TOWARDS DERIVING LOADS SPECTRA REPRESENTING OPERATIONAL LIFE: EQUIVALENT FLIGHT PROFILE VERSUS SINGLE FLIGHT PROFILES

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Abstract:
Deriving the loads spectra is an essential task for structural sizing to achieve an acceptable economical life for a product. Furthermore, compliance with the certification requirements shall be based on typical loading spectra expected in service. The task that arises consists in deriving loads spectra to represent an operational life comprised by different flight profiles whose features may vary widely from one operator to another. The current work aims to compare two approaches used to address this issue: either treating each flight profile distinctly or deriving one equivalent flight profile that intends to accommodate all the former ones. A study case defined for a hypothetical loading scenario is presented and a stress analysis is performed to compare the fatigue results from both approaches. The benefits and risks that result from adopting one approach or another are also evaluated. Finally, this work provides resources to optimize the application of the different proposed loading spectra along the overall aircraft design process.

Keywords: Fatigue, Damage Tolerance, Loads Spectra, Flight Profile, Load Sequence

INTRODUCTION

The development of an airplane requires its structural sizing in such a way to guarantee the safe operation throughout the whole operational lifetime. Moreover, for the operational utilization of an airplane it must receive its Type Certificate (TC) by the proper regulatory agency. The main regulatory agencies: FAA (Federal Aviation Administration) and EASA (European Union Aviation Safety Agency), prescribe requirements that must be totally attended to allow the emission of Type Certificate (TC). To achieve this, aircraft manufacturing companies shall provide for each requirement the appropriate Means of Compliance (MoC) substantiating its compliance. In this direction, regulatory agencies also provide a guidance for the compliance demonstration [3], [4] of some requirements. Among the requirements and rules, the fatigue and damage tolerance requirement [1] prescribes that the evaluations of fatigue and damage tolerance must include the typical loading spectra expected in service. The requirement also states that the evaluations shall include analysis supported by test evidence and the development of the maintenance plan and inspections that shall the obeyed along the airplane operation. The fatigue and damage tolerance guidance [3], states that “the loading spectrum used for crack-growth and fatigue-crack-initiation assessments (tests or analyses) should be based on measured statistical data of the type derived from government and industry load-history studies and, where data is insufficient or unavailable, on a conservative estimate of the anticipated use of the airplane”.

Considering this, theoretical loads spectra shall represent and/or exceed the loading conditions that the airplane might face during its operational lifetime. Even more, the theoretical loads spectra are also applied to the full-scale fatigue test to substantiate the analysis results, as required by the certification agencies. This is by far the most significant and expensive certification test rig and is also based on the theoretical loads spectra. In some cases, once the aircraft is operational, it has been verified that the actual loading conditions differs somehow from the theoretical one proposed for certification. In those cases, an adjustment of the full-scale fatigue test based on the actual loading conditions is requested and a revision of the aircraft's maintenance plan might be needed, increasing development and operational costs. On the other hand, if distinct loading conditions are not properly identified by the manufacturer, the fatigue and crack propagation issues may arise through the aircraft's operational life. In such case, the corrective actions are exceptionally high-priced. Deriving of representative theoretical loads spectra is an essential key not only for the certification phase, but also for the airplane competitiveness as a product in the aeronautical market since it will drive the maintenance plan and periodic inspections for the whole lifetime.

Recent studies demonstrate that aspects related to the operational usage shall be observed to derive loads spectra for an airplane under development. The research performed by Newcamp et. al [5] demonstrates that the aircraft loading patterns are correlated to the mission type, mission duration and aircraft type. In its work military attack aircraft use case was studied to investigate the influence of mission types, flight duration, aircraft design type and aircraft aging in the loading spectra. The study shows that typical aggressive mission types, like: Basic Fighter Maneuvers and Surface Attack profiles, accounted for greater occurrences of vertical load factor (Nz). On the opposite direction, Close Air Support and Navigation flight profiles are associated to a generalized lower occurrences of load factors. This shows a coherent behavior since the last mission profiles spend more time flying at 1 g condition and excessive maneuvering are not required. Moreover, the authors demonstrated that the load factor counts vary exponentially with flights duration. Such relation is expected since longer flight duration gives a pilot more opportunities to maneuver the aircraft through a wider range of load factors, leading to an increase in the occurrences. Additionally, the work compares the load factor results presented in specialized literature for different airplanes and turn evident the influence of the aircraft design type into loading patterns. Conversely, it was verified that the aircraft aging has no significant effect in the load factor occurrences recorded in a flight. The work also shows that a loads model based on the mission type can be useful for fleet planning and mission allocation strategies and for structural lifetime extension for aging aircraft.

The influence of mission types and flight duration in the loading pattern are accounted by Le Divenah and Beaufils [6]. Their work presents the Airbus state of the art to derive complex loads spectra to design modern large commercial airplanes. One relevant practice described is the cooperation with potential customers at the beginning of an aircraft design to identify the mission profiles that should be representative of operational usage for the new airplane. In its work, the authors divided the mission profile into several segments where duration, altitude, aircraft mass and disturbances are specified. The disturbance attributed to a segment is a cumulative distribution function that aims to represent the incremental stresses that occur due to a quick evolution of loads such as gusts, bumps or landing. Loads are computed for each mission segment, being compounded by the equilibrium loads (called n=1), which represents an equilibrium state of the structure, and the incremental loads derived from the disturbance model.

As observed several assumptions stated during the design phase of an airplane like mission type, flight duration and aircraft type design may differ from the actual conditions during their operational life. The differences may be attributed to changes in the mission types, modification, or addition of devices mounted in the aircraft. This is usual for military aircrafts. To keep the maintenance plan adherent to the actual usage, it is necessary the assessment of the effects of such differences. Such assessment requires a fatigue life prediction tool to enable studies concerning the effects of future configuration changes on the fatigue life of an aircraft. In this direction, Prananta et. al [7] describe the development of a generic flexible loads database system which shall be employed to generate fatigue loads sequences at the critical locations of a flexible aircraft structure for predefined or flown missions. The loads database system conception comprehends three main tasks: parametrization of the aircraft loads, development of the database system and generation of loads data to provide for the database. The parametrization of the aircraft loads consists in express the usage missions in terms of the flight conditions at which the loads data shall be determined to perform fatigue analysis. The database system, created to interpolate and extract loads for a required flight condition in a fast and efficient way, is based on loads data corresponding to a set of operational conditions selected to span the complete envelope. Such loads data that support the database system comprise the external loads (aerodynamic and inertia forces) which are obtained from aeroelastic simulations and the internal loads that consists in stresses at the critical locations of the structure and are determined using proper finite element model. The work states that such loads database system concept was successfully verified and validated against F-16 flight data. It also refers to the application of the method to provide input data for updating maintenance plan of an aircraft.

A new technique for deriving loads spectra from actual flight data was proposed by Ali et al.[8]. Such methodology aims to reduce the random service loading of actual operation into simple stress reversals which are more convenient to be applied in laboratory fatigue tests to estimate the real fatigue life. Instead of the traditional rainflow method [9], [10] this technique adopts a simplified approach for cycle counting that also considers the sequence of events. The spectrum is derived from the flight data analysis, by measuring statistical data concepts like PSD, mean value and standard deviation.

It is well established that fatigue and damage tolerance assessments shall be based on realistic cyclic loading conditions. To achieve this, it is necessary to comprehend the in-service loading environment and represent it in a proper way. Towards this, methods to generate standard loads spectra and load sequences (time-histories) have been developed. Heuler and Klätschke [11] work presents an overview of the main standardized load sequences available in the mechanical industry like: TWIST and Mini-TWIST that are applicable to transport aircraft wing root analysis and fatigue tests correspondingly and HELIX and FELIX which were developed for helicopters hinged and fixed rotors analysis respectively. The aircraft loading patterns are correlated to the mission characteristics, as demonstrated by Newcamp et. al [5] study. Considering such conclusions and the recommendation stated by Le Divenah and Beaufils [6], the initial task to derive the loads spectra for an airplane under development is the definition of the use purpose for the final product. Such task consists in identifying the group of typical flight profiles that will comprise its operational lifetime and the occurrences distribution expected for these flight profiles. However, several parameters required to define the utilization scope change from one operator to another. The group of typical flight profiles may vary widely among the possible operators leading to loads spectra that may also vary widely. Trying to cover all the potential operators may result in too conservative loads spectra, leading to inspection intervals shorter than necessary and in a worse case, it may even lead to an oversized airplane. In contrast, to focus in one specific operation may lead to a structure's design whose applications become not feasible to another operators. Finding equilibrium between a comprehensive identification of flight profiles and a competitive product it is not an easy task.

In this context, the current work presents two different approaches to derive theoretical loads spectra for application throughout the airplane design, sizing and experimental testing campaign required for certification: (i) a linear combination of each single flight profile or (ii) adopting an equivalent flight profile that aims to accommodate the contribution of all the single ones. The two approaches are compared by means of the loads spectra results on cumulative fatigue damage and the positive and negative aspects that arise from each solution, as well as the precautions that shall be taken for each case, are described. The work proposes the suitable moment to adopt one solution or another along the overall aircraft design process.

OPERATIONAL LIFE DEFINITION

The group of flight profiles that represents the operational life proposed for a certain airplane varies according to the airplane model and its applicability in the aeronautical market. The identification of the most common flight profiles arises from a detailed investigation of the market’s demands for airplanes in a given category. In order to achieve this goal, it is necessary to understand the potential operators, their most frequent routes and the parameters that typically describe the flight profiles. Moreover, for certain airplanes categories, it may also become necessary to understand particular procedures that might affect the loads spectra. It is known that different flight profiles lead to different loads spectra. In this direction, some parameters and procedures involved in a flight profile scope can play an important role in the fatigue loads spectra. To illustrate this, Figure 1 shows three flight profiles, presented at same time scale. A brief qualitative analysis of such profiles will illustrate how payload, range and routines can affect in noticeable way the final loads spectra.

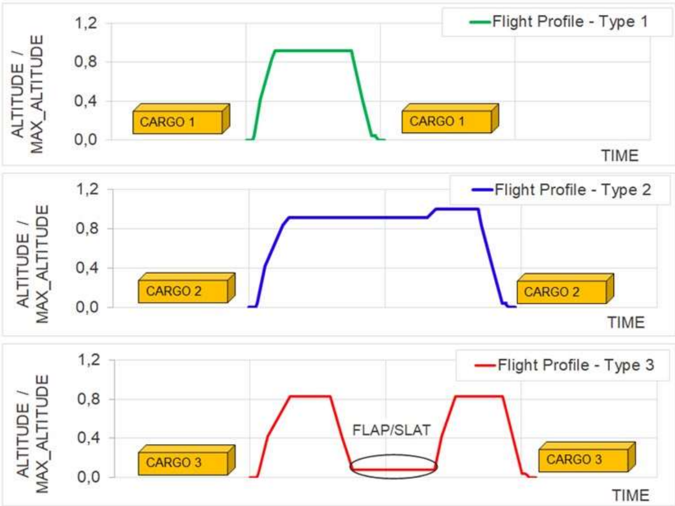

Figure 1: Different Types of Flight Profiles

The first and second flight profiles presented in Figure 1 refer to simple transport flights. In contrast, the third one refers to a flight that requires execution of dedicated procedures during a cruise at low altitude level. In this simplified illustration, it is considered that these three hypothetical flight profiles are associated to different payloads, flight time duration, cruise flight level and operational purposes. The parameters payload, flight time, and flight level partially define the scope of one flight profile and their variations may lead to substantial effects in the correspondent loads spectra. The payload directly affects the airplane total weight throughout all the flight phases, influencing the loads acting in the whole airplane from the ground handlings before the take-off up to the ones after the landing. The flight time duration shows a double effect in the loads acting in the airplane. Firstly, the larger the time, the larger the amount of fuel required to comply the flight, increasing the airplane weight along the ground handlings before the take-off and in the initial flight phases. Additionally, the larger flight time duration represents a larger exposition time of the aircraft to turbulence and flight maneuvers. Considering these two aspects, the larger flight time can be translated into greater steady loads in the initial flight phases and greater amplitude load cycles due to gusts and maneuvers during the cruise segments.

The cruise flight level determines the maximum differential pressure acting in the fuselage cabin along the flight, for a cabin pressurized design. Considering this, a brief analysis of Figure 1 indicates that the three flight profiles are related to different cycles of differential pressure, since each one is associated to a distinct flight level. For instance, flight profiles type 1 and 2 are associated to only one differential pressure cycle, while flight profile type 3 is associated to two cycles due to the altitude variation to perform the cruise at low altitude level.

As described previously the scope of a flight profile is associated to the demands of the airplane operators. As a result, some flight profiles may present flight phases or procedures adjusted to the purposes of one operator. One example is presented in flight type 3 of Figure 1. The cruise at low altitude may be determined by the demand of specific procedures whose nature may vary widely from one operator to another. Some examples of flight profiles that demand this type of cruise phase are the cargo aerial delivery for humanitarian purposes, search and rescue operation over sea or land areas, aerial fire flighting, aerial monitoring or reconnaissance. This flight phase is frequently associated to low speed to guarantee feasible conditions to identify the areas or targets. To keep such low speed, it is required the use of high lift devices such as flap and slat deflected, increasing the exposition of these components, mechanisms and attachments to additional load cycles that do not occur in a regular transport flight.

There are several other parameters and conditions that may affect substantially the airplane loads and flight profiles such as airplane market category (commercial, defense or business) and departure and arrival airports altitude and runway length. Considering these aspects, it is verified that defining representative flight profiles are the key to derive the loads spectra that shall be applied to perform fatigue analysis, structural sizing and inspection plan.

STRATEGIES TO DERIVE LOADS SPECTRA FOR AN AVERAGE USAGE

Deriving the typical loads spectra for an airplane under development comprises two basic tasks: (1) to define the average flight profile and (2) to determine the loads cycles related to such flight profile.

<u>Define Average Flight Profile</u>
This task lies on identifying the typical flight profiles that represent the operational life proposed for a given airplane. Also, it shall be determined the occurrences supposed for these typical flight profiles during the operational life. Table 1 shows a hypothetical usage distribution, adopted here as an example, considering the flight profiles shown in Figure 1.

Table 1: Operational Usage Distribution

Flight Profile	% Flights
1	30
2	60
3	10
Total	100

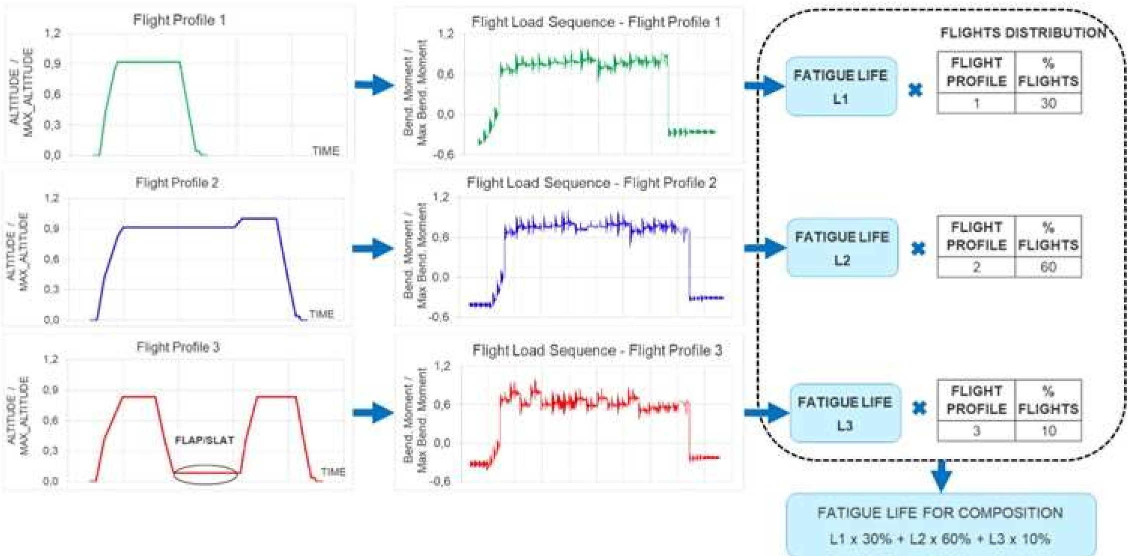

Figure 2: Single Flight Profiles Solution

The first solution illustrated in Figure 2 lies on the adoption of one single flight profile suitable to each typical flight profile that composes the operational usage. Therefore, each flight profile originates its own flight load sequences, and a fatigue analysis must be performed in terms of each one. Then, the final fatigue life is obtained from weighted linear combination of each flight profile fatigue life, by the respective flight profile percentage of occurrence.

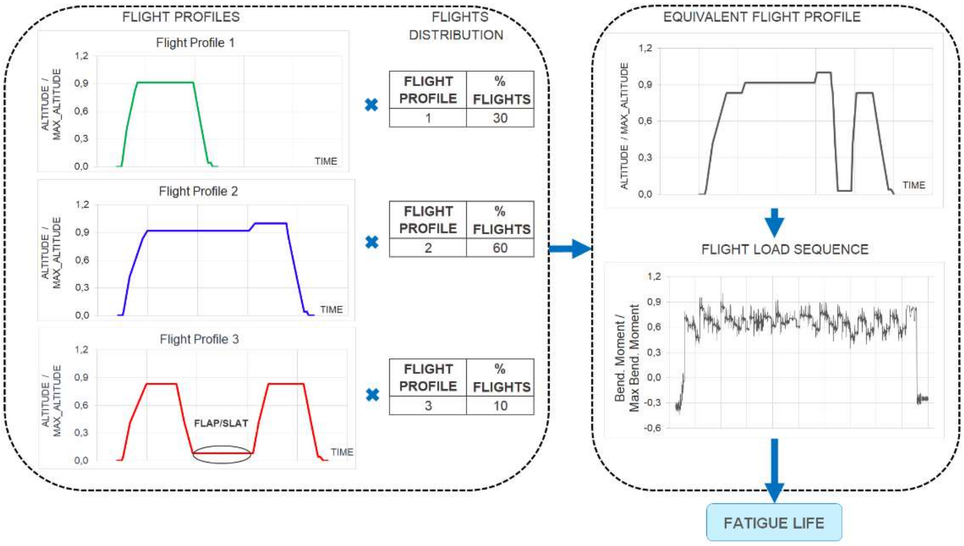

Figure 3: Equivalent Flight Profile Solution

The second solution is briefly illustrated in Figure 3. As described in the sequence, the equivalent flight profile intends to accommodate all the flight segments of all the typical flight profiles, pondering each segment duration by the corresponding flight profile percentage of occurrence in the proposed usage. In this solution, flight load sequences are derived from the equivalent flight profile and then the fatigue analyses are performed in terms of this unique flight profile loads results.

Equivalent Flight Profile: Calculation Workflow

Different from a single flight profile, the equivalent flight profile is a mathematical solution which aims to comprise in a consistent way the characteristics of the single flight profiles identified for a given aircraft / operator. In this sense, the equivalent flight profile does not represent a single physical flight.

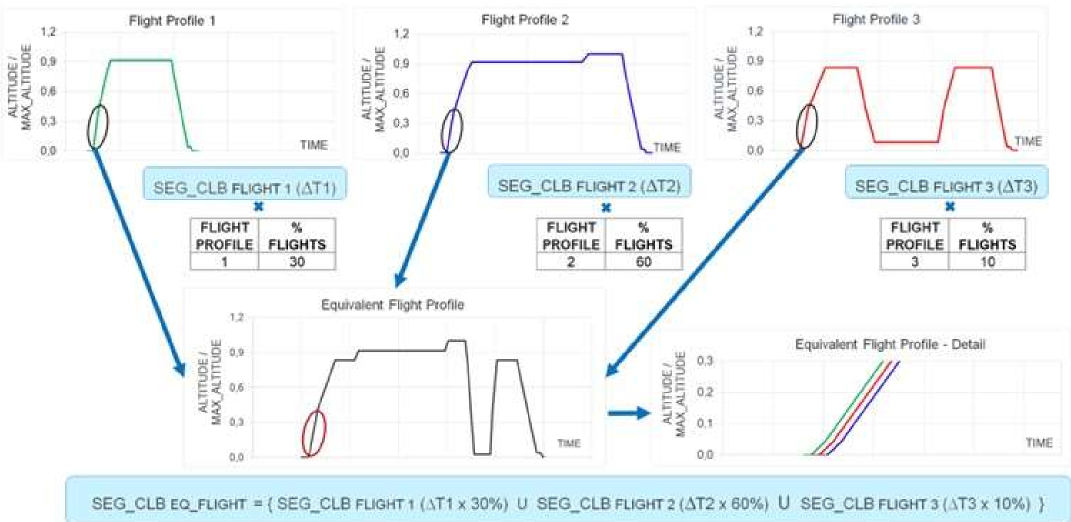

Figure 4: Construction of Equivalent Flight Profile

The workflow for calculation of the equivalent flight profile is summarized in Figure 4 taking as example the hypothetical usage considered. Primarily, it shall be observed that the equivalent flight profile is composed by all the flight segments contained in all the single flight profiles. Figure 4 illustrates the process to characterize of the initial climb segment, which occurs in the three single flight profiles, into the equivalent flight profile. First the segment of each single flight profile has its duration normalized by the respective percentage of occurrence, then each one is attributed to the equivalent flight profile, carrying with it all its features. Therefore, in the equivalent flight profile the initial climb comprises three flight segments, as shown in the Figure 4 detail. Conversely, the low altitude flight segment that appears in the equivalent flight profile has arisen uniquely from flight profile 3. The normalization of the flight segments length time guarantee achieving a coherent duration for the equivalent flight profile. In fact, the flight duration of the equivalent flight profile will be the mean flight time of operational usage assumed. Eqn. 1 presents the normalization of the flight segments length time:

$$\Delta T_{n,q\_EF} = \Delta T_{n,q} \times Dist_k \quad (1)$$

Where $\Delta T_{n,q\_EF}$ is the time duration of the equivalent flight profile flight segment that arisen from the n^{th} flight segment from the k^{th} single flight profile, ΔT_n is the time duration of n^{th} flight segment along the k^{th} single flight profile, $Dist_k$ is the percentage of occurrences of the k^{th} single flight profile in the operational usage.

The ground segments like taxi, take-off run, ground maneuvers, landing and landing roll events are treated differently on the composition of the equivalent flight profile These events occur in all single flight profiles and are not attributed simultaneously to the equivalent flight profile, since it could increase deeply its severity. Considering this, the ground segments are assigned into the equivalent flight profile block of flights in such a way that the set of segments matches the set of ones observed in one block of flights comprised by the single flight profiles, taking into account the respective percentage occurrence.

Load Cycles Characterization Workflow

After the calculation of the flight profiles, the next step towards a fatigue analysis is the determination of the corresponding load cycles. Schijve [12] describes in his work that among a variety of different loads, two major types shall be recognized: deterministic and stochastic loads. The loads are judged as deterministic when the number of occurrences and magnitudes can be determined solely based on the airplane and flight profile characteristics. Some examples of deterministic loads are the steady-state inertial and aerodynamic loads along each flight phase, which compose the mean load throughout the flight profile. For such conditions, the parameters that define the flight profile and the airplane mass configuration are enough to derive the loads associated to each flight segment. Another example is the hoop stresses induced in the fuselage skin by the airplane pressurization. In this case, the instant altitude, the pressurization schedule and the fuselage section diameter are enough to determine such loading state. In contrast, stochastic loads are defined by a statistical nature. This means that the airplane is supposed to face load cycles whose occurrences and magnitudes vary from one flight to another, even if only a single flight profile is adopted during the whole lifetime. Certain loading conditions have a recognizable stochastic nature, as turbulence (gusts), flight maneuvers, take-off and landing.

Schijve [12] describes that deterministic and stochastic loads can occur simultaneously in an airplane structure. It is possible to consider that the load cycles are combined by deterministic loads (steady-state loads) and stochastic loads, which means incremental loads to the steady-state conditions. Such composition is also described on Le Divenah and Beaufils [6] work, in which the steady-state loads are named as equilibrium loads and the incremental loads are derived from an in-house disturbance model.

Figure 5 presents a brief flowchart that illustrates the process adopted in the current work to derive a load spectrum for one flight segment. It is assumed that the load spectrum is comprised by a mean load and an incremental one. The mean load is the airplane's equilibrium load for a given flight condition. It is essentially computed from the airplane and the flight segment characteristics.

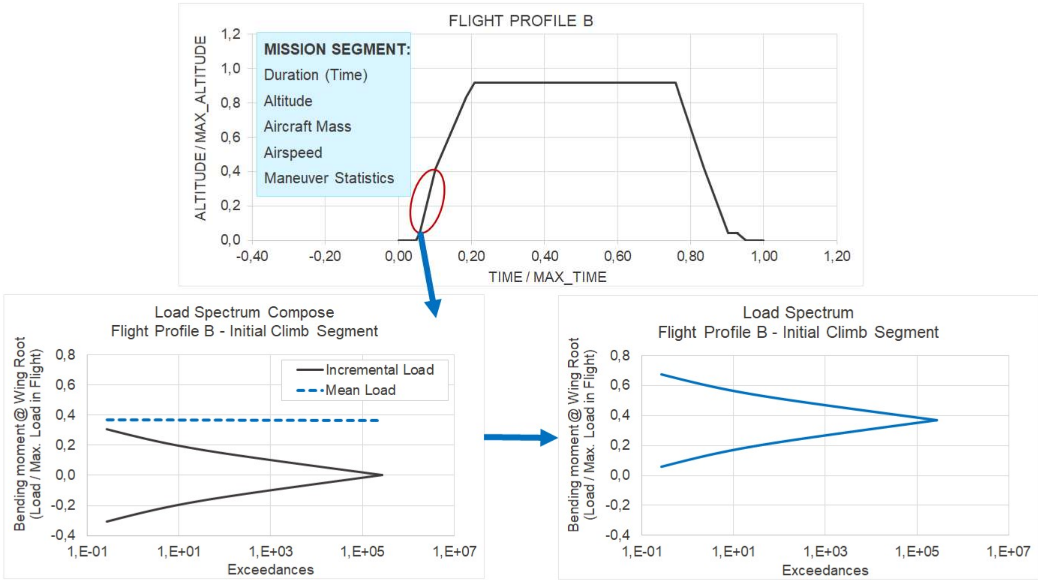

Figure 5: Deriving Loads Spectrum for a Flight Segment

Conversely, the incremental loads require a statistical model that represents the condition evaluated. The statistical model can be derived from recorded data obtained from in-service history of airplanes of similar structure operating in similar conditions available in the specialized literature, which comprises reports dedicated to present statistical data collected from actual operation of several airplane categories. Some examples are the work developed by Jones et. Al [13]; Rustenburg et. al [14], [15], [16] and Tipps et. al [17], [18], [19]. In the current work, the statistical model adopted are constructed for such airplane, for each condition and each segment from in house methods and/or in-house flight tests data. The incremental load spectrum is computed from the association of the flight segment duration to the statistical model. The load spectrum is then obtained from the sum of the mean load and incremental load spectrum. As observed, the definition of the flight profile and appropriate references for statistical data are the main requests to derive the load cycles to represent one operational lifetime.

Flight Load Sequence Definition

For practical purposes, during the aircraft's operational lifetime it is expected that in some flights the airplane become exposed to more severe conditions, for example intense gusts, circumstances in which it is expected more demanding flight or ground maneuvers, touchdown with high sink speed values or takes-off with aggressive angular rotating speed. The consequence is that these flights shall present both larger number of load cycles and larger load magnitude. On the other hand, it is also expected that in other flights the airplane will be subjected to small load fluctuations around the equilibrium flight loads, meaning that, oscillations related to the stochastic nature are negligible. In this case the load cycles are mainly defined by the deterministic loads along the flight profile.

The load cycles variability observed among the flights shall be represented in the analysis loading data. A practical way to achieve this is the adoption of the standardized load sequence concept. Heuler et. al [21] states in their work that the standardized load sequence has been recognized as advantageous for both: assessments and practical application. Heuler et. al [21] present an overview of existing standardized load sequences, their fields of application and their relevance for the fatigue behavior of materials and structures. Among the standardized load sequences showed, the TWIST method takes place as the one developed for the analysis of transport aircraft wing root. Such method was proposed by Jonge [20] in 1973 and is used in this work with minor modifications, described in the following. The TWIST method defines 10 flight types with different load intensities and occurrences in such a way that the 10 flight types counted up to the respective occurrences fulfill a block of 4000 flights, which is named as “block of flights”. The standardized load sequences method lies in building a block of flight load sequences from the set of loads spectra related to all the flight segments of one flight profile. To achieve this, the load spectrum of each flight segment shall be computed for a duration of 4000 flights. Then, such loads spectra are discretized into stepped spectrum according to the discrete level occurrences proposed in Jonge [20] work. Figure 6 illustrates the creation of the stepped load spectrum from the continuous load spectrum, computed for one block of flights. The load cycles obtained in the stepped spectrum are then split into the 10 flight types obeying the distribution proposed for the occurrences of each level. The result is a block of 4000 flights, represented by 10 flight types / load sequences. Finally, for the fatigue analysis the block of flights must be repeated up to achieve the proposed flight cycles lifetime. In this work, the flight block size adopted is 5000 flights, instead of the 4000 flights proposed in Jonge [20] work. This difference demanded the adjustment of the occurrences of the flight types and the distribution of the occurrences of each level load cycles.

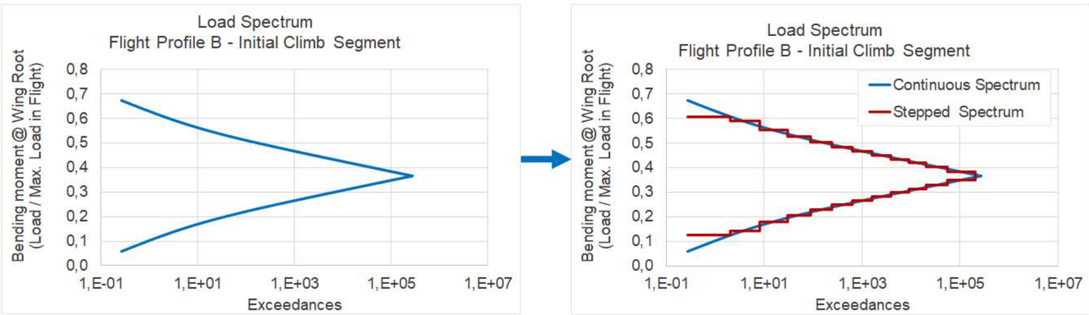

Figure 6: Deriving Stepped Spectrum for a Block of Flights

Figure 7 presents the flight load sequence for one hypothetical flight type and the loads spectrum obtained for this flight load sequence. This load spectrum was derived by cumulative ordinating the peaks and valleys loads related to the load cycles identified by means of the rainflow method. The rainflow method [10] is a standardized procedure to identify and count cycles developed by Prof. T. Endo and his colleagues in Japan around 1968. Several different methods to identify and count cycles in an irregular time-history were previously proposed and used. However, a consensus has emerged that the best approach is the rainflow cycle counting. In the current work it was adopted the algorithm proposed by Downing and Socie [9] to execute the rainflow procedure.

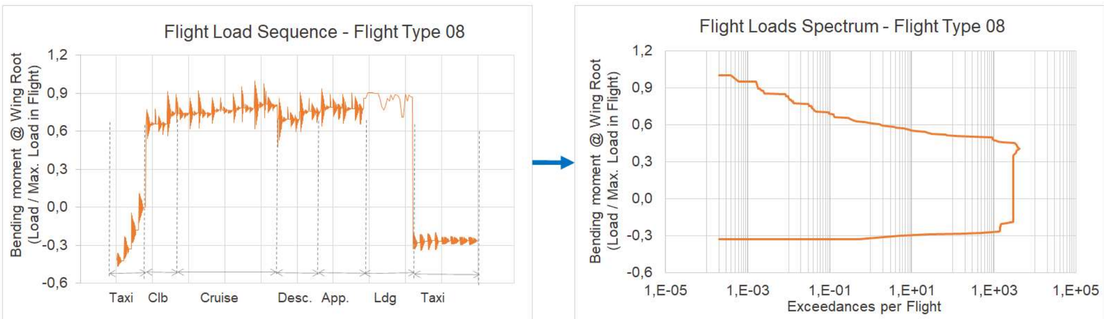

Figure 7: Load Sequence and Load Spectrum for one Flight Type

The maximum and minimum load spectrum is a format traditionally adopted to illustrate loads results, since it presents in a synthetic way an overview of the large amount of data from a flight load sequence. Considering this, the load spectrum is a valuable tool to compare loads results derived for different flight load sequences. The comparison of load spectrum results may be required, for example, to evaluate if the airplane design is viable for a new operator. One important aspect to be observed is that the peak and value loads pair related to one cycle are illustrated only in the flight load sequence format, since in the spectrum format such load pair is disconnected. Moreover, in the flight load sequence format it is possible to identify the flight segments from which minimum and maximum loads arisen.

STUDY CASE: ANALYSIS AND RESULTS

Flight Profiles

In this study case, the load spectrum is derived to represent the hypothetical operational usage of an airplane, comprising four typical flight profiles illustrated on Figure 8. The flight profiles A, B and C are simply transport flights and may be related to regular commercial flights as well as cargo transport tasks. Conversely, flight profile D represents a specific scope of operation which requires cruise at low altitude level. As previously described, such flight profile is demanded for missions whose targets are cargo aerial delivery, search and rescue procedures, aerial firefighting, aerial monitoring, or reconnaissance. This flight profile is associated to more severe loading pattern for some components as wing, due to the large exposition to gusts at low altitude level and maneuvers, fuselage due to the two pressurization cycles, and flap and slat high lift devices due to the larger exposition at the extended position.

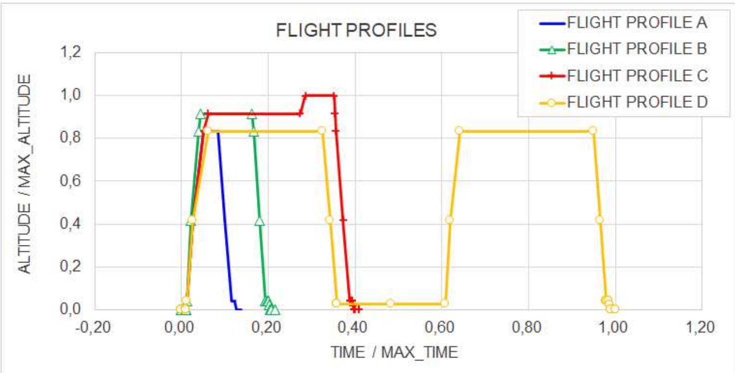

Figure 8: Flight Profiles A to D

Table 2: Flight Profiles A to D Features

FLIGHT PROFILE	BEFORE TAKE-OFF			AFTER LANDING		
	PAYLOAD (% MAX PAYLOAD)	FUEL (% MAX FUEL)	TOW (% MAX TOW)	PAYLOAD (% MAX PAYLOAD)	FUEL (% MAX FUEL)	LDW (% MAX LDW)
A	77%	28%	90%	77%	13%	92%
B	15%	33%	72%	15%	11%	71%
C	54%	54%	90%	54%	12%	84%
D	36%	100%	97%	36%	12%	78%

The flight profiles are described by Figure 8 and Table 2. The parameters that define each flight profile are presented in a normalized format. Then the altitude is presented as the percentage of the maximum cruise altitude of the airplane. On the same way, the take-off (TOW) and landing weights (LDW) are given in terms of the percentage of the maximum take-off weight (MTOW) and maximum landing weight (MLW) respectively. The fuel is shown as the percentage of the maximum fuel weight that the airplane can carry in its regular fuel tanks. The time is shown for each flight profile, as the ratio to the time duration of the flight profile D.

The time duration and percentage distribution of the flight profiles are presented in Table 3. This table also presents the equivalent flight profile mean flight time, obtained from the four single flight profiles. The equivalent flight profile is illustrated in Figure 9. The use of the equivalent flight profile has some advantages for practical purposes. It is a simplified approach to represent the operational usage by only one flight profile leading to an amount of results data and process flow smaller than the ones achieved with the adoption of single flight profiles.

Table 3: Mission Profiles Distribution and Equivalent Flight Profile Mean Flight Times

Flight Profile	**Flight Time**	**Flights** (%)
	ΔT_n	$Dist_{SF}$
A	0.12	10
B	0.20	40
C	0.40	40
D	1.00	10
EQUIVALENT	0.35	100

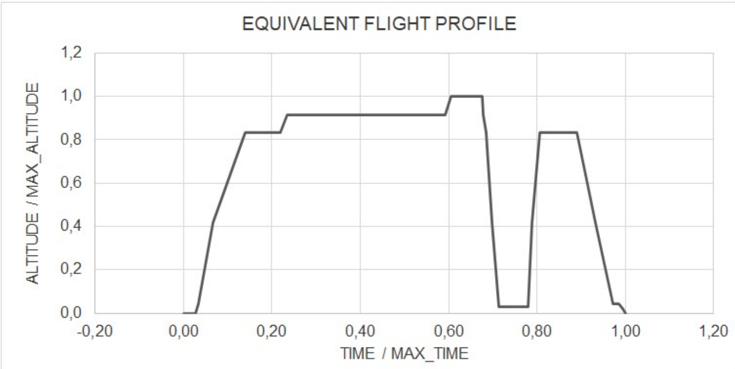

Figure 9: Equivalent Flight Profile

<u>Loads Spectra</u>
The block of flights concept proposed by Jonge et al. [20] and the standardized load sequence practice described by Schijve [12] were applied to derive the load sequences for both single flight profiles and equivalent flight profile. The correspondent loads spectra derived from them are presented from Figure 10 to Figure 13 where the loads are presented as a ratio to the maximum positive load achieved in the equivalent flight loads spectra. These spectra results were determined for the bending moment in the airplane wing root. The sign convention adopted considers that the up-bending moment is positive. Also, in order to ensure a fair spectra comparison, the exceedances are normalized by total the number of flights used to derive the spectra.

Figure 10 shows a comparison of the total loads spectra derived for one block of flights. Some differences in spectra results are observed among the flight profiles and these differences occur mainly in the spectra upper branches since the lower ones are almost the same. Flight profiles A and C present upper branches very similar to the equivalent flight profile. In contrast, flight profile B and D upper branches have clear shifts relative to the equivalent flight profile.

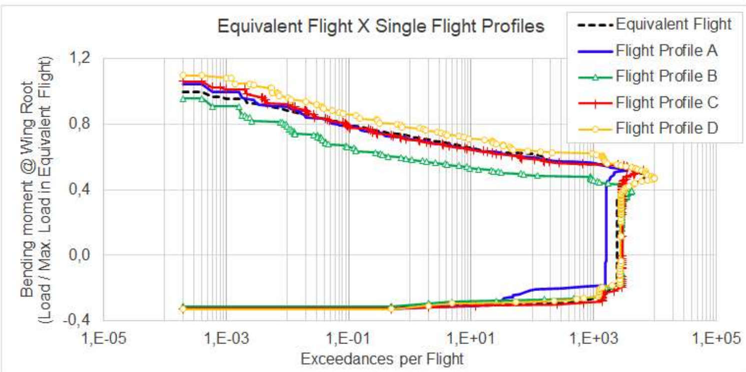

Figure 10: Loads Spectra for one Block of Flights

It is observed in Table 2 that flight profile A and C have the same take-off-weight, which corresponds to 90% of the maximum allowed one. It is significantly higher than the one achieved by flight profile B (72%). Analyzing the variation of parameters that affect the wing loads, among the flight profiles A, B and C, it is expected that flight profiles A and C achieve similar wing loads during the climb and initial cruise segments, while flight profile B achieve lower ones. Since these flight profiles cover 90% of the operational usage, the equivalent flight profile load cycles are supposed to be driven mainly by flight profiles A and C.

The spectra upper branch shift between flight profile B and the equivalent flight profile occurs because this single flight profile adopts a lower payload, only 15% of the maximum one allowed. Consequently, the wing root mean loads are related to this low payload for all phases of this flight profile. In contrast, the equivalent flight profile comprises all the phases related to the four single flight profiles. This leads to wing loads that vary in agreement with a payload that arrays from 15% to 77% of the maximum payload allowed, achieving then values noticeably greater than the ones observed in the single flight profile B.

Furthermore, according to Table 3, 40% of flight occurrences in one life are attributed to single flight profile B. Considering such distribution and the analysis presented previously, it is possible to verify that the adoption of the equivalent flight profile represents a conservative solution, since the loads spectra results do not take into account the noticeable spectra reduction associated to the smallest payload in 40% of the flights.

On the other hand, the spectra upper branches shift between flight profile D and the equivalent flight profile is promoted by the differences in flight phases duration. To compose the equivalent flight profile, each flight segment duration shall be factored by the percentage of occurrences of the correspondent single flight (Table 3). Therefore, one segment duration is always smaller in the equivalent flight profile than in the correspondent single one. Particularly, in the case of flight profile D the difference in time is due to the small percentage of occurrences (10%) leading to a noticeable reduction in time from the single flight profile to the equivalent flight profile. Moreover, this is the longest flight profile among the four ones. The larger time associated to this single flight profile is traduced into larger exposition to turbulences and maneuvers, leading to loads spectra with both greater number of occurrences and load cycles.

As proposed by Jonge et al.[20], one block of flights corresponds to 1/10 of the life cycles. Considering this, 10 blocks of flights are necessary to achieve one lifetime. The arrangement of the 10 flight blocks is different whether of it is adopted the equivalent flight profile or the single flight profiles solution to derive the loads spectra. For the equivalent flight profile approach such arrangement consists in repeating 10 times the block of flights. On the other hand, for the single flight profiles solution, the arrangement consists in a composition of single flight profiles blocks of flights, which shall be repeated according to the correspondent percentage of occurrences in lifetime. In the current work, the arrangement of single flight profiles comprises one block of flights of the single flight profile A, four blocks of the single flight profile B, four blocks of the single flight profile C and one block of the single flight profile D. The resultant loads spectra derived from such arrangement correspond to one lifetime.

Figure 11 shows the loads spectrum derived for one lifetime for the two solutions proposed in the current work. In a preliminary evaluation, a direct comparison between both cases can induce an inaccurate perception that the spectrum derived from the composition of single flight profiles is more severe than the one obtained from the equivalent flight profile. A joint evaluation of Figure 10 and Figure 11 gives some relevant information indicating that lifetime spectrum of the composition of single flight profiles does not put in evidence the partial role of the smallest spectra (flight profile B in Figure 10). This occurs because the boundaries of the composition spectrum are defined by the greater ones. Consequently, the relevant influence of the single flight profile B, which occurs 40% of lifetime, does not appear in such loads spectra comparison.

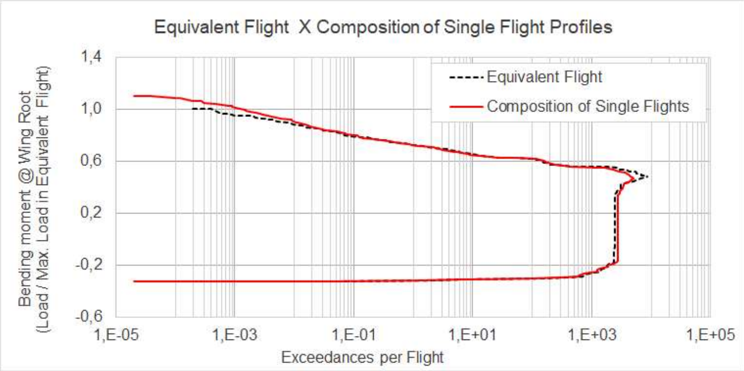

Figure 11: Loads Spectra for One Lifetime

Figure 12 and Figure 13 present an alternative spectra format to compare the loads cycles for different flight profiles. This format shows the spectra in terms of amplitude load cycles, which means that peak and valley loads related to each cycle are employed to derive a unique load value in such plot. Figure 12 indicates the same behavior observed in Figure 10, showing that the loads derived from flight profile B are lower than the ones from the equivalent flight profile. Also, one important aspect is observed in Figure 12: The amplitude load cycles accumulated up to one exceedance per flight are clearly greater than the remaining ones. Such greater load cycles consist in the GAG (ground air ground) cycles related to each single flight in one block of flights. This appreciable difference in magnitude is an indicative that during the fatigue and damage tolerance analysis the GAG cycles might have stronger influence than the remaining ones.

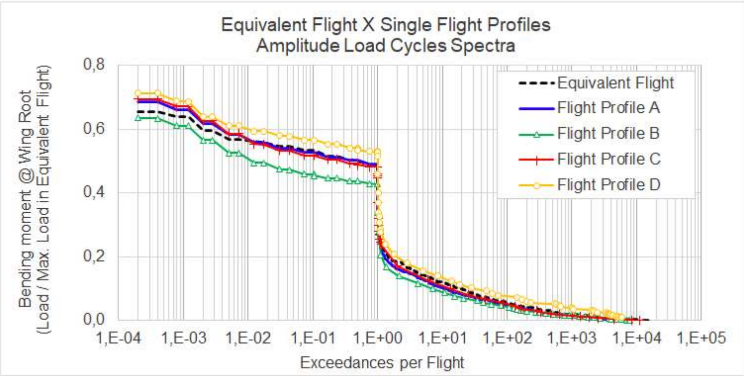

Figure 12: Amplitude Loads Spectra for One Block of Flights

In order to have a closer evaluation of such influence, Figure 13 shows the presenting amplitude load cycles spectra uniquely for the GAG cycles. This figure compares the equivalent flight profile and the composition of the single flight profiles. It is observed that for small exceedances values, the composition has a larger amplitude than the ones presented by equivalent flight profile. In the major portion of the spectra exceedances, it is observed almost the same amplitude values in both flight profiles. Conversely, for the highest exceedances it is observed reasonable differences between the two solutions proposed. Deep analysis of this region, in the detailed spectra region, shows that for more than 40% of the exceedances per flight, the composition amplitudes are up to 12% smaller than equivalent flight profile ones. This amplitude difference level associated to the large number of exceedances can play an important role in the fatigue and damage tolerance analysis. The detailed assessment of the GAG amplitude loads, for the same flight severities, indicates that 60% of the flights in the composition of single flight profiles have GAG amplitude loads lower than the correspondent ones for the equivalent flight profile. In this case, as described previously, the differences in amplitude reach up to 12%. The opposite behavior is observed in only 15% of the flights, for which the differences reach up to 10% of amplitude.

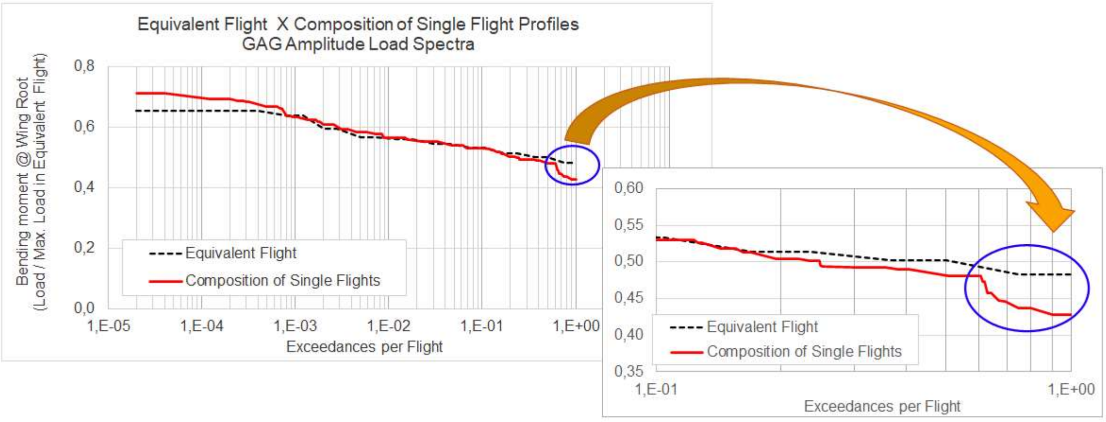

Figure 13: Amplitude Loads Spectra for One Lifetime

Fatigue Analysis

In order to quantify the impact of the different approaches, using a composition of single flight profiles or an equivalent flight profile, a stress and fatigue analysis is carried out for the hypothetical loading scenario at the wing root. The material considered for this analysis is the Aluminum, sub-class 7000, alloy 7050, temper T7451. The stress versus life (S-N) curve, required for fatigue analysis, was obtained from the handbook MMPDS-06 [23] for notch effect $K_T = 3.50$.

Table 4: Number of Lives for Single Flight Profiles, Composition of Single Flights and Equivalent Flight Profile

Flight Profile	Number of Lives
A	1.017
B	3.084
C	1.124
D	0.561

Flight Profile	% Flights	Number of Lives
A	10%	0.1017
B	40%	1.2336
C	40%	0.4495
D	10%	0.0561
Composition of Single Flights	100%	1.8409
Equivalent Flight	100%	1.0060

The results of the analysis performed are presented in Table 4. Such results are presented in terms of the number of lives that the structure could support, as if it was exposed only to one flight profile. The left side of Table 4. presents the number of lives obtained for each one of the hypothetical single flight profiles used on this study case (A, B, C and D). The results show that flight profile D is the most severe from the fatigue point of view. On the other hand, flight profile B is the least severe one from the set of proposed flight profiles. It becomes evident from these results, that the different flight profiles must be combined somehow in order to avoid over conservative designs if only the most demanding flight type (flight profile D) is used for fatigue analysis. In this direction, results of the analysis obtained from the proposed combination of single flight profiles and the equivalent flight profile are shown in the right side of Table 4.

A direct comparison between the proposed approaches reveals that the composition of single flight profiles leads to a fatigue life that is almost 80% higher than the one achieved for equivalent flight profile. In addition, the joint assessment of left and right side of

makes it clear that using only one single flight profile can result in non-conservative or over-conservative structures, depending on the selected one for design. The use of an equivalent flight profile allows the consideration of different flight types, with more conservative results than the composition of flight profiles.

DISCUSSION AND CONCLUSION REMARKS

The current work presented two solutions to derive the loads spectra for an airplane. Which is the best choice? The answer for this question is certainly based on the objectives that motivate the analysis. Considering this, the choice of the appropriate methodology must account for the goals to be achieved, whose scope might go further than the demonstration of compliance with the certification requirements.

Along the work, it was demonstrated that the use of different flight profiles, especially the ones that comprise specific and diverse routines, as observed in flight profile D, will lead to different loads spectra, that ultimately reflects in distinct results in terms of fatigue life. Depending on the characteristics of such routines, the loads spectra variations may become relevant for the fatigue analysis and impact the maintenance plan development for certain airplane segments.

The analytical study presented here demonstrates that the equivalent flight profile tends to promote an increase in the analysis severity level, if compared with the composition of different single flight profiles. Such increase is attributed to the fact that the equivalent flight profile comprises all the flight segments of all flight profiles. This arrangement allows, for instance, the flight segment attributed to most severe equilibrium loads (mean loads) to occur in 100% of flight load sequences. Such increase becomes especially evident when the assumed operational life comprises flight profiles with very distinct schedules, which may include noticeable differences in the flight range, payload and limitations in the cruise altitude. Moreover, a hypothetical demand for a substantial change in the cruise altitude, for example to perform low altitude navigation, or the necessity to execute particular routines, can promote noticeable differences among the flight profiles and correspondent loads spectra.

The development of a baseline airplane shall be conducted bearing in mind that the certification for different operational usage may be demanded to cover a wide range of operators. In this situation, it is a competitive advantage the application of a baseline airplane certified in terms of more severe loads spectra than the operational demands of operators, because it enables the reuse of the baseline airplane analysis and full-scale fatigue tests performed to demonstrate compliance with the certification requirements. In this direction, the equivalent flight profile solution derives loads spectra that have a greater potential to cover other operational usage supposed for different operators.

In addition, the use of a certified baseline airplane for different markets become easier and cheaper, once the manufacturer can demonstrate that the certified loads spectra cover the ones derived for the current usage proposed. To do this, the composition of single flight profiles seems to be the best approach, since it produces loads spectra that strictly fits the current needs and proposed usage, avoiding unnecessary conservativisms. In general, a non-conservative loads spectra are prone of being covered by the certified airplane ones.

In summary, the author's conclusion is that the equivalent flight profile can be considered an appropriate solution for the development of a baseline airplane, while the composition of single flight profiles is a suitable approach to demonstrate that a certified airplane is also viable for other operators' usage.

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