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PASSENGER COMFORT IMPROVEMENT BY INTEGRATED CONTROL LAW DESIGN

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Abstract

This paper presents comfort criteria based on ISO 2631-1 standard, and shows how these criteria can be applied to a large capacity civil aircraft for passenger comfort evaluation.

The results obtained show that fly-by-wire allows to improve comfort with respect to the natural aircraft. More over an active control of the first flexible modes allows not only to improve 'low frequency' comfort (vibrating comfort), but also 'very low frequency' comfort (motion sickness phenomenon).

This study defines tools for comfort analysis and control law design, which could be used for future large civil aircraft, like the A340-500/600 and the A3XX.

Introduction

Today, air transport growth is making the aeronautical industry become aware of the necessity of developing high capacity long-range aircraft. These large aircraft are characterized by flexible structures which lead to new technological challenges. As regards the flight control system, this flexibility increases the interaction between control laws and structural dynamics modes, the frequency of which becomes lower.

In order to cope with this problem, two ways can be considered:

- A passive approach which consists in filtering the flexible modes in order to avoid coupling with the control laws,
- An active philosophy which consists in controlling the first flexible modes.

It was shown that the second approach seems to be more convenient from the handling qualities point of view [1].

As regards comfort, it seems more difficult to make comparisons because comfort evaluation is a complicated problem.

The first objective of this paper is to define the more convenient comfort criteria for aeronautics field. These criteria must take into account both rigid-body and elastic dynamic aircraft responses. In a second step, these criteria will be used in order to choose the best methodology for control laws design.

Definition of comfort criteria

Comfort evaluation is a difficult challenge, because a lot of elements can influence it (sound, temperature, smells, passenger activity, ...). In this paper, we will focus on vibrational comfort, which is recognized to be preponderant for passenger comfort.

Numerous studies have been conducted to examine the effects of aircraft vibrations on passenger comfort. Generally, the effects of vibration on passenger comfort are considered in the frequency range [1 Hz-80 Hz].

Our experience in the design of flight control system (Concorde, A320 family, A330/A340) shows that some particular attention must be focused on frequencies below 1 Hz. Indeed, flight mechanics modes are located in this frequency band and can influence passenger comfort.

A recent international standard [2] gives some criteria for the complete frequency range. In fact comfort evaluation is split into two frequency bands:

- 'Very low frequency' range (frequency below 1 Hz),
- 'Low frequency' range (frequency above 1 Hz).

For these two bands, specific criteria are defined in order to evaluate comfort sensitivity.

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Concerning 'very low frequency' comfort, the standard is based on vertical acceleration felt by human passenger. A frequential weighting is introduced in order to represent sensitivity to motion sickness. This filtering is presented in Figure 1.

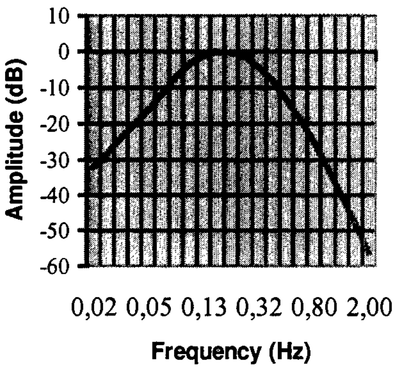

Figure 1: Motion sickness sensitivity

It consists in a band-pass filtering centered at 0.16 Hz which is considered as the critical frequency for motion sickness phenomenon.

The ISO 2631-1 standard proposes to compute a motion sickness index representative of the Percentage of Ill Passengers (PIP). PIP is defined as:

$$PIP = 1/3 * \left[\int_0^T a_w^2(t) dt \right]^{1/2}$$

where a_w is the measured vertical acceleration (m/s^2) during T seconds weighted by the motion sickness filtering.

We have to underline that this standard contains some limitations for aeronautics applications. It was derived from seaboard studies, and the specifications are only given for vertical axis. In this paper, we will consider that the specifications are also applicable to lateral axis.

Concerning 'low frequency' comfort, the standard is based on measurement or calculation of the acceleration felt by a human passenger at one point and in one direction.

As for motion sickness, frequency weighting functions are introduced in order to represent the physiological response of human body. For a seated person, two frequency weightings are used, for vertical (z axis) and lateral (x and y axis) accelerations; these filters, presented in Figure 2, emphasize the frequency range between 4 to 8 Hz for vertical acceleration and 1 Hz for the lateral ones.

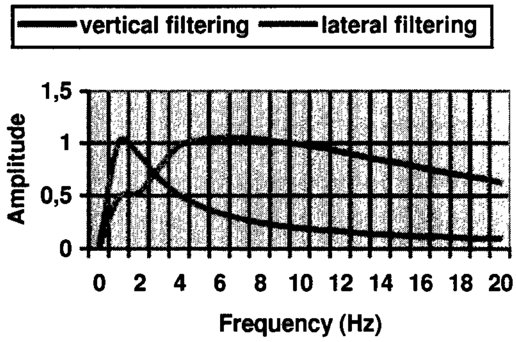

Figure 2: Frequency weighting for comfort

The standard proposes to compute the root mean square (r.m.s.) value of the weighted acceleration a_w (m/s^2) during T seconds:

$$a_{rms} = \frac{1}{T} \left[\int_0^T a_w^2(t) dt \right]^{1/2}$$

At a measurement point p, a global comfort criterion can be computed from r.m.s. values of weighted accelerations in each direction:

$$a_p = (k_x{}^2 a_{px}{}^2 + k_y{}^2 a_{py}{}^2 + k_z{}^2 a_{pz}{}^2)^{\frac{1}{2}}$$

where :

a_{px}, a_{py}, a_{pz} are r.m.s. values of weighted accelerations respectively on x, y and z axes ;

k_x, k_y, k_z are weighting factors ; for a seated person the standard proposes the following factors :

- at the supporting seat surface : k_x=1, k_y=1, k_z=1;
- at the feet : k_x=0.25, k_y=0.25, k_z=0.4.

In order to evaluate the discomfort level felt by a person, the above procedure has to be applied to each movement transmitted to the human body by supporting surfaces. Then for a seated person, vibrations at the supporting seat surface, at the feet and at the back of the seat have to be taken into account (comfort of a seated person may also be affected by rotational vibrations on the seat; the standard proposes specific frequency weightings for these ones).

When comfort is affected by vibrations at several points, the overall vibration can be computed from the r.m.s. value of global vibrations at each point:

$$a_{tot} = (a_{p1}{}^2 + a_{p2}{}^2 + a_{p3}{}^2)^{\frac{1}{2}}$$

For civil aircraft applications, rotational vibrations as well as the ones transmitted by the back of the seat may be neglected. Then only vertical (z axis) and lateral (y axis) accelerations at the supporting seat surface and at the feet are taken into account. Accelerations at the supporting seat surface are obtained by filtering accelerations at the feet with an experimentally determined filter, representative of the mean response of a seat with a person.

The standard gives approximate indications of the likely reactions to various magnitudes of frequency-weighted r.m.s. accelerations:

< 0.315 m/s^2	not uncomfortable
0.315 – 0.63 m/s^2	a little uncomfortable
0.5 – 1 m/s^2	fairly uncomfortable
0.8 – 1.6 m/s^2	uncomfortable
1.25 – 2.5 m/s^2	very uncomfortable
> 2 m/s^2	extremely uncomfortable

Large capacity aircraft application

For 'very low frequency comfort', we applied this standard to a large capacity aircraft in order to evaluate passenger comfort in different airplane locations (forward fuselage, center fuselage, aft fuselage). Standard missions were simulated including manœuvres (heading change, level change, ...) and turbulence for different configurations:

- natural aircraft without high level control law (yaw damper only),
- passive control law (filtering of flexible modes),
- active control law (control of flexible modes).

PIP in manaoeuvres were found negligible for any type of control laws and passenger locations (less than 0.1%). Concerning turbulence, some differences can be noticed and the results are shown in Figures 3 and 4 (simulations of 3 minutes in strong turbulence).

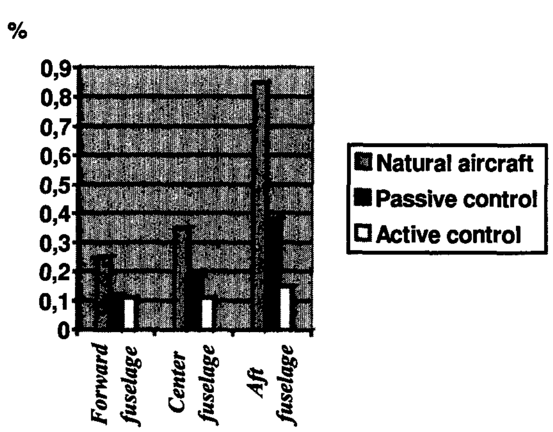

Figure 3: PIP in turbulence (lateral axis)

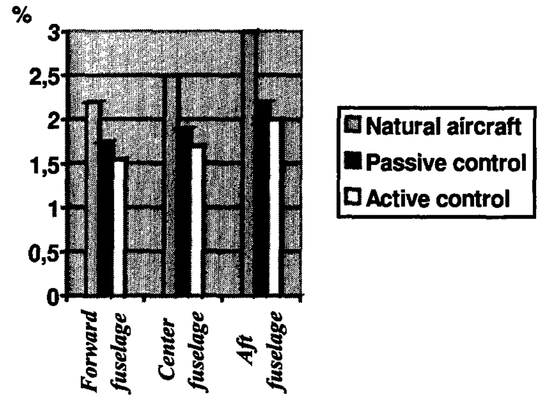

Figure 4: PIP in turbulence (vertical axis)

At first, we can notice that the PIP is small whatever the configuration (<0.9% for lateral axis and <3% for vertical axis). This means that aircraft is a comfortable way of transport. We can remark that the level of comfort depends on location in the aircraft, and that the PIP progressively increases with respect to the distance from aircraft nose (whatever the type of control law).

Control laws allow to improve comfort for all locations, and the active control seems to be the more efficient. We can explain it by the fact that the active control allows to increase control law bandwidth, and thus to accelerate flight mechanics modes (short period, dutch roll, ...). It means that the global aircraft dynamics will be faster than the motion sickness critical frequencies (about 0.16 Hz). With a passive control, which means low frequency filtering, it is not possible to significantly increase the aircraft dynamics, which can remain in the motion sickness frequencies.

These results are coherent with our experience in the field of flight control system development (sensitivity around 0.16 Hz, control law tuning, ...). The ISO2631-1 seems to be a useful tool for comfort evaluation.

Concerning 'low frequency' comfort, the standard was applied to evaluate passenger comfort in different locations all along the fuselage. Realistic turbulence during a cruise configuration was simulated for two configurations:

- natural aircraft,
- active control law (control of flexible modes).

The case of passive control law is not mentioned here since the passively controlled aircraft has the same behavior as the natural one, from a low frequency comfort point of view.

Figure 5 presents the results for a vertical turbulence, rather than the ones for a lateral one, since acceleration level due to a lateral turbulence is far less critical.

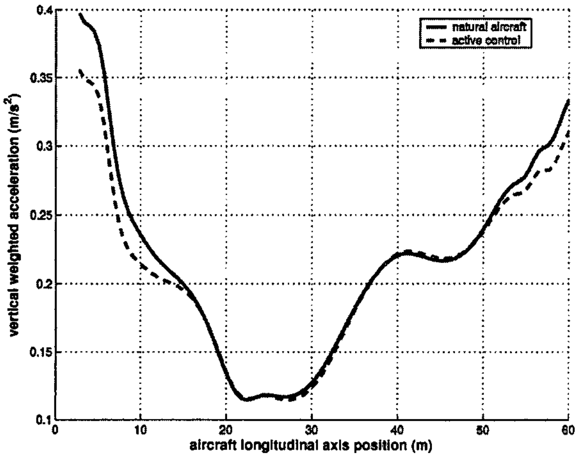

Figure 5: Comfort in turbulence (vertical axis)

Note first that computed acceleration levels are rather small. According to indications given by the standard, the aircraft is considered not uncomfortable nearly all along the fuselage; only the pilot location (at the very front of the fuselage) and the very rear of the fuselage may be felt a little uncomfortable.

The active control law improves comfort particularly at the front of the fuselage, also at the rear of the fuselage, but not at other locations. This is due to the active control of the "2 nodes fuselage bending" mode at 2.5 Hz, which appears particularly at the front and at the rear of the fuselage.

The maximum improvement of the comfort criterion due to the active control law is 10%. The significance of this improvement was successfully checked, since it was indeed noticed by passengers during laboratory tests with a vibrated seat.

Conclusion

This paper shows how comfort criteria based on ISO 2631-1 standard can be applied to a large capacity civil aircraft for passenger comfort evaluation.

The results obtained show that control laws allows to improve comfort with respect to the natural aircraft. More over an active control of the first flexible modes allows not only to improve 'low frequency' comfort (vibrating comfort), but also 'very low frequency' comfort (motion sickness phenomenon). It means that an integrated design, which actively controls both rigid and flexible modes, seems preferable for comfort improvement.

This study defines tools for comfort analysis and control law design, which could be used for future large civil aircraft, like the A340-500/600 and the A3XX.

References

[1] "New flight control laws for large capacity aircraft. Experimentation on Airbus A340", F. Kubica, in proceedings ICAS, 1998.

[2] "Mechanical vibration and shock - Evaluation of human exposure to whole body vibration", ISO2631-1, 1997.