Abstract

During the aircraft’s flight, the control surfaces that enable the aircraft to perform the required maneuvers and the actuator that control them have to withstand loads. Those loads will affect the actuators lifetime and that is why it is very important to be able to predict their amplitude in order to make sure the actuators will last long enough and be efficient enough during the aircraft lifetime. Duty cycles are thus computed in order to compute the actuators fatigue severity and endurance criteria. The problem is that during the design of a new aircraft, duty cycles generation is very long process. The aim of this thesis it to predict the evolution of actuators fatigue with respect to design parameters in order to reduce computation time during incremental aircraft design.
Introduction

During the aircraft life, the control surfaces are going to withstand very high loads sometimes as well as average loads many times. The control surface actuators have to be able to move the control surfaces to maneuver the aircraft during the whole aircraft lifetime. To make sure the actuator will last long enough, it is crucial to be able to predict how fast it will be damaged and how its lifetime will be affected by the aircraft’s operations. The aircraft manufacturer will use a certain kind of actuators but while developing new aircraft with a design only slightly different from the previous one, the manufacturer has to be sure the actuators chosen at the beginning will withstand the loads due to the new design because new actuators would cost very much.

Duty cycles are studies performed in order to know, for a particular aircraft design, the actuator lifetime compared to a reference design. The point is that such studies take a lot of time, and sometimes changing only a small part of the aircraft’s design will not affect the actuator fatigue much. The goal of this study is to perform a sensitivity study on the duty cycles, that is, after having chosen parameters linked to a new aircraft design, be able to predict how changing a certain parameter will affect the actuator’s lifetime.

First, the parameters relevant for this study have to be chosen. Then, simulations will be performed in order to compute the loads the control surfaces will stand from their deflections during a whole flight. And at the end, the actuators fatigue can be computed and the impact of the chosen parameters can be determined.

In this report, after having exposed the theoretical background of this study, the method will be explained. The results will then be presented and discussed to be able to conclude at the end on the impact of each chosen parameter on the actuators’ fatigue and lifetime.
1 Conventions

1.1 Symbols

All the symbols used in this report are going to be described in the table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG</td>
<td>Center of gravity</td>
</tr>
<tr>
<td>$Z_p$</td>
<td>Pressure altitude (feet)</td>
</tr>
<tr>
<td>$\sigma_w$</td>
<td>Root mean square of the wind</td>
</tr>
<tr>
<td>THS</td>
<td>Trimmable Horizontal Surface</td>
</tr>
<tr>
<td>THSA</td>
<td>Trimmable Horizontal Surface Actuator</td>
</tr>
<tr>
<td>$M_c$</td>
<td>Hinge moment</td>
</tr>
<tr>
<td>$\delta_p$</td>
<td>Aileron deflection</td>
</tr>
<tr>
<td>$\delta_q$</td>
<td>Elevator deflection</td>
</tr>
<tr>
<td>$\delta_r$</td>
<td>Rudder deflection</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>angle of attack</td>
</tr>
<tr>
<td>$\beta$</td>
<td>sideslip angle</td>
</tr>
<tr>
<td>$\theta$</td>
<td>deflection angle</td>
</tr>
</tbody>
</table>

1.2 Sign convention

2 Theoretical background

2.1 Duty cycles

Actuators are going to withstand loads during the whole aircraft’s life. The aircraft has to be able to sustain mean loads many times as well as high loads it will perhaps encounter. Mean loads combined with a number of cycles and flight hours enable fatigue computation.

The duty cycle mission is a profile designed to represent, combined with flight cycles, the loads the aircraft will have to withstand during its whole lifetime. This profile is simulated by the handling qualities team in order to be used by the loads and actuator department.

In order to compute the mean loads, reference performance data have to be used. A reference flight
mission profile is designed from a performance point of view giving thrust, weight, altitude and speed mainly. For one type of aircraft, several mission profile are given: short range, middle range, long range and ultra-long range.

2.1.1 Mission profile

In order not to have to simulate the whole flight each time (what is very time consuming) the mission is divided into several flight segments (ground, take off, climb, cruise, descent, landing, ground) that are going to be simulated separately. For each of these segments, weight, speed, flight level and phase duration are given. The mission can be represented as a longitudinal flight path as shown on figure 1. This study will focus on a short range mission with 45 minutes duration.

![Figure 5: Longitudinal profile](image)

The longitudinal profile is combined with maneuvers that can be turns, use of air-brakes, aileron droop, ... This profile is divided into 15 flight phases and for each one of them, the maneuver and turbulence phases are simulated separately. All the flight cases will then be merged during post-processing to rebuilt the whole flight.

2.1.2 Assumptions

Starting from this mission profile, the flight phases will be simulated. For a given aircraft, different parameters have to be chosen to define an average mission like the payload, the engine, CG location.

- It is assumed that most of the time, taxi phases and take-off are performed manually and all the other phases are performed with autopilot.
- The value of CG position, mass and flight duration are taken from average values given by airlines statistics.
- For the turbulences, a model called HOBLIT has been used. For each flight segment, different levels and different frequencies of turbulence are modelled. The turbulence model will be developed in a following section of this paper.

2.2 Simulation

2.2.1 Simulation tool

The simulations are performed using a desk simulation tool. This tool uses a core that integrates the flight mechanics equations starting from stresses and moments computed by environment models such as the type of engine, aerodynamics, ground, wind, ... It is able to compute the stresses on control surfaces and hinge moments. This computation core takes as inputs scenario files that describe the conditions obtained after an equilibrium and the necessary inputs sequence to fly a given maneuver. The models of hinge moment and turbulence used for the simulations are described in the following sections.

For each flight segment, the turbulence and maneuver are going to be simulated separately. A different scenario file (xml file) is written for each case (turbulence or maneuver) for each flight segment. At the end of each simulation, all the aircraft data time history are stored such mass, phase duration, position of CG, but also orders deflections for every surface.
2.2.2 Turbulence model

The turbulence model is based on HOBLIT Norm (see Ref(1)) and is implemented directly in the simulation tool. It represents an average turbulence function of the altitude with an occurrence model associated. The probability to encounter a turbulence level of standard deviation $\sigma$ at altitude $Z_p$ can then be expressed depending on the scale of altitude and root mean square of turbulence.

A density of probability model is added. This model gives the probability to encounter a turbulence that has a RMS (root mean square) $\sigma_w$, function of the pressure altitude $Z_p$. It depends on four parameters and is the sum of one low turbulence term (low intensity $b_1$, high probability $p_1$) and a high turbulence term (high intensity $b_2$, low probability $p_2$).

$$p(\sigma_w) = P_1\sqrt{\frac{2}{\pi b_1}} exp[-\frac{1}{2}(\frac{\sigma_w}{b_1})^2] + P_2\sqrt{\frac{2}{\pi b_2}} exp[-\frac{1}{2}(\frac{\sigma_w}{b_2})^2]$$

The four coefficients of equation 1 can be computed for altitudes between 0 and 50 000 ft, and an interpolation will give them at any altitude. Integrating the density of probability function will then provide exceedance probabilities at any altitude.

Figure 6 shows the probability levels in function of altitude and turbulence intensity (in m/s). Intensities smaller than 0.2 m/s and larger than 3.5 m/s are not taken into account for fatigue computation (red areas). For each flight phase, 4 levels of turbulence are considered: 0.2 m/s and 3 other levels chosen in a range corresponding to intensity between 0.2 and 3.5 m/s. Then the time ratio spent by the aircraft at each level of turbulence is computed as in equation 2.

$$P_i = \int_{p_{i-1}}^{p_i} p(\sigma)d\sigma$$

The turbulences are defined as follows, where $\Omega$ is the angular turbulence velocity.

$$\Phi_p(\Omega) = \frac{\sigma_w^2}{VL_w} \frac{0.8 \times (\frac{\pi L_w}{V})^{1/3}}{1 + (\frac{4\pi}{\Omega})^2}$$

$$\Phi_q(\Omega) = \frac{\Omega^2}{1 + (\frac{4\pi}{\Omega})^2} \Phi_p(\Omega)$$

$$\Phi_r(\Omega) = \frac{\Omega^2}{1 + (\frac{3\pi}{\Omega})^2} \Phi_p(\Omega)$$

Figure 6: HOBLIT probability model
The impact of the turbulence velocities \( q \) and \( r \) has to be taken into account through aerodynamic coefficients only. The interpretation of those velocities in the model is the wind \( W_1 \) (\( W_{X0}, W_{Y0}, W_{Z0} \)) and the incidence and side-slip angles \( \alpha_v \) and \( \beta_v \) and there first time derivative. The values of \( \alpha'_v \) and \( \beta'_v \) are going to be filtered with time constants \( \tau_{\alpha'} \) and \( \tau_{\beta'} \) as function of the mean speed value of the flight phase considered.

The values of the wind speed and the filtered value of incidence and side-slip angles derivatives will be added in the turbulence flight phase description used for the simulation.

2.2.3 Hinge moment model

The hinge moment is calculated following the principle of reaction forces. The forces provided by the actuators compensate the aerodynamic force on the control surface. In the computation, the model takes the aircraft aerodynamic configuration, the deflection with respect to the actuator, the Mach number, dynamic pressure, CG and aerodynamic down-wash with propeller effect as inputs. It is able to compute the force on the actuator, the deflection, the deflection at zero hinge moment, the hinge moment with respect to the surface.

2.3 Actuator: Endurance and fatigue definition

The simulation tool can compute the stresses the control surfaces will encounter, but in order to compute the fatigue and endurance criteria on the actuators, an actuator model is needed.

2.3.1 Actuator types

The actuators considered in this study can be either with servo-command (SC) or with electro-hydraulic (EHA) technology, depending on the aircraft type. The actuator can be in several configurations depending on how many actuators there are per control surface. The simplex configuration corresponds to one active actuator for the considered surface and the other in damping mode, which means that it is not commanded and then just follows the surface deflection, damping the other actuator’s movement. Duplex and triplex are configuration with 2 or 3 active actuators. Table 2 shows the several actuator configurations possible on the studied aircraft.

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Elevator</th>
<th>Aileron</th>
<th>Rudder</th>
<th>Spoiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of surfaces per wing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Number of actuator per surface</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Configuration</td>
<td>Triplex (Duplex on demand)</td>
<td>Simplex (Duplex on demand)</td>
<td>Simplex</td>
<td>Simplex</td>
</tr>
</tbody>
</table>

2.3.2 Duty cycle

This analysis of fatigue severity is based on actuator loads computed with the hinge moment simulated before. The actuator is made of a hydraulic cylinder and the fatigue accumulation appears as cracks on the material surface that can change its shape.

Each flight phase is represented by two things:

- The most damaging cycle coming from \( F(t) \) spectrum
- Number of equivalent cycles to keep the same fatigue severity corresponding to the initial \( F(t) \) spectrum extracted using Rainflow method
- The fatigue severity is computed for two materials: aluminium and a steel/titanium. It is computed using the minimum and maximum loads and the number of equivalent cycles. The equivalent load \( F_{eq} \) is computed from that.
\[ R = \frac{F_{\text{min}}}{F_{\text{max}}} \]  

(6)

From the value of \( R \), an equivalent stress \( F_{eq} \) can be computed from empirical formulas and approximation.

The unit of the fatigue severity is \( daN^a \). The value of \( a \) comes from the slope of the S/N curve of the material in the linear part as shown on figure 7. The S/N curve shows the failure of the material as a function of the stress applied and the number of cycles with a logarithm scale. The red line shows the linear part of the curve, that is used to get an empirical coefficient in the fatigue severity computations.

![S/N Curve for Brittle Aluminium with a UTS of 320 MPa](image)

Figure 7: S/N Curve for Aluminium

\[ \text{severity} = F_{eq}^a \times N_{cycles} \]  

(7)

The analysis of endurance consists in analyzing seals and roller bearing, which are defined by:

- The Stroke (in degrees) : representative deflection on F(t) spectrum
- Number of associated movements corresponding to the same total surface stroke on F(t) spectrum
- Number of small movements for seals damages. They are not calculated for the THS actuator.

\[ \text{Bearing damages} = \text{stroke} \times (\text{associated load})^3 \]  

(8)

\[ \text{associated load} = \left( \frac{\sum PML^3_{\text{interval}}}{\text{interval}} \right)^{\frac{1}{3}} \]  

(9)

\[ PML^3 = \frac{F_{i+1}^4 - F_i^4}{4(F_{i+1} - F_i)} \]  

(10)

Those five criteria have been computed for each parameter but the study mainly focuses on the fatigue severity and bearing damage criteria. They can afterwards be compared to a reference and complete the duty cycle analysis.

2.4 Chosen design parameters

The parameters that are going to be used for this sensitivity study have been chosen depending on how much they can vary during incremental design (A321NEO starting from A321 for instance) and operational aircraft use. They are all summed up in table 3. The study only focuses on those parameters because they appeared to be the most relevant ones. For example, a difference between A321 and A321NEO is that the A321NEO has sharklets, but the aircraft have mainly the same shape except that.
### Table 3: Parameters chosen for the study

<table>
<thead>
<tr>
<th>Context</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental development of Aircraft</td>
<td>Mass</td>
</tr>
<tr>
<td></td>
<td>CG position</td>
</tr>
<tr>
<td>Adding sharklets, changing nacelles's geometry</td>
<td>$C_L(\alpha_0)$</td>
</tr>
<tr>
<td></td>
<td>$C_m$</td>
</tr>
<tr>
<td>Change in Lever arm, fin size, rudder deflection</td>
<td>$Cn_\beta$</td>
</tr>
<tr>
<td></td>
<td>$Cn_\delta_r$</td>
</tr>
<tr>
<td>Control surfaces efficiency</td>
<td>$Cl_{qp}$</td>
</tr>
<tr>
<td></td>
<td>$Cm_{\delta q}$</td>
</tr>
</tbody>
</table>

### Method

#### 3.1 Computation process

After having chosen the relevant parameters to study for this sensitivity study, the computation process takes places in four steps.

- First, the scenario have to be modified in order to take the changes in the chosen parameter into account. For each value, every scenario (complete flight) can be modified (for instance the CG position, the mass). Then simulations are performed using the desk simulation tool furnished by Airbus. This tool is able to compute deflections, stresses and moments during flight phases using pilot inputs.
- Second a first post-processing is performed using *Matlab*. Its purpose is to extract deflections and stresses from the simulation output data and to write them into a *Matlab* structure.
- A second post processing step is performed that consists in extracting the cycles using Rainflow method and computing the five fatigue / damage criteria.
- Finally the critical flight phases can be determined. The value of the criteria will be compared to a reference and the impact of the chosen parameter on the control surfaces can be determined.

#### 3.2 Visualization

After the simulation, it is possible to visualize some parameters chosen before and to see how they behave with respect to time. This helps explaining the fatigue results obtained with the code.

The results are then presented as the evolution of the fatigue criteria in function of the chosen parameter compared to a reference. It is important to remember that all the fatigue computation are going to be interpreted relatively to a reference duty cycle.
4 Results

It is important to specify here that all the work that has been done for this study is relative to a reference study that belongs to the manufacturer. The purpose was to calculate the fatigue evolution compared to the reference. The parameters values have been chosen relatively to the reference as well. The reference values of weight and CG location come from fleet survey on the A321.

4.1 Mass variation

4.1.1 Chosen values

While designing a new aircraft from an existing one, changing anything in the geometry or changing the type of engine will automatically affect the weight of the aircraft.

The mass values have been chosen according to the weight-balance diagram of the aircraft. In this study the values are between $-11\%$ and $+6\%$ of the maximum take-off weight. The values are chosen accordingly to this weight so the results can then be compared with other aircraft. It is important to note that in reality, the landing speed changes according to the aircraft weight, so this fact has been taken into account and the flare / landing phase has been simulated with different speeds for every different weight.

Table 4 shows the obtained results. For the mass variation, the most affected surface is the elevator during landing.

Table 4: Mass variation results summary

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevator</td>
<td>flare landing</td>
<td>[80% − 150%]</td>
<td>[96% − 125%]</td>
</tr>
<tr>
<td>THS</td>
<td>flare landing</td>
<td>[65% − 130%]</td>
<td>[98% − 102%]</td>
</tr>
<tr>
<td>Spoiler</td>
<td>flare landing</td>
<td>[60% − 128%]</td>
<td>[71% − 114%]</td>
</tr>
</tbody>
</table>

4.1.2 Results analysis

Concerning the evolution of fatigue severity and bearing damages for the elevators and THS, it is due to the fact that if the aircraft is lighter it will fly with a lower speed during flare / landing. A lower speed will imply a smaller dynamic pressure and hence a smaller lift. If the lift is smaller, the pitch down needed during landing is smaller and the needed deflection of the elevator is smaller. The THS will be less deflected because it needs to counterbalance a smaller lift and the stresses on the THS will be smaller because of a smaller dynamic pressure.

The fatigue severity and bearing damages are smaller for a lighter aircraft because the landing speed is lower and the dynamic pressure as well. The stresses on the spoilers during landing will then be smaller.

4.2 Center of gravity location variation

4.2.1 Chosen values and summary

In a similar way as for the mass variation, changing the aircraft geometry and design will automatically be followed by a possible change of the center of gravity location.

The convention used in this report is that the location of the center of gravity is defined with respect to the leading edge of the wing. Its position is given as a percentage of the mean chord. A small value will then mean a forward CG position. The values of the CG location are chosen between the more aft and the more forward position according to the flight domain.

Table 5 shows a summary of the results obtained for the variations of CG location. It appears clearly that the most impacted surface is the THS during landing.
Table 5: CG location results summary

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevator</td>
<td>descent, flare</td>
<td>[65% – 125%]</td>
<td>[65% – 157%]</td>
</tr>
<tr>
<td>THS</td>
<td>descent, flare</td>
<td>[80% – 208%]</td>
<td>[80% – 168%]</td>
</tr>
<tr>
<td>Rudder</td>
<td>take-off, climb</td>
<td>[88% – 125%]</td>
<td>[87% – 121%]</td>
</tr>
</tbody>
</table>

4.2.2 Results analysis

The most impacted surfaces are the THS, the elevators and the rudder since those three surfaces are located at the tail. When the CG is located forward, the static margin is bigger.

The THS needs to deflect more in order to balance the aircraft because if the static margin is bigger, the pitching moment created by the lift is bigger as well and needs to be counterbalanced by a higher lift created by the THS deflection. The THS will then encounter higher stresses.

The elevators need to deflect more because with a higher static margin, the aircraft is more stable and need a higher moment created by the elevator to pitch up or down.

Concerning the rudder, the total fatigue severity also decreases while the CG location is moved backwards during turbulence phases that are the most critical. The flare phase is one of the most important also but the evolution of the fatigue is different. The fatigue increases for crosswind landing while the CG location is moved backwards. This is due to the crosswind increasing the rudder efficiency but also the fin efficiency that stabilizes the aircraft. The rudder then needs more deflection. During turbulence phases, the flight control laws depend on the CG location and that is why the rudder is more deflected for a forward CG location.

4.3 Lift coefficient variation

4.3.1 Chosen values

The value of the lift coefficient for the aircraft will be affected by changes in the aircraft overall geometry or if sharklets are added.

The Lift coefficient has been changed by removing or adding a small $\Delta C_l$. The value of the zero lift angle of attack will then be changed but the value of $C_{l_{\text{max}}}$ is assumed to stay the same. The values have been chosen in a range between $-10\%$ and $+10\%$ of the reference value. The most impacted surfaces are the THS and the elevators during landing phases. Table 6 shows the obtained results for lift coefficient variations.

Table 6: Lift coefficient variation results summary

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevator</td>
<td>landing</td>
<td>[83% – 113%]</td>
<td>[95% – 112%]</td>
</tr>
<tr>
<td>THS</td>
<td>landing, climb, descent</td>
<td>[73% – 120%]</td>
<td>[87% – 117%]</td>
</tr>
</tbody>
</table>

4.3.2 Results analysis

The lift coefficient has an influence on the surfaces acting for longitudinal control. The fatigue severity is higher for a smaller lift coefficient for both the THS and the elevator. This can be explained by the fact that flying with a higher lift coefficient is equivalent to flying with a smaller angle of attack as shown on figure 9 where $\alpha_1 > \alpha_2$. This implies a smaller down-wash on the THS and elevator.
4.4 Pitching coefficient

4.4.1 Chosen values and results summary

The pitching coefficient is also changed by any changes in the aircraft geometry.

The pitching coefficient has been changed by adding or removing $dC_m$, following the same principle as for the lift coefficient (keeping every other value the same). The values of $dC_m$ are in a range between $-10\%$ and $+10\%$ of the reference value.

Table 7: Pitching coefficient variation results summary

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>THS</td>
<td>landing, descent</td>
<td>$[85% - 120%]$</td>
<td>$[50% - 390%]$</td>
</tr>
<tr>
<td>Ailerons</td>
<td>landing, descent</td>
<td>$[96% - 112%]$</td>
<td>$[98% - 101%]$</td>
</tr>
<tr>
<td>Elevators</td>
<td>landing, descent</td>
<td>$[95% - 102%]$</td>
<td>$[60% - 125%]$</td>
</tr>
</tbody>
</table>

Table 7 shows the obtained results for the variations of the pitching coefficient. The most affected surface is the THS during the landing phase.

4.4.2 Results analysis

For the THS first, the higher the pitching coefficient is, the lower the fatigue severity is during landing flight phases. With $dC_m > 0$ the aircraft pitches more up and needs less force on the THS to be at equilibrium and less $C_l$ on the wings. The aircraft needs to fly with a smaller angle of attack and hence there is a smaller down-wash on the THS that produces lower loads on it. During landing, the elevator needs to deflect less for $dC_m > 0$ because of the smaller angle of attack.

But during the descent, the evolution of the severity is the other way around. The severity is higher for higher pitching coefficient. This is due to the fact that during the descent air-brakes are used and they produce a higher down-wash on the THS for $dC_m > 0$. The air brakes reduce the lift so the elevator needs to deflect more so the aircraft can descent.

For the ailerons, the main changes in fatigue severity occur during the landing phase, when the ailerons are used for anti-droop. It means the ailerons are deflected upwards just after the aircraft touched down in order to kill the lift and prevent the aircraft from rebounding. If the $C_m$ is higher, the lift is lower and so the ailerons will have to sustain lower loads during anti-droop.

4.5 Yawing coefficient variations due to side-slip angle and rudder deflection: $C_{n\beta}$ and $C_{n\delta r}$

4.5.1 Chosen values and results summary

While designing a new aircraft, in order to improve lateral movements, the thin size and rudder maximum possible deflection can be changed. They can be taken into account as geometry changes but they will
have a direct impact on the yawing moment.

In the model used for the simulations, the yawing coefficient is assumed to be the sum of the following contributions: Side-slip angle ($\beta < 30$ degrees), large side-slip, side-slip rate, roll rate, yaw rate, bank angle on ground, rudder, spoilers and aileron deflection, asymmetric elevator, jet effects, wind turbulence, side-slip on nose gear, effect of half a main gear extended, landing gear doors, thrust reversers, slats/flaps failure, sharklets loss. In this study only the effect of a side-slip angle smaller than 30 degrees and the rudder deflection effect are considered.

The values of $C_{n,\beta}$ and $C_{n,\delta_r}$ have been chosen as rates of the values of the reference, in order to be interpreted as effectiveness later. For the sideslip angle effect, the effectiveness has been chosen between 50% and 150%. For the rudder deflection effect, the values are between 80% and 120%. Only the variations of fatigue criterias on Rudder are going to be considered.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>sideslip angle $\beta$</td>
<td>climb turbulence, descent, landing</td>
<td>[88% – 121%]</td>
<td>[88% – 119%]</td>
</tr>
<tr>
<td>rudder deflection $\delta_r$</td>
<td>take-off, crosswind landing</td>
<td>[97% – 120%]</td>
<td>[97% – 117%]</td>
</tr>
</tbody>
</table>

Table 8 shows the obtained results for both coefficients. The impact is moderate for fatigue severity and bearing damages criteria.

### 4.5.2 Results analysis

For the side-slip angle contribution, the higher this yawing moment is, the higher the fatigue is. The most critical phases are climb turbulence phases. During those phases, the amplitude of the crosswind is the highest and the occurrence of the turbulence is high. And a higher amplitude of the wind creates a higher destabilizing yawing moment on the aircraft. The rudder needs to deflect more for high $C_{n,\beta}$ in order to compensate this moment.

Concerning the rudder deflection contribution, it represent the rudder efficiency. The most critical phases are crosswind landings, because they are the phases when the rudder needs to be efficient to de-crab the aircraft and put it in the runway axis. If the rudder is more efficient (higher $C_n$ created with same deflection) it needs to deflect less to perform the same maneuvers. That is why the higher the rudder efficiency is, the lower the fatigue severity is.

### 4.6 Aileron efficiency $C_{l,\delta_p}$

#### 4.6.1 Chosen values and results summary

Sometimes the control surfaces efficiency can be changed and it is crucial to know the fatigue evolution trend in that cases.

The aileron efficiency has been chosen following the same principle as for the yawing coefficient, choosing $C_{l,\delta_p}$ between 50% and 150% of the reference value. It is relevant to only consider the results on the ailerons.

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aileron</td>
<td>flare landing</td>
<td>[99% – 103%]</td>
<td>[99.8% – 101%]</td>
</tr>
</tbody>
</table>

Table 9 shows the obtained results. The first thing to say is that the ailerons actuator are not much affected by the ailerons efficiency at all.
4.6.2 Results analysis
The most critical flight phase is the landing. The lower the aileron efficiency is, the most the ailerons need to deflect and the actuators will fatigue.

4.7 Elevators efficiency $C_{m_{sq}}$

4.7.1 Chosen values and results summary
The elevators efficiency has been chosen between 90% and 110% of the reference value. It is only relevant to consider the fatigue variations on elevator only in order not to take any cross effect into account.

<table>
<thead>
<tr>
<th>Control surface</th>
<th>Critical phases</th>
<th>Fatigue severity</th>
<th>Bearing damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevators</td>
<td>flare landing</td>
<td>[88% – 123%]</td>
<td>[93% – 119%]</td>
</tr>
</tbody>
</table>

Table 10: Elevators efficiency results summary

Table 10 shows the obtained results. The impact is moderate.

4.7.2 Results analysis
The most critical phase for elevators efficiency is the flare / landing. During those phases, the fatigue is higher if the efficiency is lower which is consistent with the fact that if the surface is less efficient, it will have to be deflected more and the actuator will be more damaged.
Conclusion

The goal of this study was to perform a sensitivity study on duty cycles missions by simulating flight phases and interpreting the results. The study has been performed on the Airbus aircraft A321NEO. The first step consisted in choosing the relevant parameters to study in the context of incremental development of new aircraft, and then the following steps were simulating the flight phases and computing the fatigue criteria.

This study has enabled several achievements:

- Producing a sensitivity study on duty cycles for the main parameters involved in incremental A321NEO development, so the engineers will be able to decide which parameter is worth a new duty cycle computation. This sensitivity study is able to give, for a given parameter change, the trend for the fatigue and endurance criteria evolution, which surface actuator is the most affected and which flight phase is the most critical.

- Coding a matlab tool that can compute the fatigue criteria for all the Airbus aircrafts from the simulation.

- Results that can be used by other teams than Handling Qualities : Actuators and Loads teams at Airbus.

For further development this study should be performed on other aircraft of course in order to have a complete tool that can help engineers decide which parameters and flight phases to focus on while developing new aircraft. During this study, the parameters that have been considered were always considered separately but an even deeper study could consist in investigating the effect of several parameters at the same time and if some of them compensate each other.

References


