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Preliminary results on the modeling of aircraft vibroacoustic comfort

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Noise and vibration have been shown to bear a significant effect over perceived comfort in aircraft cabins. However, in order to better understand their influences and predict the passengers' perceived comfort, an analytical model must be called upon. This work presents preliminary results on such a model using data from a survey carried in an aircraft simulator at the Universidade Federal de Santa Catarina, Brazil. Volunteers were submitted to different stimuli based on real aircrafts recordings and asked to evaluate them regarding their perceived comfort. Multivariate statistical analysis then allowed exploring the relations between these environmental aspects and the passengers comfort perception, leading to a predictive vibroacoustic comfort model.

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1 INTRODUCTION

Air passenger traffic has been growing fast in the last decades, roughly doubling every ten years. Moreover, the development of regions such as Asia and Africa will keep this growth rate above five over the next two decades, representing a demand for 31,000 new aircraft[1,2,3]. However, the dispute over this share of passengers will hardly be decided by prices, since the efficiency of aircraft operators is already close to optimal[1] . The strategy must then turn to areas only scarcely explored up to now, such as passenger comfort.

In the means of transportation milieu, the term comfort is associated with a myriad of aspects and characteristics. In aircrafts, it has been shown that noise and vibration are main components of the perceived comfort, along with seat, attendance and temperature[4,5]. Additionally, this perception is affected by numerous factors, being strongly related to the consumers' expectations towards the product[6]. For instance, passengers associate certain sounds (landing gears, flaps…) with safety during takeoff, so that there is no guarantee that noise level reductions will result in sound quality improvements[5].

Traditionally, research on civil aircraft cabins was limited to airworthiness aspects. Sundback and Tingvall[7], for example, performed studies on aircrew fatigue, safety and work proficiency. Studies on the factors that affect comfort or discomfort of aircraft passengers, including vibroacoustic, were only pursued recently, by projects such as the Europeans IdEA-PACI, FACE and HEACE[8]. The current standards limitations and the sparseness of studies developed for passengers in general and Brazilian consumers in particular, suggest that further analyses relating comfort, noise and vibration are valuable.

This paper addresses the modeling of perceived vibroacoustic comfort by (i) introducing an individual aircraft cabin simulator; (ii) developing a methodology to assess comfort/discomfort based on ungraded scales; (iii) devising a predictive model using psychoacoustic metrics, weighted vibration levels and *Partial Least Squares* (PLS), (iv) providing a sensitivity analysis to study the impact of noise and vibration parameters on passengers comfort.

2 THE AIRCRAFT CABIN SIMULATOR

An aircraft cabin simulator was developed at the Federal University of Santa Catarina, Brazil, representing the typical cross section of a medium-sized aircraft. A standard economic class seat was installed in the middle of the simulator and volunteers were questioned using a touch screen interface (Figure 1).

In order to reproduce the vibroacoustic environment of a cabin, the simulator floor was suspended over isolators and electromagnetic shakers were used to reproduce vibration in all three axis. The acoustic stimuli were presented to the volunteers using a noise cancelling headphone, so that the noise from shakers, amplifiers etc. did not disturb the evaluations.

A tri-axial accelerometer monitored the vibration level during all tests and the sound reproduced through the headphones was characterized using a dummy head. Due to the intricacy of *multiple inputs-multiple outputs* (MIMO) equalizing[9], all models were based on the acquired objective data, so as to reflect the exact stimuli to which the volunteers were subject.

3 METHODOLOGY

3.1 Sample and stimuli description

The jury was composed of 38 volunteers (22 men and 16 women) aging from 18 to 37 years (mean: 24,18, standard deviation: 4,13). The sample was selected to include only subjects that had already traveled by plane. The volunteers were asked to evaluate their vibroacoustic comfort during the reproduction of 28 combinations of noise and vibration signals with different levels. All stimuli were in-flight recordings of the cruising stage of different aircrafts in normal conditions (no turbulence). So as to avoid fatigue among the jury, the signals were divided in blocks and the evaluations were spread over different days.

3.2 Subjective evaluation

Each evaluation began with an explanatory video, during which a typical aircraft noise and vibration was reproduced in the background. All signals pertaining to a block were then presented to the volunteers, so that they would be aware of all stimuli beforehand.

The subjective evaluation was based on the psychometric method of scaling using the attribute "comfort". The participants were asked to evaluate their perception of comfort by marking a point on an ungraded straight line, where the extreme values (0 and 10) were presented to standardize the assessment. The subjects were allowed to freely switch between stimuli to confirm their answers.

The collected points were converted to real numbers rounded to the tenth and compared against the psychoacoustic parameters loudness (*loud*), roughness(*rough*), sharpness (*sharp*) and tonality (*tonal*); the global sound pressure level (*SPL*); and the resultant vibration levels on each axis weighted by the ISO 2631-1:1997 ($A_w X$, $A_w Y$, $A_w Z$).

4 STATISTICAL MODELING

The model proposed in this work is based on the average comfort response of the jury. This approach was motivated by initial observations of the responses distributions, which suggested a normal behavior. The statistical analysis was then divided in three steps: (i) outlier detection, (ii) normality evaluation, and (iii) regression.

At first, extreme responses that could impair the average estimate were identified using by calculating the Mahalanobis distance as

$$M_D = \sqrt{(y_n - \mu)^T C^{-1} (y_n - \mu)}, \tag{1}$$

where y is the $N\ x\ 1$ vector of responses for the n-th stimulus and μ and C are, respectively, the $N\ x\ 1$ mean vector and the $N\ x\ N$ covariance matrix of the responses for all stimuli. This value was then compared to the χ_N^2 distribution for $\alpha = 0.05$ [10].

Secondly, before adopting the mean comfort response as the dependent variable in the regression, the normality hypothesis was verified through Q-Q plots and the Kolmogorov-Smirnov test. The latter compares the estimated cumulative distribution of the data against that of the null hypothesis, i.e., a fitted normal distribution[11].

Finally, the model itself was evaluated using PLS. This method has the same robustness to collinearity as regression over principal components (PC), with the advantage of optimizing the regression components (called *latent vectors* or *LVs*) simultaneously in the regressors and dependent variables subspace[10]. A jackknifing procedure was used to determine the appropriate number of LVs for the data, so as to minimize *overfitting*. This method removes an observation from the data set to create a new sample over which a model is fit. This model is then used to predict the left out response. This procedure is repeated for each observation and the mean square error of prediction is used as a figure of merit[12]. New LVs are added to the model as long as the prediction error is reduced.

Given the regression coefficients, a simplified sensitivity analysis of the phenomenon can be performed through their centered and normalized (*studentized*) values. It is then possible to assess which regressor variables have more influence over the dependent variable[13].

5 RESULTS

The outlier detection technique explained above identified 38 multivariate outlying responses. When pruned, none of the jury's assessments normality could be rejected ($p > 0.05$). The average responses were then taken as dependent variables for the regression.

The regression analysis started by testing different numbers of LVs and evaluating the model's prediction error using jackknifing. The lowest error was found for 2 LVs (RMS error 0.92) and the result is illustrated in Figure 2. These LVs decompose 74 % of the regressors' and 86 % of the dependent variables' variance. The low standard deviation of the model reflects on the good agreement between predictions and responses, unless for a few exceptions.

The weight of each regressor on the output of the model can be assessed by Figure 3. This circle represents the correlation between independent and dependent variables and both LVs. The first LV clearly opposes the psychoacoustic parameters to comfort, while the second LV can be interpreted as the vibration domain. It is clear that the impact of vibration on perceived comfort is lower than that of noise. This conclusion is supported by Figure 4, which presents the studentized coefficients of the model. The predominance of loudness, alongside SPL, shows the key influence of the sound level on comfort, closely followed by roughness. As expected, the regression coefficient of tonality was a reflection of the atonal nature of aircraft cabin noise. Finally, although vibration levels bear smaller effects on passengers' comfort, the Z axis contribution cannot be neglected.

6 CONCLUSIONS AND FUTURE WORKS

Aircraft vibroacoustic comfort was studied in this work by means of a statistical model. In order to assess the perceived comfort by passengers, an individual aircraft cabin simulator capable of reproducing noise and vibration was developed. Subjective responses were collected with the help of a jury and a regression model was used to study the relation between psychoacoustic parameters, vibration metrics and comfort perception. A simplified sensitivity analysis revealed the importance of acoustic aspects over vibration. Future works include the study of different regressors, larger samples and integrated models with thermal, ergonomic and lighting comfort.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

1. Embraer Commercial Jets, Market Outlook 2011-203, Report, 2011.

2. Boeing Commercial Airplanes, Current Market Outlook 2011-2030 Report, 2011.

3. Airbus S.A.S, Delivering the Future, Global Market Forecast 2011-2030 Report, 2011.

4. J. Quehl. Comfort studies on aircraft interior sound and vibration. *Doctoral Thesis*. University of Oldenburg, Germany, 2001.

5. R.F. Bitencourt et al. Relevância dos aspectos vibro-acústicos no conforto no interior de aeronaves. *XXI Meeting of the Brazilian Acoustics Society – SOBRAC*, São Paulo, 2006.

6. D.L. Bowen; R. Lyon. Mapping perceptual attributes of sound to product design choices. *Noise Control Eng. J.* **51**, 271–279, 2003.

7. U. Sundback; B. Tingvall. Investigation of the physical working environment for cabin attendants within Scandinavian Airlines System (SAS). *INTERNOISE*, Miami, 1980.

8. R.F. Bitencourt. Desempenho de métodos na avaliação do conforto acústico no interior de aeronaves. *Doctoral Thesis*. Federal University of Santa Catarina, Brazil, 2008.

9. L.F.O. Chamon et al., “An SVD-Based MIMO Equalizer Applied to the Auralization of Aircraft Noise in a Cabin Simulator”, *18th International Congress on Sound and Vibration*, Rio de Janeiro, 2011

10. J.F. Hair Jr. et al., *Multivariate Data Analysis*, 7th edition, Prentice-Hall, (2009)

11. W.J. Conover, “Statistics of the Kolmogorov-Smirnov type”, Chap. 6 in W.J. Conover, *Practical Nonparametric Statistics*, 3rd edition, Wiley Press, (1999)

12. H. Abdi, “Partial least square regression, projection on latent structure regression, PLS-Regression”, *Wiley Interdisciplinary Reviews: Computational Statistics*, **2**, 97-106, (2012)

13. A. Saltelli et al., *Global Sensitivity Analysis: The Primer*, Wiley-Interscience, (2008)

Fig. 1 – Aircraft Cabin Simulator

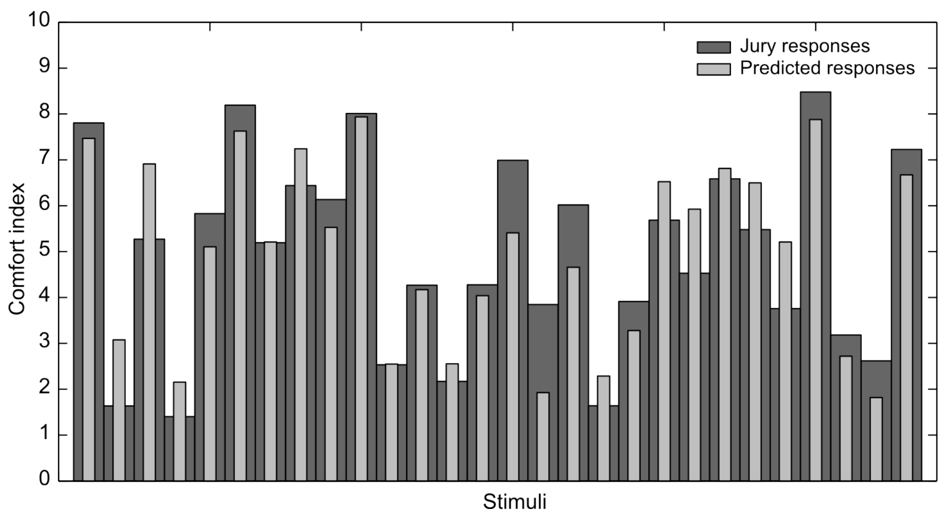

Fig. 2 – Jury responses and predicted responses using jackknife.

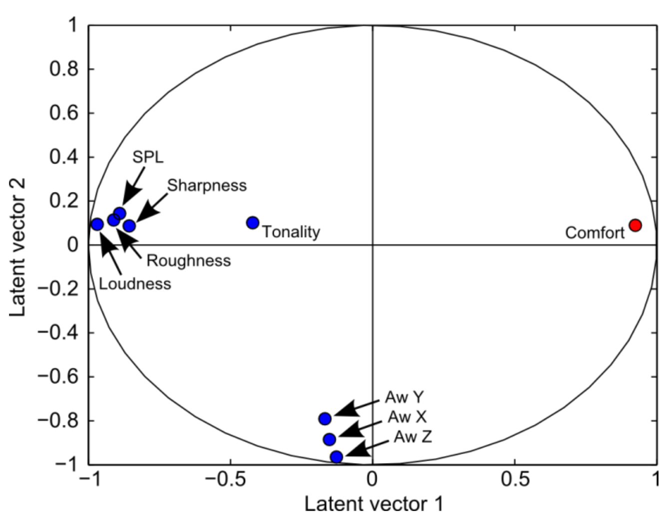

Fig. 3 – Correlation circle for the LVs.

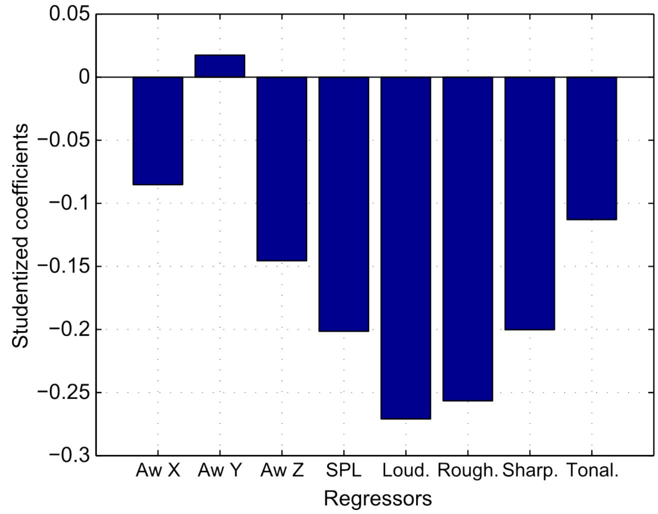

Fig. 4 – Studentized regression coefficients.