



APPLICATION OF VIBRO-ACOUSTIC AND PSYCHOACOUSTIC PROTOCOLS FOR THE EVALUATION OF INTERIOR NOISE IN THE AIRCRAFT CABIN

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ABSTRACT

The interior noise and vibration in the cabin of an aircraft is mostly generated by the engines for thrust and by flow noise. Sometimes, pronounced additional tonal components are observed. The spectral content varies along the aircraft. Vibro-acoustic measurements are reported from different flights in different aircrafts. The perception of the cabin ambience by passengers and crew is registered with the help of questionnaires and additional psycho-physiological registration. Relations between vibro-acoustic and psychoacoustic protocols or evaluation procedures and the human response in the cabin environment are investigated. The "acoustic" component in the human response is not always clearly identifiable.

INTRODUCTION

The investigation of environmental impact in the aircraft cabin on performance, well-being and health of cabin- and flight-crew is the objective of the European project HEACE ("Health Effects in Aircraft Cabin Environment", www.heace.org). One aim of the research is to develop a model which relates the impact of the ambience of the workplace of the crew to health parameters, subjective comfort, performance, well-being etc. of the crew. The model should help to derive recommendations for an improved design of this workplace. HEACE is carried out together with partners from Building Research Establishment (BRE) in UK, Medical University Vienna in Austria, EADS-CRC in Germany, CIRA in Italy, University of Patras (LFME) in Greece, itap GmbH in Germany, and Paragon Ltd in Greece.

TEST DESIGN

General

Variation of environmental conditions in real flight is obviously limited, and experimental set-ups in an airplane have to follow rigid boundary conditions. Complementing experiments are useful in a simulator facility, which provides a sufficient natural ambience. Experiments are carried out in the HEACE project in both simulators and during real flights. The question is still unsolved how "real" a simulation has to be conducted in order to allow transfer of results from the test-bed to the real-flight situation. The HEACE project could not answer this question, but is the first investigation, which uses systematically in parallel the same methodology in both, real flight and mock-up experiments.

Flight experiments serve in a first phase of the investigation to set up a data base with physical data of the cabin and cockpit environment in order to feed the simulator facilities with a realistic noise, vibration, and climatic environment. Main flight experiments are conducted in 6 long-haul flights of 8 and 12 hour duration with support of Austrian Airlines, in which altogether 132 flight attendants and 30 pilots participated. The environmental data are registered as "naturally" offered; the data from the cabin crew is recorded with the same tools and by the same means as used in the simulator experiments under precisely defined conditions. The design comprises a questionnaire and recording of numerous physiological and health indices [1].

Simulator tests are carried out in two facilities: The emergency trainer of Austrian Airlines in Vienna and in the ACE test facility of BRE in Watford [2]. The environmental condition is adjusted in a full three-step variation of the three parameters "sound and vibration" (vibration signal derived from the acoustic input), "humidity", and "temperature". The parameters are re-

corded throughout cabin and cockpit, because a certain spatial variation is inevitable, although a target value is adjusted in the simulator for the respective step. 22 pilots and 86 flight attendants serving 544 (test) passengers participated in the simulator tests.

Questionnaire design

Questionnaires are designed based on own extensive experience in psychophysical research for car industry, and on the European project IDEA PACI [3] as well as on the knowledge gained from the European project CabinAir [4]. The questions base on interviews with the respective personnel and on extraction of appropriate pairs of adjectives, differentially describing the cabin and cockpit environment. These semantic differentials are tested with experts. Mood scales, questions related to symptoms and subjective activity are included. Design and layout of appropriate scales (in general a 7-point scale as fixed by other guidelines (e.g. [5])) is formatted for electronically reading. The scales could either be bipolar (e.g. -3 to + 3), or sometimes unipolar (e.g. 1 – 7 or 1 – 5). The time frame and design for conducting the experiments in simulators and in flight is set after estimating the time to fill-in the questionnaire. Questions address some 120 items from following areas

- health and well-being (30 items)
- environmental conditions (45 items)
- demand for control over environment (8 items)
- effect of the environment (18 items)
- relative comfort contribution (18 items)
- ability to work (8 items)
- alertness and mood (9 items).

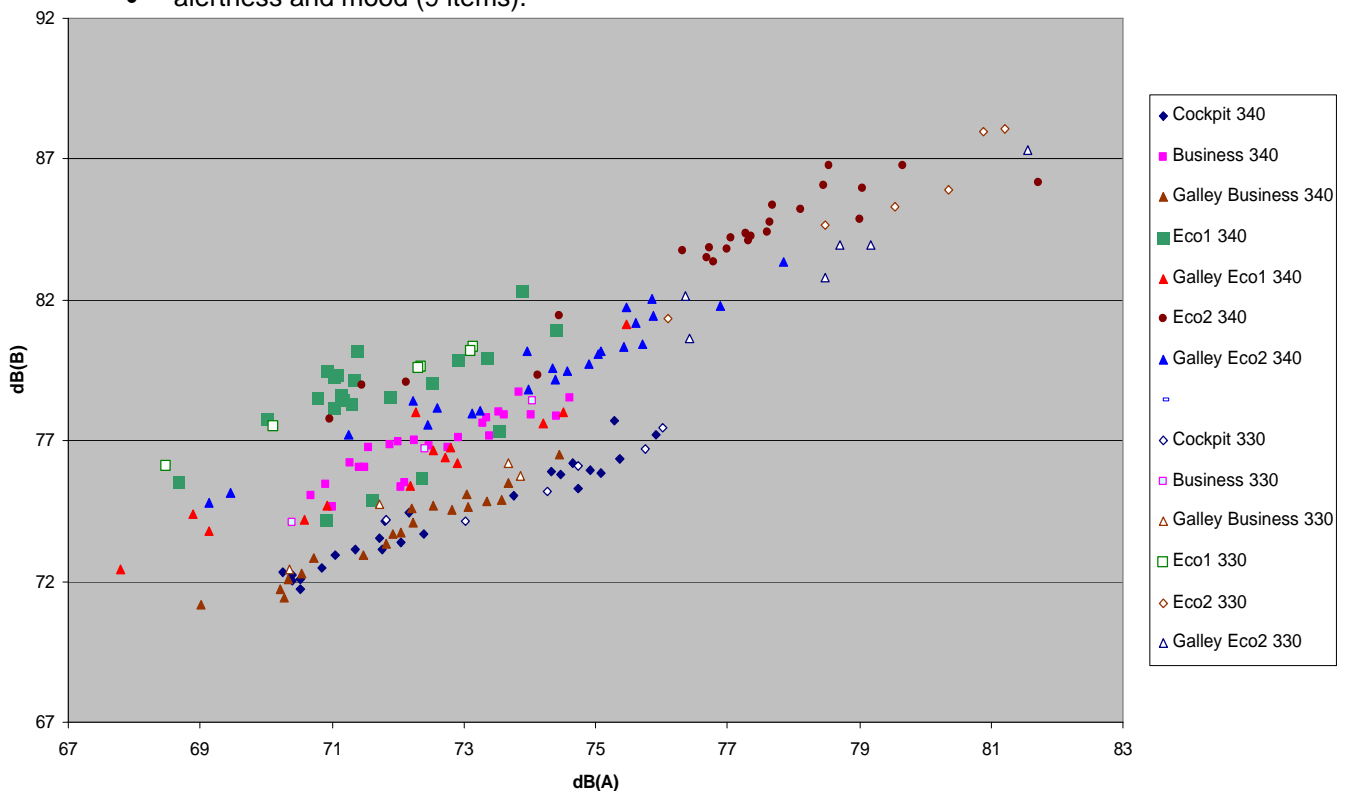


Figure 1.- Distribution of A- vs. B-weighted sound level in cockpit and cabin for A340 (filled symbols) and A330 (open symbols) during periods of filling in the respective questionnaire (location given in table). $dB(B) > dB(A)$ indicates low-frequency contribution to interior noise level.

Flight tests

Measurements of environmental parameters are made during flight in several types of passenger aircrafts. Measurements including questionnaires are conducted during long-haul flights in a A330 and A340.

Following environmental data are measured in cockpit, galleys, cabin, and crew-rest compartments during long-haul flights: Sound and vibration (time history and level), temperature,

humidity, draft, air quality (CO₂, CO, VOCs, number of germs). Physiological parameters are registered coherently the same time (heart rate and –variability, blood pressure, oxygen saturation, salivary cortisol, skin conductance) while questionnaires are filled in by the crew members.

The sound pressure level at different locations of the cabin during the long-haul flights is given in Fig. 1. A difference between A- and B-weighted levels indicates additional low-frequency contributions (most pronounced in the first economy compartment in the middle of the fuselage near the wings). Both planes have about the same noise level in cabin and cockpit during the flight tests except for the aft of the A330, where the level is slightly increased.

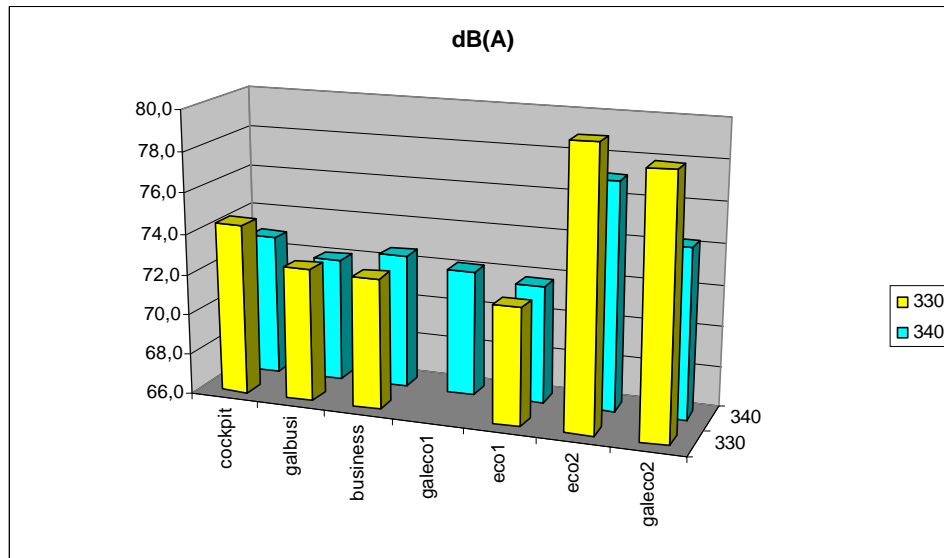


Figure 2.- dB(A)-levels in cockpit and cabin along aircrafts A330 and A340 from front to aft at respective location during long-haul flights (average in time over flight duration)

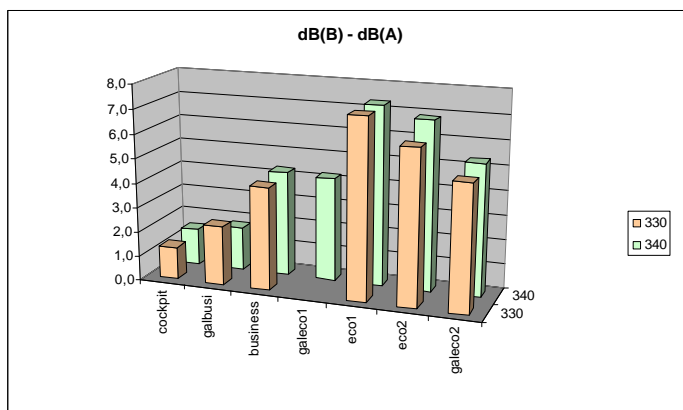


Figure 3.- Increase of dB(B) level over dB(A) level along aircrafts A330 and A340 (derived from Fig. 1).

Fig. 2 gives the dB(A) level from the cockpit location to the aft, averaged over all flights and distinguished between the two types of aircraft. A continuous increase with location is observed. Fig. 3 indicates in particular an increase of low-frequency components starting at the “economy 1”-location. The vibration levels of acceleration are measured at about the same locations and depicted in Fig. 4.

Acceleration levels are averaged values in the frequency bands 16-80 Hz, 100-160 Hz, 200-250 Hz and weighted according to ISO

2631-1. The level values in Fig. 4 are numerically reduced by 20 dB in order to provide numbers of same magnitude as sound pressure levels in order to construct a balanced input for a neural network analysis (acceleration level of 140 dB equals about 1 g – the reference in Fig. 4 is 120 dB). Measurements and input vector are provided by itap GmbH and EADS-CRC [6, 7]. The vibration level is lowest in the front part except for a slight increase in the first galley.

Fig. 5 gives the spectral content of sound sample, as accidentally measured during a long-haul flight (the sample is independent from the type of aircraft, B737, similar is measured in other large cabins as well). Low-frequency components are observed, which stem from the longitudinal modes of the air column in the cabin, and additional distinct tonal components from the gear.

Simulator tests

Pre-tests are carried out in the emergency trainer of Austrian Airlines in Vienna, which provides quite good natural ambience with respect to noise, vibration and motion, but lacks of stable conditions for temperature and humidity. Main simulator tests are carried out in the ACE at Watford, which allows for an excellent stabilization of climatic conditions (except pressure), even at very low humidity [8], but has the disadvantage not to provide motion, which lowers considerably the impression of a natural ambience. Simulated sound and vibration is based on measured cabin noise without any low-frequent or distinct tonal component.

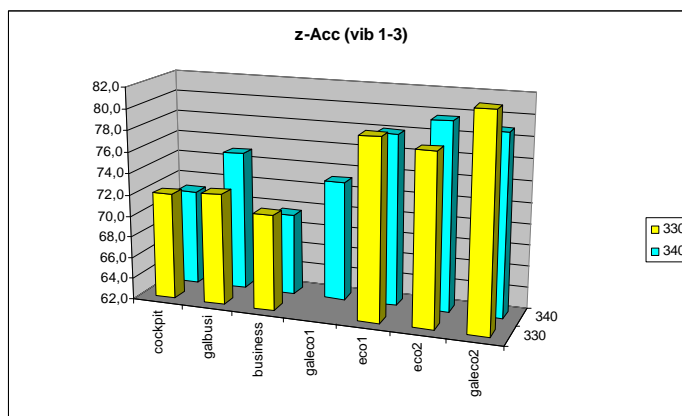


Figure 4.- Weighted vibration levels [dB] at same location as in Fig. 3. The ordinate scale is shifted by 20 dB to adjust the numbers for training of an artificial neural net (details see text).

Simulator flights take place in a full 3x3x3 factorial test design with 3 levels of noise (and vibration, which was derived from the sound signal), 3 levels of temperature, and 3 levels of humidity. The lowest noise level is determined by the background noise of the air conditioning. In short summary, a simulator flight starts with boarding, public welcome address, “start” procedure, one hour “flight” at a given noise level, catering, one hour “flight” at next noise level, catering, one hour “flight” at third noise level, landing procedure. The climatic conditions are kept constant during this session. Questionnaires are filled in by the passengers and by the crew after each service. The service of the crew includes the distribution of the passengers’ questionnaire.

Data analysis

The physical (environmental) data are measured and analyzed according to the technical state-of-the-art, e.g. loudness in Sone, speech interference level SIL, PMV of local thermal comfort, CO and CO₂, VOCs (according to procedures defined in [9]). The medical (physiological) data of each crew member and test person are analyzed by the Medical University Vienna and summarized in representative (vector) indices [10, 11, 12] characterizing:

- “load” for physiological state and physiological reaction to external stressors
- “imbalance” of subject’s physiological status
- alertness, energy, and mood
- subjective health
- performance

The ANN [6, 7] uses an input vector of pre-processed environmental data and calculates an output, which is representative for one of the indices mentioned above. The model works with an error below about ½ step-size of the subjective scales (i.e. about ±7% absolute error). Acoustic and vibration data are pre-processed following known psychoacoustic human response (e.g. text book [13]). The spectral distribution of the cabin interior noise is summarized in third-octave bands and combined with a weighted level of vibration to a so-called multi-spectrum [14], which can in principal take variations in time into account. Since the acoustic signal has more-or-less stationary spectral content in all experiments and is not subject of a defined spectral variation, the time dependency of the multi-spectral representation does not provide additional information to the ANN in the present investigation.

A principal component analysis of all data from the questionnaire (i.e. data from all tested crew members, who are at work during flight) displays clear clusters of similar perception, which can be arranged in 11 dimensions [15] with subjective noise effects as the most important factor. The correlation with physical or psychoacoustical parameters exhibits only a small (though still significant) link to the subjective perception. A simple linear correlation seems not appropriate to take the changing environmental condition, the mutual interaction, and the complex task load of

the crew into account in order to give clear evidence of relations between independent and dependant variables. ANOVA is applied to gain further insight.

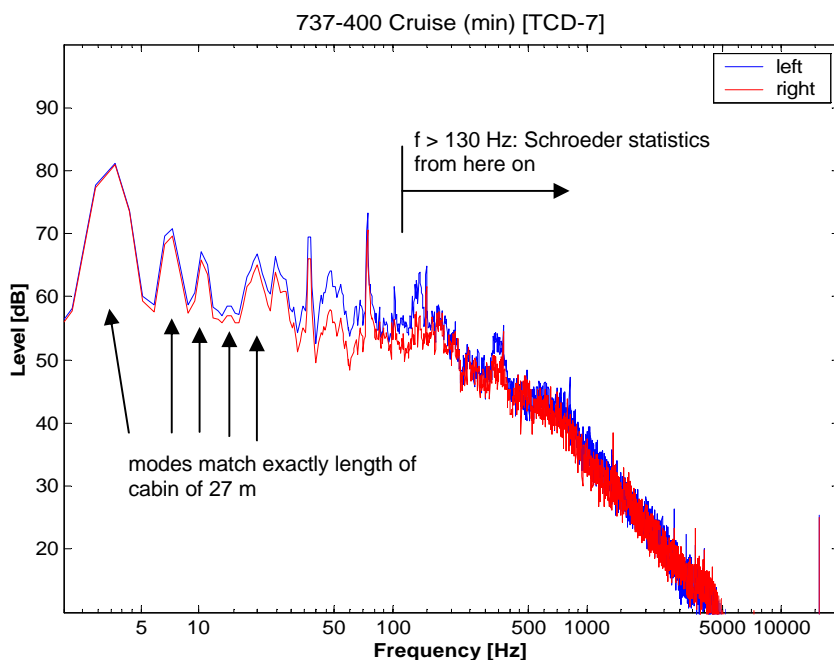


Figure 5.- Stationary spectrum of noise inside the cabin of a B737 during a long-haul flight. Modal overlap can be treated statistically above Schroeder frequency [15]

A highly significant dependency (error < 1%) is observed in the subjective development of the air quality (scale from “smelly” to “odorless”) in the cabin throughout the whole flight from the beginning to the end for all long-haul flights. The degradation of the perceived air quality is about 15% (i.e. one step of the 7-step scale). The observation does not necessarily indicate an objective change of air quality: Measurements of independent air quality parameters do not exhibit any degradation! This result points towards an increase of sensitivity of the perception of environmental conditions, which is confirmed by the analysis of a typical symptom (e.g. “Do you have swollen legs/ feet?”) during laps of flight under the condition of varying noise levels. The perception of this symptom increases significantly with the noise level in the cabin. In particular, the swollen feet become aware at the end of the flight with an increase of 43% “awareness” under noisy conditions compared to quiet conditions in the beginning. The result is highly significant with an error < 0.3%.

Another symptom, which has obviously direct impact on the ability to work, is muscle pain in the neck. A pronounced increase of pain with increasing noise level is reported. The symptom is nearly independent from the flight phase, but increases 57% (error < 0.4%) with a noise-level increase of about 8 dB(A)! This observation is not yet separated from the work-load in the respective cabin compartment, which are governed by an environmental noise level as depicted in Fig.2.

The discussed results do not take into account the direction of the flight, i.e. if the flight is going from “home” to the remote destination or back “home”. Some symptoms like the subjective ability to concentrate (also supported by psychological tests), show a pronounced influence of the flight direction. ANOVA gives a degradation of “concentration” of about 14%, averaged over all flights, when travelling “home” (error < 0.1%).

Insight into the complex interaction of the different parameters is only gained with the help of simulator experiments, which provide investigations under defined conditions with a reduced selection of variables: The full 3x3x3 factorial test design reveals significant impact of the noise level on (error in brackets): level of distraction (3 %), level of annoyance (1 %), overall satisfaction (< 1 %), perception of vibration (< 2 %) and movement (< 1 %), symptoms (< 1%) like lethargy/ tiredness, difficulty in concentration/ remembering, swollen or heavy legs/ feet,

headache. But this relation is only observed when the sound level is increasing in the test during the simulated 3-hours flight. For decreasing sound level the data exhibited no significant relations with dependant variables. A simple explanation would be that the increasing noise level in combination with time of work reduces the level for the load indices to become aware.

Up to now only (about 10 dB) variations in sound pressure (and vibration) level serve as independent acoustic variables in the test. Therefore it is not astonishing that no difference is observed when employing psychoacoustic parameters in the analysis instead of simple dB-levels. Considerable spectral variations are observed in real flights (Fig. 3 and 5), but are not yet subject of systematic investigation in the design of simulator tests. The limited statistical basis of the real flight investigation prevents so far a differentiated analysis of low-frequency impact on the representative vector indices introduced above [10, 11, 12].

CONCLUSIONS

The impact of environmental conditions like noise and vibration at the workplace of cabin- and flight crew on well-being, performance, and health is identified by measurements in long-haul flights and tests in simulators facilities. Various indices are developed to characterize the human response. A relationship between independent variables (characterizing the environment) and dependant variables (indicators of the human response) is well described by an ANN. Direct input-output dependencies of selected parameters reveal a complicated mutual interaction of numerous variables. The noise level exerts significant influence on various symptoms and health indices, in particular when the level increases with time of work. Environmental impact becomes aware with duration of flight.

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