ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

THEORETICAL EVALUATION OF AIRCRAFT COMFORT DURING TAXING PERIODS

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Abstract: *The main purpose of this work is the presentation of a method for the theoretical analysis of aircraft comfort related to vibrations during taxing periods. Runway unevenness, wheels unbalancing and tire diameter unevenness ("flat spot") were evaluated. The aircraft was modeled considering its structural flexibility, so the vibration modes were considered in the analysis, since the resonances can amplify the response to excitations, substantially changing the conclusions about the comfort level. The aircraft landing gears were modeled as multibody mechanisms, using the Adams® software for this. The ANSI S3.18-1979 standard, that defines limits of exposure for vibrations transmitted from solid surfaces to the human body, was used as a reference. The method validation was done by comparing the results obtained by the theoretical model with the results of a dedicated vibration test of the same aircraft that was modeled. The pilot position was used as reference for carrying out the comfort analysis. Focus was given to the excitation generated by tires "flat spot", since, during tests, this excitation was responsible for the highest vibration levels that could compromise the comfort, according to subjective opinions from pilots.*

Keywords: *Comfort, Theoretical evaluation, Aircraft, Taxi*

1. INTRODUCTION

1.1. Motivation and Objective

Due to the increasing competitiveness in the aeronautical market, especially in the executive aviation, the concern related to comfort in the aircraft design has increased considerably in recent years, not just in terms of interior noise, but also in terms of comfort related to vibrations during taxing and flight periods. Since the focus of the aeronautical requirements is mainly related to structural design, little has been done in theoretical field aiming the prediction of the vibration characteristics for a new aircraft. Actions are limited to correcting undesirable characteristics when the prototype aircraft is available, based on experimental techniques.

This work presents an evaluation method of the vibration characteristics considering theoretical data, analyzing standard excitations related to taxing periods, calculating the aircraft response to those excitations and comparing the results to some defined criteria considering the comfort issue.

1.2. Methodology and Models

The methodology for the theoretical evaluation of the comfort includes:

- *Definition of the standard excitations on ground:*

In this work runway unevenness excitations were evaluated, that are typically random and with an intermediate frequency content (~0.5 Hz to 20 Hz) and the excitations generated by the tires, such as wheels unbalancing and tire diameter unevenness ("flat spot"), also with an intermediate frequency content (~0.5 Hz to 35 Hz).

The runway unevenness excitations were generated using the San Francisco 28R runway, which profile is known (see Tung C. C. et al, 1964), and the runways form MIL-A-008866B, 1975.

The tire excitations were implemented using the simulation software (Adams®), programing wheels unbalancing and tire diameter unevenness functions.

- *Aircraft modeling considering its structural flexibility:*

The comfort analysis is meaningless if the aircraft vibration modes are not considered. The resonances can amplify the response to excitations, substantially changing the conclusions about the comfort level, especially if it occurs in important periods of the flight, such as operation conditions with taxing and normal cruise speeds.

In this work the Adams® software was used to do the analysis, which allowed the inclusion of flexible bodies in the multibody dynamic simulation. The model has the wing, the fuselage and the tail as flexible bodies. It allows the model to represent the dynamic behavior of the aircraft as closely as possible.

- *Comfort criteria definition:*

The ANSI S3.18-1979 standard, that defines limits of exposure for vibrations transmitted from solid surfaces to the human body, considering a frequency range from 1 to 80 hz, was studied. A methodology was created to compare the acceleration data with the standard limits.

2. STANDARD EXCITATIONS ON GROUND

For the theoretical evaluation of the aircraft comfort, some kinds of excitations were evaluated.

2.1. Runway Excitations

During the simulations done using the Adams® software, the San Francisco 28R runway and the runways form MIL-A-008866B, 1975, were used. The MIL standard presents power spectral densities for the runways roughness. They were used as a reference to generate the runway profiles used in the comfort analysis.

The formulation adopted by Brot A. and Chester D. H., 2000 was used to generate the runway profile taking into consideration the MIL-A-008866B, 1975 standard.

2.2. Wheel Unbalancing Excitations

The wheel unbalancing excitations have been implemented using the Adams® software, by adding an unbalancing mass to the tire model, as shown in Fig. 1.

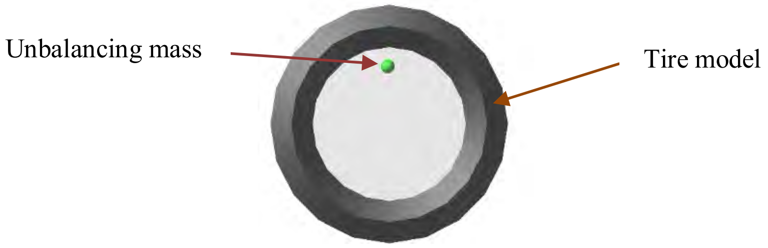


Figure 1. Wheel unbalancing model in Adams®

2.3. Tire Diameter Unevenness Excitations (“flat spots”)

“Flat spots” are tire diameter unevenness that can occur when the tires are locked during braking or when the aircraft remains stopped for long periods of time, resulting on tire deformation. This phenomenon frequently occurs during the first taxi and takeoff of the aircraft operational day, after the aircraft was stopped for a long period of time on the tires.

This kind of excitation was implemented using the simulation software (Adams®). The tire model used in the Adams® standard simulation (“Fiala tire model”, MSC SOFTWARE, Adams® 2010) was modified to consider the “flat spot”.

The “Fiala” model considers just one tire nominal radius, regardless of the wheel angular position. A modification has been done in the model in such way to consider a change in the tire nominal radius in relation to the wheel angular position. In such case the “flat spot” phenomenon could be observed in the simulation.

First of all, the “flat spot” model showed in Fig. 2.a was adopted. In this model the transition between the region with and without “flat spot” is quite abrupt. After some analysis, it was observed that the tire was exciting the aircraft really beyond the expectation. So the “flat spot” model was modified to the one showed in Fig. 2.b, with a smoother radio transition. The answers obtained by the simulations were then closer to the ones obtained in the reference tests.

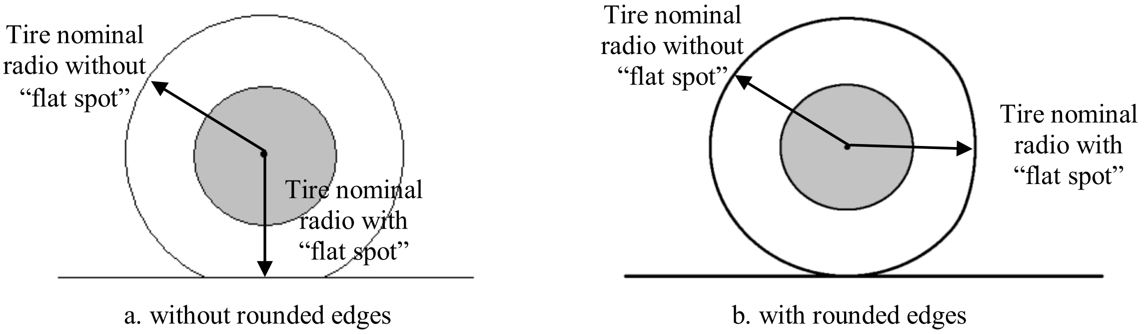


Figure 2. Tire model with "flat spot"

3. AIRCRAFT AND LANDING GEARS MODELING

3.1. Aircraft Modeling

The comfort analysis is meaningless if the aircraft vibration modes are not considered. In such case, a finite element model was considered in the analysis. The aircraft elastic model is composed by 1D and 2D Nastran elements, while the mass distribution in the main components was modeled using lumped mass elements. The modal characteristics of the model were validated by a ground vibration test. This flexible model was imported into Adams® software and used in the multibody dynamic simulation.

Figure 3 shows the aircraft flexible body used in the taxi analysis.

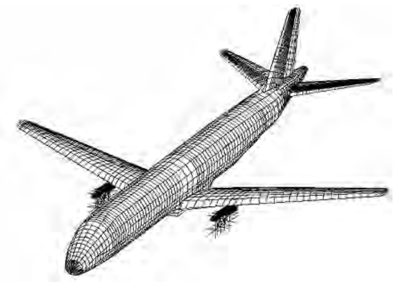


Figure 3. Aircraft flexible body

For the taxi simulation considering the aircraft flexible body, two computational tools were used: Nastran® e Adams®.

Nastran® provides normal modes (solution 103 (modal solution)) that represent the natural vibration of the body and static modes (solution 101 (linear static solution)) to take into account localized loading and deformation. Fifty normal modes and thirty static modes were used in the analyzes.

The static modes are employed to better represent local deformations due to localized loading at the landing gears attachment points, and to help decreasing the total number of modes, thus speeding up the analysis. A higher number of normal modes would be necessary to get an accurate response if static modes were not taken into consideration. The static modes are obtained by applying unit enforced displacements in the directions x, y and z (following the aircraft basic reference system) at each landing gear attachment point. The aircraft model is constrained at all the landing gear attachment points in the x, y and z directions while the enforced displacements are applied.

A file containing the static and normal modes is then generated by Nastran® software, in a format that Adams® is able to read. Adams® was used to make the taxi simulation taking into account the aircraft modal characteristics. The aircraft flexibility inside Adams® is simulated using the modal superposition technique. The differential equation governing the dynamics of a particular vibration mode is:

$$\ddot{q}_i + 2\zeta_i \omega_{ni} \dot{q}_i + \omega_{ni}^2 q_i = F_i \tag{1}$$

where:

q_i = generalized modal coordinate;

ζ_i = modal viscous damping factor (input for Adams® model);
ω_{ni} = natural modal frequency, from Nastran® model;
F_i = generalized modal force.

After Eq. (1) has being solved for each structural vibration mode, the physical deformation of a particular point P_j of the model in the z direction, for example, can be expressed as:

$$Def_{Pj_z} = \sum_{i=1}^{Nm} \Phi_i^Z(P_j) q_i \tag{2}$$

where:

Nm = number of modal shapes used in the simulation;
$\Phi_i^Z(P_j)$ = modal shape at Pj for the i^{th} mode in the direction z.

The same formulation can be used to calculate the physical deformation in the x and y directions.

These values are obtained for each time step t of the simulation. In such case, the acceleration at Pj can be easily obtained with the derivation of the physical deformation at Pj twice in time ($\ddot{Def}_{Pj_z}$), with the addiction of the aircraft rigid body acceleration in the same point (a_{CRPjz}).

$$a_{P_j} = \ddot{Def}_{Pj_z} + a_{CR\,Pj_z} \tag{3}$$

3.2. Landing Gears Modeling

The landing gears were modeled as multibody mechanisms inside Adams®.

Figure 4 shows the Adams® model with the landing gears.

Figure 4. Aircraft flexible body with the landing gears

All the landing gears used in the simulation are telescopic with a gas-oil damper, which has spring and damper characteristics simultaneously. Their dynamic behavior was validated by drop tests. Figure 5 shows a longitudinal cut of a generic gas-oil damper.

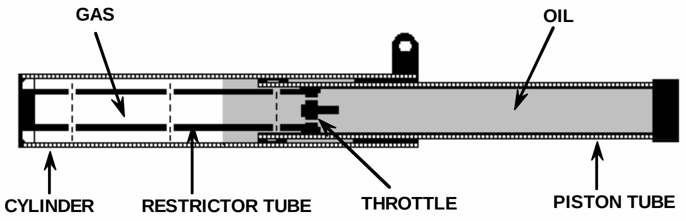


Figure 5. Longitudinal cut of a generic gas-oil shock absorber

When the shock absorber is compressed or extended, the oil is forced to go through an orifice, generating a hydraulic force, proportional to the squared speed of the strut, in the opposite direction of its movement. Simultaneously, the pressurized gas generates a pneumatic force, proportional to the shock absorber deflection, acting as a non-linear spring. The mathematical model used to represent these forces, as well as the other forces acting in the landing gear, is described in the sections 3.2.1 to 3.2.5.

3.2.1. Pneumatic Force

The air pressure force is determined by the initial strut inflation pressure, the area subjected to the air pressure (pneumatic area), and the instantaneous gas compression ratio:

$$F_{PNM} = P_{a0} * A_a * \left(\frac{V_0}{V_0 - A_a * DEF_{gas}} \right)^n \tag{4}$$

where:

P_{a0} = gas pressure with the shock absorber totally extended (without the actuation of any external force);
V_0 = gas volume with the shock absorber totally extended (without the actuation of any external force);
n = polytropic exponent of gas compression. (Between 1.0 for isothermal compression and ~1.4 for adiabatic compression);
A_a = pneumatic area;
DEF_{gas} = shock absorber deflection related to the gas compressibility.

Therefore:

$$DEF_{gas} = \frac{V_0}{A_a} * \left(1 - \left(\frac{P_{a0} * A_a}{F_{PNM}} \right)^{1/n} \right) \tag{5}$$

The oil compressibility can not be neglected for high pressures that occur inside the shock absorber. In such case, it was considered in the simulation the oil compressibility, which also contributes for the shock absorber total deflection.

$$DEF_{oil} = F_{PNM} * \frac{V_{oil}.FCO}{A_a^{\ 2}} \tag{6}$$

where:

$FCO = 1/\beta$;
β = oil Bulk modulus.

Therefore, the shock absorber total deflection (*DEF*) is the sum of the deflections resulted by oil and gas compression:

$$DEF = DEF_{gas} + DEF_{oil} = \frac{V_0}{A_a} * \left(1 - \left(\frac{P_{a0} * A_a}{F_{PNM}} \right)^{1/n} \right) + F_{PNM} * \frac{V_{oil}.FCO}{A_a^{\ 2}} \tag{7}$$

3.2.2. Hydraulic Force

The hydraulic resistance in the shock strut results from the pressure difference associated with the flow through the restriction orifices inside the landing gear. In a landing gear the orifice area is usually very small in relation to the strut diameter. In such case, the jet velocities and Reynolds numbers are sufficiently large to make the flow be fully turbulent. The hydraulic force can be expressed as:

$$\mathrm{F_{hid}} = \frac{\rho * A_h^{\ 3}}{2 * (C_d * A_n)^2} * \dot{\mathrm{DEF}}^2 \tag{8}$$

where:

Cd = coefficient of discharge;
An = net orifice area;
ρ = mass density of hydraulic fluid;
Ah = shock absorber hydraulic area;
$\dot{DEF}$ = shock absorber deflection velocity.

3.2.3. Tire Force

This force is generated in the tire due to its compression.

The tire model used in the simulation was the "Fiala", standard tire model available in Adams® software. It was modified since the original routine works with just one spring perpendicular to the runway. As this spring is deflected, (tire deflection), the force is generated by the tire. This simple model generates excessive excitations in the aircraft for "flat spot" conditions when compared to test data. With just one spring, the transition from the part of the tire without "flat spot" to the one with the "flat spot" happens quite abruptly. The modified routine has a total of 51 springs being spaced by an angle of 2° from each other (Fig. 6). The center spring is always placed perpendicularly to the runway. All the springs have the same stiffness. The number of springs that withstand the load increases with the tire deflection increase. This modification leaves the tire behavior closer to reality, making it able to anticipate the beginning of the "flat spot". In such case, the transition to the part with "flat spot" is not so abrupt anymore.

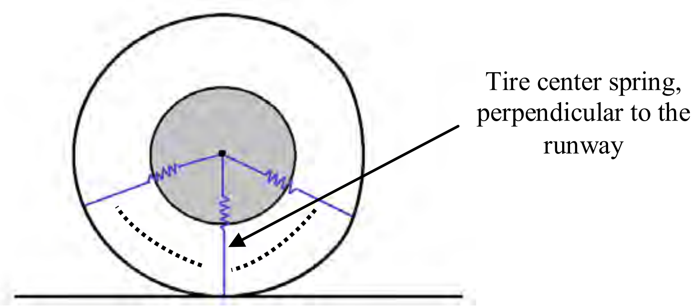


Figure 6. Tire model with many springs and with "flat spot"

3.2.4. Spring Force Due to Landing Gear Horizontal Deflection

The spring force due to landing gear horizontal deflection occurs in the horizontal direction in the wheel axle region. It appears due to the landing gear structural flexibility when it is loaded by forces generated by the friction between the tires and the ground that occurs during wheel braking and acceleration ("wheels spin-up"). For telescopic landing gears, the leg stiffness coefficient (K_{TP}) changes with the shock absorber deflection (*DEF*).

Is such case, the spring force due to the landing gear horizontal deflection (DEF_X) can be calculated as:

$$F_{ML} = K_{TP} * DEF_X \tag{9}$$

3.2.5. Structural Damping Force

The landing gear leg has a structural damping. The structural damping force is calculated as:

$$F_{AM} = C \cdot \dot{DEF}_X \tag{10}$$

where:

$\dot{DEF}_X$ = longitudinal deflection speed of the landing gear leg;
C = structural damping coefficient of the landing gear leg.

4. METHODOLOGY FOR THE COMFORT ANALYSIS

After each taxi simulation executed by Adams® software for each kind of excitation, a history of the acceleration at *z* direction at pilot seat position was extracted from the simulation. This acceleration signal was then treated, using the Matlab® software, in order to enable a comparison between the obtained results with the ANSI S3.18-1979 standard.

First of all, the acceleration signal was filtered, using a band-pass filter, in one-third octave bands in accordance to the ANSI S3.18-1979 standard.

The rainflow cycle counting method was then applied to the acceleration signal, separately for each frequency band, in order to obtain an occurrence distribution by acceleration amplitude. Transforming occurrence into exposure time through the formulation:

Exposure time = Occurrence / Frequency,

it is possible to obtain a distribution of exposure time by acceleration amplitude for each frequency band analyzed.

Considering this distribution, it is easy to take some conclusions about comfort through a comparison with the ANSI S3.18-1979 standard.

5. THEORETICAL MODEL VALIDATION FOR THE COMFORT ANALYSIS

The method validation was done by comparing the results obtained by the theoretical model (Adams®) with the results of a dedicated vibration test of the same aircraft that was modeled. The pilot position was used as reference for carrying out the comfort analysis, comparing the vertical accelerations results from the test with the vertical accelerations from the simulations. A low wing aircraft was chosen for the study, with a conventional tail and telescopic landing gears, with two wheels per landing gear. The mass and stiffness characteristics of the aircraft as well as the landing gear data used in the theoretical model were chosen to represent as closely as possible the aircraft that was tested, in order to guarantee a greater reliability in the results.

During the tests done with the reference aircraft, pilots complained about discomfort in the first series of taxing of the day, with cold tires, and with some specific speeds. In these series it was observed the presence of “flat spot” in the tires, remarkable even with visual evaluation during taxing, knowing that the aircraft had been parked for a long time, usually during the night. After some studies, it was discovered that the tires with “flat spots” of the main landing gears were exciting the aircraft in the frequency of one of its natural vibration modes (~ 5.7 hz), amplifying the acceleration signal at the pilot position, generating the discomfort. After some taxing series, the “flat spot” decreased, thus improving the comfort.

The objective of this work was then to validate the theoretical model using the results obtained in these tests. Considering the lack of accurate data about the runway used in the tests, the San Francisco 28R runway was used in the simulation, which profile is well known. This fact (different runways between test and simulation) does not have any significant impact in the results, once the “flat spot” excitation is the main one in this analysis. The runway unevenness is important just to excite the aircraft in a random way, similar to what happened in the tests.

To represent the taxi with cold tires, we considered 40 mm of “flat spot” in the main landing gears and 15 mm in the nose landing gear, considering the “flat spot” as the difference between the original nominal radius of the tire and the nominal radius considering the tire deformation. The undeformed total nominal radius of the main landing gears tires in this study is around 515 mm. For the nose landing gear, this value is around 300 mm.

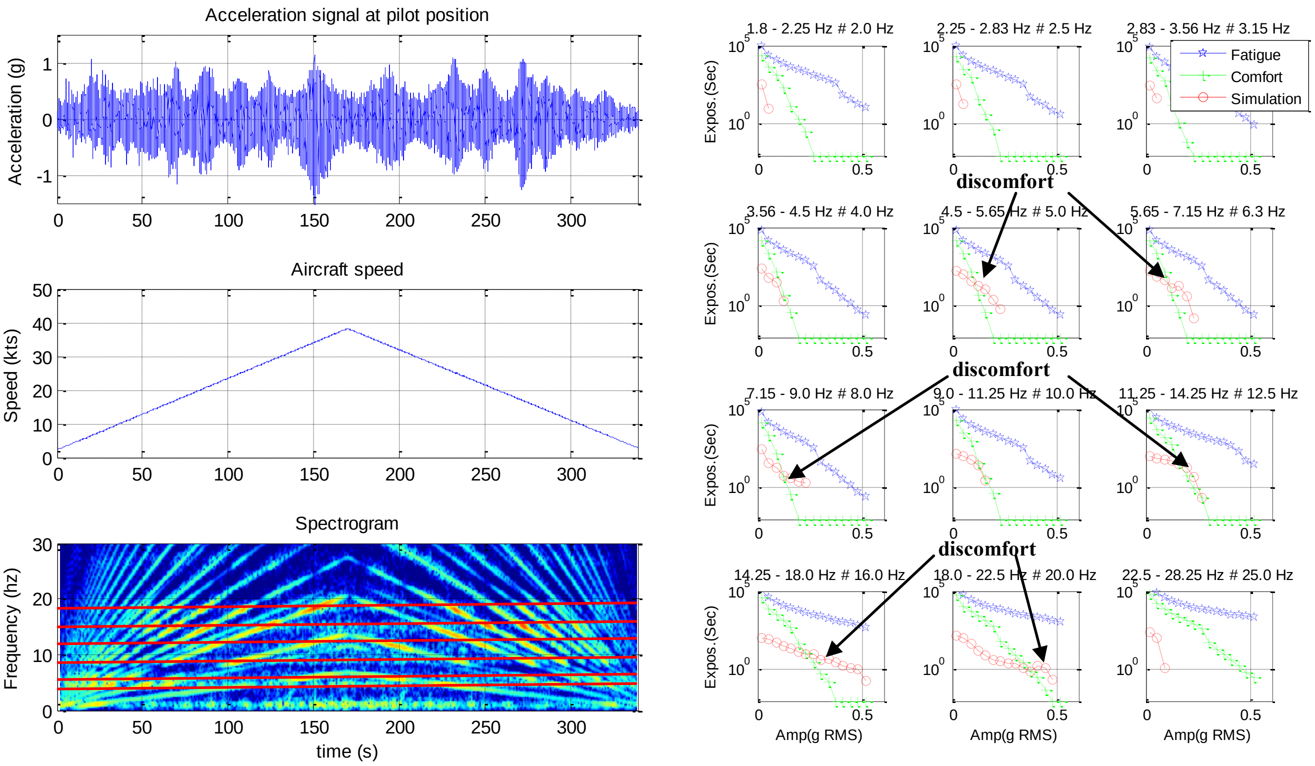
The results obtained with two simulations with “flat spot” will be shown below. The difference between these simulations is the aircraft structural damping and the “flat spot” model of the tire. These characteristics were changed in order to make the simulation results be as close as possible to the test results.

- *1st Simulation: structural damping of 1.5% for all the aircraft modes, tire model with “flat spot” without rounded edges and with just one centered spring.*

In the first simulation, a structural damping of 1.5% was adopted for all the aircraft modes. The tire model with the “flat spot” without rounded edges (see Fig. 2.a) and with just one centered spring to represent the vertical load was used.

Analyzing the results, it can be seen that the discomfort is evidenced in several frequency bands of the standard (see Fig. 7.b). This fact has not happened in the tests, where the discomfort was noticed in only one frequency range (5.65 hz to 7.15 hz), showing that the real aircraft structural damping is probably not the same for all the frequency ranges.

Observing the spectrogram of the acceleration signal (Fig. 7.a), one can notice a stronger response in several frequencies, others than 5.7 hz, and it had not been seen on tests.



a. acceleration signal

b. comparison with ANSI standard

Figure 7: Acceleration results at pilot position for the simulation 1

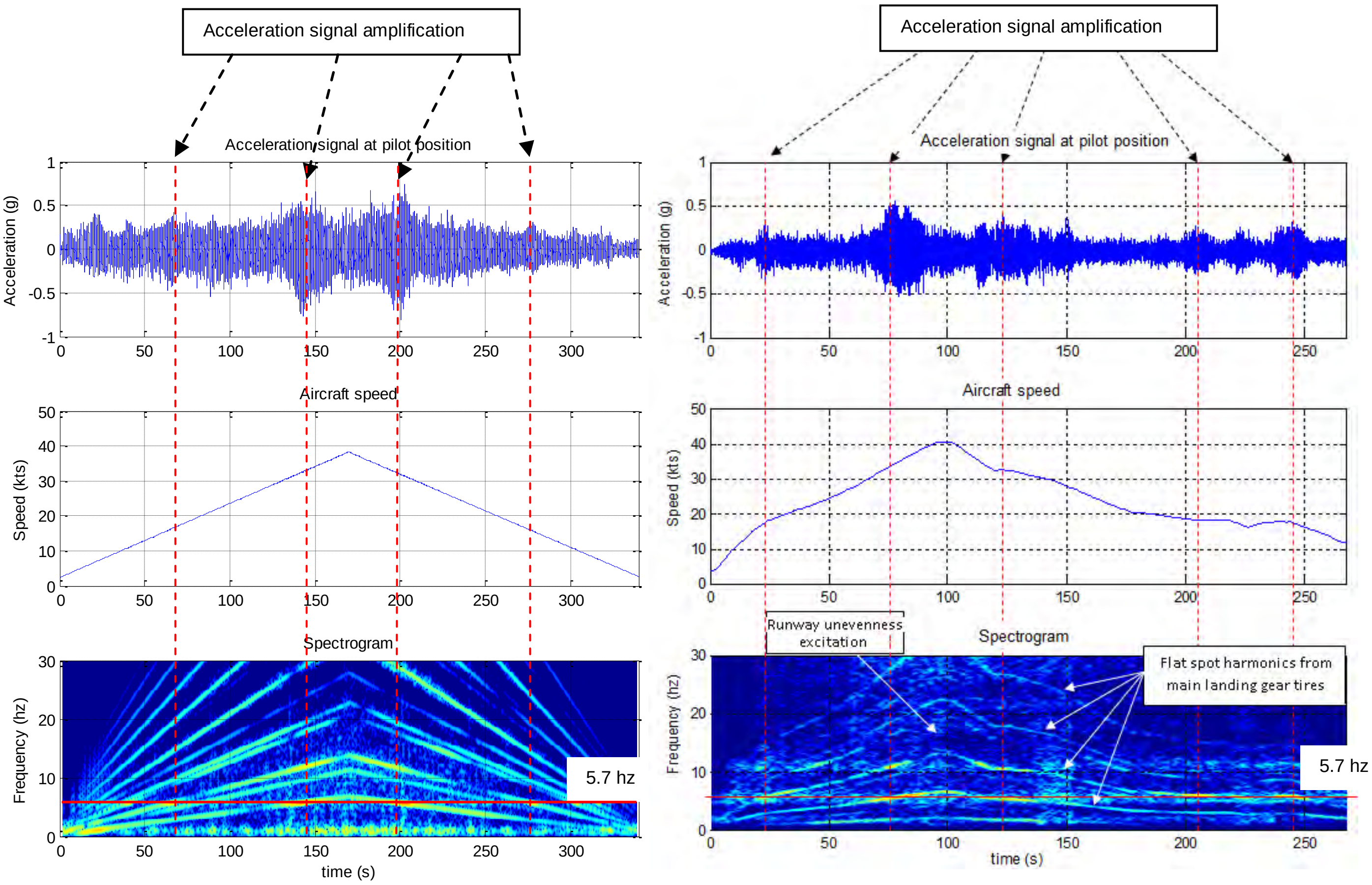
- *2nd Simulation: aircraft structural damping variable as a function of frequency, tire model with flat spot with rounded edges and with 51 springs.*

In the 2nd simulation, the aircraft structural damping was changed, leaving it as a function of the aircraft vibration frequency, in order to obtain a result similar to the one found on test. Table 1 shows structural damping values adopted in the simulation. The tire model was also modified. A model with a smoother transition between the region with “flat spot” to the one without “flat spot” was adopted (see Fig. 2.b). A total of 51 springs being spaced by an angle of 2° from each other (see chapter 3.2.3) was adopted. Figure 8 shows the results of the simulation 2.

Table 1. Structural damping values as a function of aircraft vibration mode

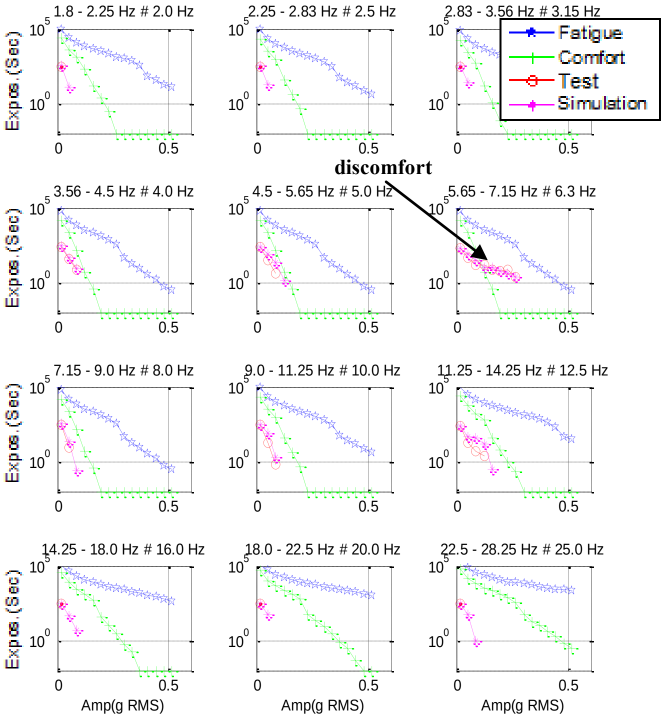
Frequency (hz)	Damping (%)
0 a 4.0	4
4.0 a 5.5	20
5.5 a 8.0	1
8.0 a 12.0	20
above 12.0	70

Observing Fig. 8.a, it can be seen that the accelerations obtained at the pilot position for critical speeds (excitation vs. resonance crossing) are amplified, reaching more than 0.5 g in some situations. The spectrogram of the acceleration signal also shows a more pronounced response in 5.7 hz in these speed ranges, and it was also observed in the tests (see Fig. 8.b). It shows a good correlation between the model of the 2nd simulation and the test. Figure 8.c shows that the comfort results obtained in the 2nd simulation improved in relation to the 1st simulation, showing a better approximation between the simulation model and the test.



a. acceleration signal for simulation 2

b. acceleration signal for test



c. comparison with ANSI standard

Figure 8: Acceleration results at pilot position for the simulation 2 and for test

6. CONCLUSIONS

The most relevant aspects of this work are discussed below:

Aircraft structural damping. First of all it was adopted a constant structural damping of 1.5% for all the aircraft modes. The results obtained with this simulation weren´t so good when compared to the test results. The discomfort was evidenced in several frequency bands form ANSI standard. This has not happened on tests, where the discomfort was noticed in only one frequency range (5.65 hz to 7.15 hz), showing that the real aircraft structural damping is probably not the same for all the frequency ranges or resonances.

In such case, the aircraft structural damping was changed, leaving it as a function of the aircraft vibration frequency (see Tab. 1). It was changed by trial and error method in order to make the simulation results be as close as possible to the test results showing only the noticeable resonances on the test, and the discomfort present in only one frequency range (5.65 hz to 7.15 hz). Even though the damping values showed on Tab. 1 seem coherent, their real consistency can be done in future works.

Considering that the purposed comfort evaluation method should be applied in the aircraft theoretical design, it was desired to know the damping values before any test done in the aircraft. In such case, it would be possible to predict the aircraft behavior only with the simulation model.

The prediction of the aircraft damping by means of theoretical method, either by an empirical way or by modeling, has been recognized as an important limitation of the purposed method. This limitation is a proposal for future works.

In the literature review done it wasn't verified so many works in this field, which requires the use of conservative values of damping (reduced ones) in the aeronautical design.

The lack of knowledge about the aircraft damping does not invalidate this method. Its usage in studies related to comfort improvements in aircrafts with damping known by tests can be really effective.

Tire model. The initial tire model adopted in the simulations considered the "flat spot" without rounded edges (chapter 2.3) and with just one centered spring to represent the vertical load (chapter 3.2.3). The model was really conservative, excessively exciting the aircraft. It was characterized by the generation of several higher order harmonics that were not seen on tests. So the tire model was modified considering a smoother radio transition from the region with a "flat spot" to the one without a "flat spot". We also considered a higher number of springs acting in the tire. The answers obtained by the simulations were then closer to the ones obtained in the reference tests.

As can be seen in chapter 5, after the structural damping adjustment and the improvements made on the tire model, the simulation results were closer to the ones obtained in the reference tests, which were coherent with subjective descriptions related by pilots. In such case, it can be concluded that the methodology proposed in this work was satisfactory for the theoretical evaluation of the comfort. The major limitation of this methodology is related to the inability to predict the real aircraft structural damping without having any test result. What is known is that the adoption of a low damping for all the aircraft vibration modes may lead to conservative results. The aircraft from the simulation will appear to be more uncomfortable than the real one.

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