A Way to Mitigate Force-Fight Oscillation Based on Pressure and Position Compensation for Fly-by-Wire Flight Control Systems*

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This paper focuses on force-fight oscillation mitigation in fly-by-wire (FBW) flight control systems (FCSs) for civil aircraft. The theory of “force fight” was first introduced after analyzing its impact on active-active actuators system. The architecture of one typical FBW FCS and the layout of an electronic hydraulic servo actuator (EHSA) were described. A force-fight mitigation algorithm applying pressure and position compensation feedback was then presented. To validate algorithm performance, an associated actuator-surface model was created to simulate force fight. Finally, the algorithm was tested using worst-case scenarios by calculating the system latency and tolerance, and verified using special “Iron Bird” tests. The results show an obvious decrease in the difference delta press (DDP) when comparing with/without mitigation, and thereby meeting force fight limitation requirements.

Key Words: Force Fight, Actuators, Fly-By-Wire, Flight Control System, Mitigation, Compensation

1. Introduction

1.1. Background

Oscillatory failure case (OFC) refers to abnormal oscillation of aircraft control surfaces due to component malfunction in actuator servo-loops. This oscillation, of unknown magnitude and frequency, can be propagated downstream of the control loop to the control surface, leading to structural loads produced by the airplane.

According to the standard requirements of FAR/CS/CCAR 25, structural load will cover the following items: 25.301, 303, 305, 307, 333, 471, 561, 571, 601, 603, 605, 607, 609, 613, 691, 521, 623, 625 and 629. These certification requirements are generally classified into four groups: dynamic loads, flutter loads, fatigue loads on actuator and control surfaces, and static load.1,2) The main source of these loads is OFC. To analyze OFC, the following effects of difference levels are studied:

Level 1—Airplane controllability: Oscillation makes it difficult for pilots to control the airplane during continued flight and landing.

Level 2—Excessive limit load: Oscillation results in excessive loads in the overall airplane, including wings, fuselage, and empennage. The magnitude and frequency of the oscillations should be kept to within an allowable limitation. Specifically, if the control surfaces are at saturation, then the channels should be shutdown within three to five OFC cycles.

Level 3—Global structural fatigue: Due to oscillation, loads are act upon the airplane structure, producing unaccepted structural fatigue and damage. The magnitude and frequency of oscillation should be defined as the number of oscillation during one flight.

Level 4—Low-cycle local fatigue (Force fight): Each actuator’s motion of one surface is out of sync because of the OFC, thus producing load. This may result in unaccepted fatigue damage on the control surface.

This study mainly focuses on Level 4. Force fight is discussed in the following section.

Flight control surface actuation systems with two or more actuators coupled to a single flight control surface typically implement one of two operational configurations: active-standby and active-active.3) In the active-standby mode, which was used by Airbus, one actuator is actively powered while the other is in standby; no redundancy management is needed. In active-active mode, which was used by Boeing, all of the actuators are simultaneously powered. This allows each individual actuator to be sized relatively smaller than the one used for active-standby mode. However, this may bring the potential resultant force fight between each active actuator,3) as shown in Fig. 1.

The voter can compare the difference between each channel and calculate the average output, and each actuator is controlled using the same command. However, due to the error accumulated during signal processing, manufacturing and installation of the valves and actuators, the displacement of each actuator is usually a different coupling, with large torsion stiffness in the control shaft. Thus, force fight occurs between the actuators, easily causing fatigue and structural failure.3)

In previous literature, mainly two approaches were proposed to mitigate the impact of force fight:

One is to eliminate the command difference by optimizing the actuator command. The opposing position signal, synchronism position reference, backlash and friction were analyzed as the main source of force fight. A corresponding way...
to optimize system performance was provided to reduce the difference.\textsuperscript{6,7} Signal rigging to eliminate the command difference by decreasing and compensating the installation constant error was also proposed by Airbus.\textsuperscript{8}

In the other approach, the addition a mitigation augmentation command was used to compensate the command difference, and this was studied in this paper. A way to equalize force using a pure integral part was proposed by Wang et al.\textsuperscript{4} The integral of each actuator’s pressure differential was used to compensate the displacement control signal; while the command compensated is calculated using a special PID. Wang et al.\textsuperscript{9} presented the mid-value-selection differential command was used to compensate the displacement control signal; while the command compensated is calculated using a special PID. Wang et al.\textsuperscript{9} presented the mid-value-selection method to balance force fight. It simulates the difference contributors using the simulation tool, Symbolic Analysis Laboratory (SAL).\textsuperscript{9} A plurality of force sensors were used by Kirkland and Mukilteo,\textsuperscript{10} of Boeing Company, to feedback the force fight value. A flight computer calculated the difference in actual actuator rates and summed up the difference with a computed difference in actuator force. Thus, position commands that equalize the actuator forces on a control surface were generated.\textsuperscript{10} Cochoy et al., from Hamburg University, proposed a new control mode: active/no-load mode beyond with active-active and active-standby mode, and studied the force fight of a mixture of actuators using an electro-mechanical actuator (EMA) and a electronic hydraulic servo-actuator (EHSAs), and analyzed the control concept based on the mathematical models.\textsuperscript{11,12}

Based on the above-mentioned references, the research concluded fell into three categories:

a. Active-standby mode, which was used by Airbus and the series, did not refer the force fight issue.

b. Active-active mode, which was used by Boeing Company.\textsuperscript{10} was achieved using EHSA. The force fight object was similar to the one discussed in this article.

c. Active-active mode, which was achieved using mixed actuator types such as hydraulic actuator (HA), electro-hydrostatic actuator (EHA) and EMA, and the object was different from the one discussed in this article.

Different from the proposal of Boeing and others, the novelty of the method proposed in this article is: The mitigation augmentation command is calculated using pressure and position feedback built into the EHSA without additional hardware support, such as additional force sensors. It is more applicable to electronic hydraulic servo-actuators (EHSAs).

1.2. System description

To explain the mitigation method proposed, the flight control system structure is described below. The flight control system structure of one type of civil aircraft is illustrated in Fig. 2.

As can be seen in Fig. 2, there are three flight control computers (FCCs) and four actuator control electronics (ACEs) that provide flight control signals for calculation and redundancy management. In addition, each surface actuator is controlled by a remote electrical unit (REU) to receive digital signals from the FCCs and ACEs. A pilot uses a side stick or pedal to transfer operation into electrical signals and send them to the ACEs. Finally, the electrical power of the FCCs, ACEs and REUs comes from four power conditioning modules (PCMs).

There are two modes of operation: Normal mode (NM) and Direct mode (DM). In NM, the FCS provides full system functions, closed-loop flight control, system monitoring, crew announcement and maintenance support. This mode runs when a sufficient sensor set is available and at least one FCC is valid. If all FCCs fail, the FCS will be degraded to DM. In DM, the FCS provides a basic mechanic link between the stick and control surfaces with body rate damping via manual airplane operation. Only basic system monitoring is offered. This mode presents a simple and deterministic control path from stick input to control surfaces.

2. Force Fight Mitigation Algorithm

Generally, in the force fight mitigation algorithm, the position and pressure sensors feedback the pressure signal, thereby removing the force fight condition from the surface. One obvious solution is to eliminate the pressure differential delta press (DP) from neighboring actuators by driving the DP in both actuators to an average value. A force fight mitigation algorithm that uses only DP as feedback is shown in Fig. 3 for two actuators on one surface. The difference DP (DDP) between each actuator and the average pressure of two actuators is used to generate an equalization signal for additional command input to each actuator.
The actuator studied in this paper is the EHSA, see Fig. 4. An electronic hydraulic servo-valve (EHSV) is controlled by the FCC and ACE to drive the piston displacement. Piston position is fed back via an embedded linear variable differential transformer (LVDT) in the main ram of the actuator.

The piezo-resistive pressure sensor of the actuator is used to measure the extended and retracted chamber pressures of the hydraulic actuator, and to transmit the data back to the ACE. DDP is used in the FCC for force fight mitigation between two adjacent actuators on a given primary surface and for oscillatory malfunction detection.

The algorithm of the force fight mitigation that actively compensates force fight on the surface is shown in Fig. 5. The essential goal of the pressure feedback algorithm is to balance the load between the actuators that are engaged.

The compensating command is implemented with a combination of position and pressure differentials between each actuator and average value. The force fight command is calculated based on the difference between the pressure differential across the piston head of a single actuator and the average pressure differential across all piston heads in the actuators engaged on the surface, as referred to in Eqs. (1)–(7).

\[
\Delta P_{\text{move}} = \frac{\Delta P_{\text{in}} + \Delta P_{\text{out}}}{2} - \Delta P_{\text{in}} \quad (1)
\]

\[
X_{\text{inddp}} = \int (\Delta P_{\text{move}} k1) dt + \Delta P_{\text{move}} k2 \quad (2)
\]

\[
\Delta P_{\text{outave}} = \frac{\Delta P_{\text{in}} + \Delta P_{\text{out}}}{2} - \Delta P_{\text{out}} \quad (3)
\]

\[
X_{\text{outddp}} = \int (\Delta P_{\text{outave}} k1) dt + \Delta P_{\text{outave}} k2 \quad (4)
\]

\[
X_{\text{Pout}} = \frac{X_{\text{Pin}} - X_{\text{Pout}}}{2} \quad (5)
\]

\[
X_{\text{Pincomp}} = X_{\text{inddp}} - X_{\text{Pout}} \quad (6)
\]

\[
X_{\text{Poutcomp}} = X_{\text{outddp}} - X_{\text{Pout}} \quad (7)
\]

where, \( \Delta P_{\text{in}} \) and \( \Delta P_{\text{out}} \) are the DP signals of the inboard and outboard actuators. \( \Delta P_{\text{move}} \) and \( \Delta P_{\text{outave}} \) are the pressure differentials between actuator pressure and average pressure of the inboard and outboard actuators. \( X_{\text{inddp}} \) and \( X_{\text{outddp}} \) are the mitigation contributors of the inboard and outboard position commands converted by DDP. \( X_{\text{Pout}} \) is the position differential between the inboard and outboard actuator ram positions. \( X_{\text{Pincomp}} \) and \( X_{\text{Poutcomp}} \) are the combined mitigation compensation commands of the inboard and outboard actuator position command. The integral path calculates the steady-state force fight mitigation, and the scaled gains \( k1 \) (inch/sec/psi) are used to adjust the commands for all engaged actuators to that of the average command from the engaged actuators. The proportional path \( k2 \) (inch/psi) is the compensation for high-rate pressure changes during actuator movement.

The compensating command is performed on the actuator piston ram position based on the current ram position, so as to reduce the algorithm dependency on pressure feedback. Ram position is always sent to the engaged actuators, even if only one actuator is engaged.

In the force fight mitigation logic, the mitigation command is calculated for each actuator separately. If some data on the corresponding logic input are wrong, the actuator will be switched to standby mode and part of the mitigation calculation based on mitigation command and pressure values is obtained as zero. Another actuator is still in active mode if valid data are received, and the mitigation calculation for that actuator will continue.
3. Actuator Simulation Model

To examine the performance of the algorithm proposed, the dynamic characteristics of the EHSA simulation mode are created using the following mathematics mode. The following equations are referenced in other literature.\(^{13,14}\)

The quantity flow rate \(Q \text{ (inch}\(^3\)/sec)\) of the EHSV valve is expressed as Eq. (8):

\[
Q = c_d w X_v \left( \frac{1}{\rho} \left( P_s - A_p P_{\text{man}} v_p - \frac{X_p}{|X_v|} P_t \right) \right) \tag{8}
\]

where \(c_d\) is the coefficient of the EHSV orifice; \(w \text{ (inch)}\) is the EHSV slot width; \(X_v \text{ (inch)}\) is the EHSV valve spool stroke to control the hydraulic pressure; \(\rho \text{ (lb/inch}\(^3\)}\) is the density of the hydraulic oil; \(P_s\) is the hydraulic supply pressure (i.e., the typical supply pressure is 3000 psi); \(A_p\) (inch\(^2\)) is the actuator piston area; \(P_{\text{man}}\) (psi/inch\(^2\)/sec) is the ratio of pressure decay between \(Q\) and pressure based on actuator internal leakage specifications; \(v_p\) (inch/sec) is the feedback of actuator piston movement speed; \(A_p P_{\text{man}} v_p\) is the supply pressure decay; and \(P_t\) is the external load from aerodynamic hinge moment. Piston movement position \(X_p \text{ (inch)}\) is expressed as Eqs. (9) and (10):

\[
v_p = \frac{Q}{A_p} \tag{9}
\]

\[
X_p = \int v_p dt \tag{10}
\]

where, \(v_p\) is the output of actuator piston movement speed and it is also used as the feedback to calculate the pressure decay in Eq. (8).

The actuator output force \(F_p\) is expressed as Eqs. (11)–(13):

\[
P_e = \frac{P_s + P_t}{2} \tag{11}
\]

\[
P_t = \frac{P_s - P_t}{2} \tag{12}
\]

\[
F_p = (P_e - P_t) A_p \tag{13}
\]

where, \(P_e\) and \(P_t\) are the pressures of extend and retract ram, respectively.

When two actuators are mounted on a surface, the surface position is balanced by the force from the two actuators and external load. The basic actuator-surface model is illustrated in the Fig. 6. The actuators and surface are regarded as a spring-damp system, and the dual actuators are linked by other springs.\(^{15}\)

To simulate the surface load, the following equivalents are used to build the model.\(^{16}\) One actuator-surface load model is defined as Eqs. (14) and (15):

\[
F_p = A_p (P_e - P_t)
\]

\[
\begin{align*}
&= M \frac{d^2(X_h)}{dt^2} \tag{14} \\
&= c \frac{d(X_p - X_h)}{dt} + K_s (X_p - X_h) \\
\end{align*}
\]

Fig. 6. Dual actuator-surface simulation model.

\[
T_h = F_p L_{\text{arm}} \tag{15}
\]

where, \(M\) is the surface mass; \(c\) is the surface damping coefficient; \(K_s\) is the surface tensional stiffness; \(X_h \text{ (inch)}\) is the surface hinge stroke; \(T_h\) is the hinge moment of the actuator; and \(L_{\text{arm}}\) is the arm of force between the actuator piston and actuator hinge.

Two actuators-surface load models are created, as shown below, Eqs. (16)–(18):

\[
T_{\text{h in}} = (T_{\text{h in}} + T_{\text{h out}}) - \left( |X_{\text{h in}} - X_{\text{h out}}| \right) K_t \tag{16}
\]

\[
X_{\text{h in}} = \frac{X_{\text{h in}} + X_{\text{h out}}}{2} - \frac{|F_{\text{pin}} - F_{\text{pout}}|}{K_s} \tag{17}
\]

\[
T_{\text{h out}} = k X_{\text{h out}} \tag{18}
\]

where, \(T_{\text{h in}}\) is the surface hinge moment; \(X_{\text{h in}}\) is the surface movement; \(T_{\text{h in}}\) and \(T_{\text{h out}}\) are the inboard and outboard actuator piston rod hinge moments, respectively, calculated using \(T_h\); \(X_{\text{h in}}\) and \(X_{\text{h out}}\) are the inboard and outboard surface hinge movements, respectively, calculated using \(X_h\); \(K_t\) is the surface torsional stiffness; and \(k\) is the scale factor between the surface stroke and hinge moment.

4. Force Fight Simulation

In order to analyze the efficiency of the force fight mitigation algorithm, worst case scenarios are used to simulate its limitation. System latency as the main contributor of force fight was analyzed to determine the worst case.

4.1. System latency

In the force fight mitigation algorithm proposed, pressure is used as feedback data. An equalization signal for inputting each actuator command is generated using the pressure differential between one actuator and the average pressure of two (or three) actuators.

The transmission delay between the change in actuator chamber pressure and the system reaction led to difficulty using this approach. After sensing pressure change, the pressure sensor processes and sends the data to a REU. Based on the pressure data received, the controller effectively removes the steady-state force fight. However fast surface movements and large chamber pressure changes result in a force fight risk; in this case, the system latency needs to be analyzed to find the worst asynchronous condition of two
The system latency allocation is expressed in Fig. 7. The worst pressure differential \( P_{\text{diff}} \) is expressed as Eqs. (19)–(22):

\[
\begin{align*}
\tau_{\text{delay}} &= \sum t_{\text{sens}} + t_{\text{ACE}} + t_{\text{FCC}} + t_{\text{trans}} \quad (19) \\
\tau_{\text{trans}}^\text{EHSV} &= t_{\text{delay}} Q \quad (20) \\
\tau_{\text{ACE}} &= \frac{1}{f_{\text{ACE}}} \quad (21) \\
\tau_{\text{FCC}} &= \frac{1}{f_{\text{FCC}}} \quad (22)
\end{align*}
\]

where, \( \tau_{\text{ACE}} \) and \( \tau_{\text{FCC}} \) are the maximum delay time of ACE and FCC, respectively, depending on the sample frequency of FCC \( f_{\text{FCC}} \) and ACE \( f_{\text{ACE}} \). \( t_{\text{trans}} \) is the maximum delay time of data transmission in the data bus. \( t_{\text{sens}} \) is the delay time of the pressure sensor phase difference. \( Q \) is the EHSV pressure flow rate. The accumulated delay time is calculated as 43.5 msec in the worst case.

Another latency case is the asynchronous clock in the ACE. The clock in the ACE has a tolerance \( \pm 10\% \), allowing each ACE to run with a slightly different execution rate. Because of large pressure gradients and these time delays, the system cannot react until the chamber pressure changes at least 480 psi. Such a large delay results in an inadequate system response to completely equalize the pressure differential.

### 4.2. Force fight simulation

Force fight is simulated for several severe cases to validate the force fight mitigation algorithm. In all of the cases simulated, the full command stroke is chosen. Two test cases are selected to simulate the worst-case conditions for force fight, which are: two actuator pressure signal transmissions are not synchronized, and two actuator command phases are inconsistent because of different ACE processing frequencies. The test case descriptions are given in Table 1.

![Fig. 8. Simulation results for case 1.](image1)

![Fig. 9. Simulation results for case 2 (480 Hz +10%).](image2)

| No. | Test case | Rational | Passing criteria |
|-----|-----------|----------|------------------|
| 1   | One pressure sensor feedback signal delay is 43.5 msec to another, with the highest deflection rate of 25 deg/sec | The transmission delay of pressure data between two actuators. | The DDP is lower than 500 psi, which is the limitation of surface strength. |
| 2   | One ACE output command frequency is 480 Hz and other is 480 Hz ±10% | The command sample clock in the ACE has a tolerance that may cause the ACEs run at different execution rates. | |

Table 1. Test case descriptions.
tuators, and the blue and green lines of the third figure are force fight mitigation commands calculated using the mitigation algorithm.

For test case 1 shown in Fig. 8, the maximum DDP of force fight is approximately 150 psi (1034 kPa) and lower than the 500 psi (3447 kPa) required by the surface structure fatigue limitation.

For scenarios of test case 2 in Figs. 9 and 10, one ACE runs with a higher/lower frequency than the other ACE. The DDP in the maximum value did not increase significantly.

5. Verification Test

5.1. Iron Bird test platform

Since the algorithm is performed using FCC software, in addition to validation by simulation, it needs to be verified using actual FCS hardware. Thus, the Iron Bird test is carried out.

The Iron Bird test platform is used to verify the FCS functions and performance where FCS hardware configurations are the same as real aircraft (including FCCs, ACEs, REUs and actuators). Additionally, the platform provides simulation and recording devices (AOA/inertia/air speed/landing gear/flare, slat external signals, aircraft mode and signal simulation system, data recording devices, etc.) to support testing. The architecture of the Iron Bird test platform is shown in Fig. 11.

5.2. Force fight mitigation test

To verify force fight mitigation capability, high-rate surface deflection tests are conducted to check the DDP value. The test command simulation system injects the high-rate surface deflection command to drive the actuators, and the data recorder measures the DDP value from FCC output data.

In order to compare the effect between the case with force fight mitigation and the one without it, an additional test case without the mitigation function is designed to express the original DDP. The mitigation algorithm is the one function of flight control software in the FCCs; if the FCCs are inactive, the direct mode would start and the force fight mitigation function is not activated.

The surface is driven by the fastest rate to achieve the maximum force fight with and without external load, as described in Table 2. The test results are shown in Figs. 12 and 13.

It can be seen that the original DDP reaches 400 psi for the case where the mitigation function is inactive. In contrast, in the cases where the actuators are driven by the highest deflection rate with external load, or in a static position, DDP is only 190 psi at the most. This indicates that the mitigation process results in an obvious decrease in force fight.

Table 2. Test case descriptions.

| No. | Test case                                | Passing criteria     |
|-----|------------------------------------------|----------------------|
| 1   | Force fight mitigation function inactive | Dynamic force fight: Triangle command with 20°/sec rate, three cycles, external load (max. hinge moment) |
| 2   | Dynamic force fight: Triangle command with 20°/sec rate, three cycles, no external load               |
| 3   | Force fight mitigation function active   | Dynamic force fight: Triangle command with 20°/sec rate, three cycles, external load (max. hinge moment) |
| 4   | Static force fight: Position command to 0°−10°→−20°→−30°→−20°→−10°→0°, stay for 4 sec, external load (max. hinge moment) | DDP <500 psi |

![Fig. 10. Simulation results for case 2 (480 Hz –10%).](image)

![Fig. 11. Iron Bird test rig.](image)

![Fig. 12. DDP test without mitigation.](image)

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6. Conclusion

A force fight mitigation algorithm has been studied for force fight OFC events in FBW flight control systems of civil aircraft. After introducing the principle of OFC (including force fight), we explored regular OFC defined in CCAR25 and illustrated the theory of force fight.

We then proposed a force fight mitigation algorithm to mitigate DDP between the actuators. The algorithm exhibits highly satisfactory results in terms of robustness and detection. The DDP mitigation results for three worst-case scenarios were also analyzed. Further investigations are necessary to monitor force fight OFC Level 4 for closed-loop actuators.

Finally, the mitigation algorithm was tested using a dedicated Iron Bird test bench with actual FCS hardware; the aim being to assess algorithm performance. The test results showed obvious mitigation of DDP enabled by using the algorithm.

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