Requirements for Servo-boosted Control Elements for Sailplanes

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Abstract

Requirements for control systems in sailplanes and powered sailplanes to be equipped with servo-powered transmission and control elements have been analyzed to provide information regarding airworthiness of such controls. A flight dynamics dataset was acquired in flight tests and used to create a six degree-of-freedom simulation in which various potential actuator failure scenarios were investigated. An exemplary functional hazard analysis was conducted. To demonstrate a servo-boosted control system for the airbrakes, a system based on an electric actuator was designed, built, and evaluated in flight. The system kept the hand force below a specified level and allowed controlled deployment of the airbrakes over the whole speed range.

Nomenclature

c	Probability of failure self-detection
CAS	Calibrated airspeed
H	Altitude
MTBF	Mean Time Between Failures
n_x	Longitudinal load factor
n_z	Vertical load factor
p	Roll rate
r	Yaw rate
V	Airspeed
β	Angle of sideslip
d_a	Aileron deflection
δ_r	Rudder deflection
λ	Failure rate
Φ	Bank angle
Ψ	Heading

Introduction

To overcome some of the problems which were introduced with the continuing development of modern sailplanes, requests for the certification of electrically powered control elements have been made. At this time, a certification is not covered by the existing regulations, and sufficient experience in this area is lacking as well.

The aim of the present investigation is to provide basic information which can be used in the formulation of requirements for servo control elements in sailplanes and powered sailplanes. The investigation was commissioned and financed by the German Aeronautic Authority (Luftfahrtbundesamt), a subdivision of the Federal Ministry of Transport, Building and Urban Affairs. The paper starts with the analysis of existing sailplane control systems which is followed by an overview of the requirements in the regulations and general requirements for actuator systems. A more detailed study on reliability aspects starts with the acquisition of a flight dynamics dataset of an ASK 21 sailplane. Based on the dataset, a six degree-of-freedom simulation is used to investigate a series of potential actuator failures. The results of the simulation are concluded in an exemplary Functional Hazard Analysis. Possibilities for the improvement of reliability are considered. Finally, the design and realization of a servo-boosted airbrake system as a demonstrator for servo-control systems in sailplanes is described.

Analysis of existing systems

Established control systems

A survey of control systems that have, up to now, been carried out in sailplanes and powered sailplanes revealed that nearly exclusively conventional systems are in use. They consist of direct mechanical links between the control organ and the aerodynamic surface by means of push rods or cables. Certain actuator-driven control systems have been realized in experimental sailplanes but did not reach series-production readiness.

In modern powered sailplanes with retractable engines, where electrical power is available from the battery, engine deployment is usually driven by a spindle. There are also retractable gears powered electrically or hydraulically. However, actuator-driven primary flight controls have not yet been implemented.

Problems with conventional control systems

Some problems with conventional control systems have been identified during the continuing development of modern sailplanes. For example, hand forces at certain control organs (e.g. the airbrakes[1]) have risen considerably. A contributing factor is the limited space in modern narrow fuselages that enforces concessions regarding the layout and positioning of control elements. This deteriorates the conditions for the pilot who, for example, may have to cross their arms to reach the gear lever.

Growing wing spans in the open class have led to longer push rods for aileron control. Their lower natural frequencies reduce the safety margin against control surface fluttering. Additionally, to avoid contact of push rods and wing structure with large aeroelastic deformations, relatively thick airfoils are required which prohibits performance benefits from thinner airfoils. These problems could be overcome by actuator-driven controls, especially for ailerons.

Requirements for systems

Requirements in the airworthiness regulations

The European airworthiness requirements for sailplanes (CS-22[2]) stipulate that control of the aircraft be possible "without exceptional piloting skill, alertness or strength, and without danger of exceeding the limit load factor under any probable operating condition". Upper limits for control hand forces are given, as well as criteria for control effectiveness in longitudinal and lateral motion. An airspeed range for the operation of airbrakes is given, along with the requirement that the time for extension or retraction may not exceed 2 s. An uncontrolled movement of wing-flap devices is tolerable if it can be demonstrated that such a movement is not hazardous. For sailplanes with retractable landing gear, normal landings with the gear retracted must be possible. Additionally, for non-manually operated landing gears, an auxiliary means of extending the gear must be present.

General requirements to actuator systems

At least for primary flight controls, an airspeed-dependent force feedback at the control organ is necessary. This would also allow for a limitation of maximum deflection angle as a function of dynamic pressure, thus avoiding structural damage of the aircraft. Still, an extended license for actuator-controlled sailplanes is undesirable. This means that the behavior of the actuator-controlled sailplane may not be different from the behavior of a conventional sailplane. Advanced automatic control systems (e.g. like a system which produces the same roll rates for the same stick deflections independent of airspeed) are therefore not acceptable. The same goes for control systems with degradation in various control laws as in the case of airliners. Similar considerations have been made by Konrad[4] for General Aviation aircraft.

An important aspect for actuator-driven control systems is their energy consumption. The primary flight controls are operated nearly continuously and therefore require much higher amounts of energy than the secondary controls being operated only at discrete times. To assess the total energy consumption, a further study would be desirable where control surface positions, hinge moments, stick positions and hand forces are recorded during representative flights. The measurements described in the following paragraph could not be used because the flights were considerably different from usual sailplane flights and no forces were recorded. A theoretical assessment is difficult and error-prone because pilot behavior and turbulence play an important role. So, the question of the required power supply remains still open.

Flight dynamics model

To simulate the behavior of an actuator-controlled sailplane after an actuator failure, a mathematical model of a representative sailplane was developed within the MATLAB®/SIMULINK® environment. The chosen aircraft was a Schleicher ASK 21. A combination of calculative and semi-empirical methods like the USAF Digital Datcom[3] yielded a first estimation of the required derivatives. Performance measurements of the Idaflieg (the association of German academic soaring groups) provided additional data. To acquire a complete and accurate dataset, flight tests with an original glider were conducted.

For the flight tests, an ASK 21 sailplane was fitted with extensive measuring equipment to record inertial (accelerations and rotational rates), GPS (position and velocity relative to Earth), air data (static and dynamic pressure, temperature and flow angles), as well as control surface positions. Angle of attack and angle of sideslip were measured by wind vanes on a nose boom that was attached to the fuselage by a specifically manufactured carrier. A schematic of the equipment is shown in Fig. 1. A total of six flights with specific maneuvers for parameter identification provided sufficient data to attain all relevant aerodynamic characteristics.

In addition to the ASK 21 model, an ASH 25 model was created to analyze the effect of a complex wing flap system with possibly redundant control surfaces. As no further flight tests could be conducted, the dataset could only be derived from calculations and Idaflieg data.

The simulation itself was implemented as a six degree-of-freedom rigid body model. The aircraft was supposed to be controlled by a "fly-by-wire"-only architecture with a separate actuator for each control surface. Consequently, the influence of each control surface had to be modeled separately to be able to assess individual actuator failures. Alternatively, simultaneous movements of, for example, all ailerons corresponded to the failure of an actuator in a central position of the aileron control line.

Failure analysis

Using the simulation, a variety of actuator failures was analyzed. The most critical case was the runaway with hardover, which means that at the occurrence of the failure the control surface is driven with maximum deflection speed into one end point, where it stayed for the rest of the failure duration. This failure type was investigated for different control elements and at different airspeeds. Consequences and possible counteractions by the pilot were evaluated. As an example, simulation results for erroneous deployment of the (single) left airbrake are shown in Fig. 2.

Evaluation of the failure scenarios

Elevator

A runaway of the elevator cannot be tolerated. With the exception of a trailing-edge up runaway at low airspeeds, it leads to the destruction of the aircraft within a short time. In all cases, control over the longitudinal motion is lost. The effectiveness of other control devices like wing flaps or airbrakes is only sufficient to compensate the emerging pitching moment from small elevator deflection angles.

In reverse, this means that the pitching moment from failures in the other control devices can be compensated for by the elevator.

Aileron

If the complete aileron system fails due to a single central actuator, roll control is lost, and in the case of a runaway, the emerging roll moment can not be compensated for. If each aileron has its own actuator however, the situation is different.

On aircraft with a single pair of ailerons like, for example, the ASK 21, the remaining aileron has to compensate the roll moment. The aircraft has to be controlled by elevator and rudder only without direct bank angle control.

In the case of aircraft with more than one pair of asymmetric trailing edge flaps, like the ASH 25, the roll moment can be compensated for by smaller deflections of the remaining ailerons such that direct roll control is still possible.

The asymmetric failure of a single wing-flap can be regarded as a single aileron failure, while at least one pair of ailerons is still intact and the induced rolling moment is small due to the small lever arm, so this case is less critical.

Rudder

A rudder failure leads to large sideslip angles. Deflecting the ailerons adversely to the rudder it is possible to stabilize the aircraft in stationary slipping flight, but directional control becomes considerably more difficult. Other effects of slipping (steeper descent with higher sink rate) are an additional source of danger.

By deflecting the ailerons in the same sense as the rudder, the aircraft reaches a steady state turn condition, but the rotational rates are high while sideslip angle still persists.

Airbrakes

A symmetric airbrake failure is not significantly different from a normal airbrake operation, although the occurrence is not anticipated. The pilot is able to stabilize the aircraft without special measures, but has to cope with the performance which is severely deteriorated by the airbrakes.

If a single airbrake fails asymmetrically, the pilot may deflect the other airbrake as well to regain a symmetric airplane, or use all primary flight controls to compensate the arising moments. The latter option has the advantage of less performance deterioration. The necessary deflection angles are small enough to allow continuing control over the aircraft.

Another point that was investigated is the influence of actuator dynamics. It was shown that fast deflection rates are favorable because the pilot's counteractions are effected earlier. However, the total influence was small.

Functional Hazard Analysis

According to the results of the simulation runs, an exemplary functional hazard analysis for the failure case of an actuator runaway with hardover was performed. For each actuator failure, the arising failure condition was categorized by its severity. Possible categories are No Safety Effect, Minor, Major, Hazardous and Catastrophic as defined in Ref. 5, see also Table 1. The resulting categorization is summarized in Table 2.

Improving reliability

For most kinds of aircraft, quantitative requirements to the probabilities of failure conditions are given in Ref. 5. For sailplanes, however, there are no such numbers. Thus, the values for Class I aircraft (single piston engine, less than 6000 lbs takeoff weight) were used in this study. These values are shown in Table 3.

To illustrate the effects of system duplication on reliability, a quantitative example calculation was performed. Its results are given in Table 4. A failure rate of $\lambda = 2 \cdot 10^{-4}$/h was assumed. This corresponds to a mean time between failure (MTBF) of 5000 h, which is a typical value, but was not taken from an existing system. The calculation revealed that this MTBF allows only such systems to be realized as simplex whose failure is categorized as minor. According to Table 4, simplex is allowable for airbrakes and wing-flaps, provided they are driven symmetrically by a single actuator.

For other control servos, at least a duplex realization is necessary. In this case, the individual systems may or may not be able to auto-detect their own failure. The probability of this auto-detection was assumed to $c = 0.9$. Three different duplex realizations were considered:

- Duplex 1: Independent Systems
  Two systems operate independently, but a single one is sufficient. A failure detection is not necessary.
- Duplex 2: Standby Sparing
  One system operating while the other is passive. After a failure occurs, the systems are switched over.
- Duplex 3: Duplication with Comparison
  Two systems perform the same task and their results are compared.

With a triplex architecture, the first failure can be detected as a deviation of one system to the other two. After the first failure, the system continues as Duplex 3.

The values from Table 4 now show that systems causing a major failure condition can be realized as Duplex 3, whereas Duplex 1, Duplex 2 and Triplex architectures are sufficient even for catastrophic failure conditions.

Flight tests with servo-driven airbrakes

To demonstrate a servo-boosted control system, a servo actuator system for the airbrakes was designed and built. The airbrakes are especially suited for this demonstration for several reasons. They are operated rather infrequently during a typical flight, thus the energy consumption of the servo system is expected to be relatively low. A safe flight and landing without operating airbrakes is possible. The effects of an actuator failure were analyzed and found to be minor.

Additionally, the airbrakes are most likely to require a servo boost system. The lever forces are higher than those of the other control organs, and a previous study[1] showed that finer control of deflection height and duration is desirable, especially in the higher airspeed regime. It was found that a slow deflection of the ASK 21 airbrakes was not possible due to excessive suction forces. Still, slower deflections lead to significantly lower peaks in the load factors.

Realization

The system was designed to keep the hand force at the airbrake lever below a user-specified maximum. A purely electric design in simplex architecture was chosen. The system consisted of a servo motor which drove the copilot's airbrake lever via a planetary gear, a gear rack and a push rod.

The control electronics were designed in SIMULINK®. This facilitated testing and evaluation, as the simulation designed for the failure analysis could be used to assess controller performance. The final implementation was realized on a Motorola MPC 555 microprocessor.

Measurements of control force and airbrake position were required as inputs for an automatic control loop to steer motor speed and clutch state. The whole system was powered by two lead accumulators located in the wing holds. The system could be separated by a clutch to allow normal aircraft operation to the pilot. An exploded drawing of the actuator is shown in Fig. 3, while Fig. 4 contains a schematic of the system.

The whole system was flight tested in the same aircraft as used for the data acquisition. Similar measuring equipment was employed.

Results

Results from a single airbrake maneuver are depicted in Fig. 5. After acquiring trim speed, the pilot releases the airbrake with a short pull at the lever (positive force). The immediate changes in lift and drag are visible as peaks in the respective load factors. The airbrake is now sucked out by the air forces, while the pilot pushes (negative force) against the lever to keep its speed low. After full deployment, the pilot pulls again shortly to ensure the limit deployment is reached. Then the airbrake is retracted again. The pushing force rises to the limit of 200 N, after which the servo starts transmitting power ("Drive" mode in the last subplot) and keeps the force at this limit. Later, the force rises again, because the pilot wanted to move the lever faster than the motor speed. The last peak in the force is due to the locking force, which was not supported by the motor to avoid damage to the aircraft.

The analysis of all test flights showed that with the system, a controlled and delayed deployment of the airbrakes was possible. The resulting changes in the load factor were significantly reduced compared to the unaugmented aircraft. Figure 6 shows (polynomially fitted) values for vertical and axial load factor changes after airbrake deployment. The curves for the servo-boosted case are compared to fast and slow manual deployment. The latter was only possible up to 210 km/h CAS.

The hand forces were clearly reduced, but only in the higher airspeed regime. With lower airspeeds, the hand forces are small anyway and a fine control of deployment is possible without servo boost, so that no effect was visible here.

For the realization of such a servo system for production, further study considering the automatic control algorithm is advisable. The basic algorithm that was used in these flight tests showed the need for improvement of handling qualities. A sophisticated force feedback system depending on dynamic pressure and lever speed seems desirable.

Conclusions

The requirements for a servo-driven control system for sailplanes were assessed. Using a simulation based on flight test data, a Functional Hazard Analysis could be conducted (refer to Table 2 for results). As an example, a servo-boosted airbrake was demonstrated in flight.

The study revealed that it is possible to realize a servo-boosted control system with today's available technology. Benefits of such a system can be the omission of heavy/bulky mechanical components and the possibility of additional control algorithms including safety functions. However, especially if primary flight controls are affected, the requirements to safety are fairly high, so that considerable effort is necessary to achieve adequate reliability. Servo systems, therefore, are expected first in the open class where the benefits from omitting mechanics are greatest. Smaller gliders will probably remain mechanical – especially regarding the fact that many glider pilots like to do the flying themselves and do not consider new control algorithms a benefit.

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Table 1

Classification of Failure Conditions[5]

Category		Effects
No Safety Effect	NSE	Operational capability not affected Crew workload not increased
Minor	Min	Slight reduction in safety margins and/or functional capability Slight increase in crew workload
Major	Maj	Significant reduction in safety margins and/or functional capability Significant increase in crew workload
Hazardous	Haz	Operational capability reduced Flight crew cannot be relied upon to perform their tasks accurately
Catastrophic	Cat	Loss of the aircraft

Table 2

Classification of actuator failures

Actuator		Category
Elevator		Cat
Aileron	central actuator	Cat
	single flap actuator, only 1 pair of ailerons	Haz
	single flap actuator, multiple pairs of ailerons	Maj
Rudder		Haz
Wing flap	central actuator	Min
	single flap actuator	Maj
Airbrake	central actuator	Min
	single airbrake actuator	Maj

Table 3

Allowable probabilities for failure conditions[5]

Category	Allowable average probability per flight hour
NSE	≤ 1
Min	$\leq 10^{-3}$
Maj	$\leq 10^{-4}$
Haz	$\leq 10^{-5}$
Cat	$\leq 10^{-6}$

Table 4

Failure probabilities for different system architectures, example calculation

System architecture	Failure probability		Category
Simplex	λ	$2\cdot10^{-4}$	Min
Duplex 1	λ^2	$4\cdot10^{-8}$	Cat
Duplex 2	$0.5\ \lambda^2$	$2\cdot10^{-8}$	Cat
Duplex 3	$2\lambda(1-c)$	$4\cdot10^{-5}$	Maj
Triplex	$3\lambda^2(1-c)$	$1.2\cdot10^{-8}$	Cat

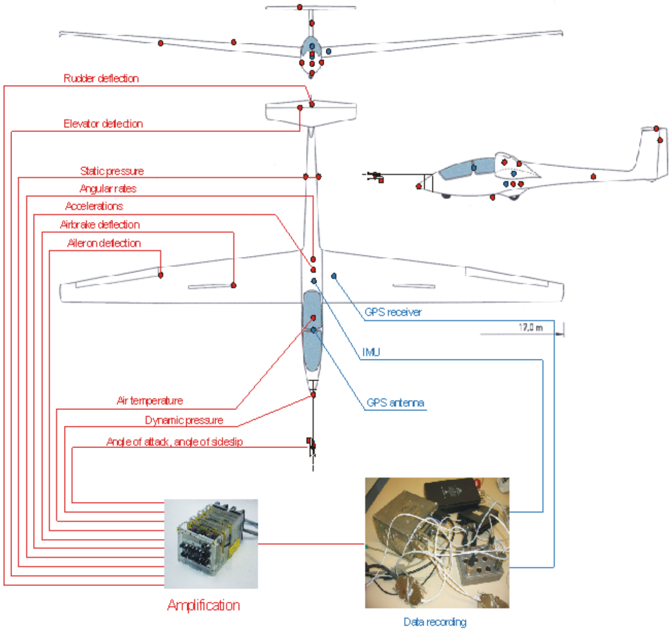

Figure 1 Measuring equipment for data acquisition

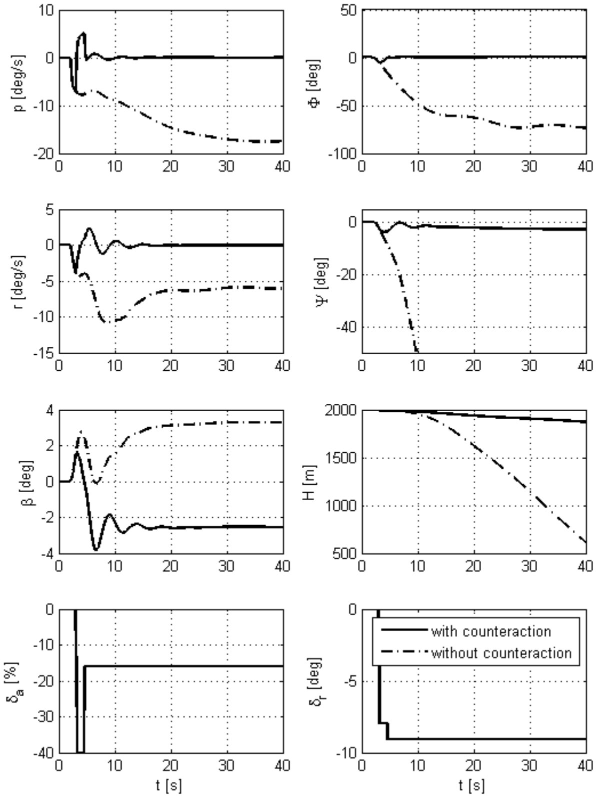

Figure 2 Simulation results for sudden deployment of the left airbrake at 130 km/h CAS, with and without counteractions by aileron and rudder

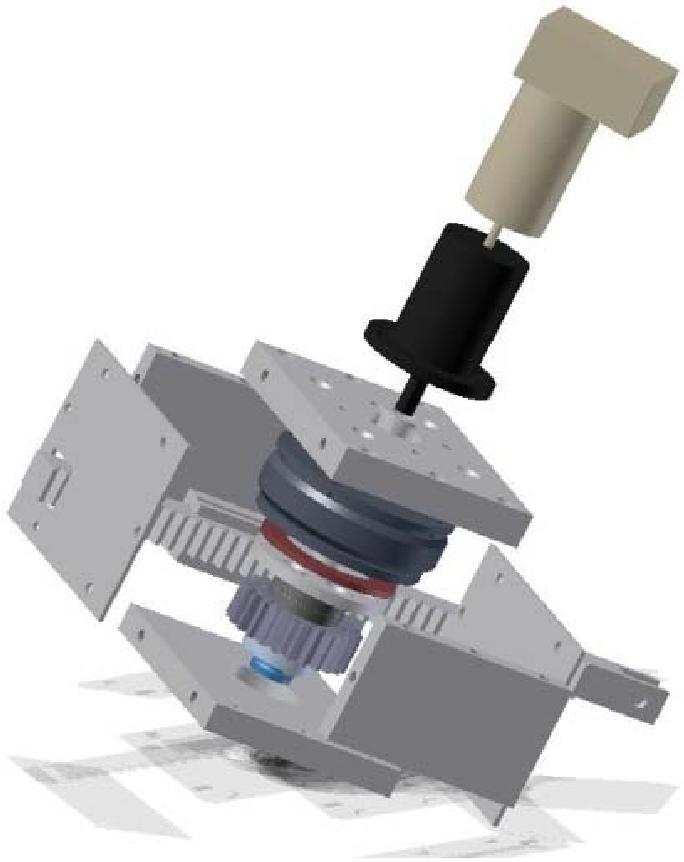

Figure 3 Exploded drawing of airbrake actuator

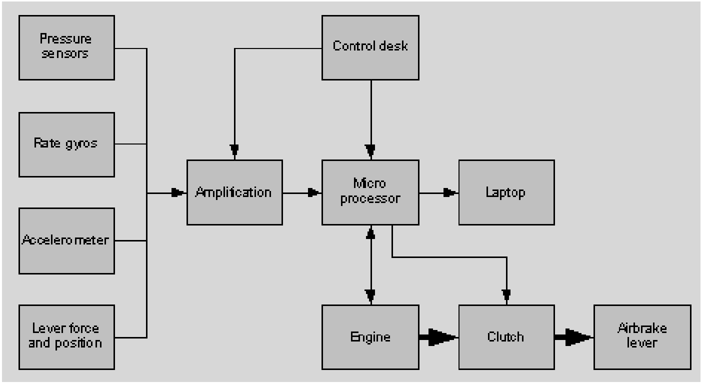

Figure 4 Schematic of the actuator components

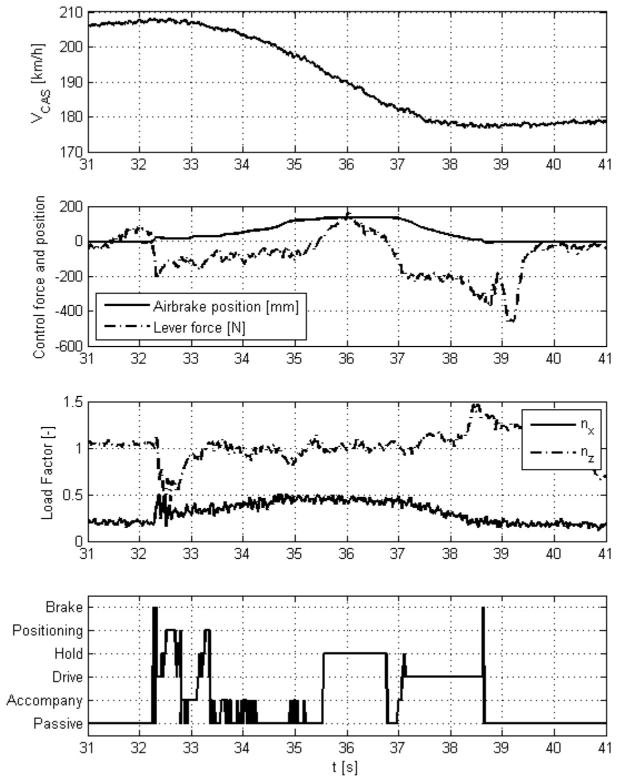

Figure 5 Typical airbrake maneuver: airspeed, lever position and hand force, load factors and control electronics mode

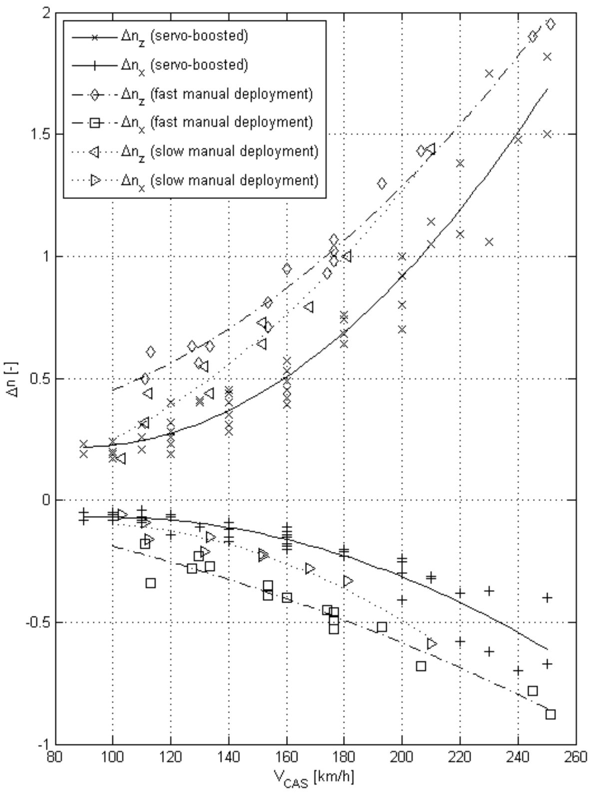

Figure 6 Measured load factor changes with airbrake deployment