APPENDIX

APPENDIX A3-1 Complete Results of the Parametric Analysis using the MATLAB Model

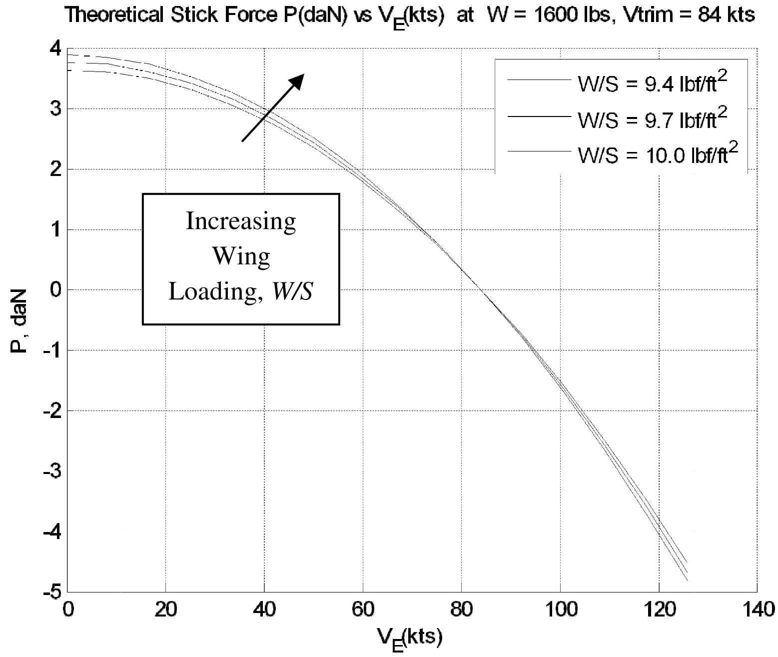

Figure A3-1, MATLAB Output: Variation of Apparent Stick-free Longitudinal Static Stability Wing Loading, *W/S* (lbf/ft^2)

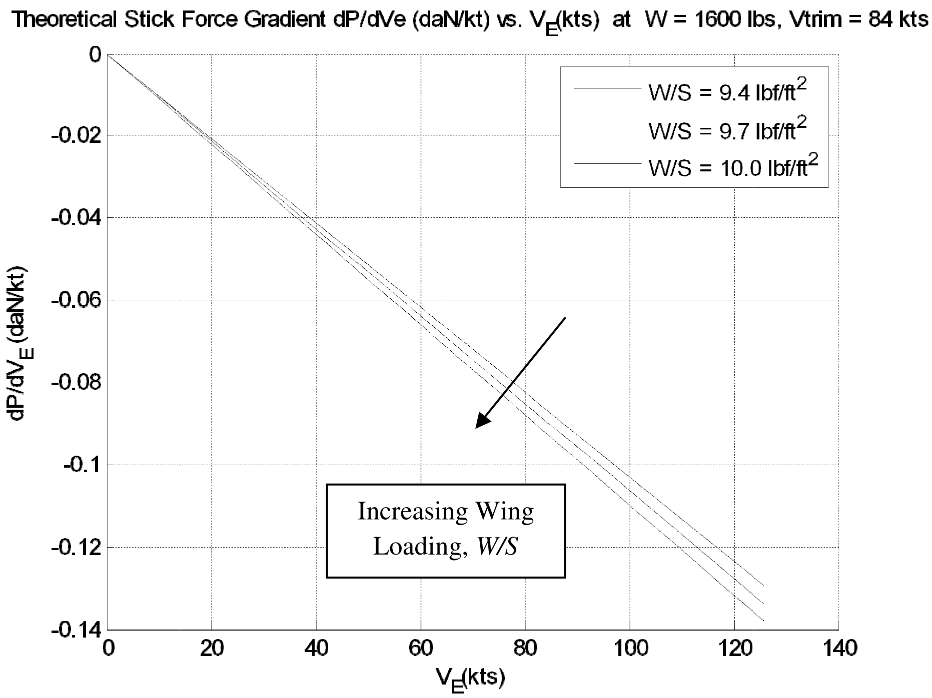

Figure A3-2, MATLAB Output: Variation of Stick Force Gradient with Wing Loading, *W/S* (lbf/ft^2)

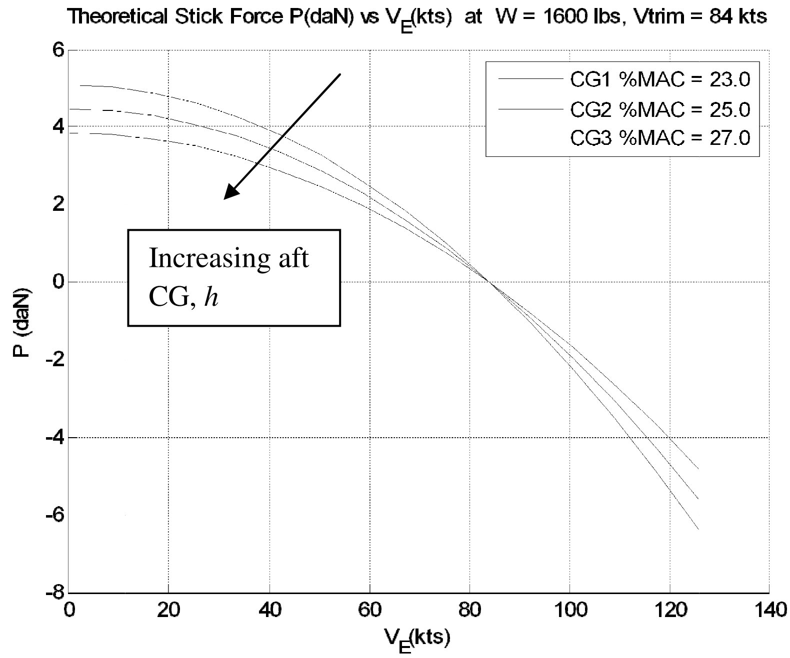

Figure A3-3, MATLAB Output: Variation of (a) Apparent Stick-free Longitudinal Static Stability with *h* (CG %MAC)

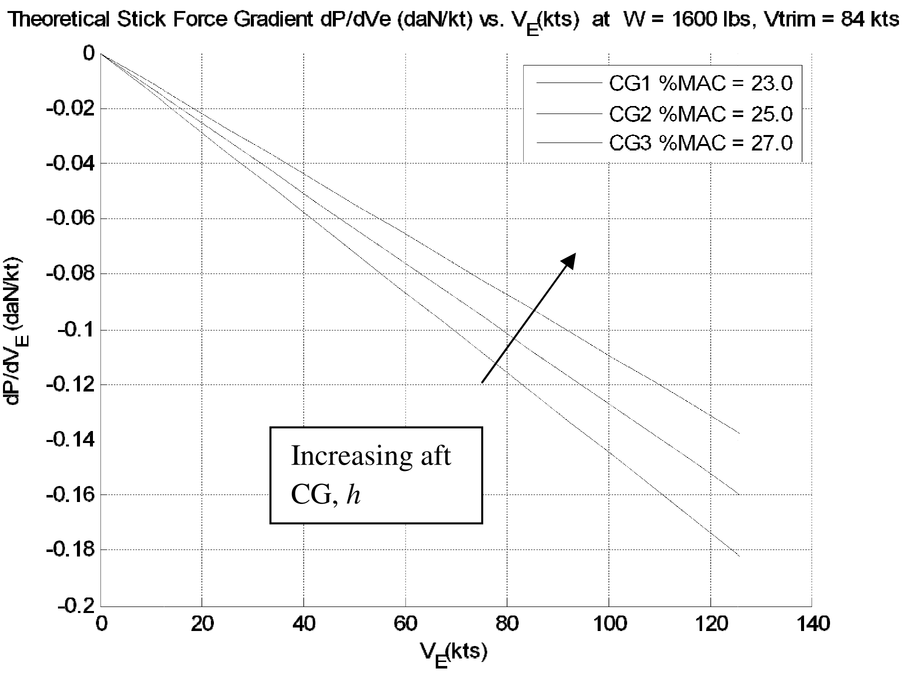

Figure A3-4, MATLAB Output: Variation of Stick Force Gradient with *h* (CG %MAC)

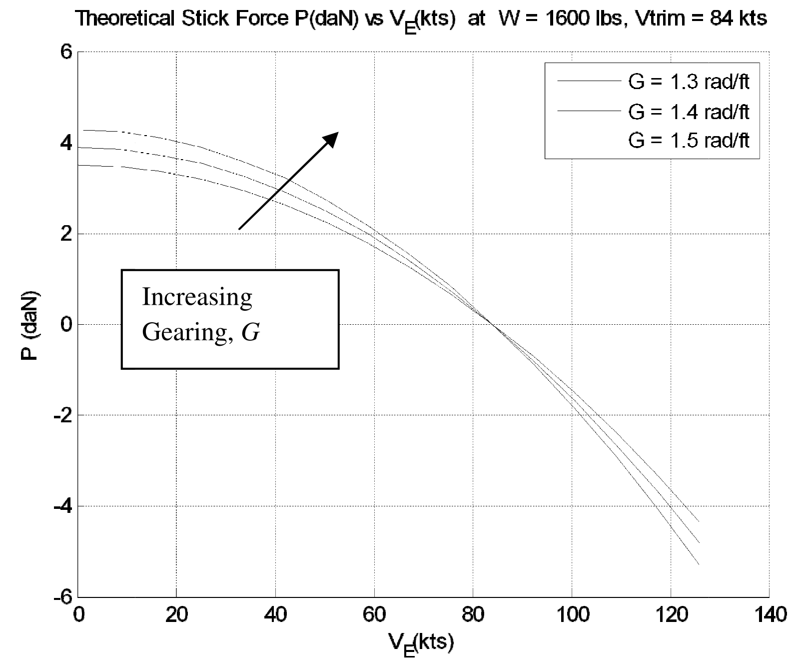

Figure A3-5, MATLAB Output: Variation of Apparent Stick-free Longitudinal Static Stability with Elevator Gearing, *G* (rad/ft)

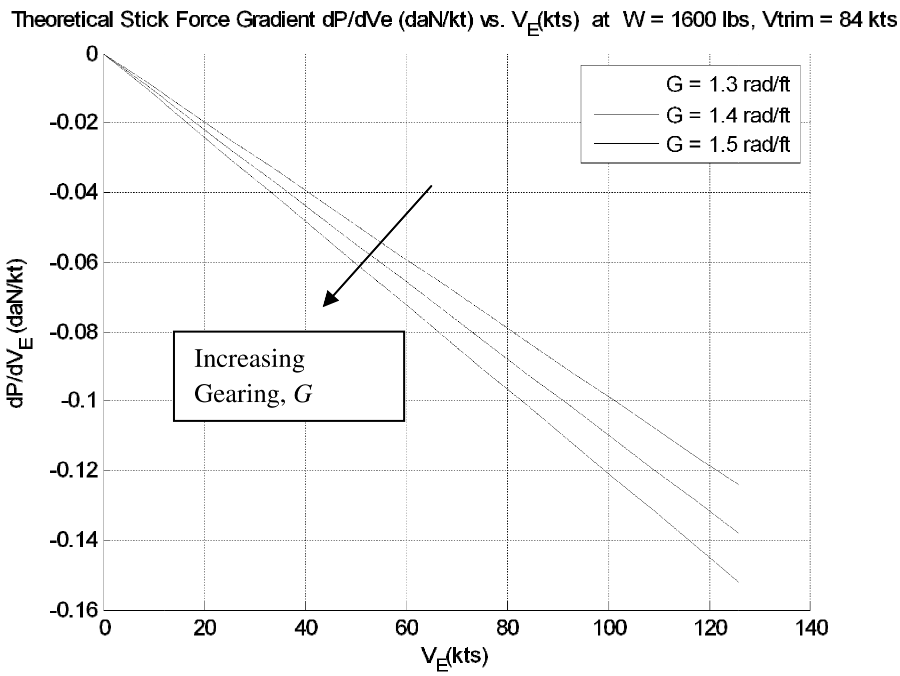

Figure A3-6, MATLAB Output: Variation of Stick Force Gradient with Elevator Gearing, *G* (rad/ft)

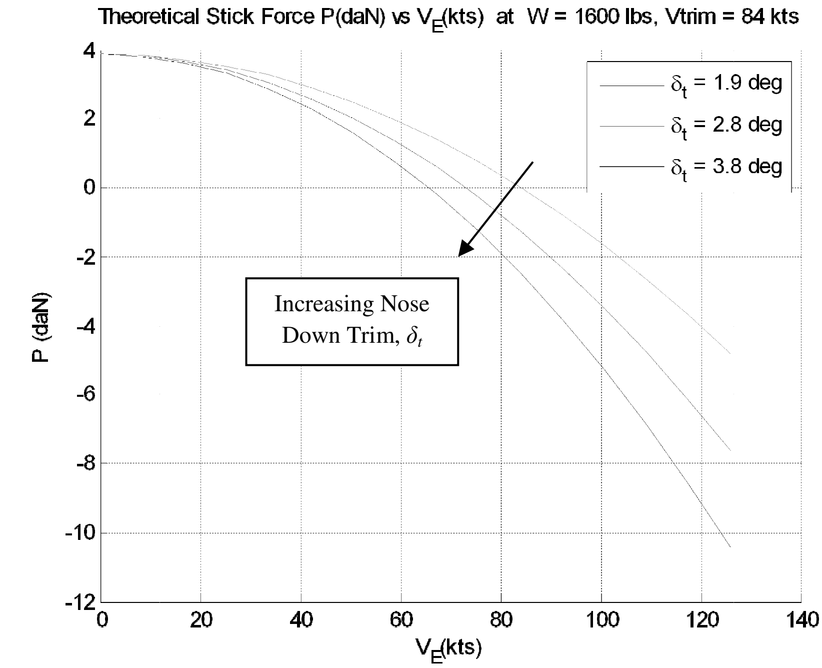

Figure A3-7, MATLAB Output: Variation of Apparent Stick-free Longitudinal Static Stability Elevator Trim δ_t (deg)

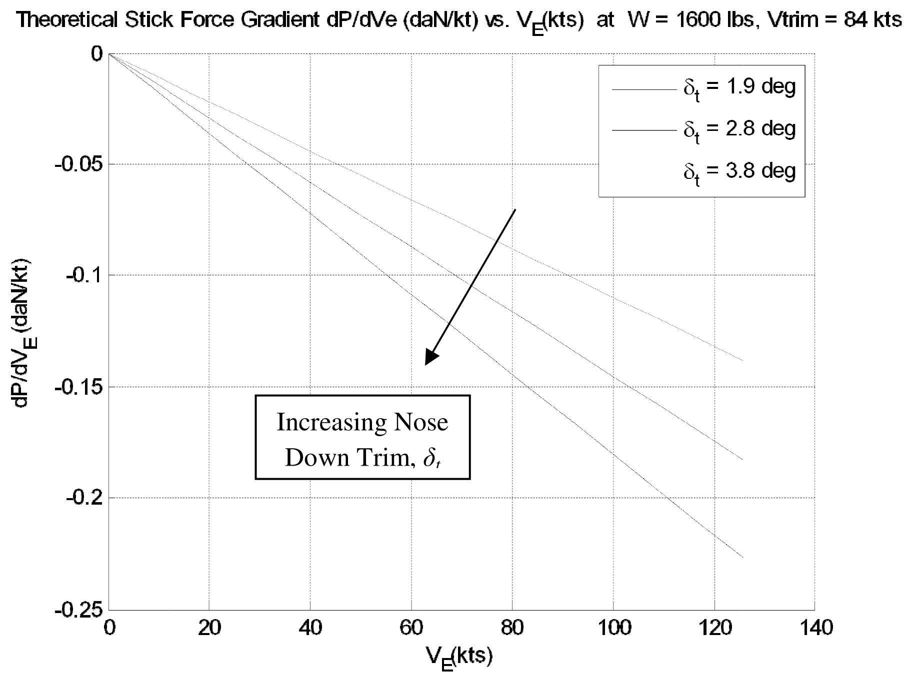

Figure A3-8, MATLAB Output: Variation of Stick Force Gradient with Elevator Trim δ_t (deg)

APPENDIX A4-1 Flight Test Programme

Table A4-1, Detailed Scope of Flight Tests (Normalised)

Test Category	Test Seq.	Description of Tests	Cooper-Harper HQRs?
1 - Longitudinal Static Stability	3	Climb & Point Track	Y
1 - Longitudinal Static Stability	4	Apparent LSS Climb Power	
1 - Longitudinal Static Stability	5	Apparent LSS Cruise Config	
1 - Longitudinal Static Stability	6	Apparent LSS Landing Config 30 Flap	
1 - Longitudinal Static Stability	7	Apparent LSS Landing Config 40 Flap	
1 - Longitudinal Static Stability	8	Effect of Elevator Trim on Power	
1 - Longitudinal Static Stability	9	Trim Change with Power @V_{minD}	
1 - Longitudinal Static Stability	10	Trim Change with Flap in Landing Config	Y
1 - Longitudinal Static Stability	11	Speed Stability Landing Config 30 Flap	
1 - Longitudinal Static Stability	12	Speed Stability Landing Config 40 Flap	
2 - Longitudinal Dynamic Stability	14	Short Period Oscillation (SPO)	
2 - Longitudinal Dynamic Stability	15	Phugoid (LPO)	
3 - Lateral & Directional Stability	16	Dutch Roll	
3 - Lateral & Directional Stability	17	Spiral Mode	
3 - Lateral & Directional Stability	18	Roll Mode	
4 - Stall Characteristics	19	Stall @ Flap 0/Idle Power	
4 - Stall Characteristics	20	Stall @ Flap 0/Power for Level Flight	
4 - Stall Characteristics	21	Stall @ Flap 30/Idle Power	
4 - Stall Characteristics	22	Stall @ Flap 40/Idle Power	
5 - General Handling/Performance	1	Normal Take-off	Y
5 - General Handling/Performance	2	Performance Climb	
5 - General Handling/Performance	13	Approach & Landing at Safe Height	Y
5 - General Handling/Performance	23	Approach & Landing	Y

Table A4-2, Flight Test Programme & Sorties

Phase 1: Aeroplane 1 (TOW/CG as %MAC/Sortie No.)				Phase 2: Aeroplane 2		Phase 2: Aeroplane 3		Phase 3: Aeroplane 4	
Model	**CG1**	**CG2**	**CG3**	**Model**	**CG1**	**Model**	**CG1**	**Model**	**CG1**
C152	**1655 lbf @24.24% Sortie: 01**	**1491 lbf @25.28% Sortie: 05**		**C152**	**1670 lbf @23.39% Sortie: 9**	**F152**	**1655 lbf @23.78% Sortie: 10**		
	1637 lbf @23.81% Sortie: 04								
F150L	**1599 lbf @25.28% Sortie: 02**								
F150 ‘M’	**1600 lbf @25.68% Sortie: 03**	**1425 lbf @27.22% Sortie: 08**	**1598 lbf @27.90% Sortie: 07**	**C150 ‘M’**	**1580 lbf @27.00% Sortie: 11**	**F150 ‘M’**	**1599 lbf @25.87% Sortie: 12**		
F150G								**F150G**	**1591 lbf @26.57% Sortie: 14**
Crew:	**2**	**1**	**2**	**Crew:**	**2**	**Crew:**	**2**	**Crew:**	**2**

APPENDIX A4-2 Flight Test - Pseudo EAS Calculation

During the flight test programme, quantitative data obtained from the Appareo GAU1000a portable flight data recorder was used to estimate 'pseudo EAS' airspeed during all flights. Pseudo EAS was determined from recorded ground speed with corrections for wind [105] and density effects.

True airspeed was derived from the aeroplane groundspeed, wind and relative angles:-

$$V_T = V_G + V_W \cos(\emptyset_{AC} - \emptyset_W) \quad \textbf{...(A4-1)}$$

Correcting for relative air density, the 'pseudo' equivalent airspeed is therefore:-

$$V_E = V_T\sqrt{\sigma} \quad \textbf{...(A4-2)}$$

Substituting for V_T from equation (A4-1), in equation (A4-2) gives:-

$$V_E = [V_G + V_W \ \ cos\ (\emptyset_{AC} - \emptyset_W\ )]\sqrt{\sigma} \quad \textbf{...(A4-3)}$$

Where relative air density σ, may be obtained from pressure and temperature ratios [106]:-

$$\sigma = \frac{\delta}{\theta} \quad \textbf{...(A4-4)}$$

And δ and θ (^{o}K) are given by:-

$$\delta = \frac{P_a}{P_o} \quad \textbf{...(A4-5)}$$

$$\theta = \frac{T_a}{T_o} \quad \textbf{...(A4-6)}$$

APPENDIX A4-3 Modelling – Input Parameters

Table A4-3, Initial Parameters for Comparison of Theoretical and Experimental Stick Force in the Climb

Parameter	Cessna C150 'M' (1975) 'Trainer'	Cessna C152 (1982)
Weight (lbf)	1580	1670
V_E (kts)	67	67
Mean Height - sHp (ft)	2,600	2,500
Flaps (deg)	0	0
Elevator Trim (deg)	10	10
Power (% BHP.)	56	66
Wing Loading W/S (lbf/ft^2)	9.91	10.47
CG aft of datum (inches)	35.69	33.56
CG, 2 POB @ TOW (%MAC)	27.00	23.39%
Estimated Elevator Gearing (rad/ft)	1.39	1.50
Estimated Downwash at Tail (deg)	2.19	2.09
Estimated Downwash Derivative	0.45	0.45

Table A4-4, Initial Parameters for Comparison of Theoretical and Experimental Stick Force in the Cruise

Parameter	Cessna C150 'M' (1975) 'Trainer'	Cessna C152 (1982)
Weight (lbf)	1580	1670
V_E (kts)	89	88
Height - sHp (ft)	3,600	3,500
Flaps (deg)	0	0
Elevator Trim (deg)	8	8
Power (% BHP)	54	53
Wing Loading W/S (lbf/ft^2)	9.91	10.47
CG aft of datum (inches)	35.69	33.56
CG as a percentage of CG range (%)	69.80	46.60
CG, 2 POB @ TOW (%MAC)	27.00	23.39
Estimated Elevator Gearing (rad/ft)	1.39	1.50
Estimated Downwash at Tail (deg)	2.19	2.09
Estimated Downwash Derivative	0.45	0.45

Table A4-5, Initial Parameters for Comparison of Theoretical and Experimental Stick Force in the Landing (30° of Flap)

Parameter	Cessna C150 'M' (1975) 'Trainer'	Cessna C152 (1982)
Weight (lbf)	1580	1670
V_E (kts)	67	68
Height - sHp (ft)	3,500	3,500
Flaps (deg)	30	30
Elevator Trim (deg)	-3	-1
Power (% Max. Avail.)	54	63
Wing Loading W/S (lbf/ft^2)	9.91	10.47
CG aft of datum (inches)	35.69	33.56
CG, 2 POB @ TOW (%MAC)	27.00	23.39
Estimated Elevator Gearing (rad/ft)	1.39	1.50
Estimated Downwash at Tail (deg)	7.96	7.86
Estimated Downwash Derivative	0.80	0.80

APPENDIX A4-4 Flight Simulation - Experimental Method

This appendix (as referred in Chapter 4.4) describes experimental subject demographics, equipment, calibration procedure and method for the purposes of replication.

Pilot Demographics

Pilot volunteers responded to a call for volunteers made via the UK general aviation pilot press and flying clubs. Fifty five respondents completed an on-line questionnaire providing demographic data and eventually 26 pilots participated in the complete programme, with 20 completing the series of tests described here. Summarised pilot demographics using SPSS [107] are presented in Table A4-6.

Test Equipment

A fixed-base engineering flight simulator device, based at Sheffield University was used to conduct all tests as this provided configurable control loading in pitch, roll and yaw using electrically driven torque motors. The external visual environment consisted of a 150° horizontal field of view by 40° vertical field of view, suitable for circuit-based flying tasks (Figure A4-1). The simulator used an approximate replica of a Pilatus PC7 cockpit with basic head down instrument panel, control stick, pedals, throttle, brakes, flaps and elevator trim (Figure A4-2). The system allowed stick force gradients to be software configured and dynamically calculated based upon flight simulator parameter outputs such as airspeed and control deflection. For this series of tests, the control loading software was configured to emulate a basic, linear stick force variation with elevator stick displacement, independent of airspeed and data output was logged at a frequency of 5 Hz. A high-wing, low-tail aeroplane flight dynamics model based on the Cessna 172, was selected from library of available aeroplanes for all tests. Minor modifications were necessary to the basic instrument panel to provide indications of elevator trim position.

Figure A4-1, PC7 Flight Simulator – External Visuals (*Courtesy: Roddy Maddocks*)

Figure A4-2, PC7 Engineering Flight Simulator – Cockpit Environment

Table A4-6, Volunteer Pilots - Statistical Summary using SPSS [107]

Characteristic	Results (n=26)
Sex:	Male 96%, Female 4 %
Age (yrs):	Mean = 52, SD = 11.2
Highest License:	PPL 88%, CPL 8%, ATPL 4%
Notable Ratings:	Night 35%, IMC 35%, FI 12%, Micro light 12%, Gliding 12%
Years since 1st license (yrs):	Mean = 15, SD = 12.8
Hours: - Total - PiC	Median = 328, IQR = 839.8 Median = 222, IQR = 791.8
Recency (hrs): last -28 days - 90 days - 1yr - 5 yrs	Median = 4.5, IQR = 8.8 Median = 11.0, IQR = 22.5 Median = 26.3, IQR = 37.5 Median= 99.5, IQR = 124.8
Most common Aeroplane type flown:	Single Engine Piston 96% Micro light/Sport Light Aeroplane 4%

Control Loading Calibration

The fixed-base simulator featured a dynamic control loading system in order to produce realistic forces on the flight controls. High performance servo motors and amplifiers produced opposing control forces to pilot applied forces. The control loading program was modified to produce an opposing force proportional to control deflection, representing a simple, linear force-displacement, multiplied by the control loading gain. Required control loads of up to 22.24 daN in the pitch axis could be defined with a precision of 0.01 daN (however due to inherent breakout and friction forces in the mechanical systems this level of precision was not achievable – see later discussion on this point). It was decided that due to the number of tasks, time constraints and costs, that two different stick force gradients would be sufficient to provide a range of results, thus requiring approximately 90 minutes for each pilot to compete them. The stick force gradients selected represented a range for light aeroplanes from approximately zero stick force gradient (allowing for break-out forces and friction), up to 0.070 daN/kt, approximately equivalent to the recommended minimum for large aeroplanes (0.074daN/kt[1]) as used for comparison of flight test results in Chapter 4.1. A calibration exercise to determine the approximate values of control loading gain required to configure the control loading system software was performed using a digital load cell mounted on the control stick and interfaced to a laptop computer using a custom-developed MATLAB script (Figure A4-3).

Figure A4-3, Digital Load Cell used for Calibration of the Stick Force Gradient

The results for the calibration of stick force gradients using the slow acceleration/deceleration flight test method [100] in the cruise for the Cessna 172 aeroplane (Figure A4-4, stick force gradient '1' and Figure A4-5 stick force gradient '2') show two markedly different gradients about the trimmed flight condition (90 kts). Apparent break-out forces were in the region of 0.5~1.0 daN with friction within the range +/- 1.0 daN. The trim speed band in the low speed range was approximately 5% of trim speed, however in the high speed range, there was a tendency for speed divergence, therefore results were only recorded up to 120 kts. This was not considered to be a problem since all flight scenarios were conducted in the range of 60 to 120 kts, within the aeroplane's normal operating range and in the circuit pattern. This speed 'run-away' was due to the mechanical design of the control loading system and the aerodynamic characteristics of the flight simulator model. The control stick was slightly forward-biased (nose down tendency) due to the inertia of the forward control linkage flywheel and push rod. The simulator aerodynamic model although based on a Cessna 172, apparently exhibited slightly lower drag characteristics than the real aeroplane (as flown by the author).

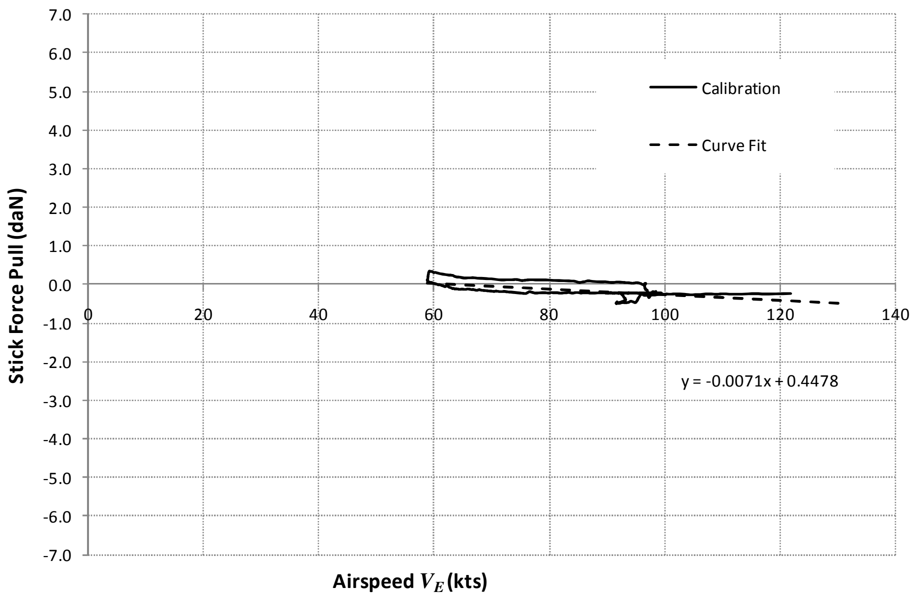

Figure A4-4, Calibration of Stick Force Gradient 1 in the Cruise using Slow Acceleration/Deceleration Method [100]

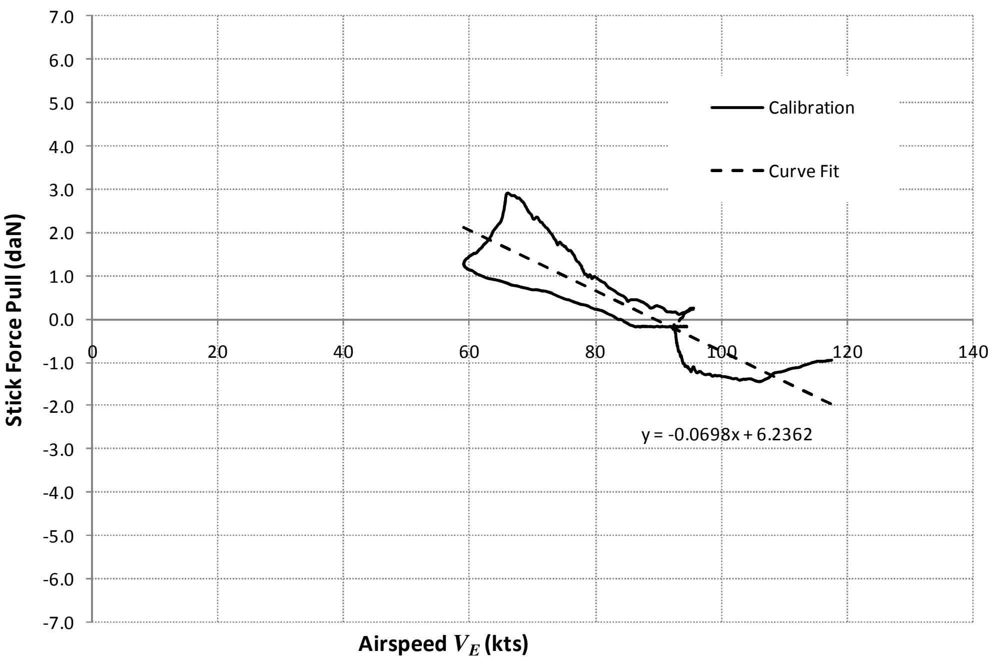

Figure A4-5, Calibration of Stick Force Gradient 2 in the Cruise using Slow Acceleration/Deceleration Method [100].

Method & Scope

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.

During the experiment, each pilot conducted 4 different flying tasks (Table A4-7) using normal operating procedures and two pre-programmed, calibrated stick force gradients designed to minimise experimental bias/familiarisation (Table A4-8). After completing a practice circuit (take-off and landing on the same runway following a right-hand, rectangular pattern around the airfield at fixed height, Figure A4-6), pilots conducted a second circuit, go-around (or aborted landing), base to finals turn. After completion of each task a NASA-TLX workload assessment [103] was completed using r/t communication. On completion of all the tasks with a given stick force gradient, the stick force gradient was changed (controlled by software) and the tasks repeated. The pilot was not informed of the nature of changes. Simulated air-ground radio communications were used for all scenarios with all pilots required to make the radio calls as necessary for flight in the circuit. In addition to the use of NASA-TLX workload assessment, a cockpit voice recorder, video recorder and intercom for simulated radio communications was used to gather additional research data.

Table A4-7, Test Scenarios

Task No.	Task	Description	Performance Targets / Pilot Decisions	Trim Condition / Configuration	Phase of Flight
1	**PRACTICE Circuit**	Fly the Aeroplane in the circuit, executing turns, maintaining airspeed, heading and altitude as required.	Practice only	**Circuit** **BRS Rwy 27 R/H, 1000' AGL**	Circuit
2	**Circuit**	Fly the Aeroplane in the circuit, executing turns, maintaining airspeed, heading and altitude as required.	Pilot to fly within 'normal' flying tolerance*	**Circuit BRS Rwy 27 R/H, 1000' AGL**	Circuit
3	**Normal Approach with requested Go-around**	Fly the Aeroplane in the take-off and climb out, maintaining airspeed, heading and rate of descent. Execute go-around on request.	Pilot to fly within 'normal' flying tolerance*	**Approach & FULL Flap Landing @65 kts, Rwy 27 2nm 700' AGL (with Go-around @ 50' AGL)**	Approach, Take-off
4	**Base to finals turn with sufficient fuel for 1 landing only (no go-around)**	Fly the Aeroplane in the take-off and climb out, maintaining airspeed, heading and rate of descent.	Pilot to fly within 'normal' flying tolerance*	**Base to Finals Turn w/landing BRS Rwy 27 R/H Mid-base 750' AGL**	Approach & Landing

Notes:- *Normal, expected flying tolerance for PPL (A) [108] are:-

- Airspeed ±15 kts
- Height ±150 ft
- Heading ±10°

Table A4-8, Test Sequence

Pilot No:	**1**		**2**		**3 etc...**	
Stick Force Gradient:	**1**	**2**	**2**	**1**	**1**	**2**
Task Scenario Sequence:	1	1	1	1	1	1
	2	2	2	2	2	2
	3	3	3	3	3	3
	4	4	4	4	4	4

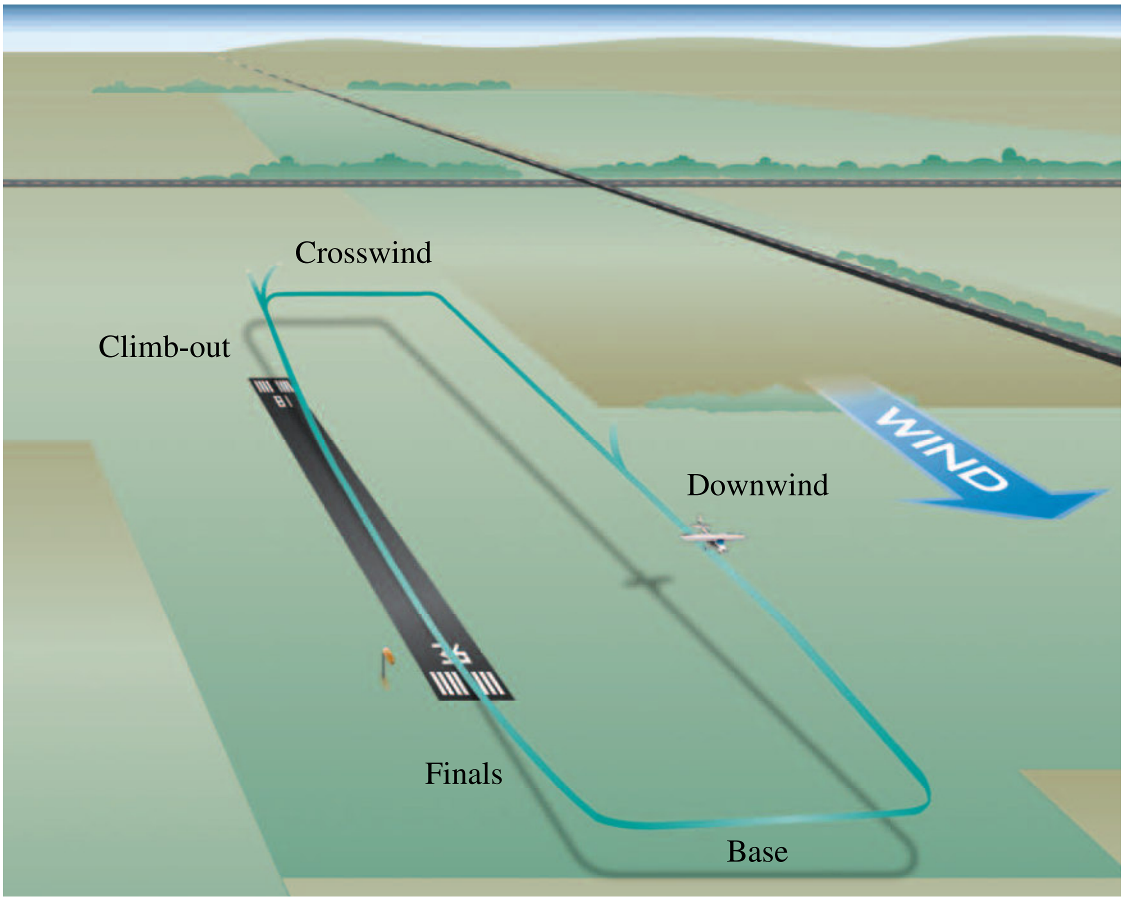

Figure A4-6, Circuit or Traffic Pattern (Right-hand) [109]

Pilot workload was assessed immediately after completion of each task using a basic, un-weighted NASA-TLX workload rating assessment [103] via the simulator intercom system. Pilots were asked to rate the performed task on a scale of '1' to '10' for mental, physical and temporal load, as well as frustration, effort and own performance (Table A4-9). Post-task assessments were completed in less than 2 minutes and scores recorded manually by the test administrator; in addition cockpit voice recordings were used for subsequent playback to confirm scores. A reversed scale was used to rate 'own performance', since this is more intuitive (i.e. 1/10 = 'poor' to 10/10 = 'good') and helped to reduce errors. The scale was re-instated in subsequent analysis to enable valid assessments of total workload for all tasks in the normal way.

Table A4-9, Modified, Un-weighted NASA-TLX Task Load Rating System

No.	Category	Rating Scale
1	Mental Demand	1 (Low) to 10 (High)
2	Physical Demand	1 (Low) to 10 (High)
3	Temporal/Time Pressure Demand	1 (Low) to 10 (High)
4	Own Performance*	1 (Poor to 10 (Good)
5	Effort	1 (Low) to 10 (High)
6	Frustration	1 (Low) to 10 (High)

Notes:-

*Reversed scale

APPENDIX A4-5 Flight Simulation – Experimental Results

Statistically significant workload results for total workload and mental demand variations with task and stick force gradient were presented in Chapter 4.4. This appendix presents the detailed results for all other sub-measures using un-weighted NASA-TLX sub-scale scores (physical, temporal, own performance, effort & frustration) for completeness. These measures were unaffected by stick force gradient.

Physical Demand

The results for estimated mean physical demand (Table A4-10 & Figure A4-6) showed little difference when all task were combined. Using conservative corrections as before, the results for repeated measures within-subjects differences (Table A4-11) for stick force gradient were nonsignificant ($p = 0.672$) but differences in flying tasks were highly significant ($p < 0.01$). The combined effect of stick force/gradient interactions were nonsignificant ($p = 0.077$).

Drilling down further for significant differences identified above, the repeated measures within-subjects contrasts (Table A4-12) for physical workload variation with tasks only, significant differences between tasks 3 & 4 were evident and this highlights the effect of additional stress once more.

Table A4-10, Effect of Stick Force Gradient on Mean Physical Demand

			95% Confidence Interval	
gradient	Mean	Std. Error	Lower Bound	Upper Bound
1	4.213	0.324	3.535	4.890
2	4.363	0.246	3.847	4.878

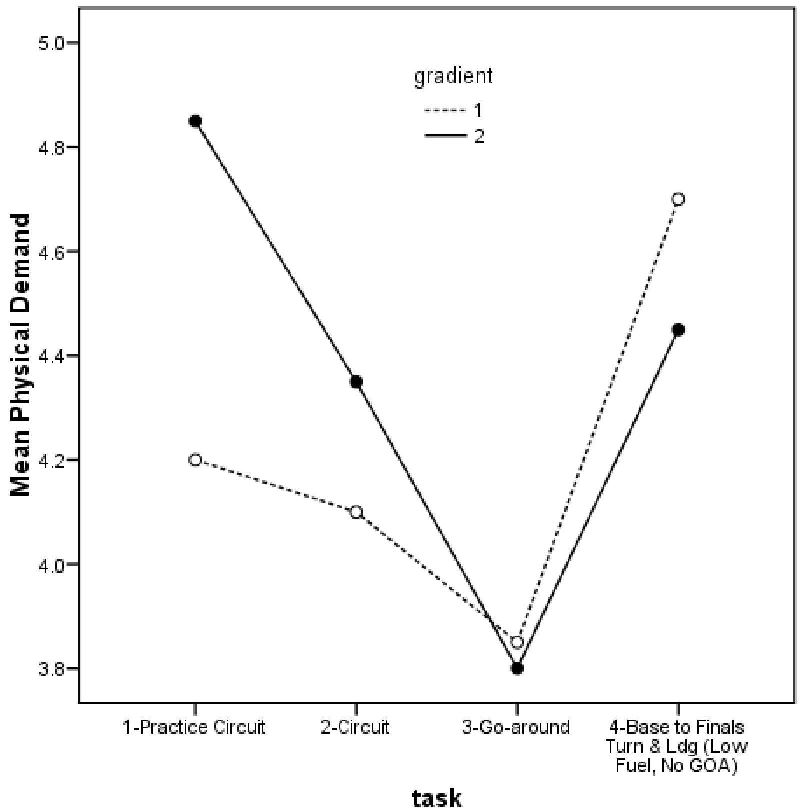

Figure A4-6, Effect of Stick Force Gradient & Task on Estimated Mean Physical Demand

Table A4-11, Sample of Multivariate Test Results for Within-Subjects Effects for Physical Demand, Stick Force Gradient, Task and Gradient * Task

Source	*p*
gradient	0.672
task	**0.004**
gradient * task	0.077

Table A4-12, Sample of Multivariate Test Results for Within-Subjects Contrasts for Physical Demand, Stick Force Gradient, Task and Gradient * Task

Source	gradient	task	*p*
gradient	Level 1 vs. Level 2		0.672
task		Level 1 vs. Level 2	0.144
		Level 2 vs. Level 3	0.084
		Level 3 vs. Level 4	**0.001**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	0.226
		Level 2 vs. Level 3	0.249
		Level 3 vs. Level 4	0.592

Temporal Demand

Estimated mean temporal demand and variation with task and stick fore gradient are shown in Figure A4-7 and Table A4-13. Applying conservative corrections, the results for repeated measures within-subjects differences (Table A4-14) for stick force gradient were nonsignificant ($p = 0.468$) however differences with flying tasks were highly significant ($p < 0.01$). The combined effect of stick force/gradient interactions were nonsignificant ($p = 0.304$).

Drilling down further for significant differences between tasks only, the repeated measures within-subjects contrasts (Table A4-15) for temporal demand showed significant differences between tasks '2' & '3' (circuit and go-around respectively) and '3' & '4' (go-around and base to finals turn respectively). Performing the go-around procedure (task '3') requires quick and decisive use of primary and secondary controls within a relatively short period to ensure safe operation of aircraft whilst in close proximity to the ground. In contrast, the circuit procedure is relatively simple with no additional time pressures. The base to finals turn (task '4') also introduced additional time pressures with the requirement to safely control the aircraft for a full stop landing with no go-around option due to insufficient fuel. Pilots were positioned on the base leg for this manoeuvre, at a height and speed that may result in an overshoot. Pilots may have been generally aware of the dangers of this manoeuvre (e.g. too much rudder can result in a stall/spin event) and this may have added to stress and hence temporal demands.

Table A4-13, Effect of Stick Force Gradient on Temporal Demand

gradient	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	4.075	0.236	3.581	4.569
2	3.913	0.241	3.408	4.417

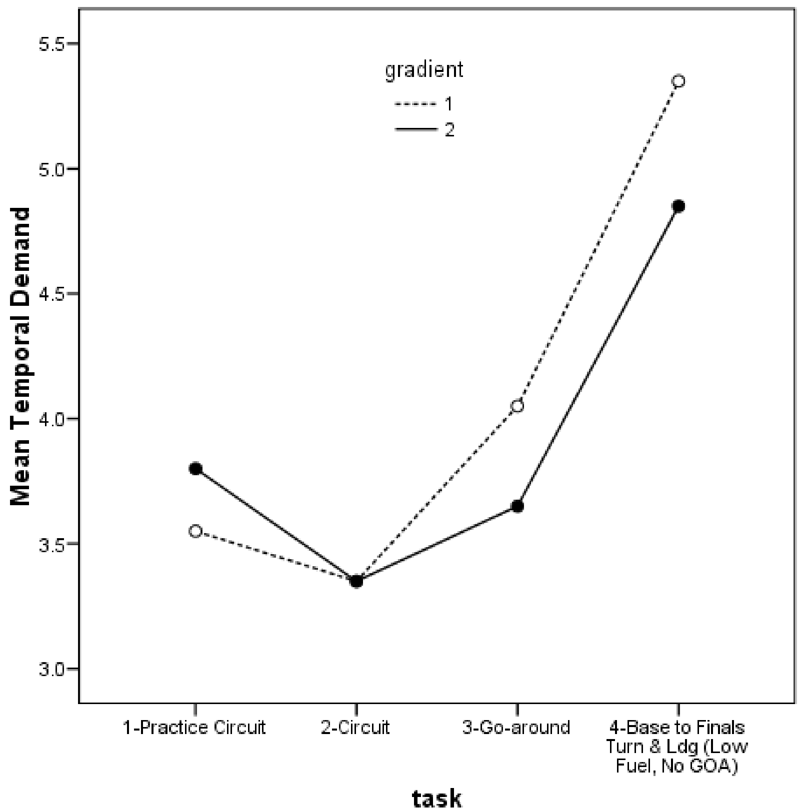

Figure A4-7, Effect of Stick Force Gradient & Task on Estimated Mean Temporal Demand

Table A4-14, Sample of Multivariate Test Results for Within-Subjects Effects for Temporal Demand, Stick Force Gradient, Task and Gradient * Task

Source	*p*
gradient	0.468
task	**0.000**
gradient * task	0.304

TableA4-15, Sample of Multivariate Test Results for Within-Subjects Contrasts for Temporal Demand, Stick Force Gradient, Task and Gradient * Task

Source	gradient	task	*p*
gradient	Level 1 vs. Level 2		0.468
task		Level 1 vs. Level 2	0.091
		Level 2 vs. Level 3	**0.049**
		Level 3 vs. Level 4	**0.001**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	0.555
		Level 2 vs. Level 3	0.322
		Level 3 vs. Level 4	0.823

Own Performance

Mean own performance and the variations with task and stick force gradient are shown in Table A4-16 and Figure A4-8. Applying conservative corrections, the results for repeated measures within-subjects differences (Table A4-17) of mean own performance with stick force gradient were nonsignificant ($p = 0.802$) however, differences with flying tasks were highly significant ($p < 0.01$). The combined effect of stick force/gradient interactions were nonsignificant ($p = 0.802$). Examination of mean own performance variability with tasks using repeated measures within-subjects contrasts (Table A4-18) were significant for all tasks ($p < 0.05$).

Table A4-16, Effect of Stick Force Gradient on Mean Performance

			95% Confidence Interval	
gradient	Mean	Std. Error	Lower Bound	Upper Bound
1	3.950	0.272	3.380	4.520
2	4.063	0.357	3.316	4.809

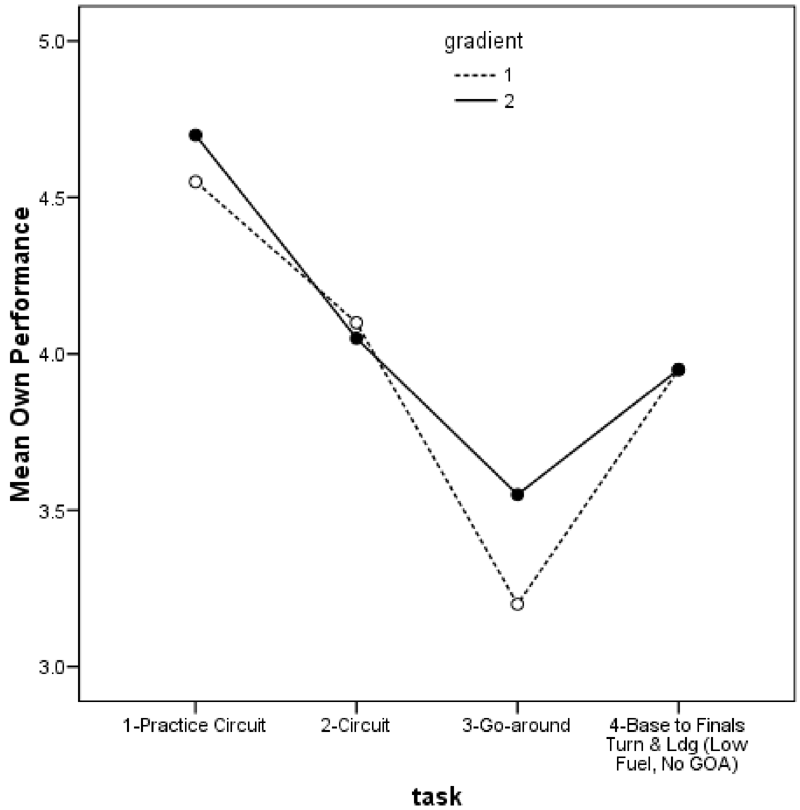

Figure A4-8, Effect of Stick Force Gradient & Task on Estimated Mean Own Performance

Table A4-17, **Sample of Multivariate Test Results for Within-Subjects Effects for Own Performance, Stick Force Gradient, Task and Gradient * Task**

Source	*p*
gradient	0.802
task	**0.000**
gradient * task	0.802

Table A4-18, **Sample of Multivariate Test Results for Within-Subjects Contrasts for Own Performance, Stick Force Gradient, Task and Gradient * Task**

Source	gradient	task	*p*
gradient	Level 1 vs. Level 2		0.802
task		Level 1 vs. Level 2	**0.020**
		Level 2 vs. Level 3	**0.004**
		Level 3 vs. Level 4	**0.044**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	0.764
		Level 2 vs. Level 3	0.359
		Level 3 vs. Level 4	0.376

Effort

Mean effort (Figure A4-9) showed apparent variations with both stick force gradient and flying task (Table A4-19). With exception of task '1', mean effort apparently increased as stick force gradient increased, however, using conservative corrections, the results for repeated measures within-subjects differences (Table A4-20) for stick force gradient were nonsignificant (*p = 0.925*) but differences in flying tasks were highly significant (*p < 0.01*). The combined effect of stick force/gradient interactions were nonsignificant (*p = 0.168*). Examination of the variability of effort between tasks using repeated measures within-subjects contrasts (Table A4-21) were significant (*p < 0.05)* between tasks '1' & '2' (practice circuit and circuit) and '3' and '4' (go-around and base to finals turn).

Table A4-19, Effect of Stick Force Gradient on Mean Effort

			95% Confidence Interval	
gradient	Mean	Std. Error	Lower Bound	Upper Bound
1	5.188	0.211	4.747	5.628
2	5.213	0.260	4.669	5.756

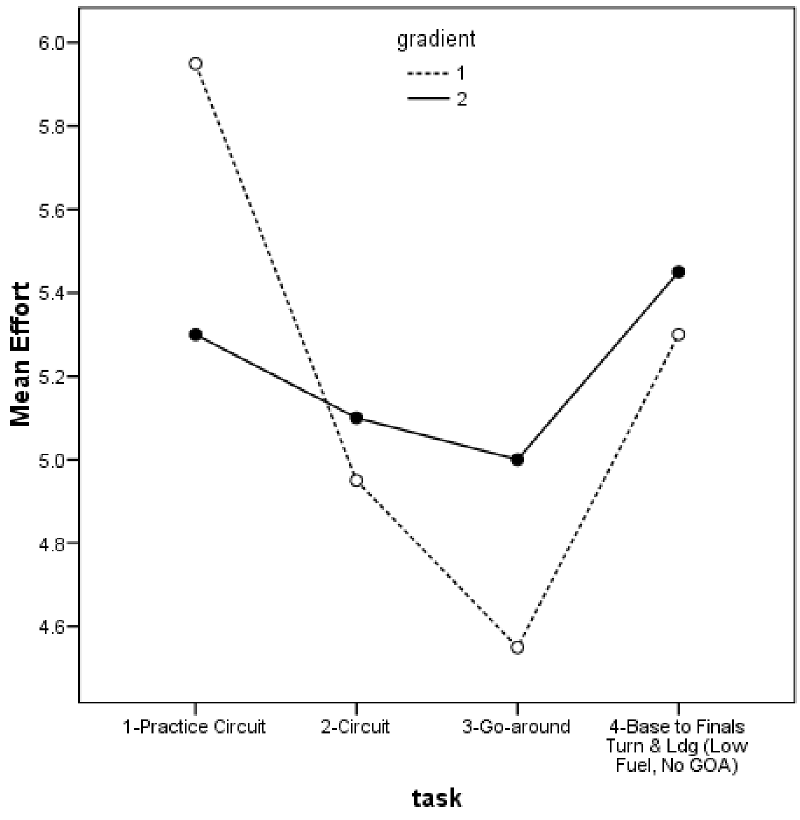

Figure A4-9, Effect of Stick Force Gradient & Task on Estimated Mean Effort

Table A4-20, **Sample of Multivariate Test Results for Within-Subjects Effects for Effort, Stick Force Gradient, Task and Gradient * Task**

Source	*p*
gradient	0.925
task	**0.001**
gradient * task	0.168

Table A4-21, **Sample of Multivariate Test Results for Within-Subjects Contrasts for Effort, Stick Force Gradient, Task and Gradient * Task**

Source	gradient	task	*p*
gradient	Level 1 vs. Level 2		0.925
task		Level 1 vs. Level 2	**0.019**
		Level 2 vs. Level 3	0.066
		Level 3 vs. Level 4	**0.006**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	0.111
		Level 2 vs. Level 3	0.500
		Level 3 vs. Level 4	0.611

Frustration

Mean frustration and the variation with flying tasks and stick force gradient are shown in Table A4-22 and Figure A4-10. Using conservative corrections for repeated measures within-subjects differences (Table A4-23) showed that variations with stick force gradient were nonsignificant ($p = 0.521$) however, variations with flying tasks were again highly significant ($p < 0.01$). The combined effect of stick force/gradient interactions were nonsignificant ($p = 0.893$). Examination of the variability of frustration between tasks using repeated measures within-subjects contrasts (Table A4-24) were significant ($p < 0.05$) between tasks '1' & '2' (practice circuit and circuit), tasks '2' & '3' (circuit and go-around respectively) and highly significant ($p < 0.01$) between '3' and '4' (go-around and base to finals turn). Frustration increased with the number of sub-tasks, their complexity and time pressures (temporal demand).

Table A4-22, Effect of Stick Force Gradient on Mean Frustration

			95% Confidence Interval	
Gradient	Mean	Std. Error	Lower Bound	Upper Bound
1	3.513	0.307	2.870	4.155
2	3.375	0.342	2.659	4.091

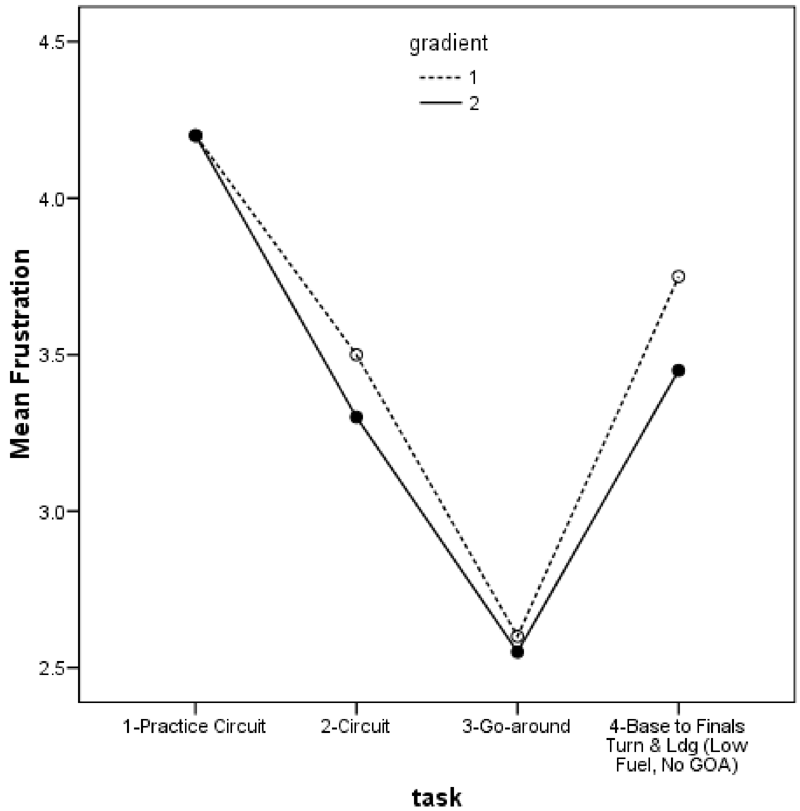

Figure A4-10, Effect of Stick Force Gradient & Task on Estimated Mean Frustration

Table A4-23, **Sample of Multivariate Test Results for Within-Subjects Effects for Frustration, Stick Force Gradient, Task and Gradient * Task**

Source	*p*
Gradient	0.521
Task	**0.000**
gradient * task	0.893

Table A4-24, **Sample of Multivariate Test Results for Within-Subjects Contrasts for Frustration, Stick Force Gradient, Task and Gradient * Task**

Source	gradient	task	*p*
gradient	Level 1 vs. Level 2		0.521
task		Level 1 vs. Level 2	**0.016**
		Level 2 vs. Level 3	**0.028**
		Level 3 vs. Level 4	**0.001**
gradient * task	Level 1 vs. Level 2	Level 1 vs. Level 2	0.817
		Level 2 vs. Level 3	0.754
		Level 3 vs. Level 4	0.514

APPENDIX A5-1 Modelling Validation – Discussion of Results

The model based upon previous work by Perkins and Hage for cruising flight was extended to estimate stick forces and gradients due to high lift devices in the climb and approach by consideration of the combined effects of wing loading, CG, elevator gearing, flaps and elevator trim setting (Chapter 3).

The predictive model, implemented in MATLAB, was validated by comparing LSS theoretical predictions with flight test results for selected aeroplane models (C150M & C152) and mean differences of ±0.025 daN/kt were observed for all combined results in the cruise, climb and landing (Chapter 4).

The following key assumptions made during the development of the theoretical model warrant further discussion under quasi-static conditions, with respect to the longitudinal axis:-

- The aeroplane structure is rigid and aeroelastic effects ignored;
- The reversible control system is both mass-less and frictionless;
- No lack of fit at the joints or stretch in the control cables;
- The direct and indirect effects of power are ignored.

Aeroelastic Effects

The aeroplane structure was 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. For the light aeroplanes with a fixed tailplane as used in the case study, the CG was ahead of the wing-body aerodynamic centre and the balancing tail load for longitudinal static stability acted vertically downwards (negative lifting tail at negative incidence with respect to the horizontal fuselage datum or waterline). The tail load tends to bend the tail boom downwards, reducing the effective angle of attack of the horizontal tailplane, reducing tail lift as airspeed increases. The reduction in tail effectiveness causes the neutral point to move forward reducing the static margin and static stability [46]. 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 control linkages are rigid). These aeroelastic effects vary with airspeed but are also likely to vary with flap setting and weight. For a high-wing, low-tail aeroplane in the landing condition, with flaps deployed, wing lift and drag moments about the CG increase resulting in a de-stabilising nose up pitching moment (for a low-wing, high-tail aeroplane the net moments about the CG may be the opposite and have a stabilising effect). This is balanced by a forward movement of the stick and reduction in tail lift when the aeroplane is stabilised and in trimmed flight. Thus, aeroelastic effects are likely to be dominant in the cruise, reducing in the climb and furthermore in the approach and landing phase where the majority of accidents occur.

The Effects of Breakout Force, Friction in the Elevator Control System

The reversible control system was assumed both mass-less and frictionless. Flight testing measurements showed the presence of breakout force and friction due to the elevator control linkages and friction in the control joints/linkages respectively. Measured breakout forces and friction were deducted from experimental flight test results to enable comparison with theoretical results. Measured breakout force and friction was small for both aeroplane types tested (≤ 0.50 daN or 1.1 lbf). Friction was assumed constant for the tested airspeed range, however some experimental results showed results showed evidence of increased in friction with increased deviation of airspeed from the trim condition in the push and pull sense. The calibrated handheld force gauge used to gather stick force data during flight testing was accurate to within ±0.25 daN and the method for measurement of stick force required the mechanical spring force gauge to be used to pull the stick back or pull the stick forward. Hence, the spring was in tension at all times under-reading in both ‘pull’ (stick back) and ‘push’ (stick forward) sense. Incorporating these calibration errors into the experimental data would increase all measurements by a small amount (+0.25daN) and slightly increase the measured gradient about the trimmed flight condition. The effect of this correction would equally increase gradients for both aeroplane models equally and therefore have little bearing on the differences observed for each Cessna model.

The Effects of Cable Stretch, Lack of Fit of Joints and Cable Tension in the Elevator Control System

Lack of fit at the joints and cable stretch was assumed negligible in the predictive modelling. Pitch stick freeplay measured prior to commencement of each LSS flight test and was found to be negligible in push or pull for all models tested and therefore can be disregarded.

Elevator cable tension was not measured during flight test due to the additional costs of inspections. All aeroplanes tested had valid certificates of airworthiness and all control cables were assumed to be tensioned within the manufacturers' recommended tolerances, however this may not be valid. The test pilot made no adverse comment with regard to excessive control hysteresis in pitch. Future flight tests should consider the measurement of cable tension prior to testing to gather additional data for evaluation.

The Effect of Flaps on Incremental Lift & Drag

The effect of drag due to flaps on the pitching moment was ignored. As the flaps are deployed both lift and drag increase, however successively larger flap deflections give relatively smaller increases in lift and relatively larger increases in drag. One of the key design changes implemented for the C152 in comparison to the C150M was restricting to 30° flap to improve the climb-out performance following a go-around [5]. To enable valid comparison of flight test and theoretical results, only 30°flap settings were used. For an aeroplane with CG ahead of the wing-body aerodynamic centre, the increased lift produced by the flaps would have a stabilising effect the increase in lift vector and aft movement of the centre of pressure would result in a greater negative (stabilising) pitching moment. The increased drag would have the opposite effect, being de--stabilising since the drag vector would increase with slight downward movement of the centre of pressure. The effects of flaps on lift were incorporated into the predictive model, however the effects of drag were excluded. Since both aeroplanes tested used the same flap settings it is unlikely that the effects of drag alone are responsible for the observed differences between theoretical and experimental results for either the C150M and C152.

The Effects of Power

The direct (engine thrust line) and indirect (propeller wash) effects of power were not considered in the predictive model. Chapter 2 presented an illustration of the longitudinal moments on a typical light aeroplane in steady flight (Figure 4). The direct effects of power may induce pitch up or pitch down moment changes due to displacement of the engine thrust line above the CG. In addition, a destabilising pitch up moment is also present due to the normal force acting on the propeller disk and this will be dependent upon the propeller RPM and climb angle.

The indirect effects of power are related to the propeller slipstream with its corkscrewing effect around the fuselage from nose cowling to tailplane. The slipstream also passes over the centre sections of the wings/flaps and may affect the downwash at the horizontal tailplane with flaps stowed or deployed. Local free stream velocity in the vicinity of the horizontal tailplane may increase due to the acceleration of the airflow over the upper surface of the wing with flaps deployed and the airflow directed downwards with increased downwash angle.

It is likely that the combined direct and indirect effects of power are partially responsible for the observed differences between theoretical and experimental results for the C150M and C152. It is suggested that the predictive model is extended to consider these effect in future by estimating pitching moment changes due to direct power effects and the effect on tailplane lift due to downwash as a result of the propeller slipstream.

Summary of Effects

Aeroelastic bending of the fuselage reduces real and apparent LSS and therefore all reasonable care should be taken to minimise these effects during the design process. The effects of cable tension are negligible and can be ignored if the aeroplane is correctly rigged within specified tolerances. Break-out forces and friction affect only apparent LSS and marginally increase the stick force gradient about the trimmed flight condition, however friction in isolation has an adverse effect on the trim speed band and this is magnified when low or zero stick force gradients are present, such as in the landing phase. The use of flaps in the landing phase affects both real and apparent LSS and depending on the setting, the changes in lift may have a positive effect of real LSS and drag may have a negative effect. The effects on apparent LSS being dependent upon the net effects of lift and drag combined. The direct effects of power with the engine thrust line above the CG have a positive effect on real LSS, however the normal propeller forces particularly at low speed, combined with indirect effects of power due to propeller wash over the wings and tail have a negative effect. The net direct and indirect effects of power on apparent LSS were stabilising for the limited airframes tested.

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