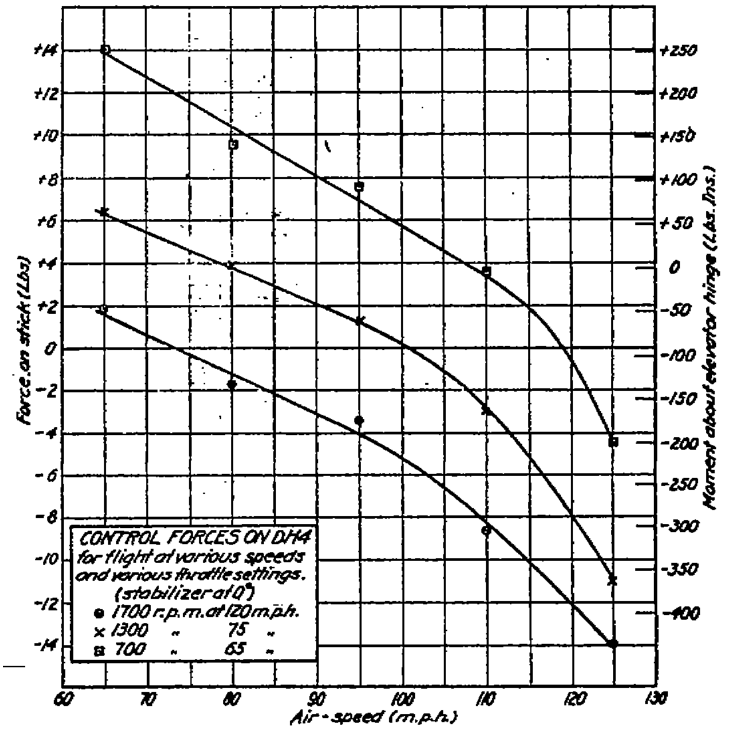


Figure 5, Variation of Elevator Stick Forces with Airspeed for the De-Havilland DH4 Power ON/OFF, as Measured by Warner & Horton [36]

Tests conducted with two different examples of the Curtiss JN-4H aeroplane under similar flight test conditions indicated variations of stick deflections and stick force gradients between models and airframes and especially highlighted the de-stabilising effects of power.

Warner & Horton specified that the degree of stability (as measured by stick force gradient) should be relatively small so as not require excessive forces on the behalf of the pilot; however, specific criteria were not defined.

In 1936, Thompson [38] suggested that lower limits for stick force gradients were necessary to allow for breakout force and friction (the stick forces necessary to initiate movement of the elevator from the trim condition) in reversible control systems, being approximately 0.89 daN (2 lbf) for light aeroplanes and 2.67 daN (6 lbf) for commercial aeroplanes. Thompson suggested an upper stick force gradient limit of 0.13 daN/kt (0.25 lbf per mph or 1.75 lbf per 6 kt) was desirable for a stable aeroplane in trimmed cruising flight, however upper gradient limits were not specified for the climb or approach.

In 1940, Soule re-assessed the criteria for a Douglas DC-4E large aeroplane using a Stinson SR-8E light aeroplane [39], implying that similar standards should be used for both light aeroplanes and larger commercial aeroplanes. The study marked the formal introduction of the study of flying qualities as a science. Soule refined the LSS flight test procedure known as the stabilised point technique, still in common use today. Soule also wrote flying qualities requirements that became the foundation for civil [40],[41] and military [42] aeroplane certification specifications covered later in this chapter.

1941 saw the first comprehensive assessment of the flying qualities of multiple aeroplanes of different types of the period by Gilruth & White [43]. They applied a scientific approach to the assessment of 15 aeroplanes and results indicated wide variations in stick force gradients with gradients as low as 0.019 daN/kt (0.05 lbf per mph or 0.26 lbf per 6 kt) for unspecified aeroplanes within the diverse group (from light aeroplanes e.g. Stinson 105 to long range bombers e.g. Boeing B17). Gilruth & White commented on the perceived relationship between pilot workload and aeroplane stability stating that:

"Positive stability eliminates the need for constant control manipulation in maintaining given conditions".

They also suggested that for the range of aeroplanes studied (15 different types/models), the de-stabilising effects of power meant that the specification of a set of generic stick gradient criteria for all categories of aeroplane was impractical. The effects of flaps were not considered in the study.

The period 1945 onwards saw the introduction of formal certification specifications and requirements for aeroplanes and the inclusion of specific requirements for suitable stability and control feel. In the United States for light aeroplanes these appeared in CAR Part 3-133 [40] and for larger, commercial aeroplanes CAR Part 4b-150 [41]. In 1962, an amendment to CAR Part 4b-151 [44] was introduced due to the difficulties in determining 'perceptible change in stick force' during flight test. A minimum stick force versus speed gradient was defined as being not less than 0.074 daN/kt (1 lbf per 6 knots). No amendments were made to light aeroplane certification specifications under CAR Part 3, discussed later in this chapter. Mechanical system characteristics can have a significant effect on the assessment of flying qualities.

The Effects of Mechanical System Characteristics on Flying Qualities

Mechanical characteristics of the longitudinal flight control systems can have a major influence on longitudinal flying qualities and control feel (Table 2, [45]).

Table 2, Mechanical System Characteristics (USNTPS) [45]

Mechanical Characteristic	Description
Breakout forces including friction (BO+F)	The longitudinal cockpit control force from the trim position required to initiate movement of the longitudinal control surface. Dependent upon elevator control system mass and friction.
Friction (F)	Forces in the longitudinal control system resisting the pilot's effort to change the control position.
Freeplay	The longitudinal cockpit control motion from the trim position that does not initiate movement of the longitudinal control surface. Dependent upon cable tension and lack of fit of joints in the elevator control system.
Centring	The ability of the longitudinal cockpit control and the longitudinal control surface to return to and maintain the original trimmed position when released from any other position. Dependent upon elevator control system friction.

Figure 6, shows the effect of typical breakout forces and friction (BO > F) on the longitudinal flying qualities of an aeroplane with a reversible elevator control system. In this example with a trimmed flight condition of 80 KCAS, the shallow stick force gradient combined with a breakout force of 0.5~0.75 daN and longitudinal friction of ± 1 daN results in non-linear control characteristics about the trimmed flight condition. Friction is unavoidable, but kept as low as is practical by efficient design and regular maintenance. The friction masks longitudinal control forces in the range of 75~88 KCAS resulting in poor trimming and the airspeed will stabilise at any speed in this range (trim speed band). Breakout force is usually present and moderate levels help to reduce the trim speed band and prevent inadvertent control inputs when the pilot rests his/her hands on the controls. Breakout forces and friction may vary with trimmed flight condition and stick position due to position of the yoke within the arc of movement. Figure 7, illustrates the situation when breakout force and friction are excluded and is typically used in the theoretical estimation of apparent LSS [24] discussed in the sections that follow. Freeplay impacts the degree of precision of control manoeuvres such as tracking and should be small. Some freeplay is acceptable since it confirms movement of the control in the desired direction via proprioceptive cues to the pilot. Excessive freeplay can cause the pilot to fly out of trim requiring continual small adjustments to maintain track. It can also lead to pilot induced oscillations due to the inherent time lag introduced into the pilot-vehicle control system.

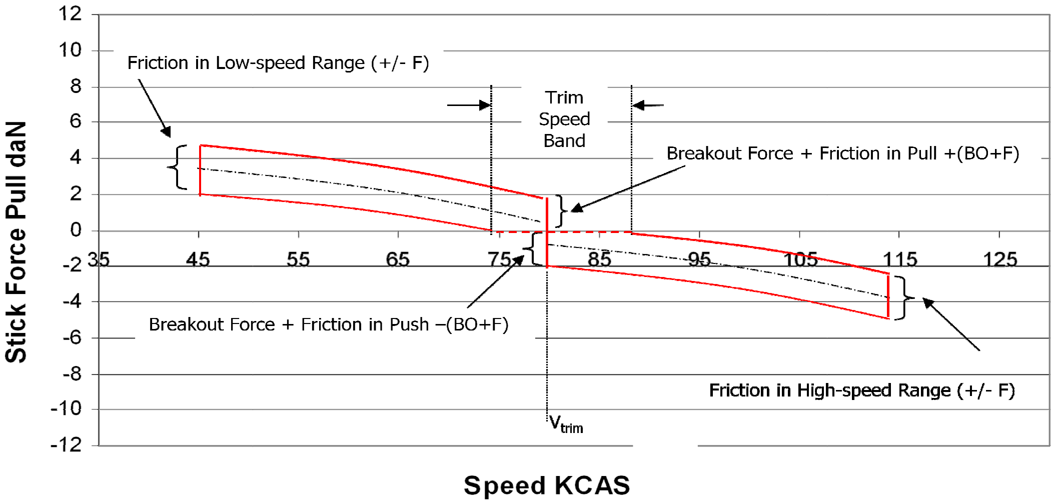


Figure 6, Longitudinal Flying Qualities Including the Effects of Breakout Force and Friction

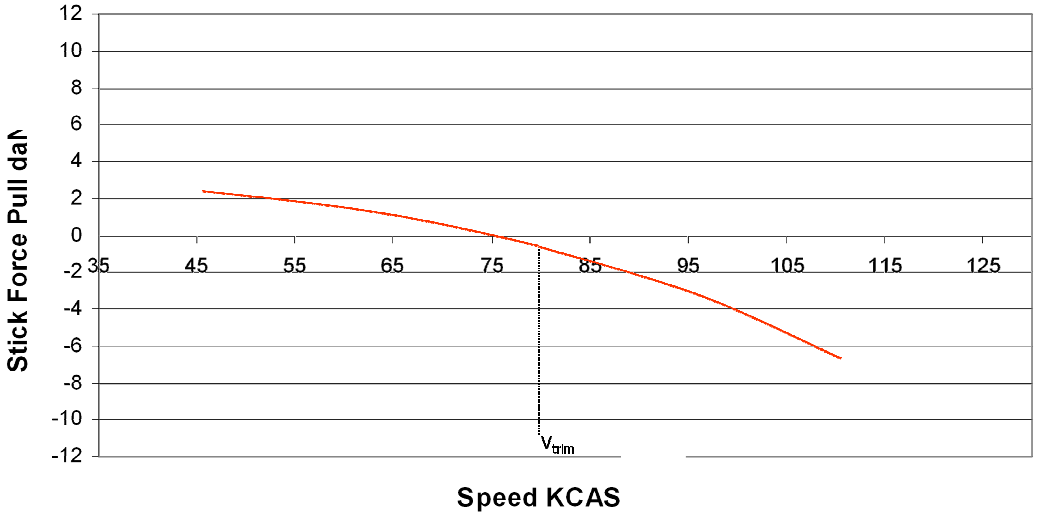


Figure 7, Longitudinal Flying Qualities Excluding the Effects of Breakout Force & Friction

Centring of the elevator control system occurs when the stick returns to its original trimmed position when released from a displaced position. The ability to return to a trimmed airspeed is an indication of positive airspeed tracking characteristics. If only small departures from target airspeed occur then pilot workload is significantly reduced since the aircraft does not demand continual attention for the pilot. In addition to mechanical system characteristics, aeroelasticity also influences aeroplane flying qualities.

The Effects of Aeroelasticity on Flying Qualities

The aeroplane structure is assumed rigid and aeroelastic effects ignored ($K_n = H_n$) but in reality due to the light weight structure some flexibility is always present [46]. Considering the static loading case only, there is an associated reduction in longitudinal static stability and control effectiveness due to the flexing of the fuselage tail boom (Figure 8). This results in rotation of the tail and horizontal tailplane in the direction of the tail load and in the case of a positive lifting tailplane a reduction in net angle of attack at the tail and conversely for a negative lifting tailplane an increase in the net angle of attack.

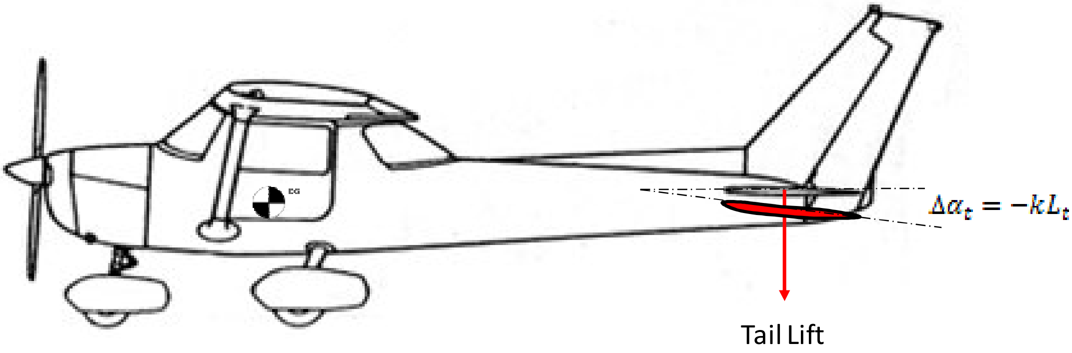


Figure 8, Effects of Fuselage Bending on the Tail

A reduction in tail effectiveness due to reduction in net angle of attack causes the neutral point to move forward, reducing the static margin and static stability [46] or conversely an increase in tail effectiveness has the opposite effect. Elevator effectiveness is also affected by flexing of the tail boom, since the elevator is deflected from its neutral position (assuming no control cable stretch and that control linkages are rigid).

The Effects of Cable Stretch and Cable Slack in the Elevator Control System

In a reversible elevator control system the control force applied by the pilot is opposed by a hinge moment induced by aerodynamic forces on the control surface. One cable is stretched (in tension) whilst the other cable is slack (‘in compression’) and if the both cables are not correctly tensioned then this results in a mismatch between elevator control input and elevator control deflection known as lost motion or freeplay [47].

The next section describes the theoretical development of quantitative estimations of apparent stick-free LSS uses in the preliminary design and development of an aeroplane.

Quantitative Assessment of Flying Qualities - Theoretical Estimation of Apparent Stick-Free LSS

Having refined the method for assessing apparent stick-free LSS from the pilot’s perspective by flight test in the pre and post-World War II periods, attention turned towards predictive methods for use in preliminary design and development. In 1949, Perkins and Hage [24] established and documented a method of estimating apparent longitudinal stick-free stick stability using estimated control surface hinge moment derivatives and elevator gearing in the cruise. Allowances were made for downwash effects at the tail and different tail aspect ratios and the slipstream effects of powerplant. In the same year, Phillips [48] produced a report summarising the results of flying qualities research of the preceding decade using 60 aeroplanes of different types. He presented the NACA requirements for satisfactory flying qualities, re-stated the reasons why they were important and presented methods for prediction. He also emphasised the important of acceptable flying qualities and their relationship to flight safety.

In 1972, Etkin [49][50] extended the work of Perkins & Hage to consider effects of part-span flaps on longitudinal trim and pitch stiffness by considering changes in lift distribution and vorticity and the affect on tail downwash. However, this extension focussed on the engineer’s perspective, and did not consider the pilot’s perspective and changes in apparent LSS due to high lift devices. For a given flight condition, the method requires known aeroplane geometry, elevator gearing, wing and tail lift/curve gradients and tailplane/elevator/tab hinge moment coefficients.

In the same year, Smetana compiled design procedures and supporting data for configuring light aeroplanes to ensure the desired static and dynamic response to pilot inputs and external gusts [51]. In 1984, Smetana implemented these procedures in a series of computer programs using the Fortran IV programming language [52].

The methods established by Etkin [49], Perkins & Hage [24] and Smetana [52] are still widely used today and have been implemented in proprietary aeronautical computer aided design packages such as Roskam's AAA [53] and Raymer's RDS [54] . This research has extended the original methods (from the pilot's perspective) to estimate apparent LSS in the climb and approach, rather than use proprietary packages with limited flexibility. The extended method has been applied to two popular training aeroplanes in a case study approach and is described in Chapter 3. The qualitative assessment of flying qualities from the pilot's perspective was initiated in the WWII period and is discussed in the following sections.

Qualitative Assessment of Flying Qualities

The first formal qualitative assessment of flying qualities was conducted in 1936 in the United States by Soule [55]. Pilot opinion ratings were correlated with the observed longitudinal static and dynamic stability characteristics for 8 different aeroplanes. Observed 'pitch stiffness' was correlated with elevator force, elevator movement and pitching in rough air on 4-point scale from 'A' (most stiffness, greatest elevator forces and movement, most pitching rough air and shortest period/greatest damping) to 'D' (least stiffness etc.). Up until the beginning of World War II, qualitative handling quality requirements were only used for sizing control surfaces for acceptable handling qualities and to establish CG ranges that were stable and controllable [56]. Immediately following World War II, the introduction of power boosted controls and stability augmented systems meant that traditional methods for assessing handling quality requirements were temporarily disregarded and research & development with respect to the HQs of reversible control systems halted. It was not until 1968 that further progress was made in the structured assessment of aeroplane flying qualities by Cooper & Harper [57]. Their general assumption was that the terms 'flying qualities' and 'handling qualities' are synonymous when considering closed loop handling qualities for aeroplanes with non-augmented, reversible control systems.

Cook [58] considers the two qualities to be different and that flying qualities are 'task related' and handling qualities are 'response related', although he concedes that the two are interdependent and 'probably inseparable'. The Cooper-Harper Rating scale enables test pilots to rate the overall acceptability of aeroplane flying qualities using a repeatable, closed loop (or pilot in the loop) testing method. For a specific aeroplane type and a defined role/task, overall HQRs are determined using a structured decision tree based upon perceived aeroplane characteristics and demands placed upon the pilot. Cooper & Harper considered the combined elements of that affect flying qualities in closed loop control (Figure 9).

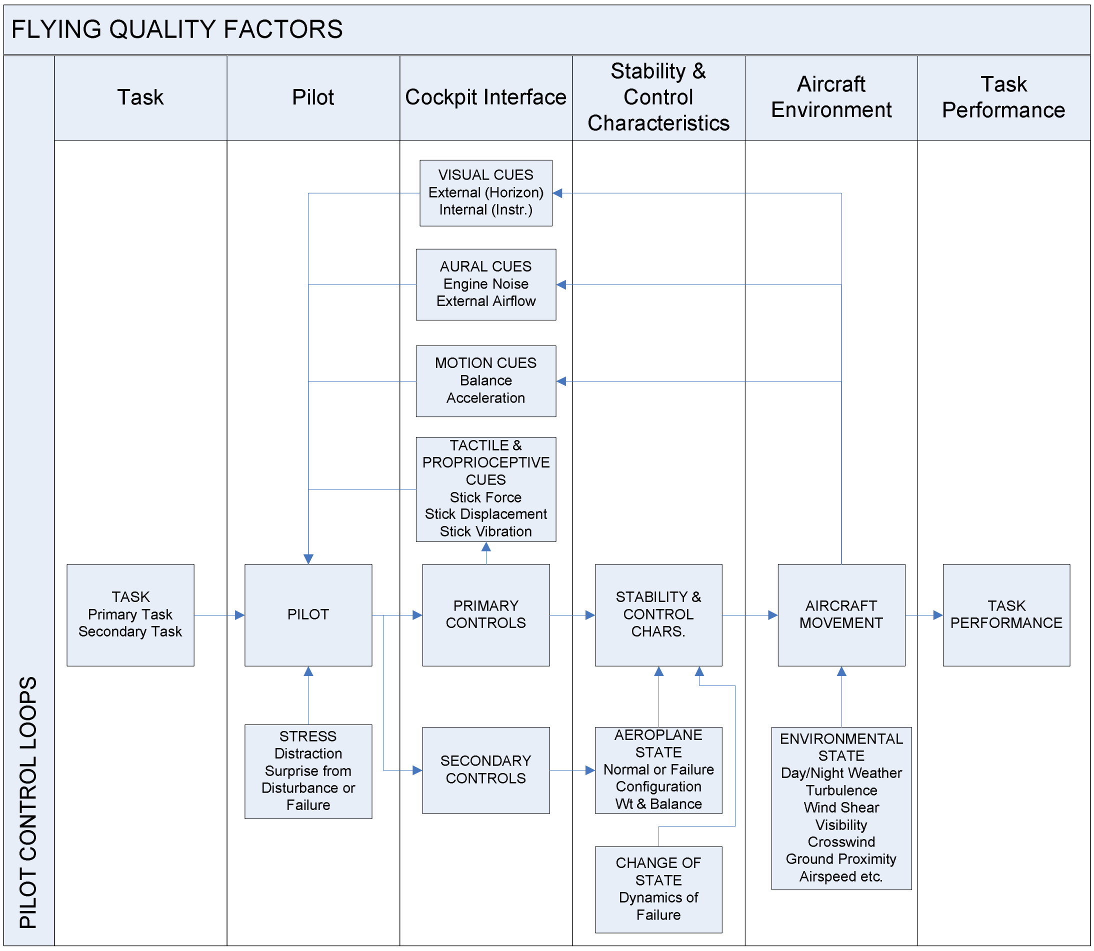


Figure 9, Elements of Control Loop that Influence Flying Qualities, Adapted from Cooper & Harper[57]

More recently, Heiligers [59] in considering the total pilot workload to perform a defined task, states that this is a combination of the task demand (the demand due to piloting tasks) and compensation demand (the demand due to changes in pilot control strategy).

The author’s interpretation of these views is that flying qualities are the combination of aeroplane handling qualities and performance to accomplish a defined task or mission. Thus from this point forward, the term ‘flying qualities’ is used to describe the closed loop interaction of pilot, control system and aeroplane.

Comparative Flying Quality Studies and Safety Concerns

The post-WWII period saw a significant increase in general aviation activity and a corresponding increase in accidents which prompted several comparative studies into the flying qualities of groups of different light aeroplanes. The first of these was conducted by Hunter [60] in 1948, who compared the flying qualities of five typical general aviation aeroplanes of the period. Hunter found that the aeroplanes tested were longitudinally stable in most of the conditions tested; however, they showed great variability between them and the aft stick position (up elevator) required to stall with power on was small in comparison to the overall stick movement and full deflection of the elevator. The stall warnings were determined as good for all aeroplanes, consisting of natural characteristics such as buffeting, aft stick movement and increased stick force without the use of stall warning systems. Hunter noted that stick movement and stick forces were noticeably smaller in the power ‘on’ condition for the majority of aeroplanes tested.

In 1966, Barber et al. [61] completed a similar study with seven typical general aviation aeroplanes of the period and concluded that all aeroplanes tested had generally satisfactory stability and control characteristics. However, they noted that these characteristics degraded with decreasing airspeed, further aft CG, increasing power and the extension of landing gear and/or flaps. Qualitative analysis was also undertaken and this showed that handling qualities were generally satisfactory for VMC and IMC in smooth air conditions, but atmospheric turbulence had a significant effect on handling qualities especially during instrument landing approaches where high precision was required. The contributing factors towards this degradation were determined to be a combination of weak static stability, excessive control friction and control surface float. The characteristics of some aeroplanes tested were considered unacceptable for an inexperienced or under-performing pilot. The characteristics manifested themselves as ‘cliff-edge’ reversals of elevator forces in the landing condition at reduced load factors, rapid roll-off and/or spins from power-on stalls and neutral or unstable longitudinal static stability with aft CG. The study suggested that acceptable criteria for control system friction and control surface float be determined. It also proposed a 'pilot workload factor' to qualitatively assess aeroplane handling qualities, based on the summation of control force input time series. However, the use of such a method is limited, since it measures only physical workload (displacement and force) and not mental workload. With respect to cockpit layout and design the study concluded that the generally poor sensitivity and positioning of the aeroplane trim systems resulted in adverse head movement which could induce vertigo.

Following this study in 1972, the NTSB initiated an in-depth study into stall/spin accidents, the primary fatal accident category, analysing trends by aeroplane make/model using chi-squared statistical analysis [62]. The study was quantitative in nature with no underlying analysis of pilot experience and grouped aeroplanes into 'high' and 'low' risk categories using a coarse banding technique. This study was the first to highlight perceived differences between makes/models, using the estimated flying hours of the aeroplane and recommended that aeroplane handling qualities and stall warning devices be improved to reduce accidents.

In 1977, Ellis [63] conducted a three-part study including statistical analysis, flight testing and in-flight simulation to investigate stall avoidance and suppression. Ellis reviewed the NTSB stall/mush accident statistics for 31 single engine aeroplanes and concluded that the majority of accidents were caused by the pilot failing to achieve or maintain flying speed, with half of those accidents occurring in the takeoff or landing phases. Stall/mush accident rates were a factor of 20:1 different between best and worst makes/models, with older designs (pre-WWII) performing the worst. Ellis conducted flight testing to assess the low speed handling qualities and stall characteristics of 6 representative makes/models out of the 31 identified in the survey (Cessna C150L, Cessna 177 Cardinal, Cessna 182, Bellanca Citabria 150, Piper PA28-140 Cherokee, Grumman American AA-1B Trainer and Grumman American AA-1 Yankee). The apparent LSS was assessed for all aeroplanes with power ON/OFF and flaps FULL/ZERO and some demonstrated showed near significantly reduced stick force gradients and 'neutral' stability (Figure 10) with full power and aft CG in the approach condition (e.g. the Cessna C150L).

Ellis' tests were conducted at MTOW with CG at the aft limit and full power, simulating the flight condition at commencement of a go-around. One aeroplane singled out by Ellis for specific criticism, was the Cessna C150L and Ellis stated that the test pilot was unable to establish a trimmed flight condition with full flap and full power at aft CG and a trim speed of 70 MIAS. Forward stick force of 1.33 daN (3 lbf) was necessary to establish and maintain the trimmed flight condition prior to measurements being taken and had insufficient nose-down trim authority, rendering it longitudinally statically unstable.

With respect to control feel, Ellis noted that stick force versus airspeed characteristics varied widely and that although gradients were stable, forces ranged from very heavy in the case of the Cessna 182 to very light in the case of the Cessna C150L, both being highly dependent upon power, flap setting and CG position. With regard to the large variations in required pull force to stall (PFtS) for any given aeroplane, Ellis stated that absolute values of pull force to stall were likely to be unreliable due to the difficulty of 'calibrating' the pilot; however, he did suggest that stick forces in excess of 9 daN (20 lbf), that needed to be continuously held by the pilot, would act as suitable inhibitor to the stall. In subsequent tests using a Navion variable stability, in-flight simulator, test pilots indicated that a PFtS of approximately 4.5 daN (10 lbf) was satisfactory and provided sufficiently strong cues of an impending stall (in addition to other natural stall characteristics such as aural/visual/buffet cues).

Earlier, Orlansky conducted a human factors study based upon previously published information and interviews with 15 jet aeroplane pilots, to determine control system design for optimum pilot sensory information by using pressure cues from the stick and rudder [64]. The results indicated that pressure sensitivity of the hands is poor below 2.2 daN (5 lbf) and control movements fatiguing above 15.6 daN (35 lbf). Orlansky recommended control forces in the range of 2.2~13.3 daN (5~30 lbf) for stick controls using one hand and 6.7~26.7 daN (15~60 lbf) for control wheels using two hands.

In line with Ellis' proposal, Thurston [65] supports the philosophy that a safe aeroplane design is one that should make the pilot exert more physical effort higher stick forces) to induce the stall once the aeroplane is set in trimmed flight. This also prevents changes in pitch attitude and airspeed due to unintentional control inputs when distracted (e.g. pilot retrieving a chart from a rear seat pocket or glancing over the shoulder to check runway alignment on climb-out).

Anderson [66] extended the work of Ellis in 1979 and suggested the development of an acceptable means to limit control pitch power to prevent complete stalling of the wing as a potential aerodynamic improvement to reduce stall/mush accidents. Anderson suggested that for those aeroplanes with 'good' stall/mush accident rates, as specified in an NTSB special study [62], the pilot had to work a lot harder to induce a stall due to their higher stick-free longitudinal stability. During the 1980s, research to improve stall/spin accident rates and safety in general centred upon aerodynamic characteristics of wing sections and limiting the progression of the stall rather than limiting elevator control power. This period coincided with the dramatic decline of GA manufacturing due to product liability concerns in the United States which continued until the introduction of the General Aviation Revitalization Act of 1994, limiting manufacturers liability [67].

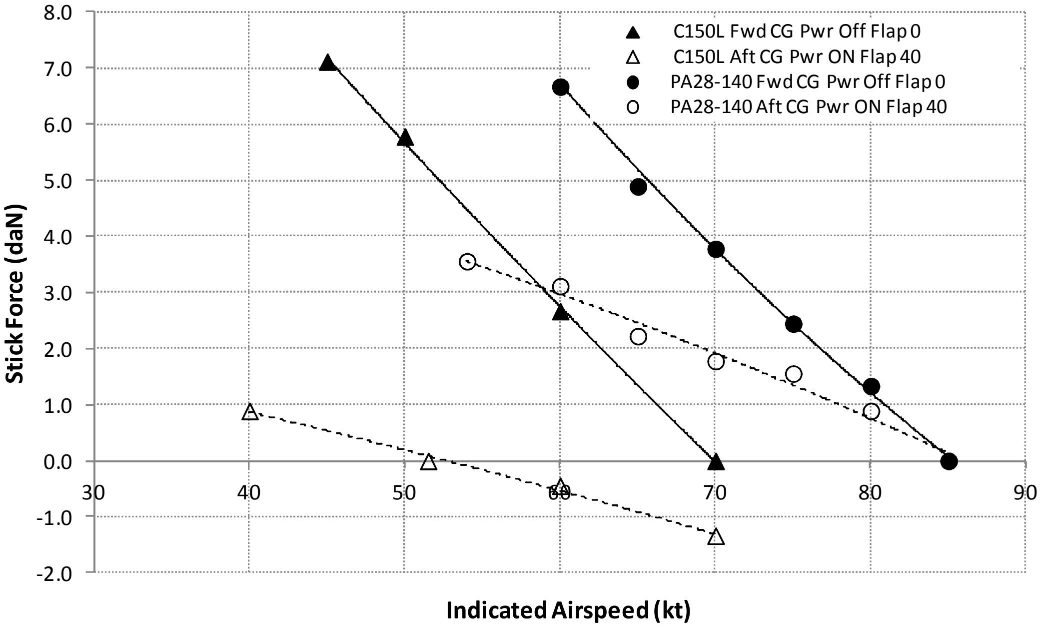


Figure 10, Comparison of Apparent Stick-Free LSS for Cessna C150L & Piper PA28-140 Cherokee, Adapted from Ellis [63]

2.3 Combining Perspectives - The Effects of Stick Force Gradients on Pilot Workload

Previous work by Barber et al [61] and Anderson [66] highlighted the implicit links between the degree of longitudinal stick-free static stability, pilot workload and safety. Early work by Abramovitz [68] assessed the effects of manoeuvring stick force gradient and gearing on tracking accuracy of a fighter aeroplane, concluding that this had no bearing on pilot performance; however, pilot workload was not measured and all pilots were experienced military test pilots.

In 1982, Hoh & Mitchell [69] represented the work of Mooij & van Gool [70] in which they conducted handling quality studies into the effect of three stick force gradients (0, 0.089 & 0.223 daN/kt) on pilot opinion ratings for holding airspeed and flying the total approach for a medium jet transport flying an instrument approach and landing. Pilot opinion ratings used in this experiment were expressed using a single dimension rating on a scale of 1 to 10 (good to poor), combining physical and mental workload. The tests were limited to three commercial, instrument rated pilots, all experienced in flight test evaluation (median PiC hrs median = 2,770, range = 4,950. The results (Figure 11 & Figure 12) suggest that increasing the stick force gradient from 0.089 to 0.223 daN/kt resulted in pilot opinion ratings for holding airspeed and flying the total approach increasing significantly ($p < 0.05$) but reducing the stick force gradient from 0.089 to 0 daN/kt was nonsignificant ($p < 0.05$). When considering these experimental results in the context of light aeroplanes and VFR flying, the nature of the ILS approach flying task in a medium jet transport aeroplane is different to that of the VFR visual approach in a light aeroplane. The former requires frequent continuous reference to cockpit instruments and navigational aids and is therefore a mainly ‘heads-down’ activity whereas the latter requires continual reference to external visual references (runway centreline and natural horizon) with occasional reference to cockpit instruments, a mainly ‘heads-up’ activity. The nonsignificant differences between pilots’ ratings as stick force gradients were reduced, can be attributed to the small sample size (n=3) and also the test pilots’ experience levels. Pilots with wide experience on a number of different aeroplane types tend to be more able to more easily modify their control strategies when confronted by a challenging flying task (i.e. compensatory, pursuit or open loop).

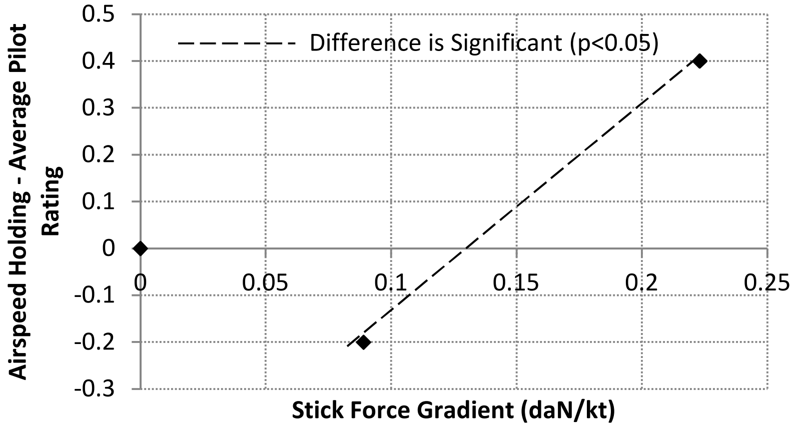


Figure 11, Variation of Pilot Rating versus Stick Force Gradient for Holding Airspeed during the Approach, Reproduced from Hoh & Mitchell [69]

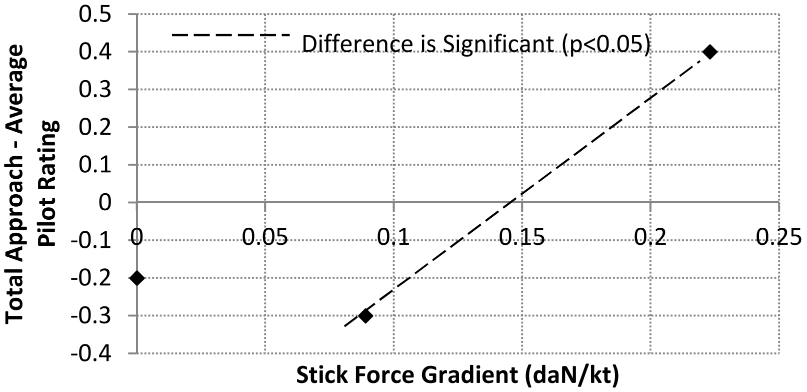


Figure 12, Variation of Pilot Rating versus Stick Force Gradient for the Total Approach, Reproduced from Hoh & Mitchell [69]

The implicit relationship between stick force gradient and pilot workload has been illustrated by Cook [71] (Figure 13). This simplistic representation assumes that the stick-free neutral point for a given aeroplane is constant and that the degree of stability is bounded by acceptable forward and aft limits. As the margin of stability increases with forward movement of the CG, stability increases, stick force gradient increases and the stick displacements become large and limiting with an associated increase in pilot workload.

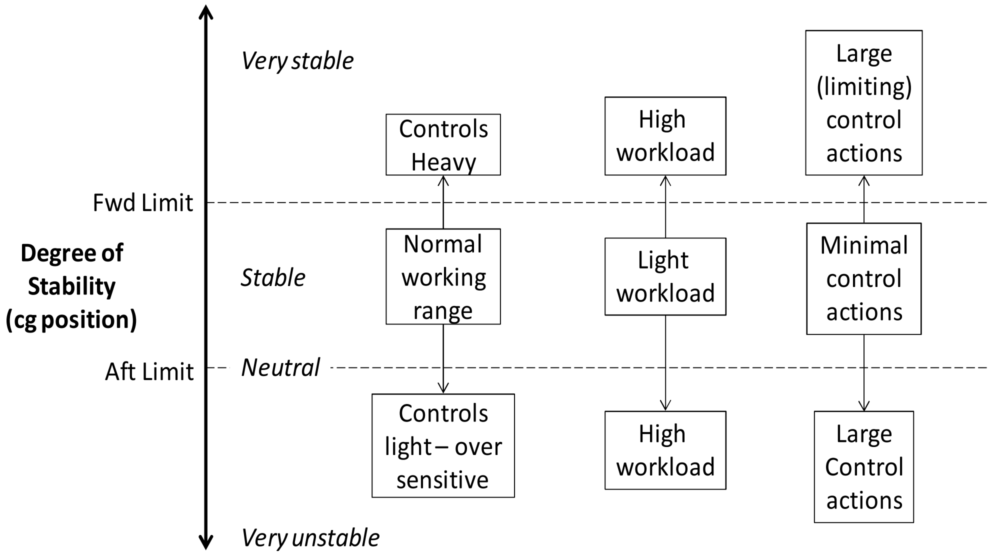


Figure 13, Stability & Control, Adapted from Cook [71]

As the margin of stability diminishes to zero with aft movement of the CG, stick force gradient decreases to zero, stick displacements increase and there is an increase in pilot workload. This representation implies that pilot workload is optimised for a given range of margins of stability and is associated with minimal control actions and moderate stick forces during typical flying tasks normally required in service. Thus, the definition of criteria for minimum acceptable stick force gradients of a non-aerobatic, light aeroplane can be used to determine optimum pilot workload (Figure 14).

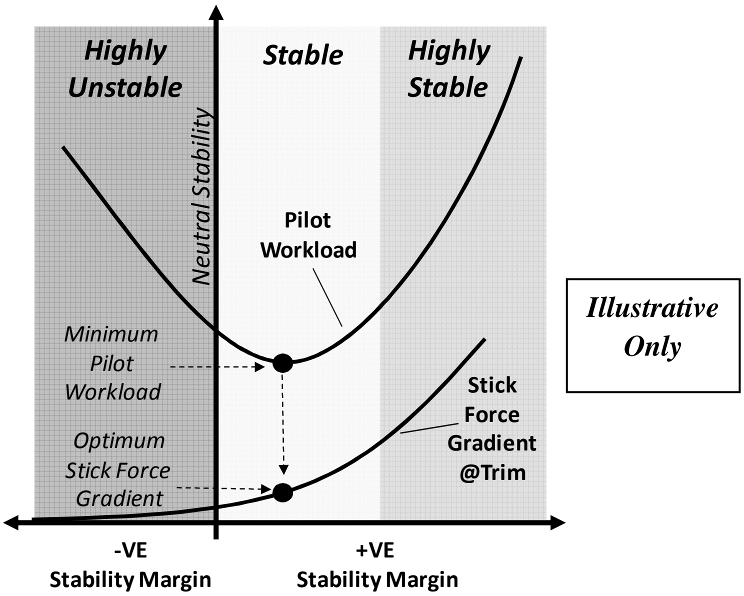


Figure 14, Effect of Stability Margin & Stick Force Gradient on Pilot Workload

2.4 The Variation of Pilot Workload and Accident Rates with Phase of Flight

Statistics show that 21.9% of all general aviation personal flying accidents occur during the take-off and initial climb and 43.6% occur during the approach & landing, despite their short duration, Figure 15 [72]. This high percentage of accidents is directly associated with increased pilot workload when the pilot is required to manage the flightpath, navigate, communicate, manage systems, execute procedures/checklists and maintain situational awareness whilst changing altitude and airspeed.

Flight simulation experimentation by the author to measure pilot workload during different phases of flight using 26 general aviation pilots, confirmed that that the highest workload was experienced (in descending order) in the approach & landing, take-off & climb-out and cruise [73].

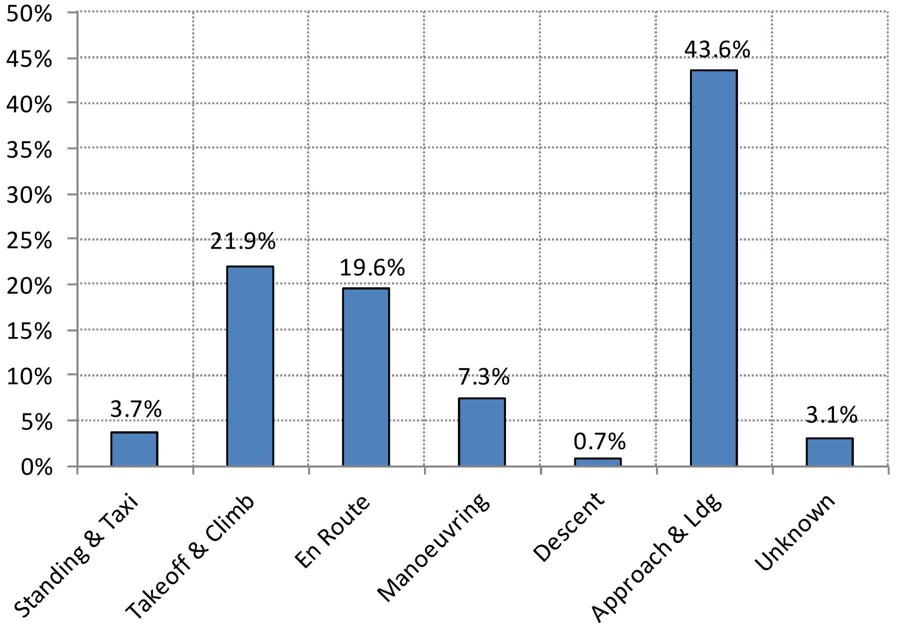


Figure 15, Phases of Flight Associated with GA Accidents in the United States, 2007-2009, Based upon NTSB Data [72]

Further experimentation by the author revealed that during a selected single phase of flight (the take-off and climb-out) the introduction of secondary tasks such as radio communication and system management, resulted in performance of the primary task degrading and workload increasing [74]. The findings concur with the work of

Lansdown [75] in the automotive field where in a driving environment, secondary task driver distraction also resulted in degradation of the primary driving task.

2.5 Certification Requirements for Stick Force Gradients

The United States introduced formal certification specifications and requirements for aeroplanes in 1945 and included requirements for stability and control feel for light aeroplanes in CAR Part 3-133 [40] and for larger, commercial aeroplanes in CAR Part 4b-150 [41]. In 1962, quantitative criteria for acceptable stick force gradients were stated for large commercial aeroplanes in CAR 4b [44] but omitted from light aeroplane certifications in CAR Part 3. These criteria have remained unchanged up until today's standards FAA Part23 for light aeroplanes and Part 25 for large commercial aeroplanes and their European equivalents.

Current standards for light aeroplanes vary across countries, regions and aeroplane categories (Table 3). Acceptable stick force gradients are only defined for European standards CS-22, Sailplanes & Powered Sailplanes [76] and CS-25, Large Aeroplanes [77] together with corresponding FAR-25 [78] in the United States. European standard CS-23 [79] for Normal, Utility, Aerobatic and Commuter Aeroplanes (General Aviation) and United States FAR-23 for light aeroplanes [80] state only 'perceptible stick force gradient', with the final judgement being left to the subjective opinion of the test pilot during initial certification of the type. Within the UK [81] and US military [82], there are no defined standards for minimum stick force gradients for light, transport or fighter aeroplane [83]. Therefore, it is apparent that for light aeroplanes within Europe and USA (and microlights within the UK) there are no specific criteria for minimum acceptable stick force gradients for safe operation. All standards require the aeroplane to show "suitable stability and control feel in any condition normally encountered". When the aeroplane is trimmed in the climb, cruise or landing, "a pull must be required to obtain and maintain speeds below the specified trim speed and a push required to obtain and maintain speeds above the specified trim speed". However, acceptable stick force gradients (stick force versus airspeed) are defined only for European standards CS-22, Sailplanes & Powered Sailplanes [76] and CS-25, Large Aeroplanes [77] together with corresponding FAR-25 [78] in the United States. European standard CS-23 [79] for Normal, Utility, Aerobatic and Commuter Aeroplanes (General Aviation) and United States standard FAR-23 [80], state only 'perceptible stick force gradient' with the final judgement being left to the subjective opinion of the test pilot during initial certification of the type.

A review and comparison of current airworthiness within Table 3 highlights inconsistencies for light aeroplanes, very light aeroplanes and microlights (UK only). Acceptable minimum stick force gradients are specified for sailplanes and powered sailplanes (lighter category) and larger commercial aeroplanes (heavier category). This is in sharp contrast to well defined criteria that exist for longitudinal manoeuvring stability (stick force per 'g'), and encompass all categories including light aeroplanes [84][85]. Stick force per g criteria was only introduced with Amendment 14, FAR Part 23.155, and was prompted by a number of accidents in the United States involving light aeroplanes with low values of manoeuvring stability [86].

The presence of such a gap in the LSS certification specifications for light aeroplanes presents an opportunity for research and potential safety improvement.

Table 3, Comparison of Current & Selected Historical Longitudinal Static Stability Certification Requirements for Different Aeroplane Categories

Category	Region	Airworthiness Requirement (Paragraph Numbers)	Minimum Stick Force Gradient	Maximum Trim Speed Band
Light Aeroplane	Europe	CS-23 [79] (143, 145, 161, 171, 173, 175)	Gradient not defined, 'positive' within ranges and in configurations given in para 175.	±10% ±7.5% (cruise conditions, commuter category only)
	USA	FAR-23 [80] (143, 145, 153, 161, 171, 173)	In general, within 15% of trim at all conditions. "any substantial speed change results in a stick force clearly perceptible to the pilot."	
Very Light Aeroplane	Europe	CS-VLA [87] (143, 145, 161, 173,175)	Not defined	±10% trim CAS
Light Aeroplane (pre-1993)	UK	BCAR Section K [88] (2-8,2-9,2-10)	Not defined	Not defined
Microlight	UK	BCAR Section S [89] (143, 161, 173, 175)	Not defined	±10% trim CAS
Sailplanes and Powered Sailplanes	Europe	CS-22 [76] (143, 145, 161, 171, 173, 175 AMC 22.173 (a))	1 N / 10 km/h (0.031 daN/kt)	Greater of ±15% or ±15 km/h
Large Transport (pre-1980)	UK	BCAR Section D [90]	1 lbf/ 6 kt or 0.167 lbf/kt (0.074 daN/kt)	±10% climb, approach and landing, ±7·5% cruise
Comm-ercial	Europe	CS-25[77] (143, 145, 161, 171, 173, 175, AMC 22.173 (c))	1 lbf/ 6 kt or 0.167 lbf/kt (0.074 daN/kt) The average gradient is taken over each half of the speed range between 0·85 and 1·15 V_{Trim}	±10% climb, approach and landing, ±7·5% cruise
	USA	FAR-25 [78] (143, 145, 153, 161, 171, 173)		
Military	UK	DEF STAN 00-970 Part 1/5 Section 2, Leaflet 40 [81]	Gradient not defined. Force & deflection must be smooth and stable or Force & deflection gradients can be zero if SAS or CAS are available. Unstable gradients allowable in transonic flight if not objectionable to the pilot.	±15% or 50 kt, whichever is less
	USA	MIL 8785C [82] (3.2.1.1)		

2.6 Chapter Summary

Adequate stability and control feel is a basic certification requirement for all light aeroplanes and the development and understanding of stability and control has been reviewed from the engineer's and pilot's perspective. The pilot's perspective, commonly referred to as the 'flying qualities' of an aeroplane, is traditionally assessed by flight testing using a combination of both quantitative and qualitative measurements. Quantitative assessment is made by the measurement of stick force gradients and qualitative assessment by use of pilot opinion ratings such as Cooper-Harper.

Comparative flying qualities studies were undertaken in the 1960s and 70s for a selection of GA aeroplanes, driven by increased accident rates and the desire to improve safety. The studies concluded that although most aeroplanes exhibited generally satisfactory stability and control characteristics, these degraded with decreasing airspeed, aft CG, and increased power and flap settings. Selected aeroplanes exhibited 'neutral' LSS and significantly reduced stick force gradients in the approach and landing.

Although there are intuitive links between longitudinal static stability and pilot workload, research has been limited to commercial jets and fighters. Experimental results suggest that there is no significant change in pilot workload as stick force gradient reduces to zero, however these experimental results are not are applicable to the general aviation environment where levels of pilot skill, experience and adaptability are considerably lower. In the general aviation environment it is possible that 'optimal' stick force gradients can minimise pilot workload in safety critical phases of flight.

In contrast to large, commercial aeroplanes, current certification specifications for light aeroplanes in Europe and the United States lack detailed criteria for acceptable stick force gradients, only requiring aeroplanes to demonstrate 'suitable stability and control feel in any condition normally encountered' and this is subjectively assessed by individual test pilots.

The extension of existing theoretical methods to predict stick force gradients in the approach and landing and tendencies towards neutral stability would prove useful in preliminary design and is discussed in the next chapter.

3. A Theoretical Method for Estimating Stick Force Gradients of a Light Aeroplane

Chapter 1 described the importance of control feel and the certification requirement that all aeroplanes “demonstrate suitable stability and control feel in any condition normally encountered in service” [13]. However, current certification standards for light aeroplanes rely upon subjective test pilot opinion and do not quantify control feel (stick force gradient). Acceptable control feel should be assessed using quantitative criteria for acceptable stick force gradients in any flight condition, as in the case for large aeroplanes [1]. This chapter presents a model for the estimation of stick force gradients that can be used to predict (potentially hazardous) tendencies towards neutral stability [15]. Previous published work in this field as described in Chapter 2, considers cruising flight only; however, since 21.9 % of GA accidents occur in the take-off & climb and 43.6% occur in the approach & landing [72], the ability to predict tendencies towards neutral stability in these phases is key. An extension to previous work is described and this considers the additional effect of flaps in these safety-critical phases of flight. The method was implemented using MATLAB [16] and a parametric analysis was conducted for a typical light aeroplane (Cessna 150M).

3.1 Estimation of Stick Force and Gradient

For a typical light aeroplane with non-augmented, reversible control systems and without the aid of down springs or bob weights, pitch control forces can be estimated using theory as described by Etkin & Reid [49].

The system (Figure 16) comprises three main components, the control stick, control system linkage and the elevator. The control system linkage represents the combination of bell cranks, rods, pulleys, cables and turnbuckles commonly found in a typical light aeroplane.

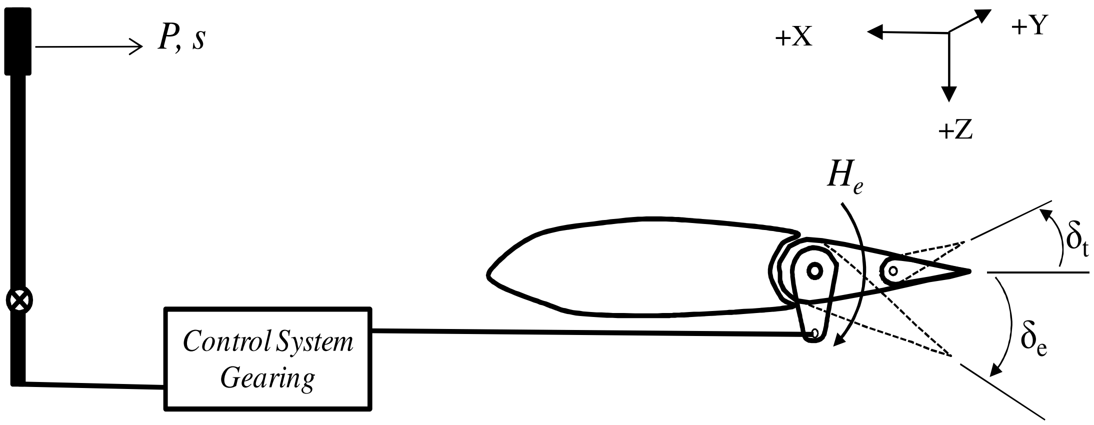


Figure 16, Simplified elevator control system (OX-OZ plane), adapted from Etkin & Reid [49]

The following assumptions have been made in the application of this theory:-

- Flow is incompressible;
- The aeroplane is in a non-stalled condition in cruising flight, with attached flow;
- Movement outside the OX-OZ plane is ignored i.e. system has 2 degrees of freedom (along OX and about OY);
- The aeroplane structure is rigid and aero-elastic effects ignored;
- The reversible control system is both mass-less and frictionless;
- No lack of fit at the joints or elasticity in control cables;
- Quasi-static conditions exist;
- Altitude is constant;
- Weight is constant;
- The elevator trim tab is fixed for the initial trim condition;
- The direct and indirect effects of power are ignored.

For a small quasi-static displacement from equilibrium and using conservation of energy, Etkin [49] shows that:-

$$P = GH_e \qquad \textbf{Eqn 4}$$

Substituting for C_{he} and $C_{L_{trim}}$ in Eqn 4 using Etkin, the simplified result obtained is:-

$$P = C + AV_E^2$$ **Eqn 5**

In the form of a 2nd order polynomial in V_E, where:-

$$C = GS_e\bar{c}_e w \frac{a' b_2}{\det}(h - h'_n)$$ **Eqn 6**

$$A = \frac{1}{2}\rho_o GS_e\bar{c}_e\left[b_3\delta_t + b_0 + \frac{C_{m0}}{\det}\left(b_1 C_{L_{\delta_e}} - b_2 C_{L_\alpha}\right)\right]$$ **Eqn 7**

Using Eqn 5, a theoretical plot of stick force (P) versus airspeed (V_E) (Figure 17) defines the apparent (as felt by the pilot at the aeroplane controls) stick-free longitudinal static stability [91]. This is a measure of the aeroplane's natural tendency to return to a trim condition in flight as the airspeed is changed and the elevator is free to float whilst the pilot is 'hands-off'.

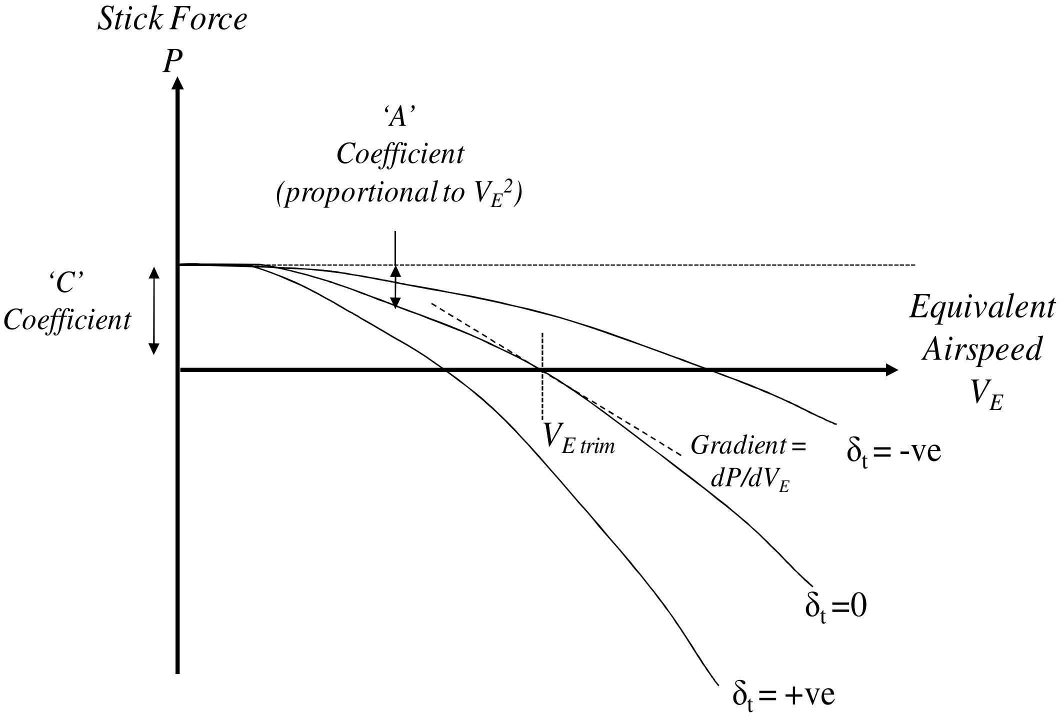


Figure 17, Typical plot of Stick Force versus Equivalent Airspeed, adapted from [49]

The estimation of stick force gradient, away from the trim condition is given by differentiating Eqn 5 with respect to V_E:-

$$\frac{dP}{dV_E} = 2AV_E$$ **Eqn 8**

Inspection of Eqn 6 suggests that the coefficient 'C' is dependent upon CG (via the term for static margin $h\text{-}h_n'$), wing loading (w or W/S) and elevator gearing (G). Inspection of Eqn 7 suggests that the coefficient 'A' is dependent upon trim tab setting (δ_t); elevator gearing (G). In summary:-

$$\mathrm{C} = \text{function}\left(h, \frac{W}{S}, G\right)$$ **Eqn 9**

$$\mathrm{A} = \text{function}\ (\delta_t, G)$$ **Eqn 10**

3.2 Effect of Flaps

Classical treatments of apparent longitudinal stick-free static stability such as Etkin [49], Perkins & Hage [24], McCormick [92] and Roskam [93], etc. have not fully considered the effect of high lift devices such as flaps. The application of flaps during the approach and landing and the retraction of flaps during the go-around have a significant effect on trim [94], [95]. The changes to the flow field have a direct influence on the elevator forces required to trim the aeroplane in these configurations as noted by Smetana [51]. Figure 18, shows the net effect of the application of flaps on the span-wise lift distribution and wake vorticity experienced at the tail [50].

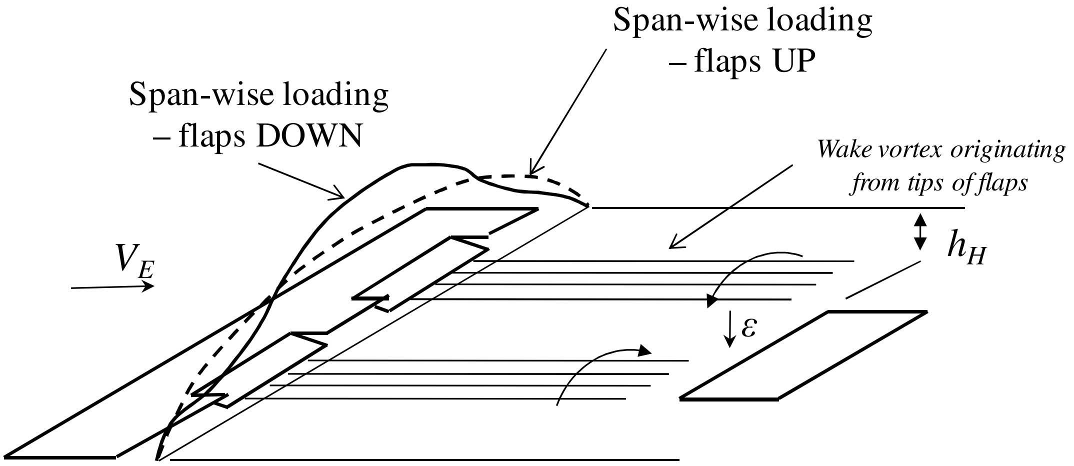


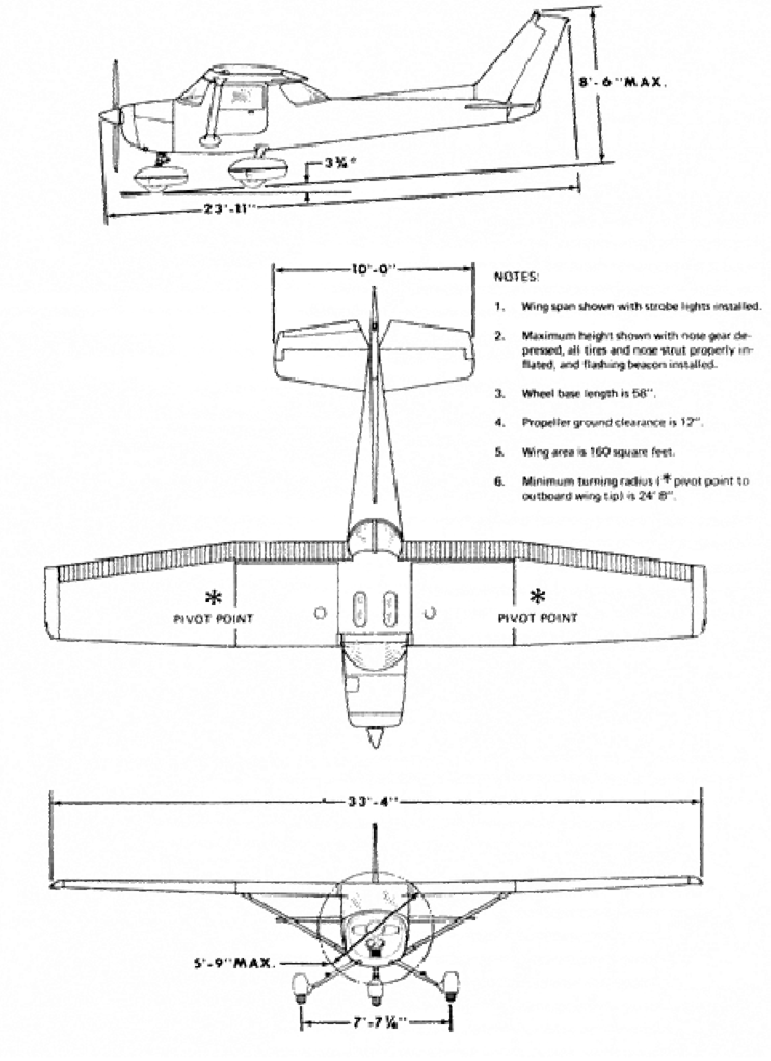
Figure 18, Effect of Part-span Flaps on Lift Distribution and Vorticity, adapted from [5050]

The deflection of flaps tends to narrow the span of the trailing vortex, increasing the strength of the vortex behind the outer trailing edges of the flaps. There is a local increase in wing section camber resulting in a negative increment in C_{m_0} and a positive increment in $C_{L_{wb}}$, requiring the pilot to push the stick forward to command a downward deflection of the elevator to maintain a given trimmed airspeed condition. The corresponding increase in downwash at the tail, results in an increase to the downwash derivative $\left(\frac{d\varepsilon}{d\alpha}\right)$ and downwash constant (ε).

3.3 Parametric Analysis using MATLAB

Parametric analysis using a MATLAB script incorporating Eqn 5 and Eqn 8 enabled the apparent stick-free longitudinal static stability (Figure 20) to be determined. Using estimated design data for a typical light aeroplane (Figure 19) [96], estimates of stick force (P) and stick force gradient $\left(\frac{dP}{dV_E}\right)$ variation with equivalent airspeed (V_E) were determined by incrementally changing the following parameters:-

- Wing loading (W/S)
- CG (h)
- Elevator gearing (G)
- Downwash derivative $\left(\frac{d\varepsilon}{d\alpha}\right)$
- Elevator trim (δ_t)



NOTES:

1. Wing span shown with strobe lights installed.
2. Maximum height shown with nose gear depressed, all tires and nose strut properly inflated, and flashing beacon installed.
3. Wheel base length is 58".
4. Propeller ground clearance is 12".
5. Wing area is 160 square feet.
6. Minimum turning radius (* pivot point to outboard wing tip) is 24' 8".

Figure 19, A Typical Light Aeroplane - Cessna C150M [96]

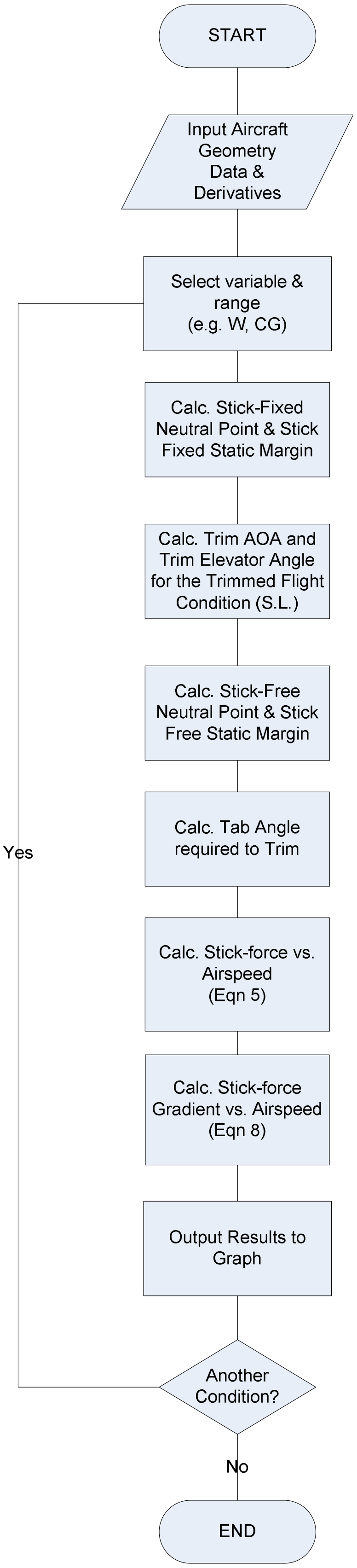


Figure 20, Flowchart for Estimation of Apparent Stick-free Longitudinal Static Stability

For the selected aeroplane geometry and given trim condition in the cruise, a first estimate of the downwash at the tail (ε) can be determined using Perkins & Hage [97] and is dependent upon the wing-body lift coefficient $C_{L_{wb}}$. This approximation assumes the theoretical value at infinity behind the wing. The corresponding first approximation of downwash derivative $\left(\frac{d\varepsilon}{d\alpha}\right)$ at the tail is determined by empirical methods for subsonic downwash both with and without flap deflection, developed by Hoak [98] within Digital DATCOM. This approach uses an empirical graphical method considering design factors related to wing aspect ratio, wing taper ratio, horizontal tail location and wing sweepback, used in combination to estimate the downwash derivative.

The variation of stick force and gradient with airspeed was estimated by varying one parameter at a time for the typical light aeroplane (Figure 19) in the cruise, at V_E=84 kt, W = 1600 lbf MTOW at sea level and standard atmospheric conditions. Selected examples (Figure 21 & Figure 22) show the sensitivity of stick force and gradient to changes in downwash derivative, complete results for all parameters under similar trim conditions are presented in Appendix A3-1.

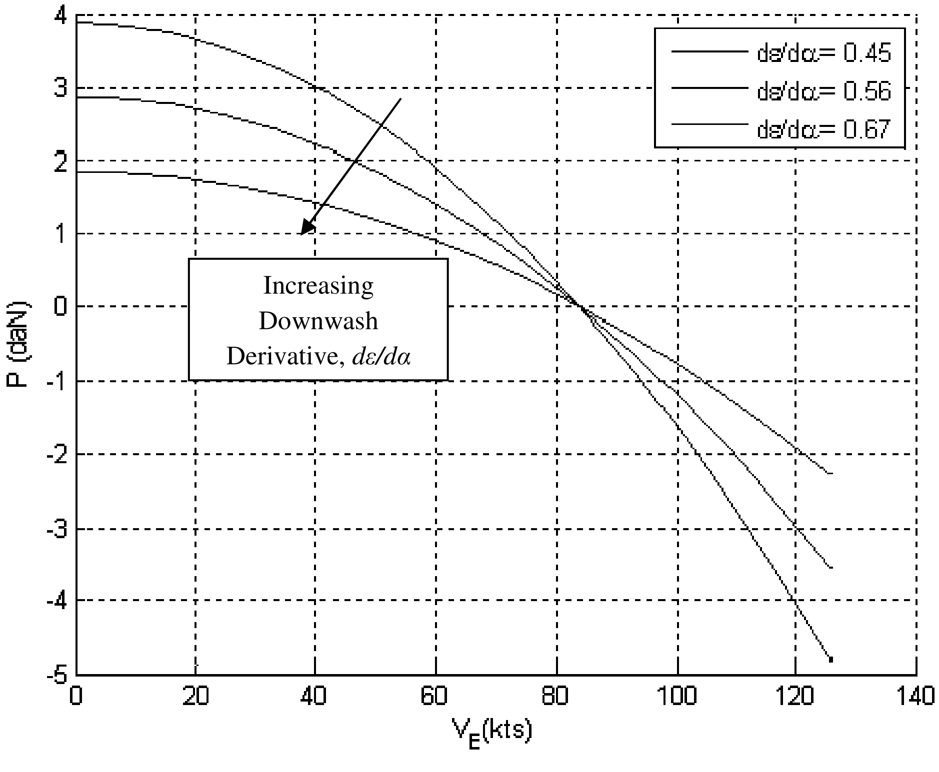


Figure 21, MATLAB Output: Variation of Apparent Stick-free Longitudinal Static Stability Downwash Derivative, *dε/dα*

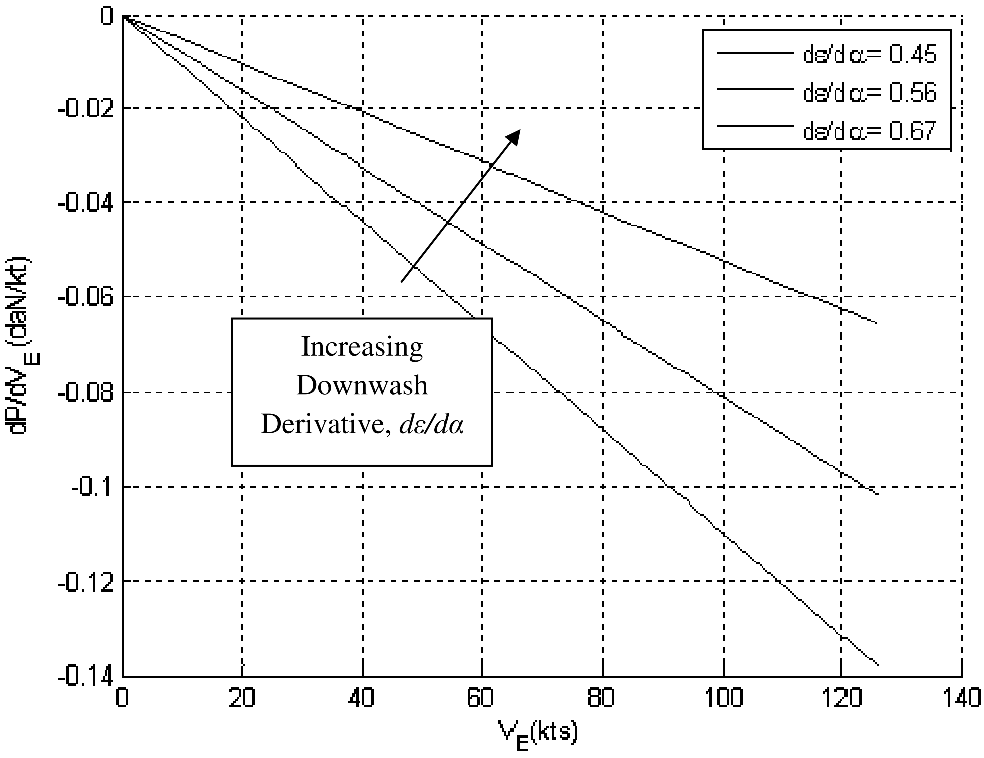


Figure 22, MATLAB Output: Variation of Stick Force Gradient with Downwash Derivative, *dε/dα*

Table 4, Summary of MATLAB Predicted Qualitative Effects of Parameter Changes on Stick Force Coefficients

Parameter	**Variable during flight?**	**Change Effect on Y intercept (coefficient 'C')**	**Change Effect on Gradient (coefficient 'A')**
Wing Loading, *W/S* increasing	No (negligible, typically <10%)	Increase	Increase
CG, *h* move AFT increasing arm	Yes, dependent upon fuel tank configuration & layout	Decrease	Decrease
Elevator Gearing, *G* increasing	No	Increase	Increase
Downwash Derivative $\left(\frac{d\varepsilon}{d\alpha}\right)$ increasing	Yes, dependent on power and flap setting	Decrease	Decrease
Elevator Trim Tab, (δ_t) increasing Nose Down	Yes, dependent upon flight condition	None	Increase

The summarised results (Table 4) show that the Y-intercept (coefficient ‘C’) and gradient (coefficient ‘A’) are dependent upon movement of CG, elevator gearing and wing loading in accordance with known theory. The elevator trim tab has no effect on coefficient ‘C’. The downwash factor has strong influence on the coefficient ‘A’ and ‘C’ but is less well documented and not explicitly highlighted in previously published theory. This is an area of specific interest during approach & landing and take-off & climb when flaps are used. Individual aeroplanes exhibit a unique combination of these key parameters due to variability of wing, tailplane and flap rigging, elevator control cable tension and basic empty weight.

3.4 Extension of the Method to the Climb and Landing Condition

The method as described earlier has traditionally been applied to the cruise condition only. This programme of research has extended the traditional method to include the climb and landing condition for completeness of the theoretical analysis and assist in the preliminary design of a light aeroplane. For the climb, without the use of flaps, the cruise method may be applied to determine both downwash angle at the tail using Perkins & Hage [24] and downwash derivative using Hoak [98]. However, during the landing condition when flaps are either partially or fully deployed, the downwash angle at the tail is significantly modified by the changed vortex pattern behind the flaps. The change in downwash angle is estimated for plain and slotted flaps using an empirical method based on curves derived from experimental tabulated test data provided by Hoak [98]. The extended method estimates the change in downwash angle using the following parameters:-

- Wing span (obtained from manufacturer’s data);
- Horizontal tailplane height above/below the wing-chord plane (estimated by inspection of scaled drawings);
- Change in C_L due to flap deflection (obtained from manufacturer’s flight test data, wind tunnel data or use of CFD methods).

For the selected Cessna 150M, change in C_L due to flap deflection for an aeroplane of similar design was used (Cessna 172) [99].

3.5 Chapter Summary

One of the key objectives of this research was to develop a model to estimate stick force gradients for a light aeroplane in any flight condition. This chapter has presented an extended model for the estimation of stick force gradients and the prediction of (potentially hazardous) tendencies towards neutral stability. Previous published work in this field has considered cruising flight only without the use of flaps, however since the majority of GA accidents occur in the take-off & climb and approach & landing, the ability to predict tendencies towards neutral stability in these flight conditions is key. The extended model has highlighted the sensitivity of stick force gradients to wing loading (W/S), elevator gearing (G), elevator trim tab setting (δ_t), CG (h) and especially downwash derivative $\left(\frac{d\varepsilon}{d\alpha}\right)$. The next chapter presents experimental flight test and simulation results to determine criteria for acceptable stick force gradients. It also compares flight test and theoretical stick force gradients, to assess suitability of the extended model for use in preliminary design and the prediction of tendencies towards neutral stability.

4. Results of Flight Testing, Modelling & Simulation to Establish Acceptable Criteria

The primary objective of this research was to establish suitable criteria for acceptable stick force gradients for a non-aerobatic, light aeroplane in any steady flight condition. This has been achieved by flight testing multiple C150M and C152 airframes to assess actual stick force gradients in the climb, cruise and approach and by assessing handling qualities using Cooper-Harper HQRs [57]. Following flight testing, simulated flying tasks were conducted with 20 volunteer GA pilots to assess the effects of stick force gradient on pilot workload by simulating aeroplanes with moderate (≈0.07 daN/kt) and 'neutral' stick force gradients. The secondary objective was to develop a model to estimate stick force gradients for a light aeroplane in any flight condition. This has been achieved by developing a MATLAB model (Chapter 3) based upon existing theory for the estimation of stick force gradients in the cruise and extended to the climb and approach by consideration of the combined effects of wing loading, CG, elevator gearing, flaps and elevator trim setting. The results of the modelling, flight testing and simulation of stick force gradients are presented and summarised.

4.1 Flight Test Experiments for the Cessna C150M and Cessna C152

Flight tests were performed to assess stick force gradients about the trim condition in the cruise, climb and landing using the stabilised point technique [100]. Subjective handling quality assessments were conducted only in the climb (due to time and cost constraints) by an experienced light aeroplane test pilot familiar with the Cooper-Harper technique. Tests were conducted as part of a wider flight test programme to assess the low-speed handling qualities of Cessna C150 and C152 aeroplanes (Appendix A4-1). Measured breakout and friction forces were deduced and eliminated to compare theoretical and experimental stick force gradients (Figure 23 & Figure 24) in similar flight conditions (e.g. Cessna C150M in the cruise, at V_E = 89 kt, W = 1580 lbf @27 %MAC). Combined breakout force + friction was measured directly using a handheld force gauge and friction estimated by inspection of the graphical results.

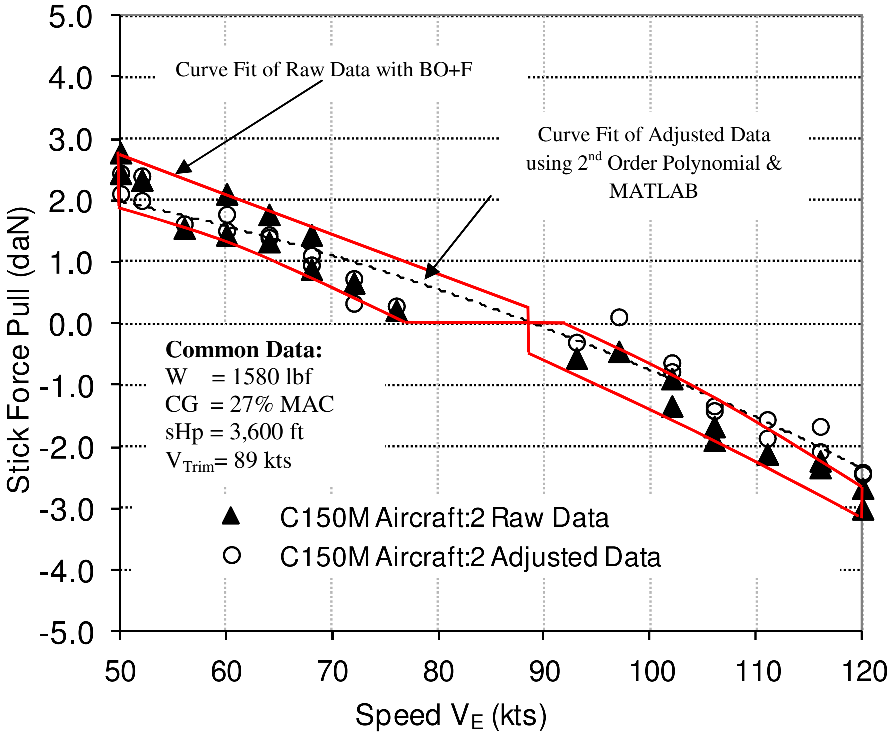


Figure 23, Sample of Experimental Results for Apparent Stick-Free LSS for the C150M in the Cruise Condition before and after removal of Breakout Forces and Friction

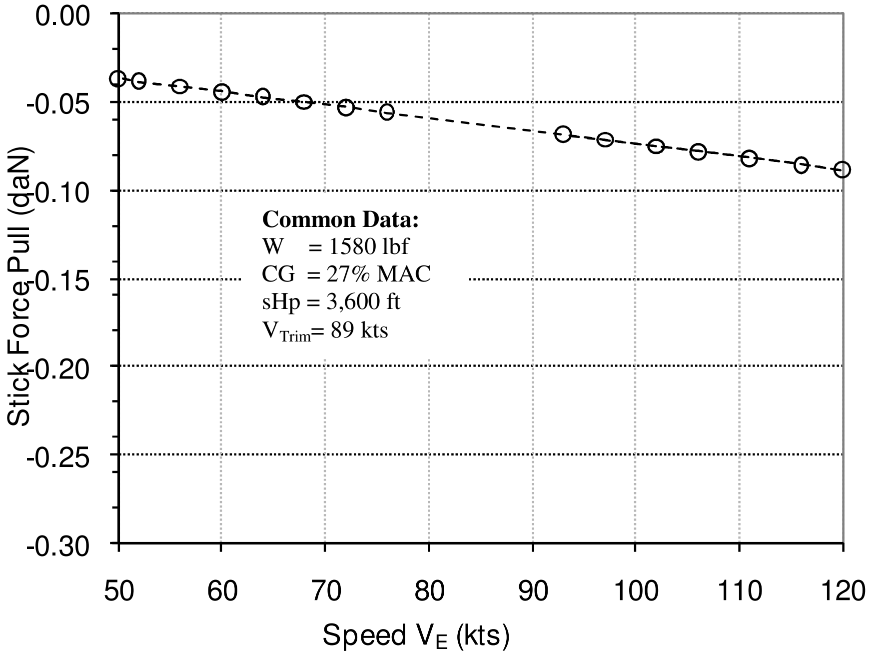


Figure 24, Sample of Experimental Results for Stick Force Gradient for the C150M in the Cruise Condition before and after removal of Breakout Forces and Friction

The adjusted data points (Figure 23) were used to define a 2nd order polynomial in V_E of the form $P = C + AV_E^2$ (Eqn…5), by regression analysis using the MATLAB curve fitting tool (*'cftool'*). The calculated polynomial coefficients ('A' and 'C') were used to determine associated stick force gradients *dP/dV* (Eqn…8 & Figure 24). The results indicate a slight reduction in stick force gradient about the trimmed condition, this method being applied to all experimental results from this point forward.

Cessna C150M

The design review of the C150 & C152 groups [4] indicated fleet-wide variations in the weight & balance and flying control mechanical characteristics. Due to variability between airframes, it was decided to conduct all flight tests using 3 airframe examples of the most popular models from each group (the Cessna C150M model and Cessna C152 model). The number of airframes was limited by practical constraints of time, cost and airframe availability.

For the Cessna C150M, apparent stick-free longitudinal static stability was assessed for all airframes in the cruise at 3,600 ft sHp and 84~89 kt (EAS) using the stabilised point technique, near to MTOW and one position (CG 25.7 ~ 27.0 %MAC). Results (Figure 25) show similar variations of stick force with airspeed over a range of 50~120 kt. Corresponding stick force gradients (Figure 26) are similar and all are below 0.10 daN/kt. All airframes exhibited limited positive stability over with stick forces of less than 2 daN/kt approaching the stall (48 kt). Pilots are likely to experience limited perception of airspeed changes with stick forces in this flight condition. Statistical analysis (Table 5) at the trim condition, show significant variations in gradient (*Mean = -0.059 daN/kt, SD = 28%*). This suggests the presence of significant fleet-wide variations of stick force gradient and prompted the selection of median results (Aeroplane 2) as the 'baseline' C150M airframe for future analysis and comparison with theoretical results in all flight conditions. All airframes tested were compliant with current specification requirements for apparent longitudinal stick-free static stability in the cruise as specified within CS-23 para 175(b) [101].

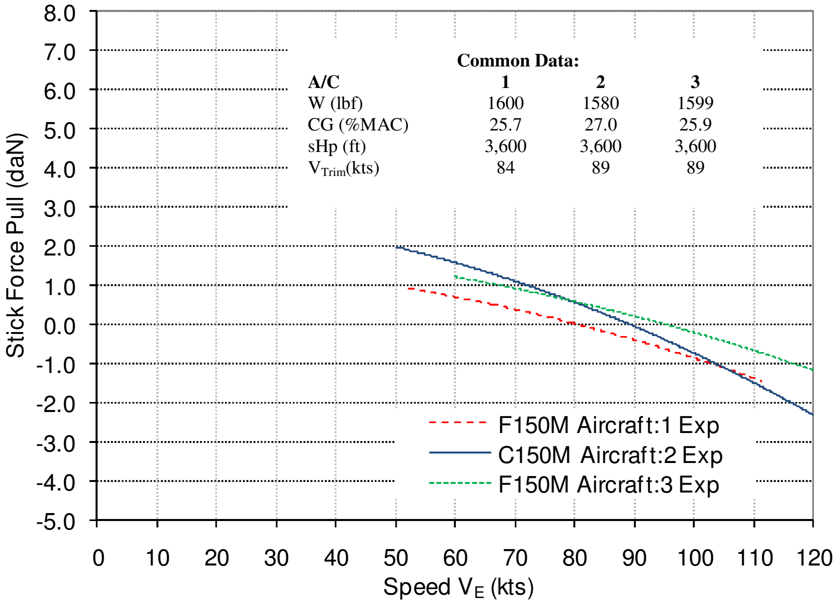


Figure 25, Experimental Apparent Stick-Free LSS for three Cessna F150M/C150M Models in the Cruise Condition

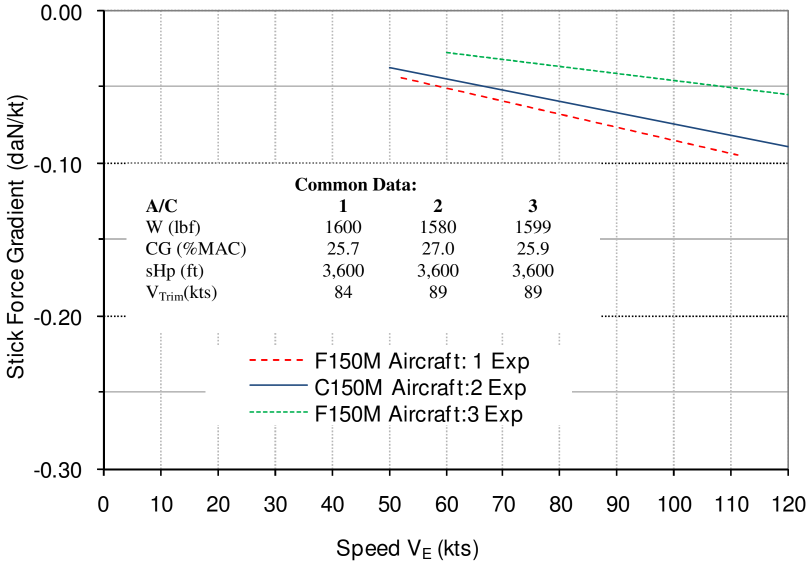
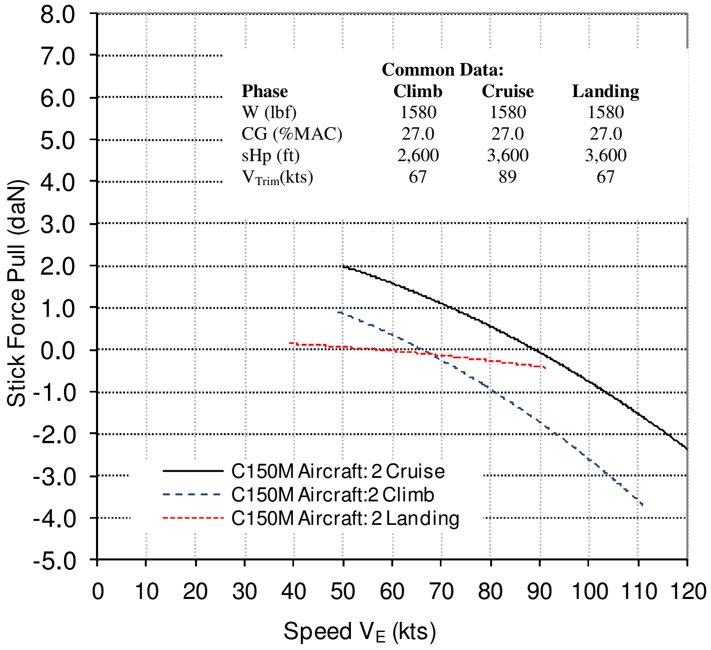


Figure 26, Experimental Stick Force Gradient for three Cessna F150M/C150M Models in the Cruise Condition

Table 5, Comparison of Stick Force Gradients for 3 x Cessna F150M/C150M Airframes in the Cruise Condition at V_{Trim}

	Stick Force Gradient (daN/kt) at V_{Trim}					
Description of Tests	**Aeroplane 1: Cessna F150M**	**Aeroplane 2: Cessna C150M**	**Aeroplane 3: Cessna F150M**	**Mean**	**Median**	**SD**
Apparent LSS Cruise Condition	-0.070	-0.066	-0.040	-0.059	-0.066	0.016

Apparent stick-free LSS was assessed for aeroplane 2 in the climb and landing condition (30º flap) at 3,600 ft sHp and 67~68 kt (EAS) using the stabilised point technique with aeroplane near to MTOW and one CG position (27.0 %MAC). During flight testing of the Cessna C150M models, the test pilot was unable to establish the trimmed flight condition with full flap setting of 40˚ and the available elevator trim authority for the majority of sorties with at MTOW using mid or mid-aft CG. For this reason (and to allow comparison with C152 models where required) 30˚ flap was used for all flight tests using model Cessna C150M aeroplanes. The results (Figure 27) show similar variations of stick force over an airspeed range of 50~120 kt in the climb and cruise but significantly lower forces over an airspeed range of 41~90 kt in the landing. Stick force gradient (Figure 28) was below -0.02 daN/kt in the landing, tending towards 'zero'. The airframe exhibited limited positive stability in the cruise and climb and near 'neutral' stability in the landing, with a stick force of ≈0.1 daN in the proximity of the stall (41 kt). Pilots would experience limited perception of airspeed change with stick force in the climb and cruise condition and negligible perception in the landing condition. Pilot distraction during the landing can result in significant deviations from the target approach speed due to poor tactile cues via the control yoke.



Common Data:

Phase	Climb	Cruise	Landing
W (lbf)	1580	1580	1580
CG (%MAC)	27.0	27.0	27.0
sHp (ft)	2,600	3,600	3,600
V_{Trim}(kts)	67	89	67

Figure 27, Experimental Apparent Stick-Free LSS for the Cessna 150M in Climb, Cruise & Landing Condition (30º Flap)

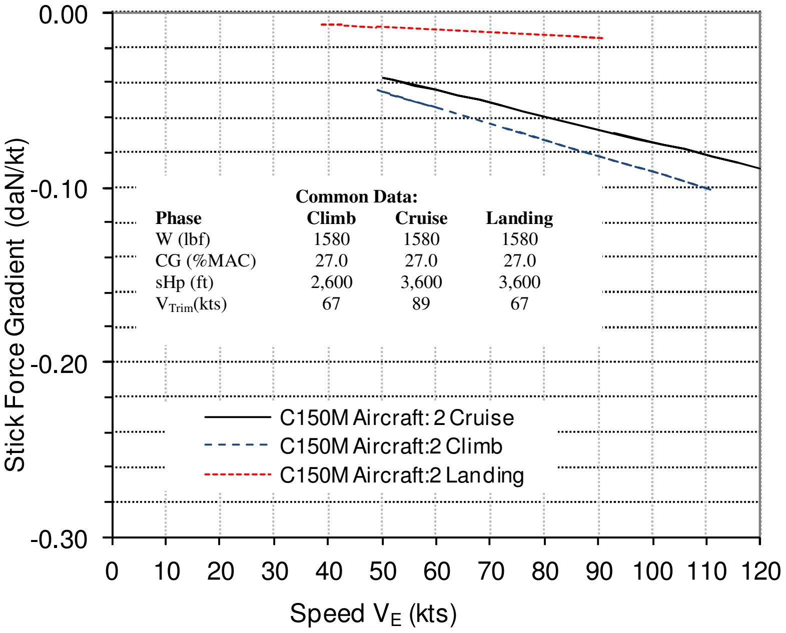


Figure 28, Experimental Stick Force Gradient for the Cessna 150M in Climb, Cruise & Landing Condition (30° Flap)

Table 6, Summary of Experimental Apparent Stick-Free LSS Flight Tests, Cessna C150M

Test No.	Description of Tests	Power	% BHP	Flaps (deg)	Stick Force Gradient at V_{Trim} (daN/kt)	Stick Force Gradient Change relative to the Cruise (daN/kt)	CS-25.175 Compliant?
1	Apparent LSS Climb	Full	56	0	-0.060	-0.006	No
2	Apparent LSS Cruise Condition	Level Flight	54	0	-0.066	0.000	No
3	Apparent LSS Landing Condition (30° Flap)	Level Flight	54	30	-0.020	-0.046	No

The airframe tested was compliant with requirements for apparent stick-free LSS in the climb and cruise as per CS-23 para 175(b) [101] but in the case of the landing was marginally compliant.

The absence of specific criteria for acceptable stick force gradients for light aeroplanes within CS.23, prompted comparison with available, defined criteria for large aeroplanes within CS.25 [1]. These require a minimum stick force gradient of

-0.074 daN/kt (1 lbf per 6 kt) in all flight conditions and the Cessna 150M airframe tested did not satisfy these criteria in any flight condition (Table 6).

In addition to the flight assessment of stick force gradients, a qualitative assessment of aircraft handling qualities was conducted in the climb. A compensatory tracking task for a steady climb was defined using the Cooper-Harper method [57]. The pilot was required to maintain a best rate of climb speed (V_Y = 69 kt) through a vertical distance of at least 1,500 feet sHp, whilst maintaining a fixed heading (into wind where possible) using desirable CH airspeed tolerance of +/- 2 kt and adequate airspeed tolerance of +/- 5 kt. Ground speed (kt) and geopotential altitude (ft) was obtained during the climb using a portable FDR (Appareo GAU 1000a [102]) with an effective sampling rate of 4 Hz. Ground speed was converted to 'pseudo Equivalent Airspeed' compensating for density effects (Appendix A4-2) enabling graphical time-series plots to be prepared. Results (Figure 29) show that HQR5 was recorded at the start and mid-point of the climb reducing to HQR4 at the end suggesting that 'moderate to extensive' pilot compensation was necessary and handling qualities of the aeroplane were unsatisfactory. The decrease in HQR (-1) at the end of the climb indicates increased pilot familiarity with a revised compensation model and having more time to properly trim the aeroplane. The time-series plots (Figure 30) show deviations from the target airspeed in the range of +/- 3 kt (allowing for an apparent headwind of 16 kt).

Repeating the test for a second C 150M airframe with W = 1425 lbf, CG = 27.0% MAC (Figure 31 & Figure 32), showed scores of HQR7 for the entire climb. The resultant time-series plot shows more frequent deviations from target airspeed and that these were in the range of +9/-3 kt (no apparent headwind) and occurred at the start and end of the climb. Examination of the portable CVR recording for the flight showed that these points coincided with unplanned secondary piloting tasks being conducted by the pilot (ATC requests for the pilot to change radio frequencies). The pilot commented that 'the indicated airspeed tended to wander between 70~90 kts with frequent small, ASI corrections required'. This suggests an increase from 'moderate' to 'extensive' pilot compensation whilst performing a secondary (communication) task in parallel with the primary task.

Quantitative and qualitative flight test results have been presented for the Cessna 150M airframe and the results of similar tests for the Cessna 152 are presented for comparison.

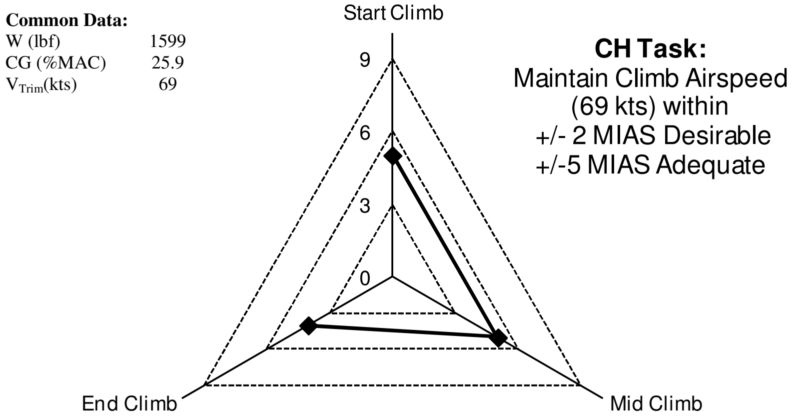


Figure 29, Climb and Point Tracking Task for the Cessna 150M – Cooper-Harper HQR

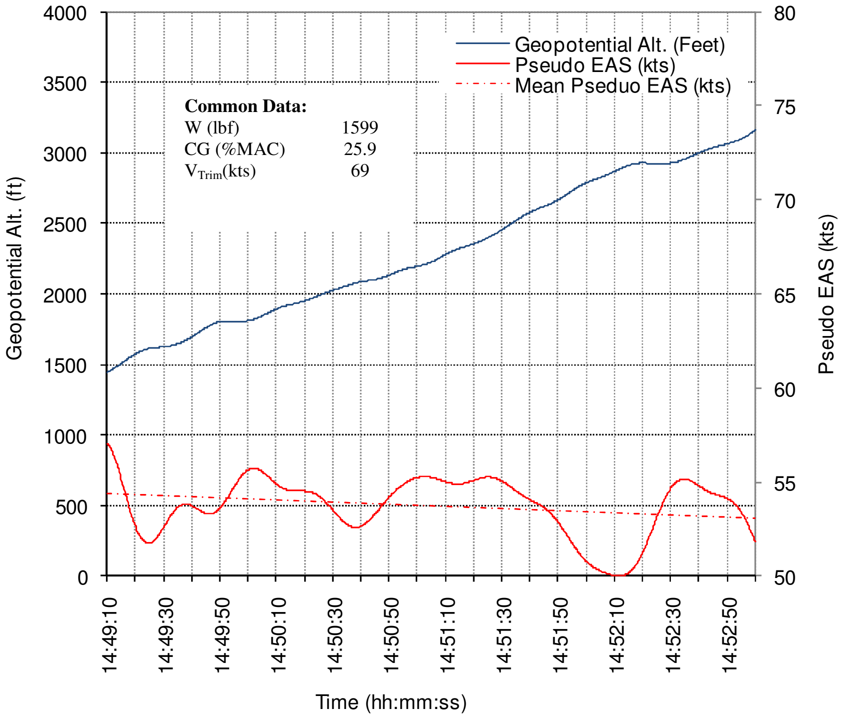


Figure 30, Climb and Point Tracking Task for the Cessna 150M - Time Series Plot

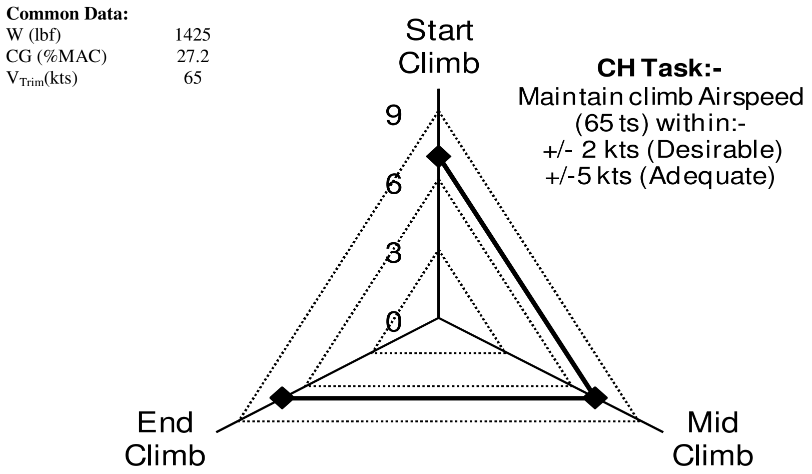


Figure 31, Climb & Point Tracking with Secondary Task Cessna F150M - Cooper-Harper HQR

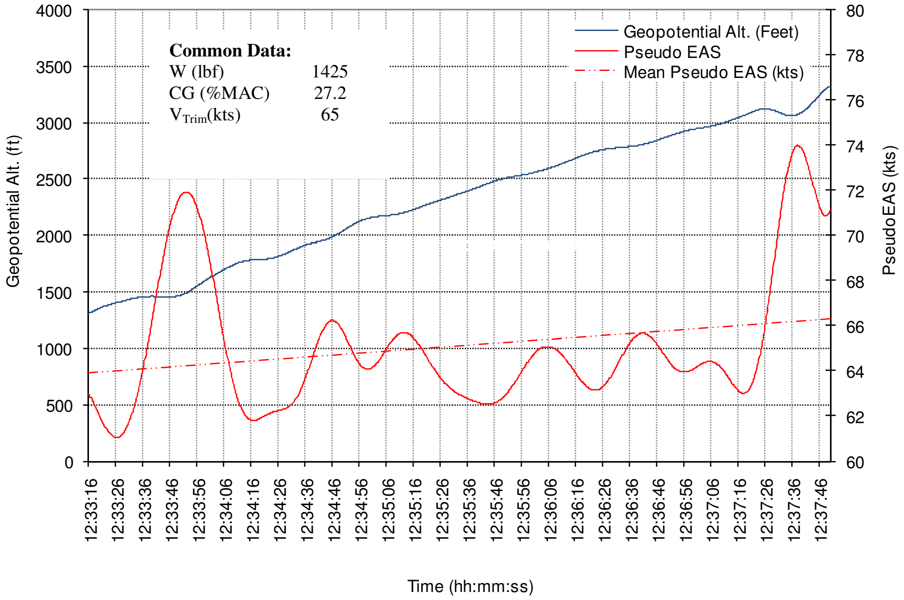


Figure 32, Climb & Point Tracking with Secondary Task Cessna F150M - Time-Series Plot

Cessna 152

Apparent stick-free LSS tests conducted with the Cessna 150M airframes were repeated for three Cessna 152 airframes in the cruise at 3,500 ft sHp and 88 kt (EAS) using the stabilised point technique with aeroplane near to MTOW and one CG position (23.4 ~ 23.8 %MAC). Results (Figure 33 & Figure 34) show similar variations of stick force and gradient over an airspeed range of 60~120 kt for all three airframes and all stick force gradients are greater than 0.07 daN/kt. All airframes exhibited positive static stability with stick forces ≥ 2.5 daN/kt approaching the stall (48 kt). Pilots would experience moderate perception of airspeed changes with stick forces in this flight condition. Statistical analysis (Table 7) at the trim condition shows significant variation of gradient (*Mean = -0.133 daN/kt, SD = 23%*). Aeroplane 2 was selected as the 'baseline' airframe for all further analysis and comparison with theoretical results in all flight conditions. All airframes tested were compliant with requirements for apparent stick-free LSS in the cruise as specified within CS-23 para 175(b) [101].

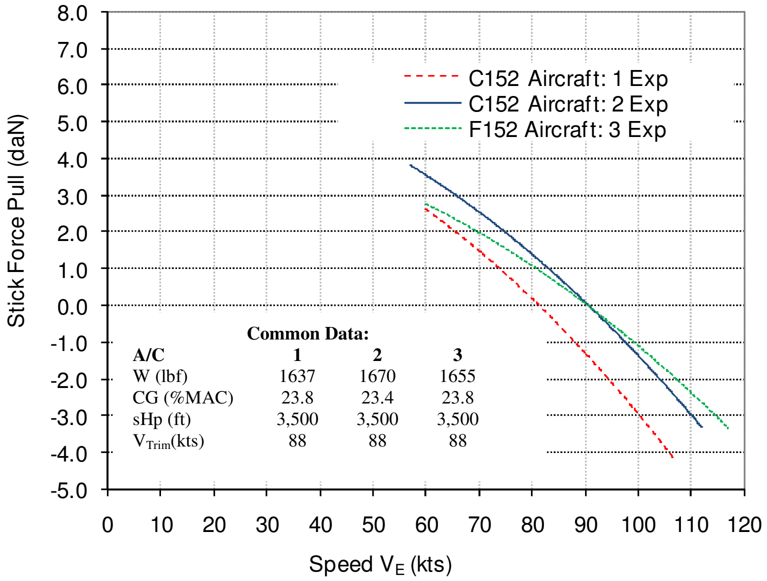


Figure 33, Experimental Apparent Stick-Free LSS for three Cessna C152/F152 Models in the Cruise Condition

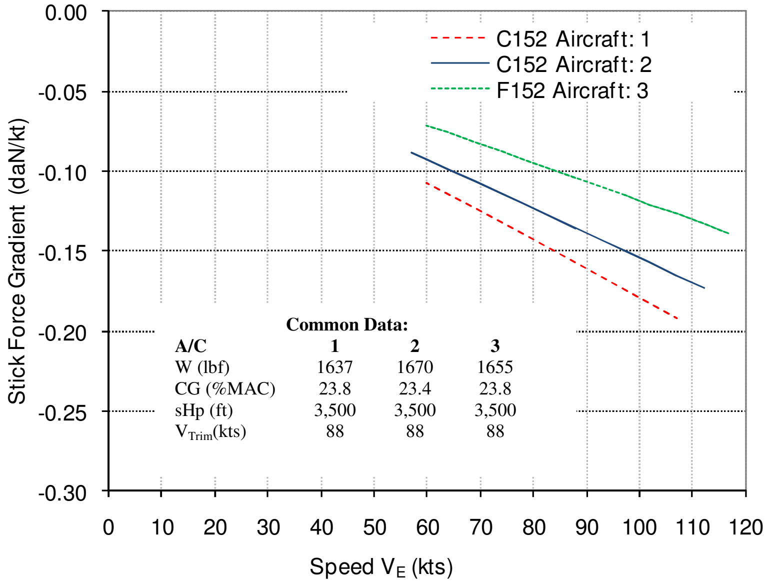


Figure 34, Experimental Stick Force Gradient for three Cessna C152/F152 Models in the Cruise Condition

Table 7, Comparison of Stick Force Gradients for 3 x Cessna 152/F152 Airframes in the Cruise Condition at V_{Trim}

	Stick Force Gradient (daN/kt) at V_{Trim}					
Description of Tests	**Aeroplane 1: Cessna C152**	**Aeroplane 2: Cessna C152**	**Aeroplane 3: Cessna F152**	**Mean**	**Median**	**SD**
Apparent LSS Cruise Condition	-0.160	-0.136	-0.100	-0.133	-0.136	0.030

Apparent stick-free LSS was assessed for aeroplane 2 in the climb and landing condition (30° flap) at a height of 2,500 to 3,600 ft sHp and airspeed of 67~68 kt (EAS) using the stabilised point technique, near to MTOW and one CG position (23.4 %MAC). Results (Figure 35) show moderate stick forces over an airspeed range of 50~120 kt in the climb and cruise condition only slightly reducing in the airspeed range of 41~90 kt for the landing. The variation of stick force gradient with airspeed (Figure 36) was similar in the cruise and landing condition but significantly higher in the climb (≥ -0.18 daN/kt). The airframe exhibited positive stability in the cruise, climb and landing condition, with stick force approaching the stall ≥ 2.2 daN/kt (41 kt). Pilots would experience similar, moderate perception of airspeed changes with stick force in the cruise and landing condition and increased perception in the climb. The airframe was compliant with requirements for apparent stick-free LSS in all flight conditions for CS-23 para 175(b) [101] and also for large aeroplanes CS-25 [1], where all gradients were > -0.074 daN/kt in all flight conditions (Table 8).

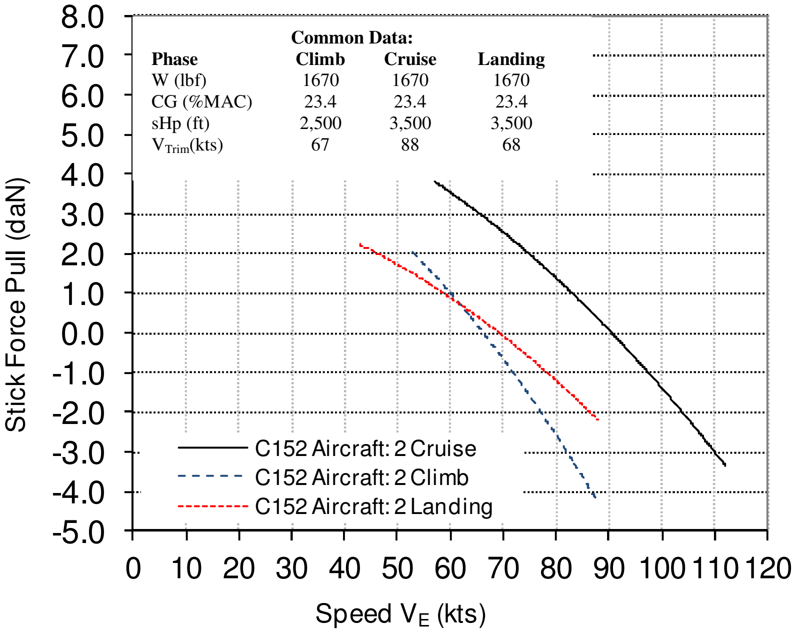


Figure 35, Experimental Apparent Stick-Free LSS for the Cessna 152 in Climb, Cruise & Landing Condition (30º Flap)

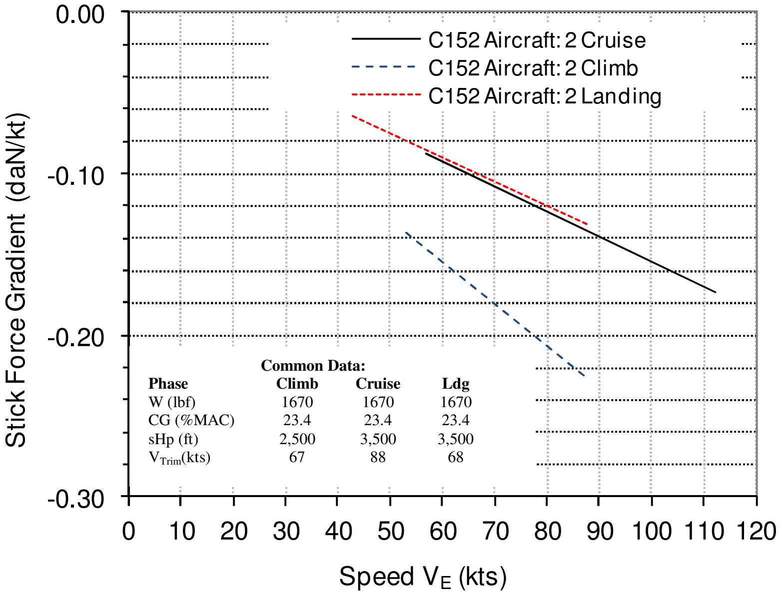


Figure 36, Experimental Stick Force Gradient for the Cessna 152 in Climb, Cruise & Landing Condition (30º Flap)

Table 8, Summary of Experimental Apparent Stick-free LSS Flight Tests, Cessna C152

Test No.	Description of Tests	Flaps (deg)	Power (% BHP)	Stick Force Gradient at V_{Trim} (daN/kt)	Stick Force Gradient Change relative to the Cruise (daN/kt)	CS-25.175 Compliant?
1	Apparent LSS Climb	0	Full 66%	-0.170	+0.034	Yes
2	Apparent LSS Cruise Condition	0	PLF 53%	-0.136	0.000	Yes
3	Apparent LSS Landing Condition (30° Flap)	30	PLF 63%	-0.098	-0.038	Yes

The compensatory tracking task for a steady climb using previously defined Cooper-Harper criteria was repeated for the Cessna 152 with $V_Y = 69$ kt, W = 1655 lbf @CG 23.8 %MAC (Figure 37). Results show that scores of HQR3 were recorded at the start and mid-point and HQR4 at the end of the climb suggesting that 'minimal' pilot compensation was required and that the handling qualities of the aeroplane were satisfactory. The time-series plot of pseudo-EAS and geopotential altitude versus time (Figure 38) shows deviations from the target airspeed were in the range of +/- 2 kt (allowing for a variable apparent headwind of approximately 13 kt).

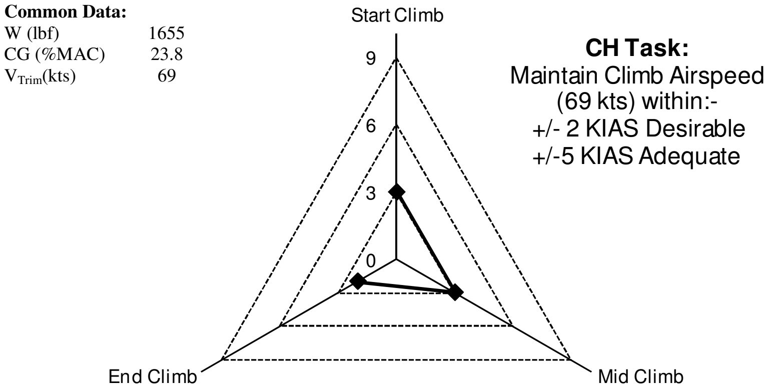


Figure 37, Climb and Point Tracking Task for the Cessna F152 - Cooper Harper Handling Quality Ratings

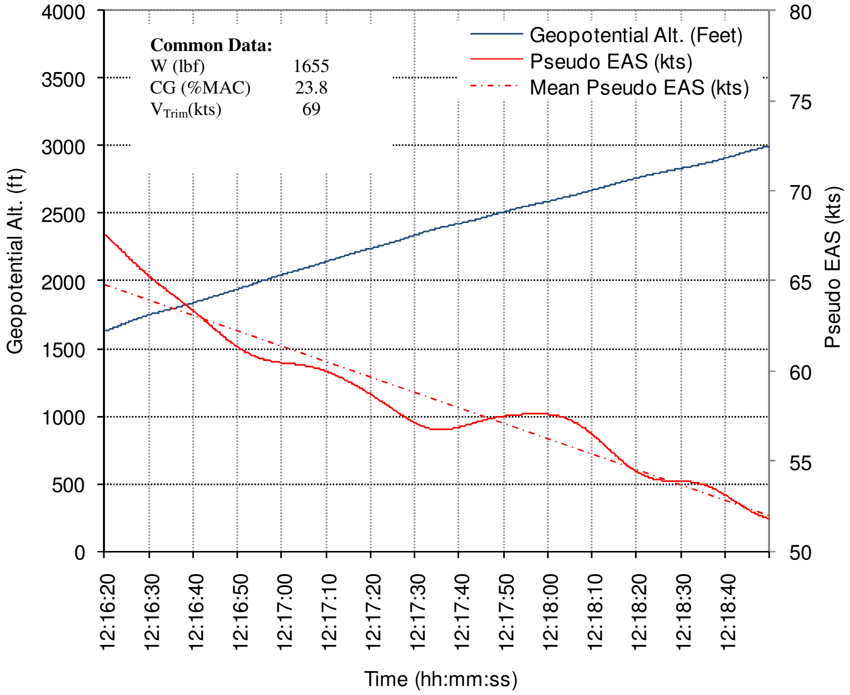


Figure 38, Climb and Point Tracking Task for the Cessna F152 - Time Series Plot

Summary

Flight tests were performed to assess stick force gradients in the cruise, climb and landing for multiple Cessna 150M and Cessna 152 airframes. Subjective handling qualities were assessed in the climb. Both groups exhibited fleet-wide variations with gradients for the Cessna 152 (0.10~.17 daN/kt) being 2~5 times greater than those for the Cessna 150M (0.02~0.07 daN/kt) in all flight conditions. The greatest differences occurred in the landing condition when the Cessna 150M demonstrated nearly ‘neutral’ longitudinal static stability, the Cessna 152 being positively stable in all conditions. Stick forces in the proximity of the stall in the landing condition, were 22 times greater for the Cessna 152 (≈2.2 daN) than the Cessna 150M (≈0.1 daN). This suggests that pilots of the Cessna 150M are likely to experience limited perception of airspeed change with stick force in the climb and cruise and negligible perception in the landing. Pilot distraction during the landing can result in significant deviations from the target approach speed towards either the stall or flap limiting speed. It is also apparent that stick forces, acting as a natural inhibitor to the stall during landing, are significantly higher in the Cessna 152 than the Cessna

152. Subjective handling quality assessments during a compensatory tracking task (primary) in the climb confirmed differences between the aeroplane groups, the Cessna 152 being satisfactory (≈HQR3) and the Cessna 150M being unsatisfactory (≈HQR5) tending to unacceptable (HQR7) at aft CG when a secondary task was performed. The Cessna 152 was compliant with subjective requirements of CS-23.175 in all flight conditions however for the Cessna 150M compliance in the landing was questionable. When compared with specific stick force gradient requirements of CS-25.175 for large aeroplanes, the Cessna 152 was compliant but the Cessna 150M was non-compliant in all conditions. The HQR scores together with the quantitative measurements also confirm that differences in handling qualities exist between the Cessna 150M and Cessna 152, as first indicated in the preliminary estimates of pitching moments conducted during the design review summarised in Chapter 2.

Having gathered real-world stick forces and gradients for a typical light aeroplane, the next section describes the results obtained using the estimation method described in Chapter 3, under similar trimmed flight conditions determined during flight tests.

4.2 Theoretical Estimation of Stick Force Gradients for the Cessna 150M and Cessna 152

A theoretical model for the estimation of stick forces and gradients in all flight conditions for a light aeroplane was presented in Chapter 3. Here, the model is applied to Cessna 150M and Cessna 152 aeroplanes using trimmed flight conditions derived during flight testing as discussed in the previous section (4.1). Key model input parameters such as wing loading, CG, elevator gearing, flap deflection & elevator trim determined during the design review (see Chapter 2) and downwash estimations at the tail (see Chapter 3) are summarised in Appendix A4-3. Tailplane, elevator and trim tab hinge moment coefficients were obtained from published manufacturers' data for similar airframes [99] and also input to the model.

Cessna 150M

Theoretical apparent stick-free LSS (Figure 40 & Figure 40) was estimated using 'baseline' data (aeroplane 2) in the climb, cruise and landing condition (30º flap) using trimmed flight conditions established during previous flight tests in CG position (W= 1580 lbf, 27.0 %MAC). Predicted stick force gradients about the trimmed flight condition (Table 9) indicate moderate gradients in the cruise (-0.086 daN/kt) increasing in the climb (-0.110 daN/kt) but significantly reducing in the landing (-0.018 daN/kt), tending towards 'zero'. Estimated stick force in the proximity of the stall (41 kt) in the landing condition was ≈ 0.2 daN.

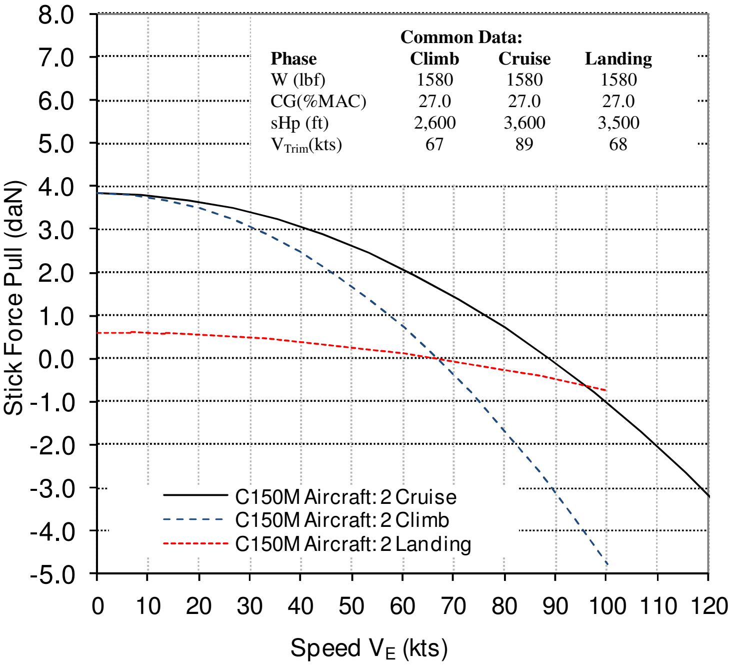


Figure 39, Theoretical Estimation of Apparent Stick-free LSS for the Cessna C150M in the Climb, Cruise & Landing Condition (30º Flap)

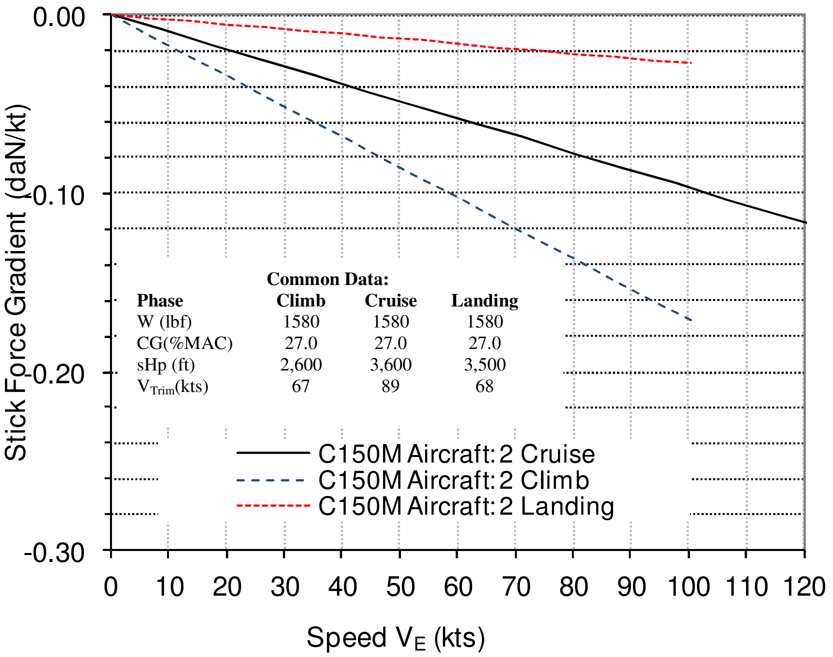


Figure 40, Theoretical Estimation of Stick Force Gradient for the Cessna C150M in the Climb, Cruise & Landing Condition (30° Flap)

Table 9, Theoretical Stick Force Gradients at V_{Trim} for the Cessna C150M for the Climb, Cruise and Landing Condition (30° Flap)

Test No.	Description of Tests	Stick Force Gradient at V_{Trim} (daN/kt)	Stick Force Gradient Change relative to the Cruise (daN/kt)
1	Apparent LSS Climb	-0.110	-0.024
2	Apparent LSS Cruise Condition	-0.086	0.000
3	Apparent LSS Landing Condition (30° Flap)	-0.018	+0.068

Cessna 152

Similarly, theoretical apparent stick-free LSS for the Cessna 152 (Figure 41 & Figure 42) was estimated using ‘baseline’ data (aeroplane 2) in the climb, cruise and landing condition (30° flap) using trimmed flight conditions established during previous its flight tests in one CG position (W= 1670 lbf, CG = 23.4 %MAC). Predicted stick force gradients about the trimmed flight condition (Table 10) indicate moderate gradients in the cruise (-0.100 daN/kt) increasing in the climb (-0.170 daN/kt) but moderately reducing in the landing (-0.058 daN/kt) and not tending towards ‘zero’. Estimated stick force in the proximity of the stall (41 kt) in the landing condition is ≈ 1.2 daN.

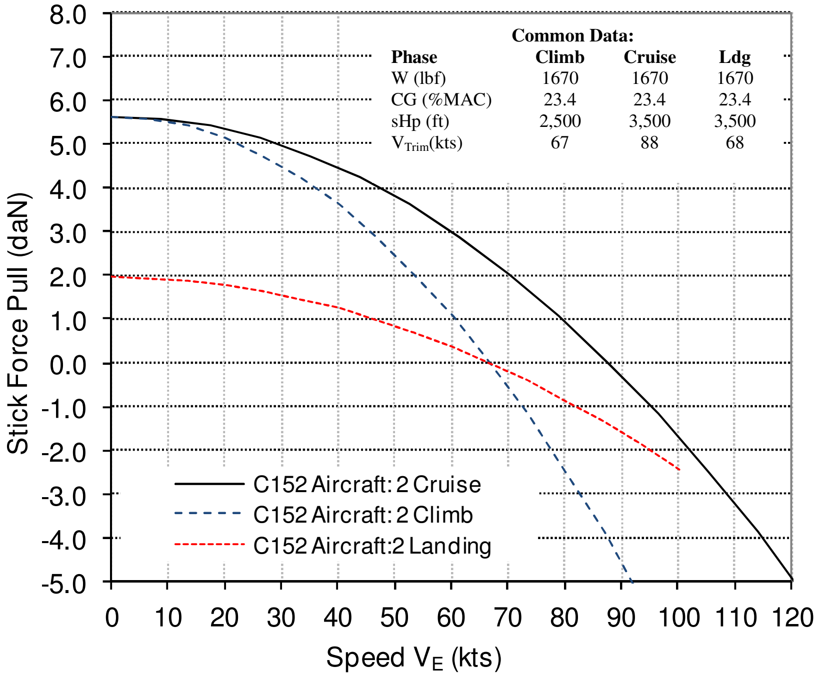


Figure 41, Theoretical Estimation of Apparent Stick-free LSS for the Cessna C152 in the Climb, Cruise & Landing Condition (30º Flap)

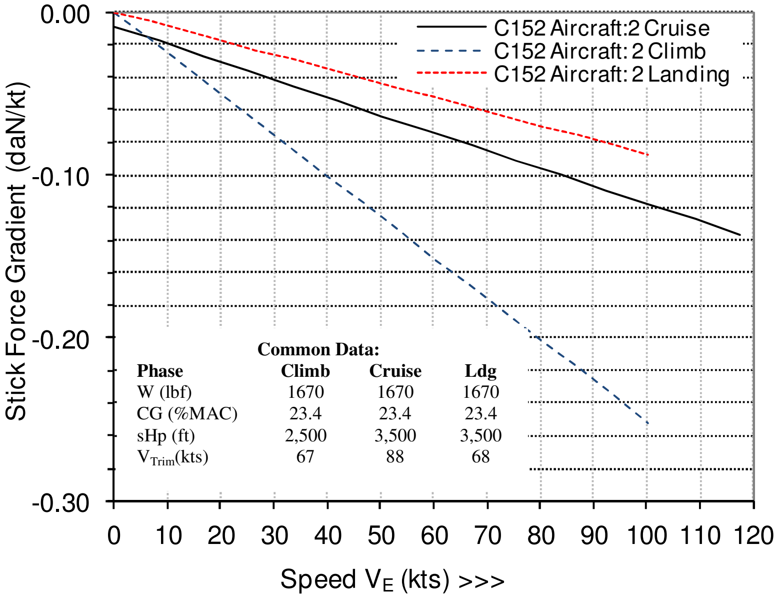


Figure 42, Theoretical Estimation of Apparent Stick Force Gradient for the Cessna C152 in the Climb, Cruise & Landing Condition (30º Flap)

Table 10, Theoretical Stick Force Gradients at V_{Trim} for the Cessna C152 in the Climb, Cruise and Landing Condition (30° Flap)

Test No.	Description of Tests	Stick Force Gradient at V_{Trim} (daN/kt)	Stick Force Gradient Change relative to the Cruise (daN/kt)
1	Apparent LSS Climb	-0.170	-0.070
2	Apparent LSS Cruise Condition	-0.100	0.000
3	Apparent LSS Landing Condition (30° Flap)	-0.058	+0.042

Summary

The estimated stick force gradients in comparable trimmed flight conditions for the Cessna 152 were 1.2~3 times greater than the Cessna 150M in all conditions. Estimates for the Cessna 150M showed tendencies towards ‘zero gradient’ or ‘neutral stability’ in the landing condition and estimated stick forces in the proximity of the stall were higher for the Cessna 152 (≈1.2 daN) than the Cessna 150M (≈0.2 daN). Having developed a model for the estimation of apparent stick-free LSS and applied it to the Cessna 150 ‘M ‘ and Cessna 152 aeroplanes, the next section compares theoretical and experimental results and assesses the suitability of the model for the preliminary design of a high-wing/low-tail light aeroplane.

4.3 Comparison of Theoretical and Experimental Stick Force Gradients for the Cessna 150M and Cessna 152

Experimental flight test measurements (section 4.1) showed that stick force gradients for the Cessna 152 were 2~5 times greater than the Cessna 150M, with the greatest differences occurring in the landing where the Cessna 150M demonstrated ‘neutral’ longitudinal static stability. The previous section (4.2) showed that theoretical stick force gradients for the Cessna 152 in the cruise, landing and climb were 1.2 to 3.2 times higher that those of the Cessna 150M. The model predicted tendency towards ‘neutral’ longitudinal static stability in the landing condition for the Cessna 150M. Theoretical and experimental results are compared for the Cessna 150 ‘M and Cessna 152 to assess the accuracy of the computer model and the ability to predict (safety-critical) tendencies towards neutral stability.

Cessna C150M

Using identical trimmed flight conditions for the cruise (V_E = 89 kt, W = 1580 lbf @27%MAC, Flaps = 0°, PLF) the comparison of theoretical and experimental results for apparent LSS (Figure 43 & Figure 44) shows good correlation for the Cessna 150M. Stick force gradient at the trimmed condition in the cruise differed by -0.020 daN/kt. In the landing condition (V_E = 68 kts, W = 1580 lbf @27%MAC, Flap = 30°, PLF) the results (Figure 45 & Figure 46) show excellent correlation with negligible difference in stick force gradient at the trimmed condition (+0.002 daN/kt). In the climb (V_E = 67 kt, W = 1580 lbf @27%MAC, Flap = 0° MCP) results (Figure 47 & Figure 48) showed poor correlation, predicting significantly higher gradient (-0.050 daN/kt) at the trim condition. During the flight testing, the C150M airframe required ‘full’ power (54~56% BHP) to maintain level flight in conditions tested. Although mean differences between experimental and theoretical were -0.024 daN/kt (Table 11), the model correctly predicted tendencies towards neutral longitudinal static stability in the landing, the phase of flight where the 43.6% of GA accidents occur [72] Similar comparisons were also made for the Cessna 152 aeroplane and are discussed in the next section.

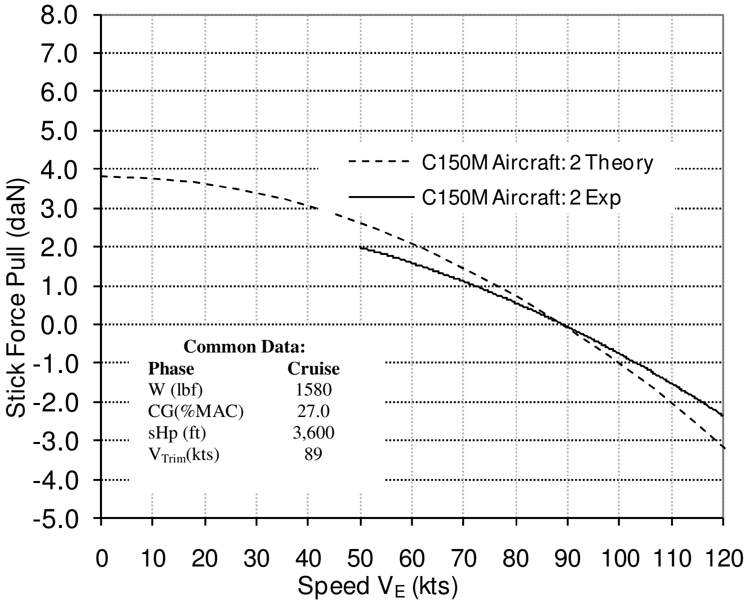


Figure 43, Comparison of Theoretical and Experimental Data, Apparent Stick-free LSS - C150M in the Cruise Condition

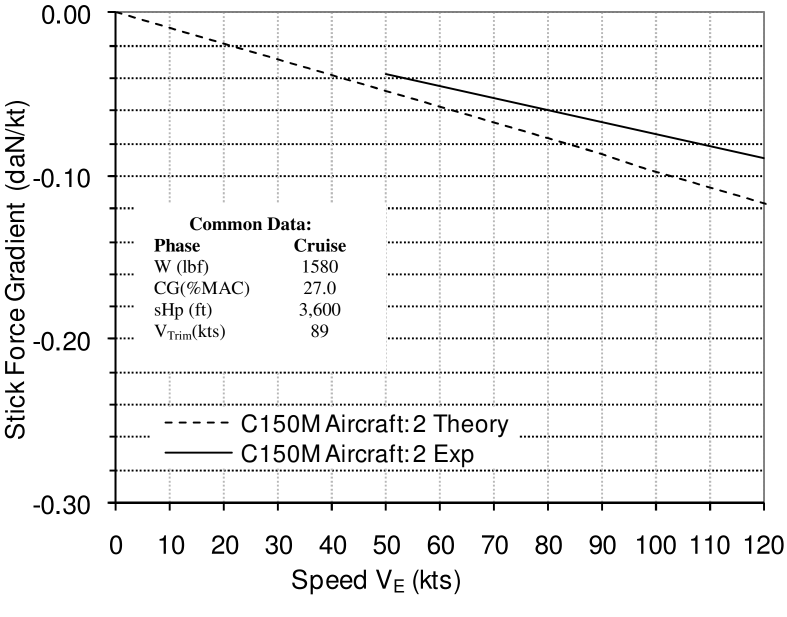


Figure 44, Comparison of Theoretical and Experimental Data Stick Force Gradients - C150M in the Cruise Condition

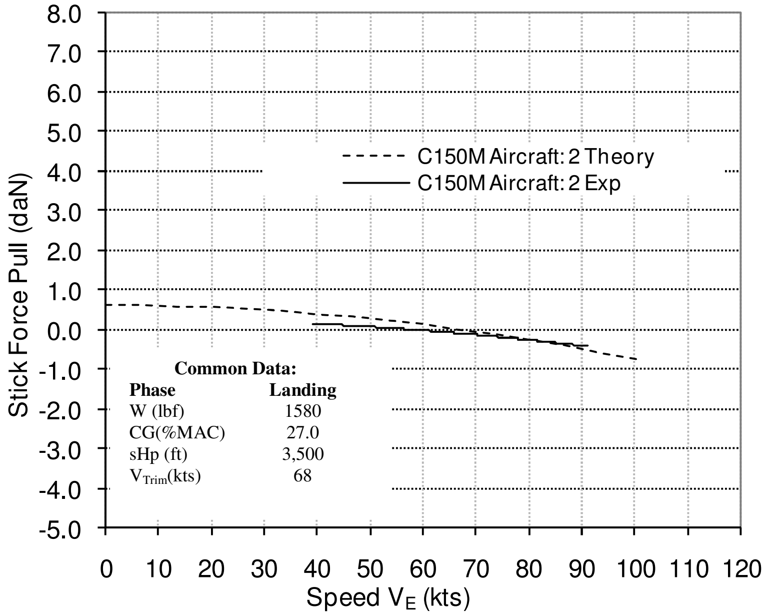


Figure 45, Comparison of Theoretical and Experimental Data, Apparent Stick-free LSS – Cessna C150M in the Landing Condition (30º Flap)

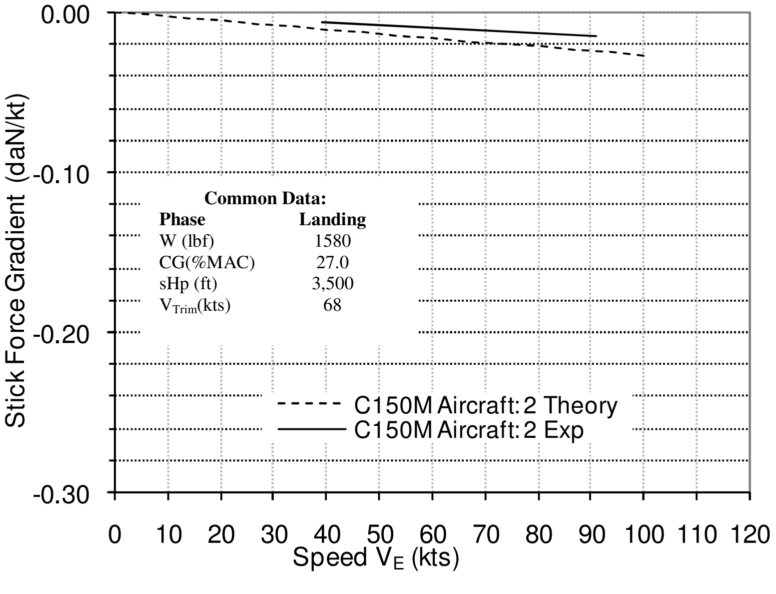


Figure 46, Comparison of Theoretical and Experimental Data, Stick Force Gradients – Cessna C150M in the Landing Condition (30º Flap)

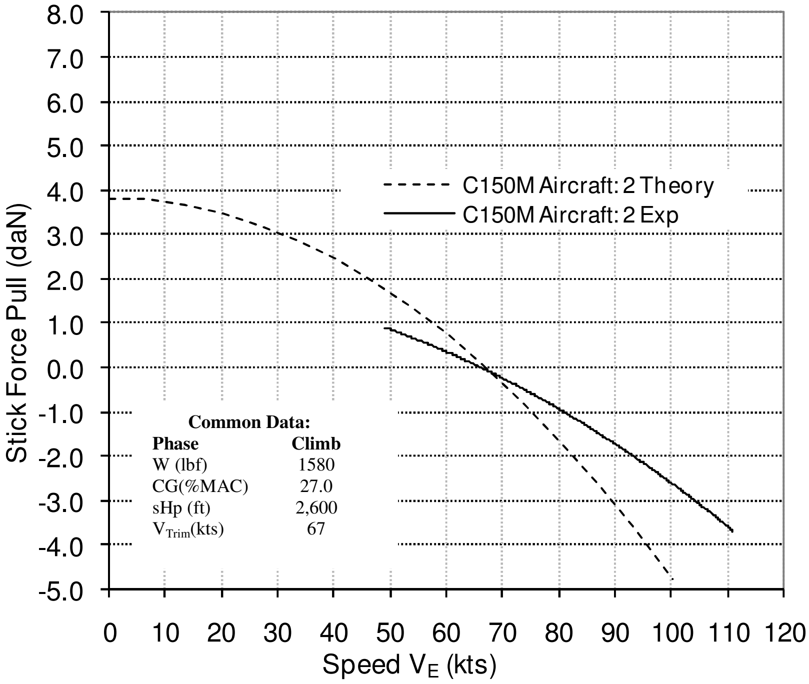


Figure 47, Comparison of Theoretical and Experimental Data, Apparent Stick-free LSS – Cessna C150M in the Climb

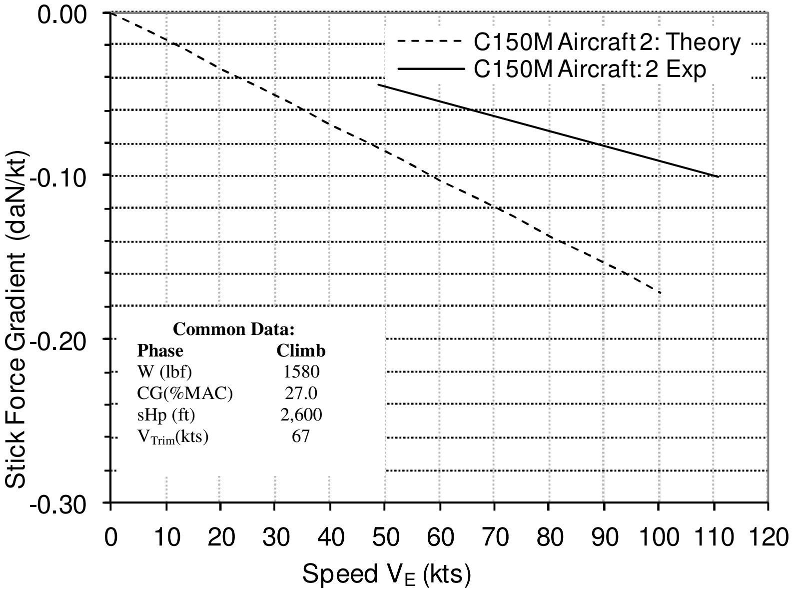


Figure 48, Comparison of Theoretical and Experimental Data, Stick Force Gradients– Cessna C150M in the Climb

Table 11, Comparison of Theoretical and Experimental Stick Force Gradients at V_{Trim} for the Cessna C150M in the Climb, Cruise and Landing

Test No.	Description of Tests	Vtrim (kts)	Power (BHP)	THEORY	EXP.	DIFF-ERENCE (THEORY–EXP.)
1	Apparent LSS Climb	67	56	-0.110	-0.060	-0.050
2	Apparent LSS Cruise Condition	89	54	-0.086	-0.066	-0.020
3	Apparent LSS Landing Condition (30° Flap)	68	54	-0.018	-0.020	0.002
	Mean			-0.071	-0.049	-0.023
	Standard Deviation			0.048	0.025	0.026
	Range			0.092	0.046	0.052

Cessna C152

Similarly, for the Cessna C152 in the cruise (V_E = 88 kts, W = 1670 lbf @23.4%MAC, Flaps = 0°, PLF) the results of gradient comparisons (Figure 49 & Figure 50) show reasonable correlation, with a difference in stick force gradient (Table 12) of +0.036 daN/kt at the trim speed. In the landing (V_E = 68 kt, W = 1670 lbf @23.4%MAC, Flap = 30°, PLF) the results (Figure 51 & Figure 52) show reasonable correlation with a gradient difference in the trim condition of -0.040 daN/kt. Good correlation was obtained in the climb (Figure 53 & Figure 54) with identical gradients in the trimmed flight condition. During flight tests for this particular airframe, the required power setting to maintain level flight in the landing condition (V_E = 66 kts) was 10% greater than the cruise, whilst full power in the climb was 13% greater than the cruise condition.

Mean differences between experimental and theoretical gradients at the trim were +0.024 daN/kt (Table 12), the opposite sense to the differences observed for Cessna 150M, however the model again correctly predicted relaxation of longitudinal static stability in the landing condition.

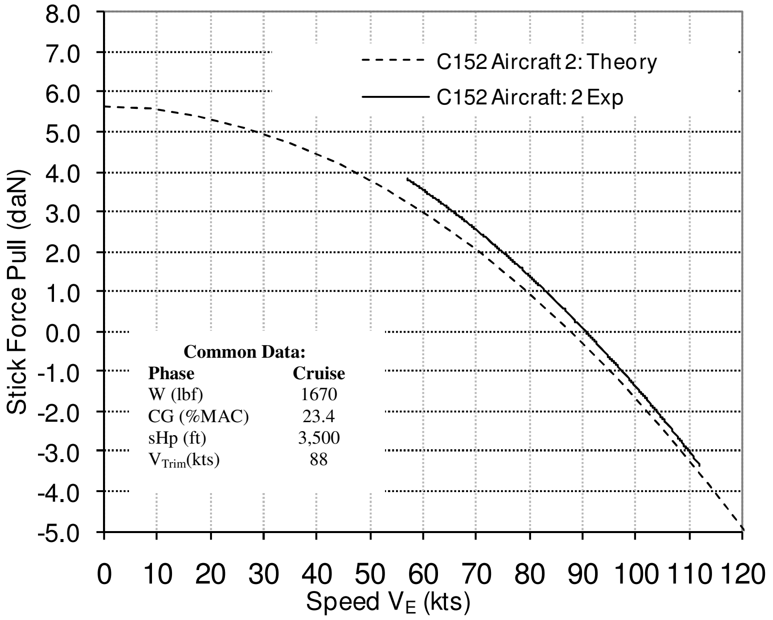


Figure 49, Comparison of Theoretical and Experimental Data, Apparent Stick-free LSS - C152 in the Cruise Condition

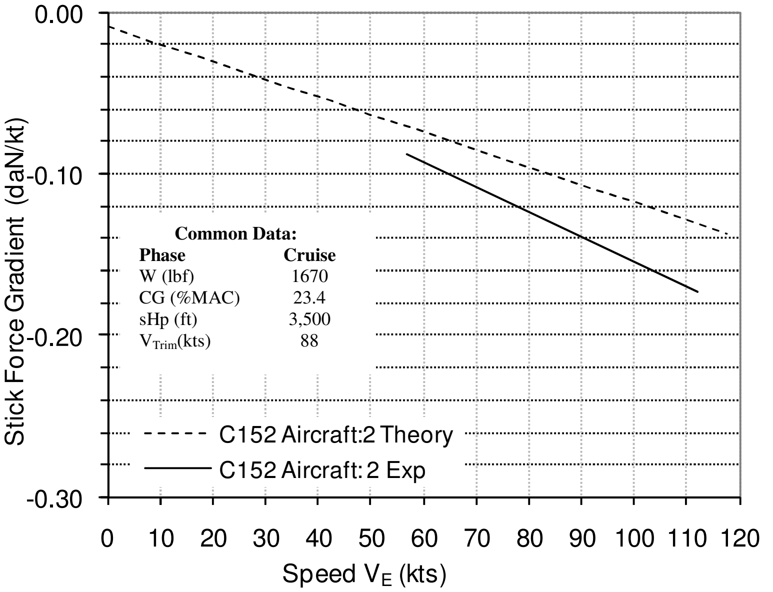


Figure 50, Comparison of Theoretical and Experimental Data, Stick Force Gradient - C152 in the Cruise Condition

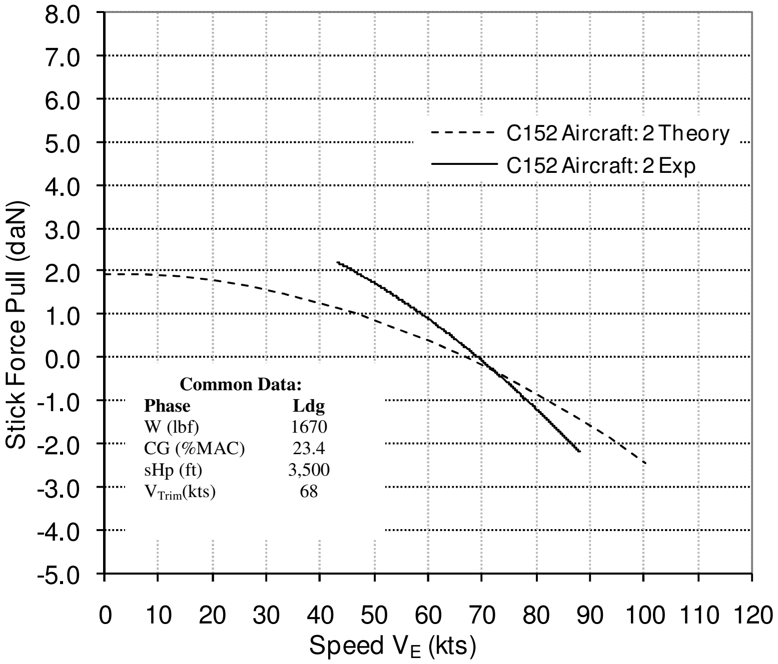


Figure 51, Comparison of Theoretical and Experimental Data, Apparent Stick-free LSS – Cessna C152 in the Landing Condition (30° Flap)

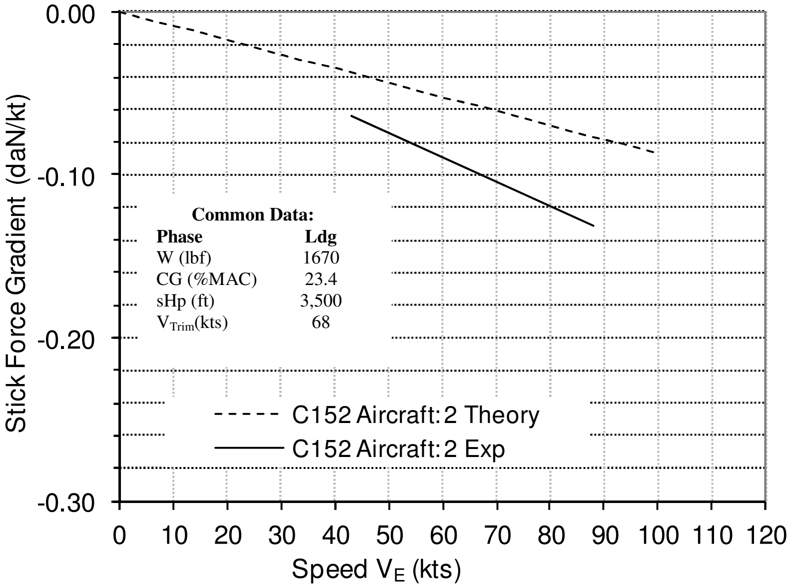


Figure 52, Comparison of Theoretical and Experimental Data, Stick Force Gradient – Cessna C152 in the Landing Condition (30° Flap)

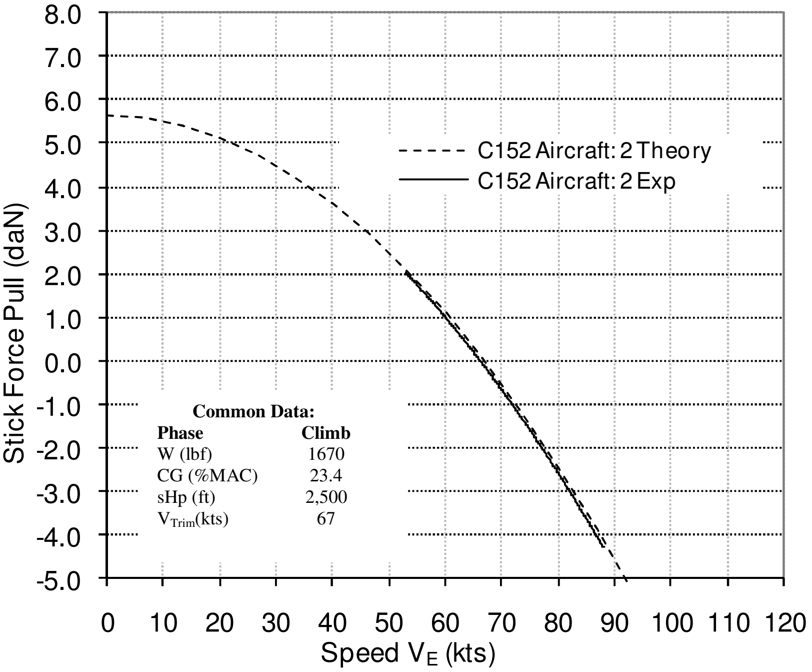


Figure 53, Comparison of Theoretical and Experimental Data, Apparent Stick-free LSS – Cessna C152 in the Climb

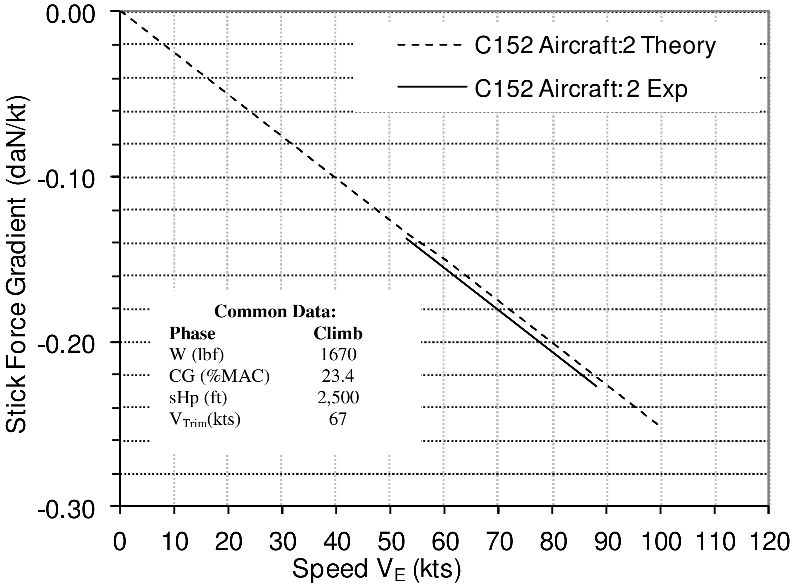


Figure 54, Comparison of Theoretical and Experimental Data, Stick Force Gradient – Cessna C152 in the Climb

Table 12, Comparison of Theoretical and Experimental Stick Force Gradients at V_{Trim} for the Cessna C152 in the Climb, Cruise and Landing Condition (30° Flap)

Test No.	Description of Tests	Vtrim (kts)	Power (BHP)	THEORY	EXP.	DIFFERENCE (THEORY-EXP.)
1	Apparent LSS Climb	66	73	-0.170	-0.170	0.000
2	Apparent LSS Cruise Condition	88	58	-0.100	-0.136	0.036
3	Apparent LSS Landing Condition (30° Flap)	66	69	-0.058	-0.098	0.040
	Mean			-0.109	-0.135	0.025
	Standard Deviation			0.057	0.036	0.022
	Range			0.112	0.072	0.040

Summary

The comparison of theoretical and experimental results for apparent longitudinal stick-free static stability about the trimmed flight conditions yielded mean differences of ±0.025 daN/kt. Predicted stick force gradients for the Cessna 150M were generally greater than experimental measurements (-0.024 daN/kt), whereas for the Cessna 152 they were less than experimental measurements (+0.025 daN/kt). The differences occurred in different flight conditions, notably in the climb for the Cessna 150M (-0.050 daN/kt) with full power and in the landing condition with 30° of flap for the Cessna 152 (+0.040 daN/kt) with power for level flight. For all experimental results presented, the effects of breakout force and friction were removed to simplify comparisons of experimental with theoretical data. Break out forces and friction were similar for each aeroplane group (C150 'M" Mean = +0.50/-0.66 daN, C152 Mean = +0.53/-0.52 daN). Notwithstanding these limitations, the theoretical method for the estimation of stick force gradient about the trim, correctly predicted tendencies towards relaxed/neutral stability for both aeroplanes in the landing condition and therefore is appropriate for preliminary estimation in this safety-critical flight condition. Having established that the theoretical model can be used for the preliminary assessment of stick force gradients in all flight conditions and to estimate tendencies towards neutral LSS, the next section presents and discusses the results of simulator experimentation to explore the effects of variations of stick force gradient on pilot workload in the cockpit.

4.4 Flight Simulation Experimentation: The Effects of Stick Force Gradient on Pilot Workload

Flight testing (section 4.1) using pre-defined Cooper-Harper criteria indicated differences in the degree of pilot compensation required (+2 HQRs) to execute a compensatory tracking task during the climb with two apparently similar aeroplanes exhibiting dissimilar stick force gradients (C150M = -0.086 daN/kt & C152 = -0.170 daN/kt) The test pilot commented that 'small, continuous adjustments to pitch attitude were necessary to maintain V_Y within desirable (±2 kt) or adequate (±5 kt) airspeed tolerances' when stick force gradient was lower in the C150M. These findings prompted the development a flight simulation experimental programme to evaluate the effects of stick force gradient on pilot workload. A précis of the programme is presented in the following sections and a complete description of pilot demographics, equipment, calibration, method given in Appendix A4-4 & results in Appendix 4-5.

Experimental Hypotheses & Independent/Dependent Variables

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 pilot workload and associated sub-measures.

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 plus with median PIC hours of 222 (Appendix A4-4, Table A4-6).. All pilots held a current medical and the most common aeroplane types flown were single engine piston aeroplanes (96%) or 3-axis microlight (4%)

Equipment

A single seat fixed-base simulation device based upon a Frasca PC7 cockpit seat was used in all tests (Appendix A4-4, Figure A4-1 & Figure A4-2). The device included a software configurable control loading system to provide realistic control 'feel'. All tests were designed within the capabilities of the simulation device by considering the limitations of the visual, sound systems and cockpit environment. The representative sample of GA pilots flew a simulated aeroplane model based upon the Cessna 172 (one of a limited number of available simulated models), with two simulated variable stick force gradients.

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 method [103] for the assessment of workload.

NASA-TLX was selected for the assessment of pilot workload in preference to Cooper-Harper . Cooper-Harper only describes pilot compensation as described in Chapter 2). NASA-TLX is straightforward to use, un-obtrusive and provides additional levels of detail via drill down into sub-scale measurements where desirable. 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 workload 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 task. The use of un-weighted NASA-TLX meant that all sub-measures were treated with the same levels of importance. The use of weighted NASA-TLX requires the subject to rank the contribution of each sub-measure to workload for a specific task using pair-wise comparisons. Individual sub-measure ratings are then weighted according to the pre-determined relative contribution. 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 negligible or 'neutral' stick force gradient, approximately 0.007 daN/kt and gradient '2' approximately 0.070 daN/kt, a significantly larger gradient (1:10) comparable with existing CS-25.175 certification specifications for large aeroplanes (0.074 daN/kt[1]). As a result of inherent break-out force and static friction present in the simulator elevator control system, calibration of the two different stick force gradients was limited to ±0.005 daN/kt. However, this was not considered a major problem since the difference between gradients was of key interest and not the absolute values in the evaluation of the effects of stick force gradient on pilot workload.

Each of the 20 pilot volunteers was required to complete 4 flying tasks using normal operating procedures (tasks 1~4) and 2 different stick force gradients in alternate sequence so as to minimise experimental bias, resulting in a total of 160 simulator tasks.

Statistical Analysis

Statistical analysis of the results was conducted using repeated-measures ANOVA [104] with two variables, stick force gradient and 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 at least 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 total workload, mental demand, physical demand, temporal demand, own performance, effort and frustration (dependent variables).

Results

A summary of all tests for statistical significance (using $p < 0.05$ or less than 5% probability that observed differences are due to chance) of total workload and all workload sub-measures versus stick force gradient, task and combination of stick force gradient/task is given in Table 13. The results show that of all sub-measures, only mental demand was directly affected by changes in stick force gradient. It was seen to increase significantly ($p < 0.05$) as stick force gradient decreased from 0.070 to 0.007 daN/kt ('zero' stick force gradient). The nature of the flying tasks had a significant effect on total workload, physical demand, temporal demand, own performance, effort, frustration and mental demand. Stick force gradient and task interactions had no significant effect on total workload or its' sub-measures.

Table 13, Summary of Significance Tests ($p < 0.05$)

	Stick Force Gradient	**Task**	**Stick Force Gradient x Task Interaction**
Total Workload (from addition of sub-measures)	Nonsig.	Sig.*	Nonsig.
Mental Demand	***Sig.***	Sig.	Nonsig.
Physical Demand	Nonsig.	Sig.*	Nonsig.
Temporal Demand	Nonsig.	Sig.*	Nonsig.
Own Performance	Nonsig.	Sig.*	Nonsig.
Effort	Nonsig.	Sig.*	Nonsig.
Frustration	Nonsig.	Sig.*	Nonsig.

Notes:

Sig.	Significant at $p < 0.05$ level
Sig.*	Significant at $p < 0.01$ level
Nonsig.	Nonsignificant at $p < 0.05$ level

Statistically significant and detailed results for total workload and mental workload are presented in the following sections with further results for physical, temporal, own performance, frustration and effort sub-measures presented in Appendix A4-5 for completeness.

Total Workload

The results of mean total workload versus stick force gradient and task (Figure 55 & Table 14) show similar patterns for both stick force gradients and respective flying tasks. Tests for statistical significance analysis were conducted using repeated measures ANOVA, sample multivariate, within-subject tests (Table 15) using conservative Greenhouse-Geisser assumptions of sphericity (to confirm that differences between data taken from the same participant are consistent) with corrected values ($p < 0.05$). These results showed that when considered as a group, stick force gradient had no significant effect on total workload ($p = 0.657$) or gradient/task interaction ($p = 0.934$). However, the nature of the task performed did have a significant effect on total workload ($p < 0.01$). The nature of the task is characterised by the number and complexity of the sub-tasks and time pressures. If a detailed analysis is completed for each flying task, it is clearly evident that pilot activity involves a combination of sub-tasks including aviate, navigate, communicate, execute procedures, manage systems and maintain situational awareness. It is the sequence, complexity and concomitant processing of these sub-tasks in combination with pilot capability that determines perceived total workload.

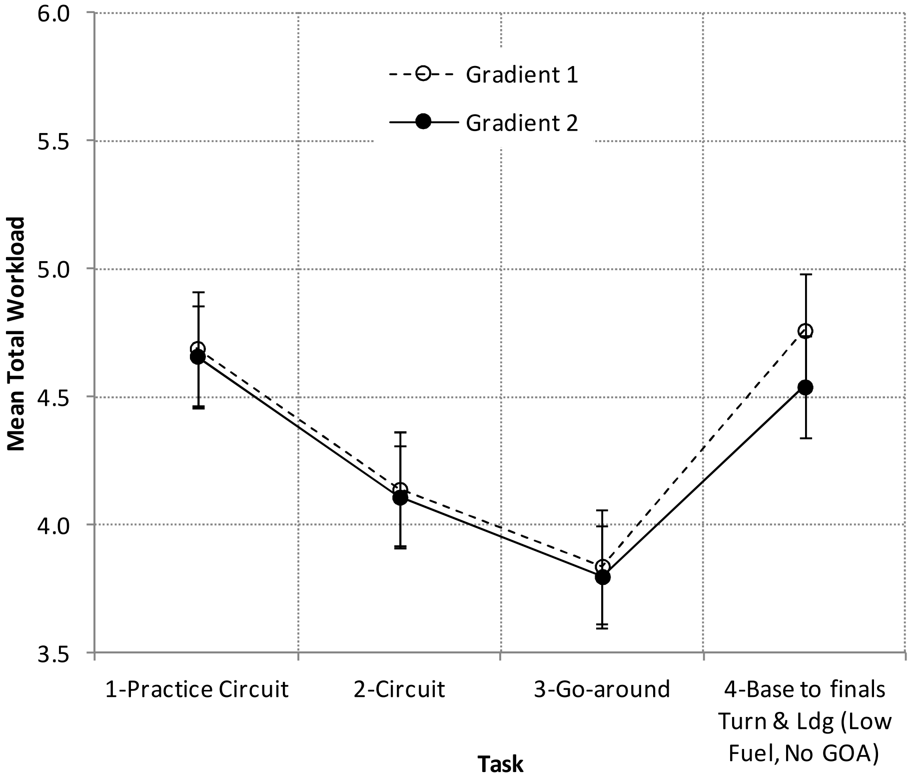


Figure 55, Effect of Stick Force Gradient & Task on Estimated Mean Total Workload (Std Error Bars)

Table 14, Effect of Stick Force Gradient on Estimated Mean Total Workload

gradient	Mean
1	4.358
2	4.277

Table 15, Sample of Multivariate Test Results for Within-Subjects Effects for Total Workload, Stick Force Gradient, Task and Gradient * Task

Source	p
gradient	0.657
task	**0.000**
gradient * task	0.893

A detailed drill-down of results using repeated measures within-subjects contrasts (Table 16) showed significant differences between tasks 1 & 2 ($p < 0.01$) and tasks 3 & 4 ($p < 0.01$). The complexities of Task 1 (practice circuit) and Task 2 (normal circuit) were identical, and were completed shortly one after the other. The results indicate increased familiarisation with experimental method, aircraft model and cockpit environment. Task 3 (go-around) and task 4 (base to finals turn with insufficient fuel for a go-around) both involved an approach but task 4 introduced additional stress (temporal demand) since the pilot was instructed that a go-around option, in the event of a poor approach was not available due to insufficient fuel. This increased stress was also evident in increased temporal demand (see Appendix A4-5, Table A4-15).

Table 16, Sample of Multivariate Test Results for Within-Subjects Contrasts for Total Workload, Stick Force Gradient, Task and Gradient * Task

Source	gradient	task	p
gradient	Level 1 vs. Level 2		0.657
task		Level 1 vs. Level 2	**0.007**
		Level 2 vs. Level 3	0.160
		Level 3 vs. Level 4	**0.000**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	1.000
		Level 2 vs. Level 3	0.978
		Level 3 vs. Level 4	0.598

Mental Demand

Estimated mean mental demand versus gradient and task (Figure 56) suggested variations of mean mental demand with both stick force gradient and flying task, the only sub-measure to yield such results. Mental demand for all flying tasks combined, was ≈ 10% (of mean) higher for stick force gradient '1' as compared gradient '2' (Table 17). Using conservative corrections for sphericity, for repeated measures within-subjects differences (Table 18) the variation of mental demand with both stick force gradient and flying task was significant ($p < 0.05$). The combined effect of stick force gradient/task interactions were nonsignificant, suggesting there was no interrelationship between flying task and gradient. Drilling down further, the repeated measures within-subjects contrasts (Table 19) for mental workload variation with flying tasks showed that differences between tasks ‘1’ & ‘2’ (practice circuit and circuit) and task 3 & 4 (go-around and base to finals turn) were both highly significant (*p < 0.01*).

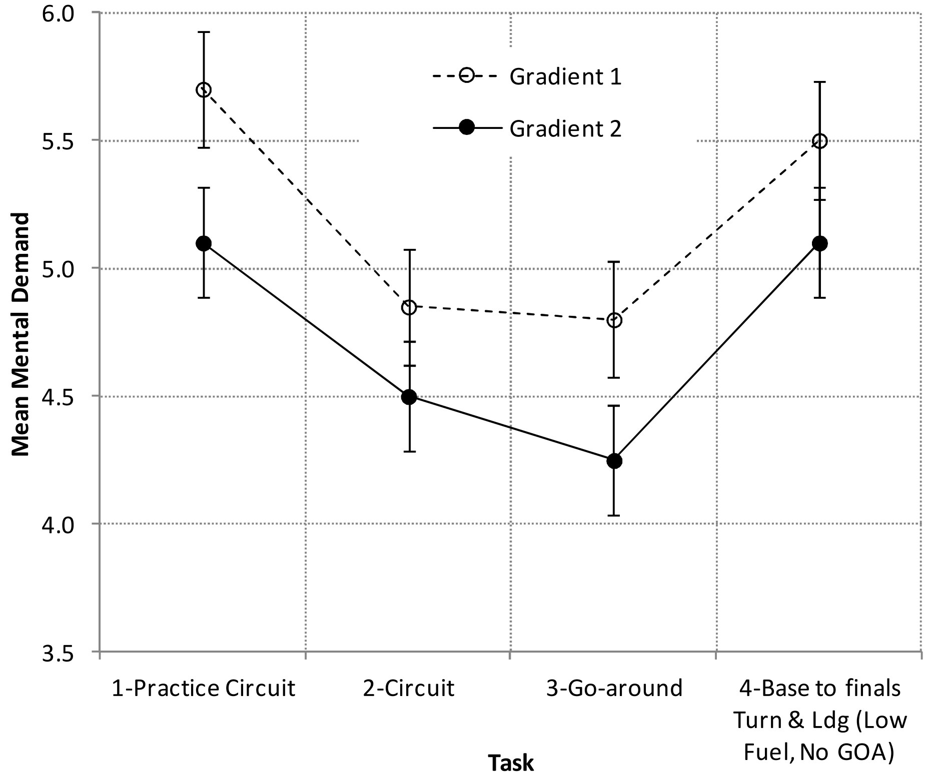


Figure 56, Effect of Stick Force Gradient & Task on Estimated Mean Mental Demand (Std Error Bars)

Table 17, Effect of Stick Force Gradient on Mean Mental Demand

gradient	Mean
1	5.213
2	4.738

Table 18, Sample of Multivariate Test Results for Within-Subjects Effects for Mental Demand, Stick Force Gradient, Task and Gradient * Task

Source	***p***
gradient	**0.037**
task	**0.012**
gradient * task	0.892

Table 19, Sample of Multivariate Test Results for Within-Subjects Contrasts for Mental Demand, Stick Force Gradient, Task and Gradient * Task

Source	**gradient**	**task**	***p***
gradient	Level 1 vs. Level 2		**0.037**
task		Level 1 vs. Level 2	**0.005**
		Level 2 vs. Level 3	0.655
		Level 3 vs. Level 4	**0.005**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	0.514
		Level 2 vs. Level 3	0.592
		Level 3 vs. Level 4	0.764

Summary

Simulated flying tasks performed by volunteer GA pilots and assessed using un-weighted NASA-TLX have shown that mental demand increased significantly ($p < 0.05$) as stick force gradient decreased from ‘moderate’ (0.070 daN/kt) to ‘zero’ (0.007 daN/kt). The nature of the flying tasks had a significant effect ($p < 0.01$) on total workload, physical demand, temporal demand, own performance, effort and frustration and a significant effect ($p < 0.05$) on mental demand. Stick force gradient and task interactions were nonsignificant ($p < 0.05$) for total workload and all sub-measures. 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 tending towards zero (all sub-measures were treated equal and no weightings applied).

4.5 Chapter Summary

The primary objective of this research was to establish suitable criteria for acceptable stick force gradients for a non-aerobatic, light aeroplane in steady flight during the cruise, climb and landing condition. This was achieved firstly through flight testing Cessna 150M and Cessna 152 aeroplane models (high-wing, low-tail) similar in appearance but with dissimilar safety records and the measurement of stick force gradients in all flight conditions.

Both groups exhibited fleet-wide variations in stick force gradient at trimmed flight conditions with gradients for the Cessna 152 being 2~5 times greater than those for the Cessna 150M. The greatest differences were evident in the landing condition when the Cessna 150M demonstrated nearly 'neutral' longitudinal static stability. Stick forces in the proximity of the stall in the landing condition, were 22 times greater for the Cessna 152 than the Cessna 150M. This implies that Cessna 150M pilots are likely to experience only limited perception of airspeed change with stick force in the climb and cruise condition and with negligible perception in the landing condition. Pilot distraction during the landing condition is more likely to result in significant deviations from target airspeeds in the Cessna 150M than the Cessna 152. It is also possible that the higher stick forces experienced in the Cessna 152 in the proximity of the stall, acts as a 'natural inhibitor' especially during the safety-critical landing phase or go-around from the landing phase. Subjective handling quality assessments during a compensatory tracking task in the climb suggested that the Cessna 152 with generally higher stick force gradients was satisfactory (≈HQR3) and that the Cessna 150M was unsatisfactory (≈HQR5) tending to unacceptable (HQR7) when lightly loaded with an aft CG and a secondary task was performed by the pilot. The Cessna 152 was compliant with subjective requirements of CS-23.175 in all flight conditions however for the Cessna 150M compliance in the landing condition was questionable. When compared with specific stick force gradient requirements of CS-25.175 for large aeroplanes (not a certification requirement for this class of aeroplane), the Cessna 152 was compliant but the Cessna 150M was non-compliant in all conditions. The HQR scores together with the quantitative measurements of stick force gradient and airspeed deviations confirm that differences in handling qualities exist between the Cessna 150M and Cessna 152 exist and that these may relate to differences in their safety records.

To understand how these differences in stick force gradients influence safety, simulated flying tasks were performed by volunteer GA pilots and pilot workload was assessed for contrasting, two stick force gradients. The un-weighted NASA-TLX scores indicated that mental demand increased significantly as stick force gradient decreased from ‘moderate’ to ‘neutral’. The nature of the flying tasks had a significant effect on total workload, physical demand, temporal demand, own performance, effort and frustration and mental demand. These results support earlier findings during flight test which indicated that increased pilot compensation was required to execute a compensatory tracking task in similar aeroplanes when stick force gradient was decreased.

The secondary objective of this research was to develop a model to estimate stick force gradients for a light aeroplane in any flight condition and this was achieved by developing a MATLAB model. The model based upon existing theory for the estimation of gradients in the cruise only, was extended to the climb and approach by consideration of the combined effects of wing loading, CG, elevator gearing, flaps and elevator trim setting. The comparison of theoretical and experimental results for stick force gradients about the trimmed flight conditions yielded mean differences of ±0.025 daN/kt. Predicted stick force gradients for the Cessna 150M were generally greater than experimental measurements, whereas for the Cessna 152 they were less than experimental measurements. The differences occurred in disparate flight conditions, notably in the climb for the Cessna 150M with full power and in the landing condition with 30° of flap for the Cessna 152 and power for level flight. Notwithstanding these limitations, the model for the estimation of stick force gradient about the trimmed flight condition, correctly predicted tendencies towards relaxed/neutral stability for both aeroplanes in the safety-critical landing condition.

The following chapter discusses the combined results of experimentation and modelling in relation to the original objectives and previous work in the field. It proposes specific criteria for acceptable stick force gradients and PFtS for a non-aerobatic light aeroplane, determined within the limits of this research.

5. Criteria for Acceptable Stick Force Gradients, Flight Test Assessment, Modelling and Implications for Future Flight Training

This chapter proposes acceptable stick force gradient criteria with respect to current and future light aeroplane design based upon flight test and flight simulation experimental results building upon previous work in the field and extended theory. A flight test method to assess current and future light aeroplanes is proposed. The application of predictive modelling to current and future light aeroplane assessment and design is described and extensions to the model are proposed for additional safety-critical, flight conditions. The implications of the improved awareness and understanding of control feel with respect to future pilot training are discussed.

5.1 Minimum Stick Force Gradient in Trimmed Flight

Findings obtained during the course this research showed that stick force gradient varies with aeroplane make/model and flight condition and are consistent with the results of earlier comparative flying qualities studies conducted by Ellis [63]. When cross-referenced with the fatal stall-related accident rates for selected aeroplane make/models [3], those models with stick gradients ≥ 0.1 daN/kt in all flight conditions are associated with lower rates.

Regarding the variability of pilot workload with stick force gradient, previously published experimental data is limited. Previous work conducted by Mooij & van Gool [70] suggested that pilot workload is unaffected when stick force gradient is reduced from moderate to zero gradients. Those conclusions contradict the intuitive relationship between pilot workload and the degree of stability as depicted by Cook [71]. Cook suggests that pilot workload increases as controls become light and oversensitive and large control actions are necessary when CG is at or beyond the aft limit resulting in neutral or negative LSS. The author's interpretation of Cook's diagram has been extended to illustrate the effects of stick force gradient on pilot mental workload, the most significant contributor to pilot workload, proposing that pilot mental demand is minimised for any given flight condition when stick force gradient is at some optimum value.

Flight simulation tests conducted during the course of this research using 20 volunteer GA pilots, showed that as stick force gradient was reduced from a moderate (0.07 daN/kt) to near-zero gradient, pilot mental demand increased significantly ($p < 0.05$).

The increase in pilot mental demand is believed to be primarily due to the pilot having to adapt control gain (force input/airspeed output) to compensate for the reduced 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 (aeroplane nose in relation to the horizon) and even slower outer-loop internal visual cues (cockpit airspeed instrument with instrument lag).

The author believes that the differences between experimental results obtained by the author and those obtained by Mooij & van Gool as stick force gradient approaches zero are due to the:-

- Smaller sample size used in the Mooij & van Gool study (n=3) when compared to that used in this research (n=20);
- Relatively higher pilot experience levels of pilots used in the Mooij & van Gool study (median PiC hours = 2,770) when compared to the GA pilots used in this research (median PiC hours = 222);
- The nature of the flying task evaluated in the Mooij & van Gool study was an instrument ILS approach in a medium jet transport, whereas the tasks used in this research were simulated flying tasks such as the circuit, go-around and base to finals turn conducted in a light aeroplane in VMC.

With regard to aerodynamic LSS, accepted design guidelines for a light aeroplane [22][31] typically suggest that a minimum stick-fixed static margin of 5% MAC is desirable for LSS in all flight conditions normally encountered in service. Extending this guideline to the stick-free static margin, implies that a non-zero stick force gradient is also desirable.

Regarding upper limits for stick force gradient, Thompson's qualitative study [38] proposed an upper stick force gradient limit of 0.13 daN/kt (1.75 lbf per 6 kt) for desirable flying qualities of training aeroplanes in trimmed cruising flight to avoid tiring the pilot.

Considering the results of flight test, flight simulation and statistical analysis in conjunction with previously published work, minimum stick force gradients in the range 0.10~0.13 daN/kt about the trimmed flight condition would seem appropriate for a non-aerobatic light aeroplane in all flight conditions normally encountered in service, whilst being flown by a pilot without exceptional piloting skill, alertness or physical strength.

The EASA certification specification for light aeroplanes [79] does not presently specify a quantitative minimum acceptable stick force gradient for the range of flight conditions normally encountered by a light aeroplane in service. Instead, assessment and decisions with regard to compliance are left to the subjective opinion of the test pilot. In contrast, minimum acceptable stick force gradients are defined for sailplanes/powered sailplanes (0.031 daN/kt) [76] and large commercial aeroplanes (0.074 daN/kt) [77]. The reasons for adoption of minimum stick force gradients for large commercial aeroplanes are reported to have been due to the difficulty in determining perceptible change in stick force during flight test evaluations [44]. The same reasoning can be applied to light aeroplane certification compliance and therefore the introduction of minimum acceptable stick force gradients within CS-23.175 is recommended.

Light aeroplanes with a stable stick force gradient and minimum acceptable stick force gradient at the trimmed flight condition should also display a positive PFtS which in magnitude, is likely to be approximately equal to the gradient around the trim condition multiplied by the speed margin between trim and stall speeds (depending upon the degree of linearity of elevator control system).

5.2 Minimum Pull Force to Stall (PFtS)

During the incipient stage of an unintentional stall, the low speed characteristics of the aeroplane e.g. control buffet, nose attitude etc. provide cues to the pilot to stall proximity, prompting the pilot to initiate stall avoidance or stall recovery if it becomes fully developed. The use of stick force as a cue to stall proximity for light aeroplanes was first proposed by Ellis [63] and supported philosophically by

Thurston [65]. Ellis' experimental results, based on the subjective opinion of two evaluation pilots flying the approach in a Navion In-flight Simulator, suggested that the PFtS in the trimmed landing condition for satisfactory pilot cues was 4.5 daN (10 lbf), including the effects of BO+F. Orlansky's earlier human factors study [64] based upon previously published information and pilot interviews, indicated that stick forces in all flight conditions for optimum pilot sensory information using one hand, should be in the range of 2.2~13.3 daN (5~30 lbf).

Flight test results conducted during the course of this research, confirmed the conventional understanding that PFtS varies with stick force gradient at the trimmed flight condition and between aeroplane models.

Particular attention to these variations is required with regard to any configuration likely to be used for low-speed manoeuvring close to the ground, with combinations of flap/landing gear/power as typically used in the circuit during the base leg, base to finals turn and the go-around when pilot task demand is high. Flight test results suggest that in the landing condition, models with PFtS $\geq$ 1.2 daN (excluding the effects of BO+F) were associated with lower fatal stall-related accident rates.

Considering Ellis' and Orlansky' findings in conjunction with limited experimental flight test results obtained during the course of this research, a minimum PFtS using one hand on the yoke/stick (including the effects of BO+F), in the range of 2.2~4.5 daN (5~10 lbf) is suggested for all flight conditions, with particular attention to the low-speed manoeuvring close to the ground with combinations of flap/landing gear/power.

The evaluation of PFtS, stick force gradient, and flying qualities for any existing or future aeroplane design, should be conducted using established flight test techniques, appropriate to the required flight conditions.

5.3 Flight Test Evaluation of Stick Force Gradient and PFtS

The evaluation of stick force gradient and PFtS for a selected aeroplane should be conducted for the range of flight conditions normally encountered in service, in a specified role (e.g. flying training, aerobatics, cross-country). Appropriate flight test methods should enable quantitative data to be obtained in a safe and efficient manner within the intended (or certified) flight envelope.

Flight Test Requirements and Conditions

The work of this research programme has evaluated stick force gradients in the climb, cruise, landing conditions. Additionally a series of flying qualities tasks were flown, with particular concentration upon the climb condition, using the Cooper-Harper method to quantify required pilot compensation. It is hoped that future programmes will build upon this research, with particular attention to certification of new or modified light aeroplane types. It is recommended that light aeroplane certification practice be improved to better ensure the safe operation of new and modified aeroplane designs. This could be achieved by including the determination of stick force gradients around typically flown trim conditions and the PFtS from those conditions, then comparing against minimum acceptable criteria which are likely to include both minimum PFtS and minimum stick force gradient in the approach, landing and go-around conditions (Table 20). All tests should be performed at a minimum safe height in case of inadvertent stall/spin entry and aft CG, being the worst case loading condition when the stick-free static margin is lowest. Theoretical modelling of stick force gradients as presented in Chapter 3 showed that stick force gradient decreases as wing loading decreases due to fuel consumption (Table 4). Consequently, the worst case loading scenario may occur when at a weight less than MTOW, therefore two aft CG weights are recommended for evaluation heavy-aft, being MTOW at the aft CG limit and light-aft, being equivalent to solo flight with minimum allowable fuel reserves.

Table 20, Proposed Tests for Quantitative Measurement of Stick Force Gradient & PFtS for Selected Flight Conditions at a Safe Height

			Aft Heavy CG		**Aft Light CG**	
Flight Condition	**Flaps**	**Power**	**Stick Force Gradient @ Trim**	**PFtS**	**Stick Force Gradient @ Trim**	**PFtS**
Approach	Partial	Approach	X	X	X	X
Landing	Full	Approach	X	X	X	X
Go-around	Full	Full	X	X	X	X

The next section describes the recommended test methods to be used in the assessment of stick force gradient and PFtS.

Quantitative Test Method for the Assessment of Stick Force Gradient and PFtS

Flight testing conducted during this research for the evaluation of stick force gradients, used the stabilised point technique [100] and a hand-held spring force gauge, accurate to within ±0.25 daN. This manual method with the force gauge attached to the control yoke with the spring in tension, is only suitable for quasi-static measurements.

Given the inclusion of the incipient stage of the go-around and the possibility of neutral or even negative LSS in this flight condition, collecting sufficient data points using this manual method is difficult. Therefore, it is recommended that the slow acceleration/deceleration flight test method [18] be used in conjunction with semi-automated, digital, real-time recording of stick forces and airspeed for this and all other flight conditions for evaluation. This semi-automated method was used in a fixed base flight simulator for the calibration of the configurable control loading system (Appendix A4-4) and should also be applied to flight test, where suitable equipment is available. This alternative method will reduce pilot workload during the measurement process, increase sampled data points, accelerate data reduction and analysis, enabling real-time presentation of apparent LSS and observation on-board the aeroplane during the flight testing. The ability to review real-time data will enable erroneous data points or trends to be identified immediately, enabling the tests to be repeated or the method refined for improved data quality. This method is routinely used in the flight testing of large commercial and military aircraft although, to the authors knowledge not presented in real-time. The availability of low cost force measurement COTS technology and MATLAB software using portable laptop computers enables high value flight test techniques to be adopted by low budget GA flight test programmes.

In the development stage of current light aeroplanes or the design stage of future light aeroplane designs, the estimation of stick force gradients and PFtS should be performed using the predictive model to reduce development time and cost.

5.4 The Prediction of Stick Force Gradient and PFtS

Predictive modelling for the estimation of stick force gradients and PFtS in all flight conditions, assumed quasi-static, longitudinal, non-manoeuvring flight in 1-g loading conditions and was found to be accurate to within ±0.025 daN/kt. The differences are attributed to the exclusion of drag due to flaps, power and aeroelastic effects from the modelling process (Appendix A5-1).

Perkins & Hage [24] showed that lift due to flaps and the direct and in-direct effects of power modify the stick-free and stick-fixed neutral points, modifying the respective static margins, resulting in changes to aerodynamic and apparent LSS. The effects of break-out force and friction, if significant, mask the aerodynamic LSS, modifying stick force gradient and trim speed band (Figure 6 & Figure 7). The effects of break-out force and friction increase as stick force gradient tends towards zero, subsequently increasing the trim speed band. Break-out forces and friction maybe estimated from flight test measurements of similar designs and used during the design stage to refine predictive modelling and estimate the effects on trim speed band.

Notwithstanding these limitations, predictive modelling can be used in preliminary design to provide initial estimates of gradients and PFtS in the climb, cruise & landing condition and assist in identifying tendencies towards a zero gradient (apparent neutral LSS). Extensions to the model are recommended to consider the incipient stage of the go-around by consideration of the direct and in-direct effects of power with full flap and additional drag due to flaps. Estimations of BO+F should also be included to further refine the model and estimate the trim speed band.

The concept of apparent LSS (and the use of stick force gradient or Fs/V relationship) is accepted practice in flight test and certification compliance testing, however the concept of PFtS is not universally known.

5.5 The PFtS Concept

The specification of a minimum pull force to achieve the stall (LSS) is similar in concept to the specification of a minimum stick force to achieve a positive limiting manoeuvring load factor (LMS) which exists in current certification specifications for light aeroplanes [84][85]. Exceeding the PFtS, which can be considered as a ‘soft boundary’, can result in an inadvertent stall which may or may not be recoverable, whereas exceeding the positive limiting manoeuvring load factor, a 'hard boundary', will result in a structural failure.

Ellis [63] noted that the use of an absolute value of stick force to indicate proximity to the stall can be unreliable, since individual pilot perception of force levels will vary across the pilot population. The combined effects of non-linear gearing in the elevator control system [65] and non-linear variation of wing lift with angle of attack in the proximity of the stall can also result in variations of PFtS.

Further experimentation is recommended to determine, feasibility and possible design criteria for acceptable PFtS, and this should include:-

- Flight tests with commonly used non-aerobatic light aeroplanes using semi-automated, digital, real-time recording of stick forces and airspeed in low LSS flight conditions to determine actual PFtS and the effects of non-linearities (elevator control systems gearing and lift with angle of attack) approaching the stall;
- Simulation tests in controlled simulation environment using a reasonable, representative sample of GA pilots ($n \geq 20$) stalling the simulated non-aerobatic light aeroplane in selected flight conditions with a series of pre-defined values of PFtS, and determine qualitative acceptability;

Such experimentation would precede any recommendations with regard to certification standards for non-aerobatic light aeroplanes. Notwithstanding these recommendations, the awareness and understanding of stick force gradients, PFtS and control feel has direct implications for future pilot training.

5.6 Future Pilot Training

Improved awareness and understanding of the variation of control feel with flight condition and CG for a given aeroplane class would be beneficial to pilot training, since as highlighted in Chapter 1, its importance is often understated [7][8]. The findings of this research with respect to the importance and variability of control feel should be incorporated into pilot training syllabi for class ratings, differences and familiarisation training.

Theoretical Knowledge

The author recommends that additions be included within theoretical knowledge subjects to emphasise the importance of control feel, the variability with flight condition and the associated effects on mental demand. Theoretical knowledge subjects for review and amendment include: human performance & limitations, flight performance & planning and principles of flight (Table 21).

Table 21, Recommended Additions to Pilot Training - Theoretical Knowledge Syllabi

Subjects	Sub-topic	Indicative Content/Additions
Human performance & limitations	Basic physiology	The sensations of touch & feel and how these are used by the pilot
	Basic psychology	The central decision making channel, mental workload how this changes with flight condition and piloting task(s), impact on safety margins (the difference between pilot capability and task demand), effects of pilot distraction
Flight performance & planning	Mass & balance	How control feel changes with CG & flight condition and conditions for susceptibility to over-controlling
Principles of Flight	Three dimensional flow about an aeroplane	The effects of downwash, direct and indirect effects of power and how they affect control feel in different flight conditions
	Trimming controls	Effects of elevator trim on control feel, importance of the ability to trim, the effects of incorrect trimming on control feel and pilot workload, likelihood of mis-controlling
	The stall	Disruption of airflow over the tailplane, the effects on control feel, reliability/unreliability of natural low-speed characteristics approaching the stall, sensing and releasing back pressure and how this changes with flight condition
	Stability	Relationship between aerodynamic and apparent LSS, the effects of break-out force & friction on control feel and trim speed band, the effects of a poorly maintained elevator control system on control feel

Flying Training

Similarly, revisions should also be included within associated flying training exercises. Flight exercises for review include: the effects of controls, take-off & climb, straight & level flight, descending, circuits, approach & landing, slow flight, stalling, emergencies and basic instrument flying (Table 22).

Table 22, Recommended Additions to Pilot Training - Flying Training Syllabi

Flight Exercise	**Indicative Content/Additions**
Effects of controls	Variation of control feel (in pitch) with flight condition and CG, flying the same make/model of aeroplane with CG at the fwd and aft limits, use of elevator trimming controls & flaps and the effects on control feel, the effects of pilot distraction/inattention on airspeed management
Straight & level flight	Variation of control feel & stick position with airspeed & trim, effects on maintaining airspeed control
Climb	Variation of control feel in the climb with flaps up/down, effect of trim & incorrect trim setting, effects on maintaining airspeed control
Descending	Variation of control feel in the descent with flaps up/down, effect of trim & incorrect trim setting, effects on maintaining airspeed control
Slow flight	Variation of control feel in slow flight with flaps up/down, effect of trim & incorrect trim setting, significance of stick forces and importance of trim in maintaining steady deceleration as flaps are deployed to avoid the stall
Stalling	Variation of control feel up to the point of aerodynamic stall, variation of reliability of natural, stall warning characteristics (& systems where fitted) for specific makes/models and flight conditions, concept of PFtS, effect of incorrect trim setting and conditions for increased susceptibility to stall
Take-off & climb	Variation of control feel with CG, over-controlling with aft CG, effect of incorrect trim setting
Emergencies	Variation of control feel in the incipient stage of EFATO, effect of incorrect trim setting during EFATO
Circuit, approach & landing	Variation of control feel during the circuit, approach, landing & go-around with power on/off, effect of incorrect trim setting, importance of airspeed control in the base to finals turn and go-around, reduced PFtS, effect of pilot distraction, increased susceptibility to stall

Differences Training

Pilots are required to undertake differences training including theory and instruction with an appropriately qualified flight instructor in order to change to a different type or variant of an aeroplane within the same class rating. Any features likely to result in changes in control should be incorporated into theoretical knowledge and flying training.

Familiarisation Training

Familiarisation training is advisable (and sometimes mandated by individual organisations) to change to a different type or variant of an aeroplane within the same class rating, when differences training is not required. The acquisition of additional theoretical knowledge is advisable and the means of achievement may vary, dependent upon circumstances e.g. assistance of a flight instructor, assistance of another pilot experienced on the type or by self-study. Flight tests conducted during the course of this research using selected aeroplane models of apparently similar design and performance but dissimilar control feel, have highlighted a problem in relation to familiarisation training. Pilots converting between either of the models in question (C150M & C152) are not required to undertake differences training but only familiarisation training. Thus, only theoretical, knowledge is imparted and no flight instruction in differences in flying qualities is received. Given the lack of emphasis with regard to control feel within flight training syllabi at all levels and the lack of published flight test data, pilots converting to similar aeroplane models may be unaware of significant variations of control feel in comparable flight conditions, the impact on pilot mental demand and potential implications for flight safety. The results suggest that an intermediate category of training, between ‘differences’ and ‘familiarisation’ would provide substantial safety benefits for apparently similar models with significantly different flying qualities and that this requires sound pre-flight briefing (theoretical knowledge) followed by relevant flight exercises to fully appreciate differences in control feel.

5.7 Flight Instructor Awareness

Building upon the earlier recommended changes to flying training syllabi, this section describes the impact of aeroplane flying qualities on instructional flying technique for consideration by flying instructors.

Flying by Reference to Pitch Attitude

The awareness and understanding of control feel has direct relevance to flight instruction for flying by reference to pitch attitude, however to master this flying skill, control force change with airspeed must be easily perceptible to the pilot. In VMC, the practice of flying by reference to pitch attitude encourages the development of psycho-motor skills using control feel and the natural horizon to reduce pilot workload by reducing the frequency of 'head down' cockpit airspeed instrument scanning.

The Use of Elevator Trim

The use of the elevator trim is taught to 'reduce pilot workload', the pilot uses stick force inputs to first establish, then maintain the desired target airspeed, gradually reducing the stick force to zero by re-positioning the elevator trim tab, holding the elevator in the desired position. The proper and accurate use of elevator trim in all flight conditions requires perceptible stick force change with airspeed in all conditions. If stick force gradients are low or zero and trim speed band is large, improper use of the elevator trim is likely, leading to increased pilot mental demand. The variation of stick force gradient between aeroplane makes/models means that aeroplane makes/models with moderate to high stick force gradients in all flight conditions are more suitable for properly training pilots in flying by reference to pitch attitude and the use of control trim to minimise pilot mental demand.

Stall Awareness

Flight testing has shown that stick force gradient and PFtS varies with flight condition and CG, reducing greatly in the landing condition with aft CG. This can result in the pilot over-controlling during the approach and landing if the pilot fails to adapt control (input) gain to compensate for a stick force gradient. In the landing condition, when the aeroplane is normally flying at $1.3V_S$, the angle of attack of the complete aeroplane is higher than in either the climb or cruise condition. This results in a relatively smaller stall margin (difference between actual angle of attack and critical angle of attack) in combination with lower LSS (as evidenced by flight tests during this research using two different aeroplane models).

The combination of lower stick force gradient, lower PFtS and reduced stall margin is likely to increase the probability of a stall in the landing condition and this should be incorporated in stall awareness flight briefing and instruction.

5.8 Chapter Summary

This chapter has proposed criteria for acceptable stick force gradients in all flight conditions for current and future light aeroplane designs based upon the results of flight tests, flight simulation experiments and previous published work in the field.

Criteria for minimum PFtS as a cue to stall proximity has also been proposed, based on limited flight test results and further flight testing and simulation experimentation is recommended. A flight test programme to quantitatively assess stick force gradient and PFtS for current and future light aeroplane designs has been proposed for use by test/evaluation pilots. In addition, a real-time, semi-automated evaluation method using COTS technology has been recommended and this will enable increased data points to be obtained, data reduction & analysis to be accelerated simultaneously reducing pilot workload and improving safety.

The application of predictive modelling to current and future light aeroplane assessment and design has been described and extensions to the model proposed to account for the effects of drag due to flaps, power and break-out force and friction in all flight conditions. The concept of PFtS has been evaluated and limitations identified. Further experimentation is recommended to determine feasibility and refined criteria using flight testing of examples of commonly used light aeroplanes and simulation tests with a representative sample of GA pilots.

The benefits of improved awareness and understanding of the variation of control feel with flight condition in pilot raining have been discussed. Indicative additions to pilot training syllabi, differences and familiarisation training in respect of theoretical knowledge and flying training have been recommended. In support of the recommended additions to pilot training, relevant notes for flight instructors are presented in relation to instructional techniques and desirable flying qualities to develop flying skills around control feel. The final chapter concludes with a re-statement of criteria for acceptable stick force gradients and the limitations of predictive modelling, in accordance with the original research objectives.

6. Conclusions

Flight test results using a limited range of aeroplane models showed that pitch stick force gradients varied with model and phase of flight, and were substantially lower during the landing condition when flaps were deployed. The approach and landing phase accounts for the highest number of GA accidents (43.6%), and corresponds with higher pilot workload due to the execution of multiple secondary piloting tasks such as re-configuring the aeroplane for the landing condition, re-trimming, navigating, communicating with ATC, executing procedures, monitoring systems and looking out for other traffic.

Aeroplane models with stick force gradients > 0.1 daN/kt and correspondingly higher levels of pull force to stall, were associated with superior, in service safety records. Subjective handling qualities assessments using Cooper-Harper, suggest that the aeroplane response to pilot control inputs, degrades as stick force gradient tends towards zero. Handling qualities also degraded as secondary tasks were performed by the pilot and task performance declined.

Flight simulation tests with 20 representative GA pilots showed that pilot total workload varies with the flying task and that mental demand increases significantly ($p < 0.05$) as stick force gradient tends towards zero.

Predictive modelling for the estimation of stick force gradients assuming quasi-static, longitudinal, non-manoeuvring flight in 1-g loading conditions was found to be accurate to within ±0.025 daN/kt. Differences were attributed to the exclusion of aeroelastic and power effects in the modelling process. Notwithstanding these limitations, the modelling should be used in preliminary design to estimate gradients and PFtS in any phase of flight and to identify tendencies towards apparent neutral longitudinal static stability.

Considering flight test and flight simulation results in combination, it is proposed that stick force gradients for a non-aerobatic, light aeroplane flown by a GA pilot without exceptional piloting, skill, alertness or physical strength, should be non-zero and between 0.10~0.13 daN/kt in all flight conditions normally encountered in service.

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