EFFECTS OF TAILORED CONTROL SURFACE COMPLIANCE ON AIRCRAFT STABILITY AND CONTROL

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Abstract

The aircraft design problem is an example of a highly integrated design, which calls for a multidisciplinary approach from the very beginning. With every generation of aircraft, it gets more difficult to make substantial improvements since so much have already been done to make aircraft as possible. Next generation civil aircraft needs to take every possibility to increase efficiency. One potential area of improvement is to reduce drag due to the requirement of positive stability. However, with the present state of the art it is difficult to get a system that can artificially stabilize an aircraft, certified. If this can be overcome, there are potential gains in drag, since all horizontal surfaces can be used for lift. Another advantage is that a wider range for center gravity can be allowed. In flight control the input signal to the aircraft are usually taken to be position of control surfaces. This is then translated to requirements on the actuation system, where the natural compliance of these systems is regarded, as something unwanted, when in fact it can also be used to tailor characteristics also at the aircraft level. This is relevant to both civil and military aircraft. The approach used here is to look at control surface actuators and different means to utilize also force control, possibly together with position control, and to introduce compliance in proper positions of the system. The pressure feedback is evaluated in a simulation environment using HOPSAN simulation package. Furthermore, an experiment is performed with the pilot in the loop to evaluate the different values of feedback gain. Statistical analysis of the results shows a significant influence of feedback level in the ability of the pilot to control the aircraft.

1 Introduction

Looking at future aircraft concept, one recurring concept is that of aft mounted prop fans. This is a problematic configuration from a center of gravity (CG) point of view, where a large portion of the weight is located aft. Therefore, the distance between wing and tail becomes short, resulting in considerable trim drag, unless a canard configuration is used. This is aggravated by the fact that the CG position is changing considerably between empty and fully loaded. One example of an aircraft using this three wing configuration is the Piaggio Avanti. However, in order to minimize drag the optimum lift distribution between the wing surfaces would result in an unstable configuration, Kendall [2].

Canard wing configuration is also common in military aircraft, pioneered in the Saab AJ37 Viggen in the sixties and subsequently in the Saab 39 Gripen, the Euorfighter Typhoon, the Dassault Rafale etc. Modern fighters are always are dynamically unstable and relay on an electronic control system for stabilization.

A hydraulic concept of a dynamic load trim actuator is shown in Fig. 1 as an example. It is essential that the solution is robust to ensure certification, e.g. implemented with passive control for civil aircraft. This system is nothing more than an adjustable spring, represented by the accumulator and thus need no active servo control.

The valve is used for trim and can in principle be a manual valve that is actuated to change the lift distribution between the wings. In the example demonstrated here, a position feedback with low gain is used, but a pressure control could be used either instead, or in a combination with the position feedback.

By having a preloaded spring that transmits the force to the fuselage, a dynamic control surface is achieved. In the extreme case, with an infinite compliance, the wing would just float and would in principle, provide no contribution to the dynamic properties of the aircraft. With a preload of the spring it still provides the lift, but not with the negative influence on stability. The stability characteristics of a compliant wing was derived in Krus [3], where it was demonstrated that introducing flexibility in wing in the right way has a stabilizing effect on an aircraft/bird without the need for sophisticated control systems. The free wing concept is an old concept, studied in Ro et al [8] and [?] that is also related to this. In the free wing concept, the wing can freely rotate and the angle of attack is controlled by control surfaces. This does, however, have the disadvantage that a wing with positive moment cannot be used, which means a less efficient profile has to be used.

2 Influence of compliance in a canard

Consider the influence of the moment around the CG on the aircraft in pitch by a canard wing:

$$M_{cg} = (C_{L2\alpha}(x_{w2} - x_{cg}) + C_{M\alpha})Sq(\alpha + \delta) \quad (1)$$

Here S is the wing area of the canard and the lift coefficient:

$$C_{L\alpha} = \frac{\partial C_L}{\alpha} \quad (2)$$

q is the dynamic pressure:

$$q = \frac{\rho v^2}{2} \quad (3)$$

where ρ is the air density and v is the speed.x_{cg} and x_{w2} is the position of center of gravity, and canard aerodynamic center, distance from the nose of the aircraft.

The torque acting on the canard is:

$$M_{x_{w2}} = C_{M\alpha}Sq(\alpha + \delta) \quad (4)$$

Introducing κ such that

$$M_{x_{w2}} = \kappa M_{y,cg} \quad (5)$$

yields

$$\kappa = \frac{C_{M\alpha}}{C_{M\alpha,T}} \quad (6)$$

where

$$C_{M\alpha,T} = C_{L\alpha}(x_{w2} - x_{cg}) + C_{M\alpha} \quad (7)$$

Assuming that the deflection of the canard is proportional to the torque on the canard through the complience c_δ yelds:

$$\delta = \delta_0 - c_\delta M_{y,x_{w2}} \quad (8)$$

This can also be written as:

$$\delta = \delta_0 - c_\delta \kappa M_{y,cg} \quad (9)$$

The moment around the centre of gravity (index cg) can then be written as:

$$M_{y,cg} = (C_{L\alpha}(x_{w2} - x_{cg}) + Sq(\alpha + \delta_0 - c_\delta \kappa M_{y,cg}) \quad (10)$$

This can then be rewritten as:

$$M_{y,cg} = \frac{C_{M\alpha,T}Sq(\alpha + \delta_0)}{1 + c_\delta \kappa C_{M\alpha,T}Sq} \quad (11)$$

This means that the moment derivative with respect to angle of attack will become:

$$\frac{\partial M_{y,cg}}{\partial \alpha} = \frac{C_{M\alpha,T}Sq}{1 + c_\delta \kappa C_{M\alpha,T}Sq} \quad (12)$$

This means that the compliance introduces a reduction of the derivative. Expressed in the sloop of the moment coefficient instead:

$$\frac{\partial C_{M\alpha,T}}{\partial \alpha} = \frac{C_{M\alpha,T}}{1 + c_\delta \kappa C_{M\alpha,T}Sq} \quad (13)$$

Since a canard is positioned in front of the CG it means that it is normally destabilizing the aircraft. A reduction of the moment derivative will then have a stabilizing effect on the aircraft. If the compliance is infinite there will be no negative influence at all of the canard on stability. However, by selecting the angle δ_0 a lift (and moment) can be selected arbitrary.

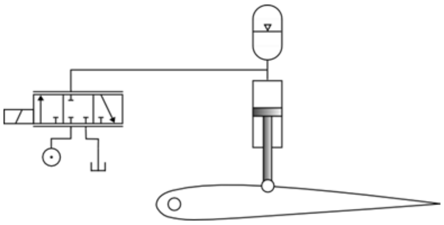

Fig. 1 Hydraulic system for dynamic trim canard

3 Force control

An extension of this kind of control system is force controlled flight control actuators in general. This corresponds to an infinite compliance. In conventional flight control systems, actuators are position controlled. E.g. to have a actuators, where a force (or torque) is controlling the rotational speed of the aircraft, since the objective of flight control surfaces is to provide a control force. Until now, it has had little use in aircraft, although manual control system can be argued to be like this. There are potential benefits in this approach, e.g. it is likely to produce less stress on the airframe, and effects such as rate limitations and actuator stall will be more benign. There is also scope to reduce gust sensitivity by simple means, for e.g. passenger comfort.

4 The dynamic trim canard

A hydraulic concept of a dynamic trim canard is shown in the picture as an example. It is essential that the solution is robust to ensure certification, e.g. implemented with passive control for civil aircraft. This system is nothing more than an adjustable spring, represented by the accumulator and thus need no active servo control. The valve is used for trim and can in principle be a manual valve that is actuated to change the lift distribution between the wings. In the example demonstrated here, a position feedback with low gain is used, but a pressure control could be used either instead, or in a combination with the position feedback. The dynamic trim canard was demonstrated through simulation for a civil three wing transport aircraft in [5].

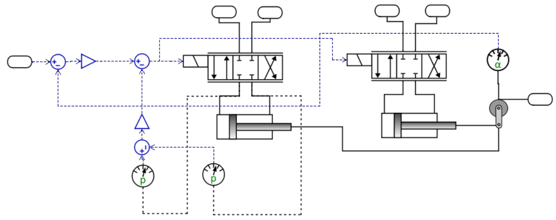

Fig. 2 Hydraulic tandem servo with pressure feedback

5 Pressure/force feedback to canard

A similar but perhaps more general concept is to introduce the same effect through electronic feedback. This is shown in Fig. 2 where the subsystem of the tandem servo used for the simulation is shown. In this case the pressure differens over the piston is used for the feedback, since it is proportional to the force, if friction is neglected. The pressure (or force feedback) will reduce the stiffness of the servo, see Merrit [6], and thus introduce more compliance, that is stabilizing.

This does not provide the same level of fail safe as the dynamic trim canard, but it introduces more flexibility. It should, however, be noted that the pressure feedback also can be realized through a hydro-mechanical feedback, with possibly a higher degree of reliability.

5.1 Gust sensitivity

Since a pressure compliance in the canard can move the neutral point, it can also affect the gust sensitivity. A neutrally stable aircraft would have a low gust sensitivity since a vertical wind gust do not produce any torque. Therefore gust sensitivity can be expected to increase with increased compliance/pressure feedback gain, of the canard. If gust insensitivity is a requirement e.g. for areal photography, the compliance can be adjusted to precisely put the neutral point at the CG. Stabilization can then be achieved e.g. by feedback of other (global) states, such as pitch rate.

6 Full System Simulation

Using full system simulation the pressure feedback was evaluated using human in the loop simulation. The system is implemented in the Hopsan simulation package developed at Linköping University. HOPSAN is a system simulation software where e.g. a full aircraft system can be simulated as demonstrated in Krus et al. [4]. The system model is shown in Fig. 4. The flight dynamics model is based on a 6 degree of freedom rigid body model that is connected to an aerodynamic model. A gust model is introduced that is used to give a strong upward gust at a specific time to disturb the aircraft. This is done to see how gust response is affected by the pressure feedback.

The aircraft is loosely based on the F-16 but with a canard configuration as in Fig. 3. The wing area of the main wing is 27 m^2 the canard wing area is 36% of the main wing. The mass of aircraft in the flight condition is 11000 kg. The main wing (wing 1) includes also effects of the fuselage. The lift coefficients are $C_{L1} = 2.1$ and $C_{L2} = 2.2$ The position of the main wing is 3.5 MAC (Mean aerodynamic cords), the position of the canard is at 2 MAC and the center of gravity is at 3.15 MAC. Here MAC is set to 1.67m.

The stability margin can be calculated starting from the moment around the center of gravity x_{cg} or expressed in units of mean aerodynamic cords, indexed with zero x_{0cg}:

$$M = L_1(x_{cg} - x_{w1}) + M_1 + L_2(x_{cg} - x_{w2}) + M_2 \tag{14}$$

Here M_1 and M_2 are the moments generated by the wing profiles. Eqn. ((14)) can also be written as:

$$M = (S_1(C_{L1}(x_{cg} - x_{w1}) + C_{M1}) \tag{15}$$
$$+S_2(C_{L2}(x_{cg} - x_{w2}) + C_{M2})q \tag{16}$$

Introducing the stability derivative as:

$$\frac{\partial M}{\partial \alpha} = (S_1 C_{L\alpha 1}(x_{cg} - x_{w1}) + S_2 C_{L\alpha 2}(x_{cg} - x_{w2}))q \tag{17}$$

Introducing the stability margin $-x_h$ in meter, as:

$$\frac{\partial M}{\partial \alpha} = x_h(S_1 C_{L\alpha 1} + S_2 C_{L\alpha 2})q \tag{18}$$

This yields

$$x_h = \frac{S_1 C_{L\alpha 1}(x_{cg} - x_{w1}) + S_2 C_{L\alpha 2}(x_{cg} - x_{w2})}{S_1 C_{L\alpha 1} + S_2 C_{L\alpha 2}} \tag{19}$$

Introducing the distance units in MAC instead, and expressing the area of wing 2 as a fraction of wing 1 area such that:

$$S_{20} = S_2/S_1 \tag{20}$$

yields

$$x_{0h} = \frac{C_{L\alpha 1}(x_{cg} - x_{w1}) + S_{20} C_{L\alpha 2}(x_{0cg} - x_{0w2})}{C_{L\alpha 1} + S_{20} C_{L\alpha 2}} \tag{21}$$

With the values used here we have for a configuration with a fixed canard:

$$x_{0h} = \frac{2.1(3.15 - 3.5) + 0.362.2(3.15 - 2)}{2.1 + 0.362.2} = 0.061 \tag{22}$$

Hence, since it is positive, the configuration is slightly statically unstable. If the canard is deleted we simply get:

$$x_{0h} = (3.15 - 3.5) = -0.35 \tag{23}$$

Which is a stable configuration. Since the compliance of the canard can be used to effectively reduce the lift sloop of the canard, it will have a stabilizing effect on the aircraft longitudinal dynamics, and any value between these two extremes can be achieved.

The aerodynamic model is here based on a static version of the model presented in [1], although the unsteady effects can of course also be included.

The control surfaces are modeled with both a linear increase of lift force with deflection and the corresponding increase in induced drag. In this way, also the effect of trim drag on performance is automatically included. The system also includes a simple control system.

7 Human in the loop simulation

In order to get some indication of the controllability of an aircraft with different degrees of pressure feedback we performed an experiment

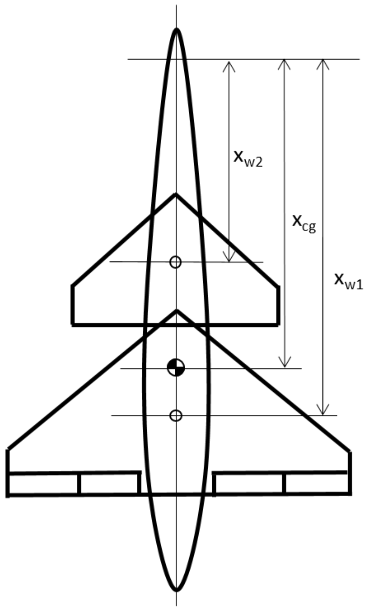

Fig. 3 Aircraft with canard configuration used for the simulations.

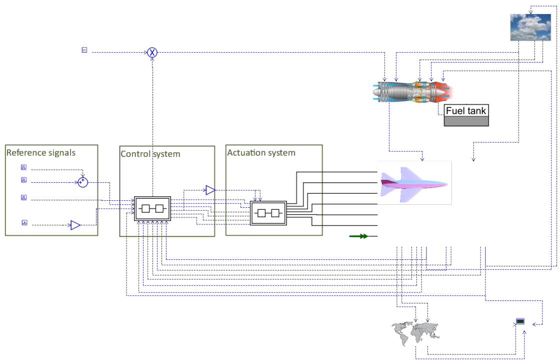

Fig. 4 Model for full system simulation

Table 1 Factors and levels of the experiment

Factor	Description	Levels
A	Feedback	$0; 2e^{-12}; 5e^{-12}; 1e^{-11}; 2e^{-11}; 5e^{-11}; 1e^{-10}$
B	Pilot	1; 2; 3; 4; 5; 6; 7; 8
C	Phase	1; 2; 3; 4

to evaluate the longitudinal controllability with the pilot in the loop. The main goal is analyzing how different values of feedback gain affects the ability of different pilots to control the aircraft. As no professional pilot was involved, the experiment was limited to pitch control, without considering maneuver or commands on the other axes.

A statistical analysis of the data collected in the experiment is used to test following hypotheses:

- **Null Hypothesis (H0)**: There is no influence on the aircraft controllability from the feedback gain level of the proposed system.

- **Alternative Hypothesis (H1)**: There is influence on the aircraft controllability from the feedback gain level of the proposed system.

The experiment was designed to analyze the contribution of three factors to the difficulty in controlling the aircraft pitch: the pilot, the flight phase and mainly, the feedback gain for the proposed system. Each factor is evaluated at different levels. The phase factor refers to the division of one brief flight into the four phases for the purposes of this experiment, as illustrated in Fig. 5. The pilot factor refers to the participants: a set of 8 PhD and MSc students from the Aeronautics Institute of Technology. These students had different levels of familiarity with piloting flight simulators, none of them is a certified pilot. The feedback gain factor has seven levels, varying from 0 to $1e^{-10}$. Table 7 summarizes the factors and levels considered in the experiment.

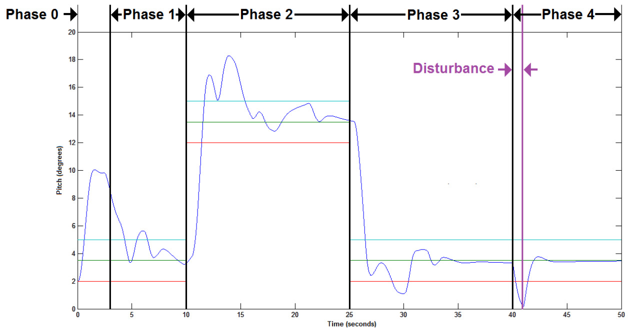

Fig. 5 Reference maneuver with disturbance

The experiment follows the Randomized Complete Block Design (RCBD), with two replications. Each pilot performed a total of 14 flights, composed of 4 phases, resulting into 112 flights and 448 error measurements since the error of each phase is considered a separate value. A MatLab script selected randomly the order of the feedback gain values tested with each pilot each time that the experiment was performed.

The resulting data is analyzed considering the following model of the output variable:

$$Y_{ijk} = \mu + A_i + B_j + C_k + A_iB_j + A_iC_k + B_iC_k + A_iB_iC_k + \varepsilon \quad (24)$$

where:

- Y_{ijk} is the measured error;
- μ is the overall average of the error;
- A_i corresponds to the variance of factor A (feedback gain);
- B_j corresponds to the variance of the factor B (pilot);
- C_k corresponds to the variance of the factor C (phase);
- A_iB_j, A_iC_k and B_iC_k corresponds to the interaction between the two factors;
- $A_iB_jC_k$ corresponds to the interaction between the three factors;
- ε refers to the random error of the experiment.

The HOPSAN model described in the previous section was exported to MatLab/Simulink as an S-function, in order to be integrated with a joystick (Saitek X52 Pro) and allow the pilot to provide the command input to the aircraft. The model was adapted to include the necessary signal routing, model configuration and data recording algorithms for the experiment.

The HOPSAN/Simulink model also provided a visual feedback to the pilot, which was composed of a reference maneuver and an expected error margin. The pilots were required to follow the reference and try to maintain the error with the specified tolerance. Initially, a more realistic visual feedback was implemented, based on the FlighGear simulator. However, we observed that additional cockpit information could distract the participants and interfere in the results, therefore the information presented to the pilot is limited to aircraft pitch and reference margins in a two-dimensional plot as exemplified in Fig. 5.

The reference maneuver adopted in the experiment consists of flying with a pitch angle of 3.5^o for 10 seconds. Then, the pilot should change to a pitch angle of 13.5^o and maintain it for 15 seconds. After that, he should return to the previous pitch angle and maintain it until the end of the flight, each flight lasting 50 seconds. At 40s into the flight, an upward wind gust of 10 m/s is introduced as an external perturbation, lasting for 1s. Since the system is intended for longitudinal stability, the external perturbation is designed so it would affect only this axis. The expected error margin for the pitch is of $+/-1.5^o$ during the whole flight. Any excursion from these margins is considered to be an error, as illustrated in Fig. 6.

The difference between actual pitch and the margin is summed up until the pitch returns to the specified levels. The error from each flight phase is then divided by the length of each phase in order to account for the difference in time length of each one.

Each of the pilots that performed the experiment were volunteers, they were presented with basic information regarding the experiment, and were instructed that their goal was to maintain the

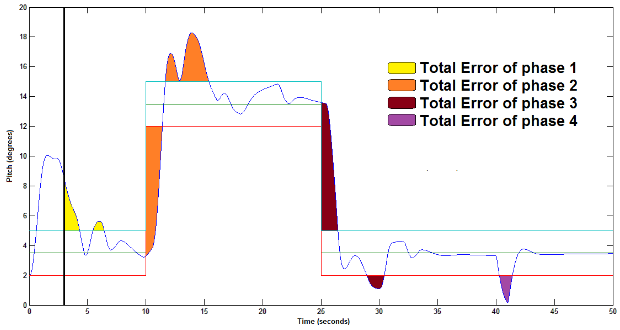

Fig. 6 Output variables from the experiment

pitch within the specified margins as best as possible, after this the controls and interface was presented, and the experiment began upon receiving confirmation that the procedure was understood and that they could perform the experiment without interruption for the next 15 minutes. The first flight of each pilot was a test flight that allowed them to adapt to the pace of the experiment, the interface, and the goal. All subsequent flights were recorded and the resulting data processed to be used in the analysis, since all flights were performed with a random feedback level there was no way of predicting if the test flight was to be with a controllable setup or not, nevertheless the objective of allowing this flight is allowing the pilot to adapt to the pace and interface for the subsequent flights.

8 Results

The statistical software R is used to analyse the data obtained from the experiment. A first analysis is made by drawing a boxplot. It showed that Pilot 3 had an exceptionally large variance and error mean. Its variance is more than thrice the second largest variance of a pilot, and its average error is more than twice the second largest mean (Fig. 7). As data collection was anonymous, it is not possible to investigate if the pilot was not subjected to any unusual condition, either temporary or permanent, such as psychological stress or physical problem. Therefore, we decide to eliminate Pilot 3 from the analysis.

After eliminating data from Pilot 3, the resulting boxplots of the 3 factors are is presented

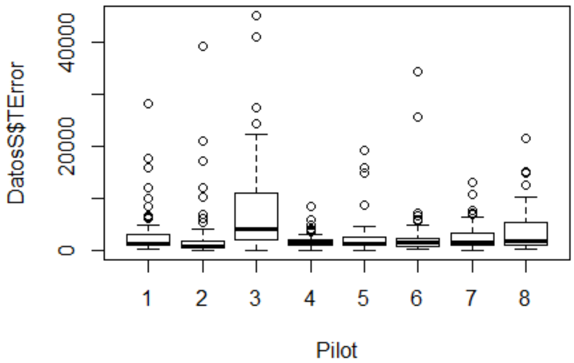

Fig. 7 Boxplot for factor B (Pilot) - Dataset with 8 pilots

in Figs. 8, 9 and 10.

An Analysis of Variance (ANOVA), see [7], is performed to verify the influence of each factor and combinations of factors in the output variable. The result is presented in Fig. 11. The observed value of the test statistic (F value) and the test value P. We adopted a level of significance of 95%, which means that a P-Value lower that 0.05 corresponds to a factor or interaction of factors that influence the output variable of the experiment. The number of asterisks indicates the level of significance of the factor or interaction of factors.

From Fig. 11 we can clearly see that the feedback gain is the most influencing factor, followed by the Flight Phase. The interaction between feedback gain with phase and interaction of feedback value with pilot are significant to a lower, yet important degree. The output from R includes the P-Value for the lowest possible level of significance for each factor, in the present case any significance lower than 0.05 (one dot, in the nomenclature above), would allow to reject the null hypothesis.

In order to detect systematic errors introduced in the experiment, we checked the residues. The normality plot of the residues is presented in Fig. 12 and confirms the absence of systematic errors. The plot is considered normal when the points scattered on the plot resembles a

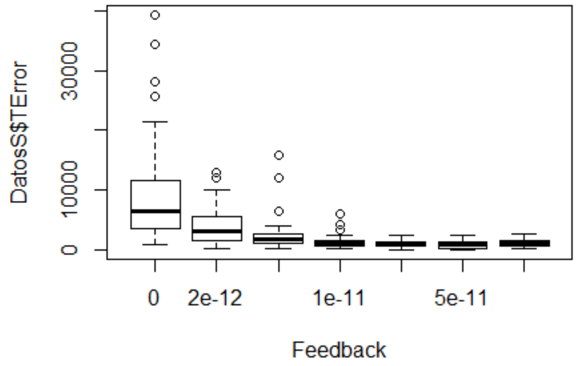

Fig. 8 Boxplot for factor A (Gain) - Dataset with 7 pilots

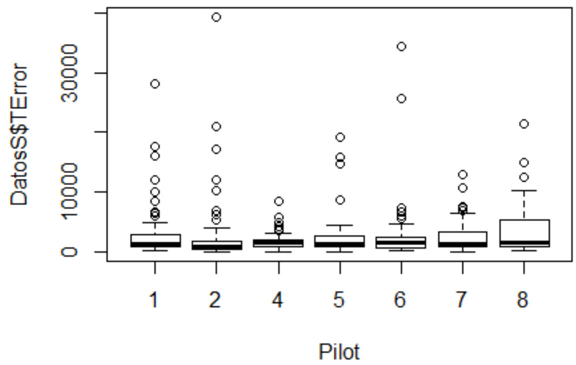

Fig. 9 Boxplot for factor B (Pilot) - Dataset with 7 pilots

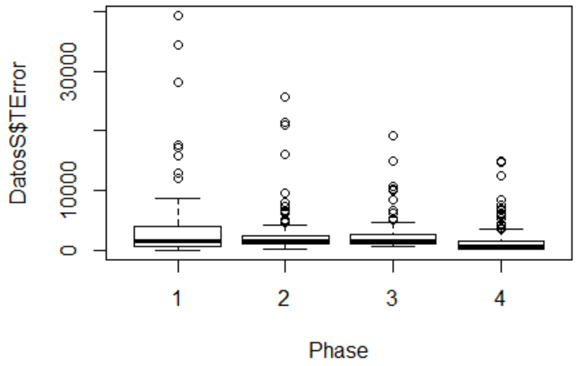

Fig. 10 Boxplot for factor C (Phase) - Dataset with 7 pilots

	Degrees of Freedom	Sum of Squares	Mean Squares	F-Value	P-Value	
Feedback Level	6	3,084E+09	5,140E+08	46,620	2,00E-16	***
Pilot	6	1,193E+08	1,988E+07	1,803	0,097829	.
Phase	3	2,07E+08	6,885E+07	6,245	0,000393	***
Feedback:Pilot	36	5,923E+08	1,645E+07	1,492	0,039095	*
Feedback:Phase	18	3,34E+08	1,854E+07	1,682	0,041037	*
Residuals	322	3,55E+09	11025085			

Fig. 11 ANOVA results - Dataset with 7 pilots

straight line along its central region.

The same experiment data set is also used to evaluate the influence of the feedback level in the impact of the disturbance in the controllability. However, since the disturbance occurs near the end of the flight, we compare the impact considering the error variance from a shorter, steady-state flight phase occurring just before the disturbance to another short phase just after the disturbance.

For performing this, the averages of the error only the 5 seconds before and after the disturbance are considered and then a new ANOVA is performed, replacing factor C by factor D, which has two levels: with or without disturbance. For this arrangement, we have 196 error measurements.

The results presented in Fig. 13 suggest that there is no significance on the error caused by the interaction of feedback gain and the disturbance, nor by the disturbance itself.

However, the observation of the pilot reactions and recorded data suggest that in fact there

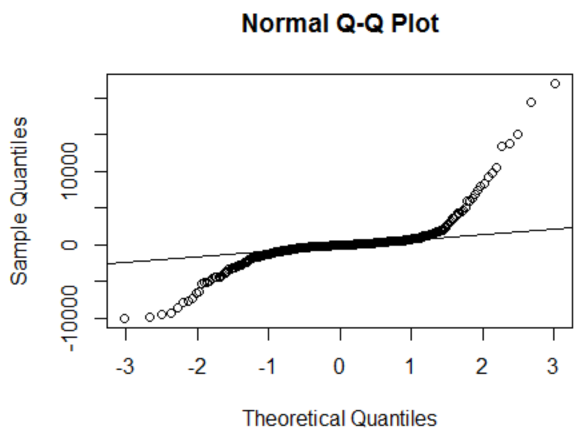

Fig. 12 Normality plot of residuals

	Degrees of Freedom	Sum of Squares	Mean Squares	F-Value	P-Value	
Feedback Level	6	2,447E+10	4,078E+09	24,640	2,00E-16	***
Pilot	6	1,025E+09	1,709E+08	1,033	0,4068	
Disturbance	1	2,859E+08	2,859E+08	1,728	0,1909	
Feedback:Pilot	36	9,477E+09	2,633E+08	1,591	0,0301	*
Feedback:Disturbance	6	1,407E+07	2,345E+06	0,014	1	
Residuals	140	2,317E+10	1,655E+08			

Fig. 13 ANOVA results for flight disturbance

is a noticeable effect of the feedback gain on the behaviour of the aircraft during the disturbance. The effect of the disturbance on the aircraft appears to be proportional to the feedback level: for feedback gains that allow the aircraft to be more controllable, the visible impact of the external disturbance increases, while for feedback gains that result in a more complicated behaviour for a human pilot, the effect of the disturbance decreases to the point of being barely noticeable, even for a near-steady flight.

This would suggest that the effect of the interaction between the disturbance occurring in the flight and the feedback level of each flight is confounded among the other factors. At least for the higher level of feedback gains, it would be expected that a larger error after the disturbance in comparison to before it. These results however, require to be confirmed by an experiment designed to evaluate that particular case.

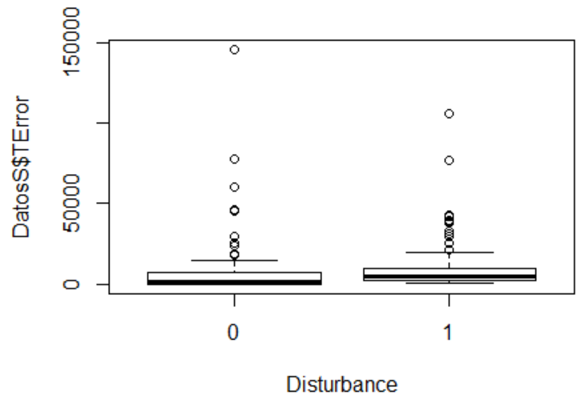

Fig. 14 Boxplot for factor D (Disturbance) - Dataset with 7 pilots

9 Conclusions

Compliance in a control surface can occur naturally or artificially by different means. If this control surface is forward of the center of gravity, this will increase the longitudinal stability of the aircraft. In this way, a passive system can be obtained that should be much easier to certify than a system with an active control system. This makes it is possible to realize an aircraft that can fly in a geometrically unstable configuration and hence with greatly reduced trim-drag. Force control as a complement to position control is also in general a concept that can have many advantages, e.g. for simplifying flight control systems.

The results obtained from an experiment with the pilot in the loop confirm without doubt that the feedback gain of the pressure has an important effect on the aircraft controllability. An ANOVA analysis with three factors (feedback gain, pilot and phase) indicated the gain as the most influential factor in controllability of the aircraft. Analysing the remaining data from the ANOVA results, we can affirm that for the flight profile used, the feedback level has the same impact on all flight phases; it has no significant different impact on any particular phase. While for the effect on the disturbance phase, we recommend performing a dedicated experiment to measure this particular scenario. The feedback level change also affects each pilot differently, some pilots being able to adapt to the change in aircraft response better than others.

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Copyright Statement

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