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AIRCRAFT CONTROL USING ACTUATOR CURRENT

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ABSTRACT

From an actuation systems point of view, fly-by-wire aircraft are manoeuvred by controlling the position of the surfaces. In this paper, it is proposed to control the aircraft by the current through the electrical motors that move the surfaces. When friction is neglected, this variable can be transferred to a surface force. Using this force, it is possible to steer the aircraft. This paradigm change has several advantages, including natural gust load alleviation of structures and actuator, better exploitation of the actuator performance, avoidance of force-fight in redundant actuators, simplified actuator control and no need for stiff attachment points and actuators. These advantages can lead to lighter aircraft without adding extra cost. This in turn leads to more economical and environmental friendly aircraft. To validate the method, tests on a motion simulator as well as a CS-25 certified small aircraft (Cessna Citation 550) have been successfully carried out.

KEYWORDS

Primary flight control, EMA, current control, force control, ACAF, gust load alleviation, force-fight

I INTRODUCTION

Since fly-by-wire aircraft have been introduced, the position of the actuator, and thereby the position of the surfaces has been used to control aircraft. This is a natural choice for hydraulic actuators, where the actuator speed is controlled by a servo valve. Opening the valve leads to a constant speed of the actuator and a position control is therefore the most logical control mode.

Currently, a move to the electrification of aircraft, and thereby also actuators can be seen. In contrast to hydraulic actuators, electro-mechanical actuators (EMA) need elaborate control algorithms for a position hold task and consume significant energy while keeping a load.

On the other hand, electromechanical actuators have the possibility to directly influence the force/ torque by varying the motor current. Besides more direct control, this has also further advantages:

1. Gust load alleviation of aircraft structures
2. Load alleviation of actuator loads
3. Direct access to the complete actuator performance and simplified dealing with actuator limits, especially for low-powered actuators
4. Avoidance of force-fight in parallel actuators on a single surface
5. Simplified actuator control
6. No stiff actuators, actuator attachments are needed

A possible further advantage is an increased passenger comfort due to the reduced gust forces. Furthermore, adding a realistic force-feedback to the pilot can be made more accurate by using the actual actuator current as a force indication that can be scaled and fed back to the pilot.

Figure 1. Cessna Citation 550 test aircraft.

It must be noted that current control of actuators is a special case of aircraft control using the forces on the surfaces where surface and actuator friction are low with respect to the control forces. If large static friction is present, a pure current control is not expected to work satisfactory, as stiction and the effecting stick-slip effect of the drivetrain will greatly hinder the controllability of the aircraft.

The credibility of the proposed current control for “fly by wire” airplanes is supported by the history of aviation. Conventional, (mechanical) cable driven airplanes are in fact centrally force-controlled by the pilot. To achieve a maneuver the pilot induces forces. The control surfaces move so that equilibrium is reached between aerodynamic forces and pilot forces. This for example leads to larger deflections at low speeds and smaller deflections at high speeds.

II AIRCRAFT CONTROL USING ACTUATOR CURRENT

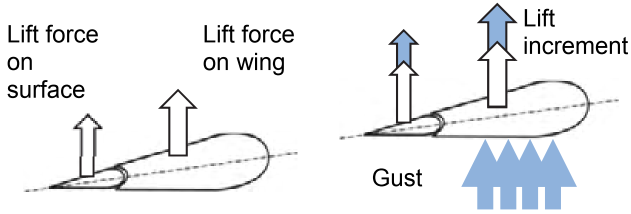
Aircraft motion is dictated by forces and moments. By commanding a current input on the actuators, the actuator motor produces a torque that is transferred into a steering force that acts on the aircraft. This is caused by the deflection of the surface that is caused by the different torque balance. When a surface deflects, the air moving around the surface will introduce a force in the opposite direction. The deflection of the surface will therefore be a result of the equilibrium of the actuator and aerodynamic forces.

This property leads to the fact that the controls will be largely independent on the flight velocity and height. This is in contrast to standard position control, where the control surface deflection must be scaled with the aircraft speed and height to allow for a consistent experience for the pilot.

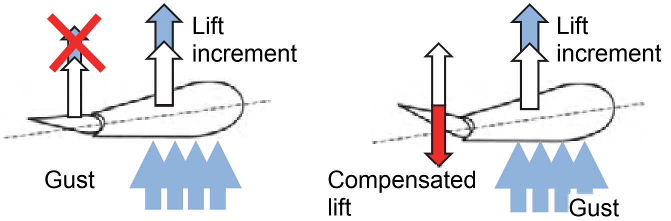
2.1 Gust load alleviation

Gust and maneuver load alleviation is standard: a free by-product of current control. Stiffly held actuator positions allow loads induced by external disturbances to be directly propagated into the airframe structure. Current controlled actuators inherently “give way” to external disturbances, avoiding the introduction of these loads. The principle is sketched in Figure 2 (a, b, c) and has always been an inherent feature of classical mechanically controlled aircraft. By using active force control that reacts to external loads, a larger load alleviation reduction can even be reached than the aforementioned load alleviation. This method bases on the local measuring of the surface forces using the force sensors on the actuators. By short term overcompensation for external loads, it may even be possible to further decrease the effect of a gust on the airplane (see Figure 2d). This over-compensation is done using the actuator controller, thereby using the very fast internal control instead of the Flight Control Computer (FCC) with large delays.

Actuator-based load-alleviation functions are highly effective as they can react extremely fast to gust loads due to the fast control loops on the actuators (typically > 2 kHz). A very short gust of 30 ft length is traversed at 900 km/h in 36.6 ms (gust length are typically between 30 and 300 ft). As typical flight control computers control rates are around 50Hz, the delay between registering a gust and actively steering against it (without any sensor-delays and A/D conversions) is therefore 20 ms at best. More realistic response times will be around 50-60 ms, making classical gust load alleviation schemes unsuitable for short term gusts and posing a large penalty in effectiveness for long gusts. A notable exception will be methods based on forward looking sensors such as LIDAR (Fezans & Joos, 2017).



a) No gust situation. *b) Gust on position-controlled surface.*



c) Gust on force-controlled surface. *d) Gust on smart active force controlled surface (experimental)*

Figure 2: Gust loads on aircraft with position- and force-controlled surface.

2.2 Simulations

To predict the effect of integrating current controlled actuators in a large twin-engined passenger aircraft, extensive simulations have been carried out. These simulations include elastic wings and gust injection. To simplify these simulations and showcase the possibilities of the method, all friction in the actuator and surface has been neglected. Using a passive current-controlled method (as used in Figure 2 b & c), an explorative study has shown a reduction of 1-2% of the wing root bending moment during gust loading, while simultaneously reducing the actuator peak loads by over 45% (see Figure 3). In this study, only the inboard aileron has been equipped with force control. By using an active actuator based current control function (Figure 2 d), the load alleviation is expected to increase to 3-5% reduction in structural peak load, still using only the inner ailerons. In this case however, no reduction of the actuator loads can be observed.

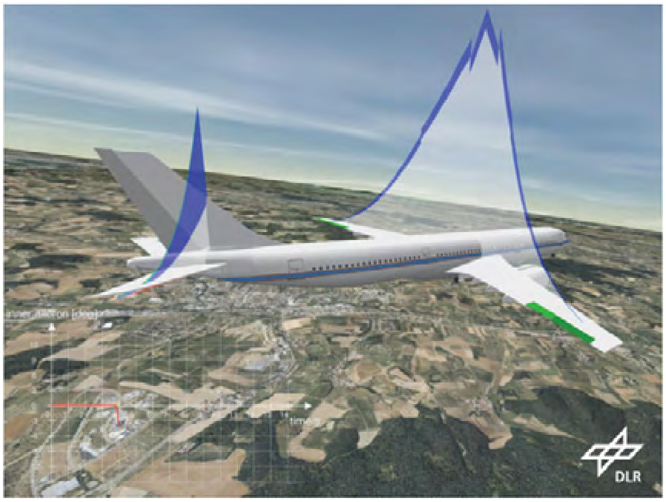


Figure 3. Aircraft simulation using force controlled actuators. The blue areas indicate the maximal loads for a conventional aircraft during a gust, the white areas indicate the maximal gust load using active force controlled inboard aileron actuators.

2.3 Virtual Damping

The stiffness and damping is zero for perfect current controlled surfaces without friction. This can potentially lead to flutter. Furthermore, the control of these surfaces has in simulation been proven to lead to limit cycles. To avoid this, it is needed to add virtual damping to the actuators to limit unwanted oscillations of the actuators. This can be achieved by adding an extra term to the current control:

$$i_{Act} = i_{FCC} - \omega d \qquad (1)$$

In this equation i_{Act} is the commanded actuator current and i_{FCC} the current as commanded by the flight control computer, d can be proportionally dependent on the actuator speed (ω), temperature and flight state.

III MOTION SIMULATION AND FLIGHT TESTING

The TU-Delft operates a Cessna Citation II (PH-LAB), which can be equipped as a fly-by-wire testbed by means of add-on autopilot modes that give direct access to the control surface servos (Zaal, et al., 2009). This allows the systems architecture to configure the servos to be current controlled. Since the servo amplifiers in this aircraft originally were not designed for current control and are based on a voltage and speed feedback, a feedback loop was used on top of this control loop to control the actuator current using a current sensor that was added to the servo amplifier. Since this leads to a not optimal situation for current control, the bandwidth of the current control loops is limited to approximately 3Hz. A direct current control loop is expected to achieve a bandwidth well over 100 Hz. This control mechanism leads to an artificial damping of the surfaces as also introduced in Section 2.3.

Using this configuration, the PH-LAB was flown using a direct current control mode by the pilot, as well as a manual Rate Control Attitude Hold (RCAH) controller based on Incremental Nonlinear Dynamic Inversion (INDI) (Grondman, et al., 2018).

Figure 4. The robotic motion simulator supports the flight dynamics simulation and provides a flexible interface to process pilot input and give force feedback.

Control Laws that is directly commanding the actuator currents (pitch and roll). The RCAH controller was adapted from the controller proposed by (Grondman, et al., 2018).

3.1 INDI Current control (CUR-INDI)

Incremental control techniques are increasingly gaining popularity in the domain of primary flight control. These methods compare commanded and measured reference signals at an acceleration level and use a local linearization of the control effectiveness to compute corrective increments. This eliminates the need for integrating complex aerodynamic databases in the control algorithms. In case of high controller sampling rates, the model-dependency can be reduced even further as the state transition dynamics can be neglected compared to the input dynamics. Incremental Nonlinear Dynamic Inversion (INDI) plays a prominent role within this class of methods (Acquatella B., et al., 2013) (Sieberling, et al., 2016).

Given that fly-by-wire systems are usually bound to position-controlled actuators, INDI commands an incremental control surface deflection $\Delta\delta_{a,e,r}$ that is added to the measured total deflection corresponding to the prevailing time instance. In order to make INDI compatible with current-controlled actuation systems, the position increment is used to make an estimate of the contemporary hinge moment. This mapping is performed by means of a linear regression model that describes the dimensionless hinge moment aerodynamics in terms of the relevant mechanical and aerodynamic system states. Consider the first-order Taylor expansion of the elevator hinge moment dynamics (Mulder, et al., 2009):

$$\begin{aligned} C_{h_e} \cong C_{h_{e_0}} &+ \frac{\partial f(\boldsymbol{p})}{\partial \delta_e}\Big|_{\boldsymbol{p}=\boldsymbol{p_0}} \Delta\delta_e + \frac{\partial f(\boldsymbol{p})}{\partial \dot{\delta}_e}\Big|_{\boldsymbol{p}=\boldsymbol{p_0}} \Delta\dot{\delta}_e \\ &+ \frac{\partial f(\boldsymbol{p})}{\partial \alpha_h^*}\Big|_{\boldsymbol{p}=\boldsymbol{p_0}} \Delta\alpha_h^* + \frac{\partial f(\boldsymbol{p})}{\partial \dot{\alpha}_h}\Big|_{\boldsymbol{p}=\boldsymbol{p_0}} \Delta\dot{\alpha}_h \end{aligned} \qquad (2)$$

Where $\boldsymbol{p} = (\delta_e, \dot{\delta}_e, \alpha_h^*, \dot{\alpha}_h)$ and α_h^* represents the total angle of attack at the horizontal tailplane. Following the time-scale separation principle that is key to INDI at high control rates, the state transition dependency can be removed. In addition, the regression term related to the elevator velocity $\dot{\delta}_e$will be neglected given that its size is typically an order of magnitude lower compared to the position term. As a result:

$$\Delta\hat{C}_{h_e} \cong \frac{\partial f(\boldsymbol{p})}{\partial \delta_e}\Big|_{\boldsymbol{p}=\boldsymbol{p}_0} \Delta\delta_e \tag{3}$$

Subsequently, the estimate for the incremental hinge moment can be used to compute the incremental actuator current ΔI_{a_e} by statically inverting the flight control system dynamics. This effectively only requires information about the FCS geometry and servo transmission properties (Lubbers, 2009), creating a relationship between the actuator current and surface hinge torque:

$$\Delta I_{a_e} \approx \frac{r_d \bar{q} S_e \bar{c}_e}{l_{\delta_e} K_t K_{g_e}} \Delta\hat{C}_{h_e} \tag{4}$$

In this equation, r_d represents the servo drum radius, l_{δ_e} the mechanical elevator moment arm, $\bar{q}$ the dynamic pressure, S_e the elevator surface, $\bar{c}_e$ the mean elevator chord, and K_t and K_{g_e} the torque and power gear ratio constants, respectively. The current increment is subsequently added to the measured servo current corresponding to the prevailing time instance:

$$I_{a_{e,com}} = I_{a_{e,0}} + \Delta I_{a_e} \tag{5}$$

A similar derivation can be made for the aileron channel.

3.2 Flight test preparations using the RMS motion simulator

All flight controls have been prepared using the DASMAT Simulink model (Linden, 1996). By coupling this simulation model to the robotic motion simulator (RMS) (Bellmann, et al., 2011), system simulations and assessment could be carried out. Furthermore, it is possible to connect an actuator test rig with load simulation to the motion simulator for hardware-in-the-loop simulations. As the servo-amplifier (not included in the testrig) has proven to be the limiting factor, the added value for flight test preparation is at the moment limiting. However, it is planned to test the algorithms with a dedicated current control servo amplifier for high bandwidth current control demonstrating the full potential of the method in the future.

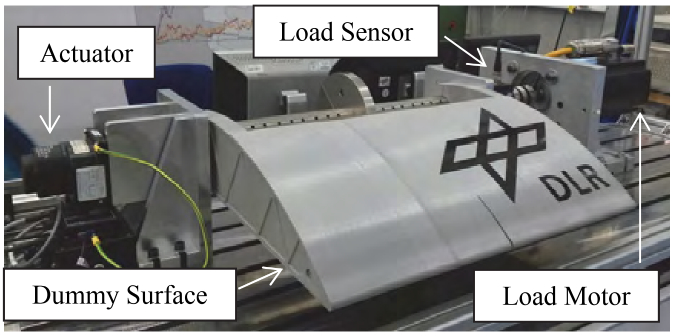


Figure 5. Actuator test rig including a Citation 550 servo actuator for hardware-in-the-loop simulations.

IV RESULTS

In this Section, the results of the simulations and flight testing will be presented.

4.1 Simulation results

Using current-controlled actuators, the natural gust- actuator load alleviation of a large passenger aircraft-based reference model using only its inner ailerons leads to a reduction of around 1-3% for the wing root bending moment and over 45% for the actuator forces (see Figure 3). Furthermore, the DASMAT Citation model has been successfully extended with current controlled actuators as well as a high fidelity actuator model with cables and pulleys including elasticity and friction (Lubbers, 2009). In Figure 6 to Figure 8, the response of a current stop is shown, demonstrating that current control can be used to control an aircraft.

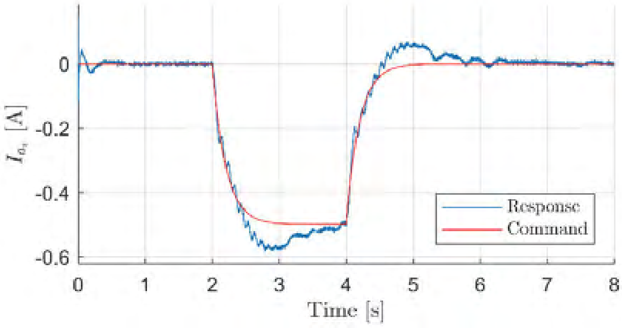


Figure 6. Simulated current reference and response for the elevator servo amplifier.

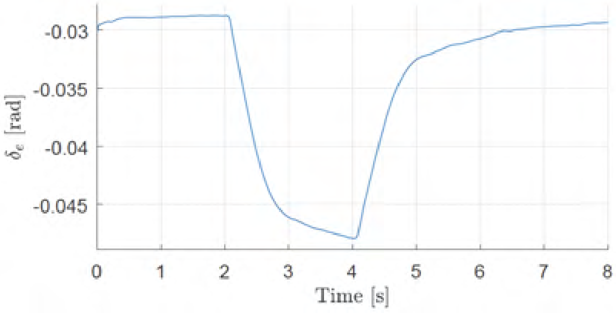


Figure 7. Simulated response of the elevator to the current step defined in Figure 6.

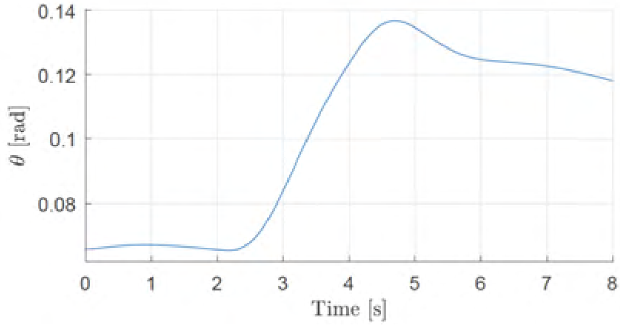


Figure 8. Simulated response of the pitch response of the aircraft to the current step defined in Figure 6.

4.2 Flight Test results “Direct current control”

Flight tests have shown that free flying the PH-LAB is possible using the current of the actuators only. Direct control of the aircraft is possible, although pitch is limited in control authority without re-trimming the aircraft (The actuator is easily saturated without trimming). The results of an example the lateral response of free-flight manoeuvres can be seen in Figure 9 (Knots-Indicated Air Speed (KIAS) 200, Flight Level (FL) 170).

To demonstrate the effect of a disturbance on a current controlled surface, the trim tab of the elevator has been moved to simulate an external force on the elevator. As expected for current control, the elevator gives way to such a disturbance. This maneuver proves the assumption that a current controlled surface can in principle be used for load gust alleviation as the surface gives way to an external load. Furthermore the actuator-load will be automatically limited to the set load, also proving the actuator load-limiting.

4.3 Flight Test results CUR-INDI

The modified incremental RCAH controller was subjected to numerous longitudinal and lateral tracking tasks under various flight conditions. Generally, the in-flight results show excellent tracking performance. This is for instance reflected by the aircraft’s roll dynamics in manual flight, visualized in Figure 11. The aircraft accurately follows the attitude references commanded by the pilot, showing a high degree of responsiveness. However, it can be observed that the system consistently overshoots the reference roll rate. This can be attributed to the fact that the effect of control surface velocity is not considered in the control allocation step (see Equation 3).

When the aircraft was set in approach configuration (flaps 15°, gear up), the tracking accuracy of the system reduced by a certain extent. It is hypothesized that this is due to a change in the immediate input effectiveness as a result of different aileron hinge moment aerodynamics that could not be observed by the current control setup. This shows that an accurate aerodynamic hinge moment model is needed to ensure consistent performance throughout the full flight envelope.

Similar results were found for the pitch channel. The incremental nature of the control laws enabled the possibility to operate the aircraft’s certified autotrim system in parallel, which significantly enlarged the authority on the elevator. This illustrates the ability of current control to make simple and efficient use of the complete actuator performance.

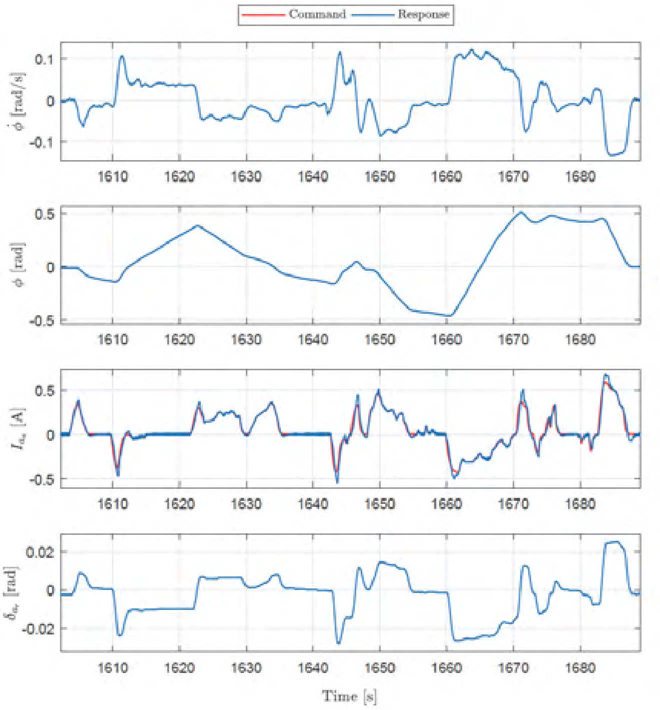


Figure 9. Flight test results: Aileron servo and lateral aircraft response during manual control of servo current (KIAS 200, FL170, clean)

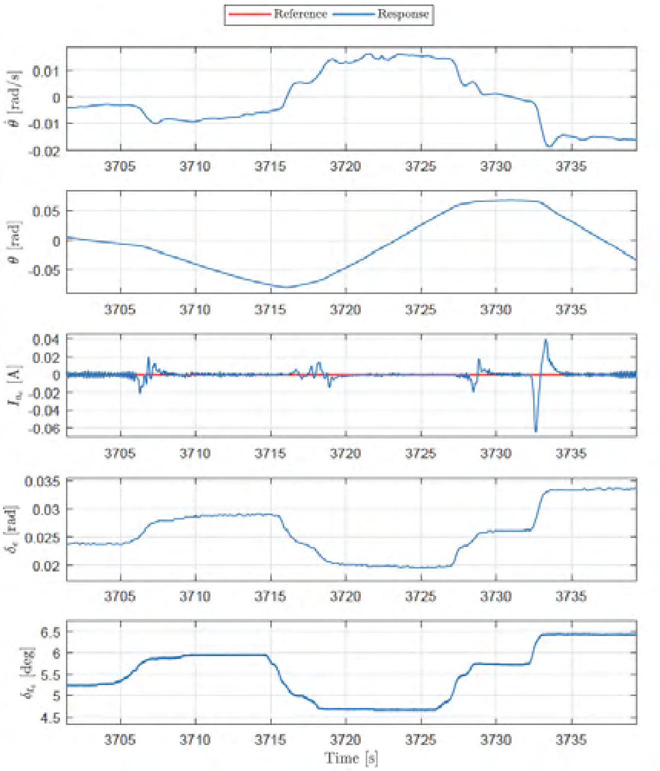


Figure 10. Flight test results: Elevator servo and longitudinal aircraft response during manual trim tab operation, direct servo control (KIAS 200, FL120, clean)

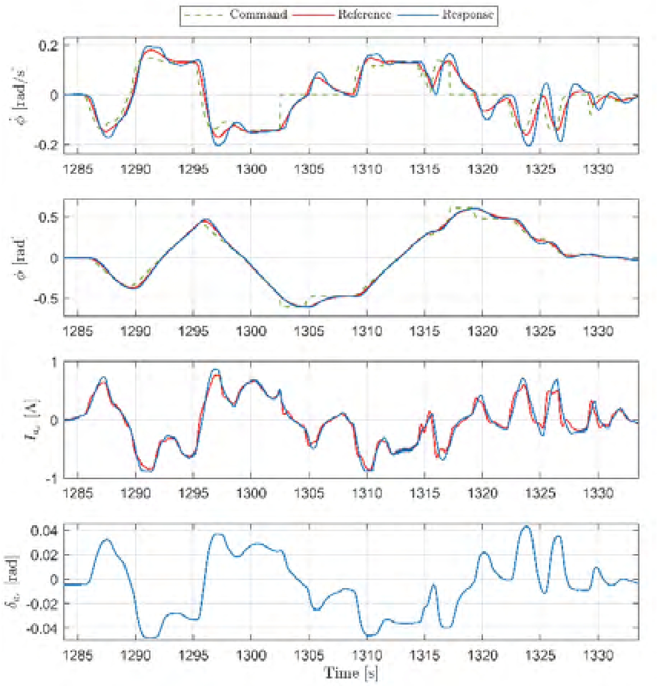


Figure 11. Flight test results: Lateral tracking performance CUR-INDI during manual flight (KIAS 200, FL120, clean)

V CONCLUSION

The purpose of this research was to investigate, validate, and demonstrate the use of current-controlled actuators in the context of primary fly-by-wire (FBW) control for the purpose of making optimal use of the strengths and advantages offered by electro-mechanical actuators (EMAs). As it forms a pioneering study, the main objective was to establish a proof-of-concept rather than to explore secondary aspects such as handling qualities or control efficiency. The desired end-product in this respect was two-fold, consisting of two parts:

1. ’direct control’ or ’open-loop’ servo control architecture that directly couples the FBW control interface (commonly a sidestick) to an actuator current reference.
2. Integrating of this new type of servo control framework with existing advanced flight control laws.

Both goals and thereby the purpose of the study have been fully met through extensive simulation analysis and in-flight demonstration on a CS-25 certified laboratory aircraft.

In-flight demonstrations confirm that the aircraft can indeed be accurately maneuvered in pitch and roll with current as the servo control variable, in a way that is analogous to a position controlled system. An eminent result from in-flight experiments is the aircraft’s agility to stick inputs in this mode. Similar demonstrations with CUR-INDI show very good tracking performance in both roll and pitch over a wide range of different flight conditions. The closed-loop aircraft response proved to be very agile while accurately following the imposed system dynamics. This is also the case in different aircraft configurations, although some deteriorating effects due to effectiveness mismatches can be observed as a result of changing chord-wise and span-wise aerodynamic profiles. This shows that the internal aerodynamic hinge moment models may need to be extended for this type of situations. Nevertheless, the observed flight performance even exceeds the baseline performance of conventional position-based INDI (Grondman, et al., 2018). Based on these results, it has been proven that current-controlled actuators form a viable solution for primary flight control applications.

VI OUTLOOK

The implementation of force-controlled actuators has the potential to save structural weight on commercial airliners due to its potential in gust load alleviation. At the same time it is possible to alleviate actuator loads (when no active smart load alleviation is used). A rough estimate calculates weight savings between 500 and 1000kg for a typical twin-engined large passenger aircraft.

The performed flight tests demonstrated that it is possible to maneuver a CS-25 certified aircraft using only the actuator currents. However, for commercial use of the proposed methods, further research and development is needed in several fields:

- Proof that by controlling surfaces using current or force control does not lead to flutter of the surfaces and/or wings.
- Current controlled actuators effectively put the aircraft (without control system) in a stick-free condition, which typically has negative effects on its static stability characteristics. Further research must be invested to see if this might pose a problem. On the other hand, current control for canards will increase the stability of an aircraft.
- From an aircraft over-all design perspective, for some control surfaces force control may beneficial, for others not (see previous field). Control surfaces like ailerons are also part of the wing and require permanent loading to contribute to wing lift. Differentiating this from disturbance loads must be handled reliably.
- Use of direct hinge moment control instead of current control to avoid static friction.
- Demonstrate an actuator suitable for direct hinge moment control with enough accuracy for flight control.
- Certification: It must be validated that the proposed new way to control an aircraft can be certified using current regulations. For a successful application, new acceptable means of compliance might be needed.

VIII DISCUSSION

It is expected (but unconfirmed) that large static friction or highly variable friction will lead to unsatisfactory flight control behavior. To counteract this and also obtain a higher degree of control certainty and counteract static as well as varying friction in the drivetrain, a force sensor can be used to actively control the surface forces (Linden, 2016). In 1995 (Williams, 1995) filed a patent for the controlling of a rocket using a similar approach. It is unknown to the authors if this principle has ever been flown.

REFERENCES

Acquatella B., P., van Kampen, E.-J. & Chu, Q. P., 2013. Incremental Backstepping for Robust Nonlinear Flight Control. *Proceedings of the EuroGNC 2013, 2nd CEAS Specialist Conference on Guidance, Navigation & Control,* pp. 1444-1463.

Bellmann, T. et al., 2011. The dlr robot motion simulator part i: Design and setup. *IEEE, International Conference on Robotics and Automation (ICRA),* pp. 4694-4701.

Fezans, N. & Joos, H.-D., 2017. Combined Feedback and LIDAR-Based Feedforward Active Load Alleviation. *AIAA Aviation 2017 - Atmospheric Flight Mechanics Conference.*

Grondman, F., Looye, G. H. N., Chu, Q. P. & van Kampen, E., 2018. *Design and Flight Testing of Incremental Nonlinear Dynamic Inversion based Control Laws for a Passenger Aircraft.* s.l., s.n.

Linden, C. v. d., 1996. *DASMAT-Delft University aircraft simulation model and analysis tool: A Matlab/Simulink environment for flight dynamics and control analysis.* Delft: Delft University of Technology.

Linden, F. L. J., 2016. *Aktuator-Scharniermoment-basierte Flugregelung.* Germany, Patent No. DE201610117634.

Lubbers, B., 2009. *A model of the Experimental Fly-By-Wire flight control system for the PH-LAB – Performing flight tests, system identification and parameter estimation,* Delft: Delft University of Technology, Faculty of Aerospace Engineering.

Mulder, M. et al., 2009. Aerodynamic Hinge Moment Coefficient Estimation Using Automatic Fly-by-Wire Control Inputs. In: *Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit.* Chicago (IL): s.n., pp. --.

Sieberling, S., Chu, Q. P. & Mulder, J. A., 2016. Robust Flight Control Using Incremental Nonlinear Dynamic Inversion and Angular Acceleration Prediction. *Journal of Guidance, Control, and Dynamics* , pp. 1732-1742 .

Williams, A. S., 1995. *Actuator system and method.* US, Patent No. US5593109A.

Zaal, P. et al., 2009. Design and Certification of a Fly-by-Wire System with Minimal Impact on the Original Flight Controls. In: *Guidance, Navigation, and Control and Co-located Conferences.* s.l.:American Institute of Aeronautics and Astronautics, pp. --.

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