Table IV. Results of the hypothesis tests (+: true, -:false) for the acoustic parameters measured in the two experiments (Experiments 1 and 2). *: for $DAL/|A_M - A_m|$, **: for DAL/T_0 (H1.2), pilot 1; P1: pilot 1, P2: pilot2.

Acoustic Parameters	Hypothesis 1		Hypothesis 2		Hypothesis 3	
	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2
$\langle F_0 \rangle$	-	+ (H1.2) P1	-	+ P1	-	+ (H1.2) P1
CV	+	-	+	-	+	-
$\langle J \rangle$	+	-	+	-	+	-
JF	+	-	+	-	+	-
S	+	-	+	-	+	-
SF	+	-	+	-	+	-
DAL	+*	+**	+*	+**	+*	-
SCG	+	-	+	-	+	-
SBF	-	-	-	-	-	-
EBF	-	-	-	-	-	-
M_n	+ for M_2	-	+ for $M_{2,3,4}$	-	+ for M_2	-
F_i	-	-	-	-	-	-
λ	+	+ (H1.1) P2	+	+ (H1.1) P2	+	-

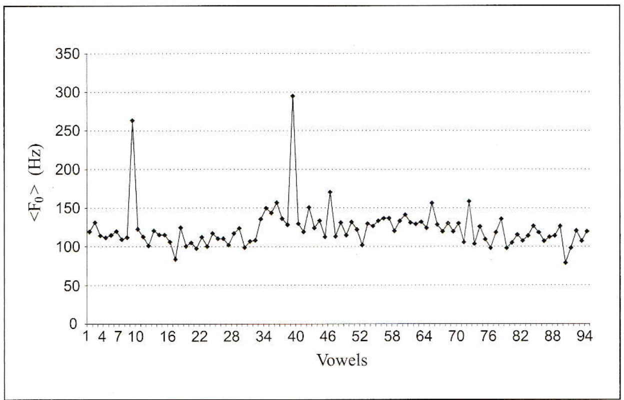

Figure 2. Mean fundamental frequency $\langle F_0 \rangle$ for each vowel uttered by the pilot 1 in the experiment 2.

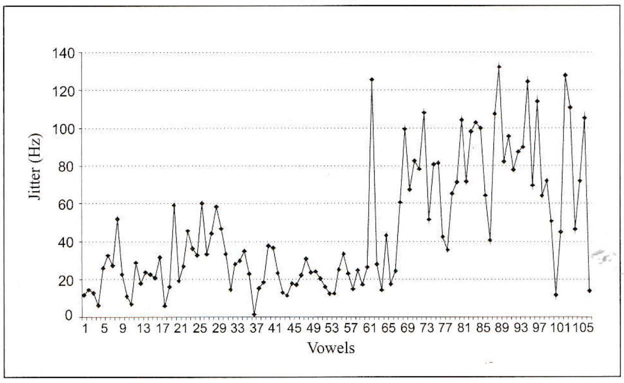

Figure 3. 100 times jitter for each vowel of the experiment 1.

shimmer and the shimmer factor. The major result is that all these parameters vary significantly for the third recording but with a mean fundamental frequency that remains constant. The voice prosody is not affected by sleep inertia. Micro-variations of the glottal pulse cycles appear over time and in amplitude. Figure 4 is an example of a [ə] vowel in the recording 3 of the first experiment show-

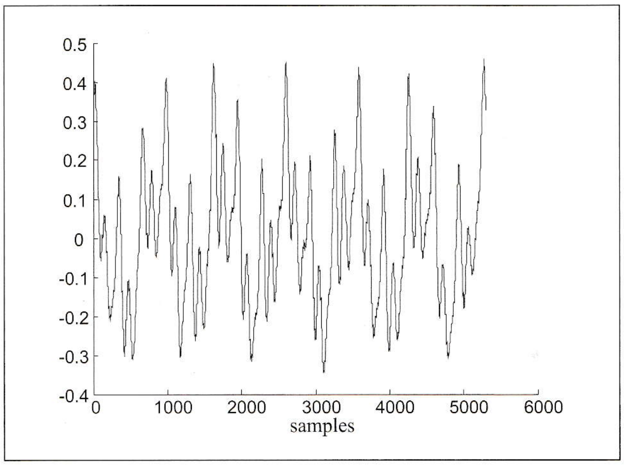

Figure 4. Time waveform of a [ə] vowel from recording 3 in the experiment 1.

ing the greatest jitter variations (jitter = 1.31 Hz with a $\langle F_0 \rangle / F_{0\mathrm{cepstrum}}$ ratio = 0.97).

For fatigue or drowsiness, these short term modifications do not exist. But an increase of mean fundamental frequency is observed for pilot 1 (Figure 2).

These results suggest the assumption that for events which were long to create effects like fatigue or drowsiness, prosody would be involved. But for sudden situations, like awakening, micro-prosody would be involved. It is possible that control of utterance is difficult in surprising situations. Finally, the main assumption is that the time nature of the event inducing modification of the speaker's condition induces a corresponding time nature for the time domain features.

5.2. Numeric amplitude length of the signal (DAL) and derivative parameters

Only $DAL_{T_0}/|A_M - A_m|_{T_0}$ for the first experiment and DAL_{T_0}/T_0 for the second one (pilot 1) have a chronological display which shows variations linked to the assump-

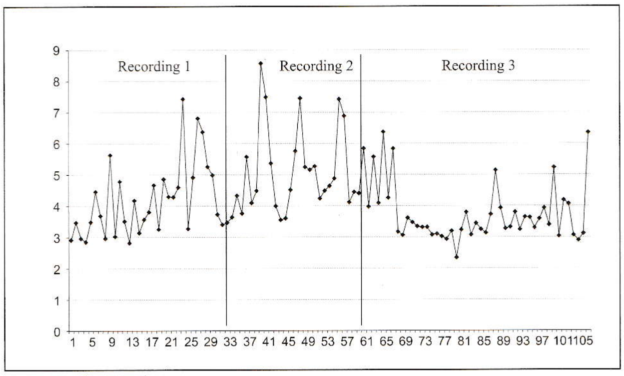

Figure 5. $DAL_{T_0}/|A_{\max} - A_{\min}|_{T_0}$ for each vowel of the experiment 1.

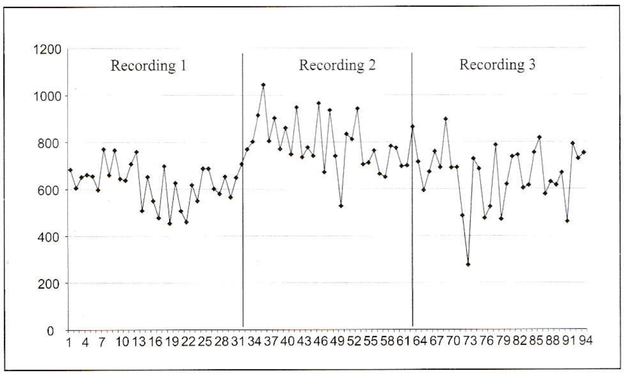

Figure 6. DAL_{T_0}/T_0 for each vowel uttered by the pilot 1 in the experiment 2.

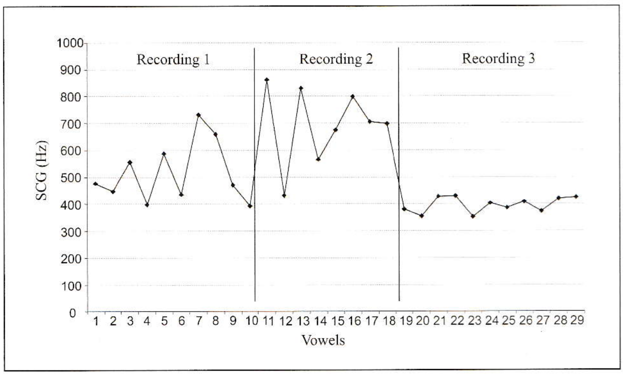

Figure 7. Spectral Center of Gravity (SCG) for [o] vowels in the experiment 1.

tions of the study (Figures 5 and 6). A significant decrease is observed for recording 3 of the first experiment (Figure 5) and an increase for recording 2 of the second experiment (Figure 6).

The observation made for the mean fundamental frequency (Figure 2) appears again here for DAL_{T_0}/T_0 but more clearly (Figure 6). It is perhaps the advantage of this parameter against $\langle F_0 \rangle$ as an effect of drowsiness on vowel signals. In accordance with the H1.2 hypothesis (Table IV) for which the drowsiness could appear at any moment of the recordings, the DAL_{T_0}/T_0 variations show a jump from the beginning of recording 2 (Figure 6). On that basis,

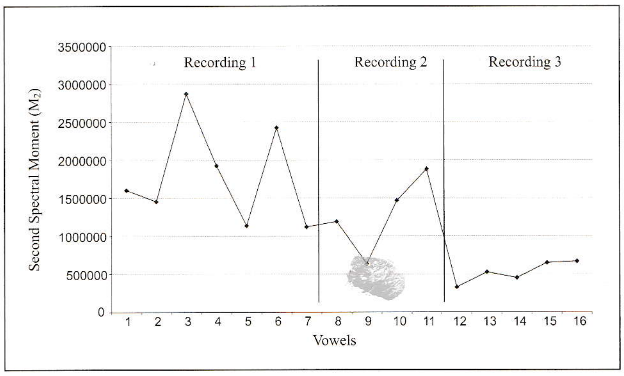

Figure 8. Second spectral moment (M_2) for [i] vowels in the experiment 1.

this parameter could be an indicator of drowsiness. From a unique observation and for only one speaker, the assumption needs to be confirmed by more investigations associated with medical measurements in laboratory experiments.

In the first experiment, this feature does not give such a result probably because mean fundamental frequency is quasi-invariant. But DAL_{T_0} divided by a local maximal peak-to-peak amplitude makes it possible to isolate recording 3 from the two others (Figure 5). The feature appears to be a combination of jitter (from DAL_{T_0}) and shimmer properties from amplitude differences during periods of the signal.

5.3. Spectral domain results

Unexpected results are obtained: neither the formant frequencies, nor the spectral balance frequency, nor the energy balance frequency are modified in the two experiments and for all types of vowels: [a], [e], [ɛ], [ə], [i], [o].

Only the spectral center of gravity (SCG) and the moments ($M_{2,3,4}$) vary for the first experiment. For SCG, a decrease appears in the third recording (Figure 7). This is mainly the case for [i] and [o] vowels. It is less noticeable for the [a] and [ə] vowels. A decrease also exists for M2 and an increase appears for normalized M_3 and M_4 (for all [a], [e], [i], [o] vowels). These variations are statistically significant for M_2 (Figure 8).

These results suggest that the sound levels weighting is shifted towards the lower frequencies. Additionally, the spectral envelope shape is skewed beyond SCG and modified leading to a greater presence of sound levels around SCG.

5.4. Spectral distance (SD)

Table V, Figure 9 and Table VI present the results of spectral distance measurements between vowel sets of two recordings respectively for experiment 1 and 2.

From hypothesis 1 in the study, recording 3 contains the vowels uttered in a disturbed state: after awakening for experiment one and with a maximal fatigue for experiment two. Results show that SD between recordings 2 and 3 is always smaller than SD between recordings 1 and 2 for the

Table V. Spectral distance between recordings (Rec.) of the experiment 1 for each vowel type (32 MFCC coefficients).

	[a]	[ə]	[i]	[o]
Rec.1-Rec.2	6.28	4.22	4.56	4.40
Rec.2-Rec.3	3.23	3.88	2.65	5.39
Rec.1-Rec.3	7.72	6.36	5.31	6.69

Table VI. Spectral distance between recordings (Rec.) of the experiment 2 for each vowel type (32 MFCC coefficients).

		Pilot 1	Pilot 2
[a]	Rec. 1 – Rec. 2	5.51	5.47
	Rec. 2 – Rec. 3	3.85	2.15
	Rec. 1 – Rec. 3	3.52	5.92
[e]	Rec. 1 – Rec. 2	5.10	7.76
	Rec. 2 – Rec. 3	4.61	2.66
	Rec. 1 – Rec. 3	2.41	6.12
[ɛ]	Rec. 1 – Rec. 2	5.64	5.59
	Rec. 2 – Rec. 3	5.70	4.02
	Rec. 1 – Rec. 3	3.96	3.69
[i]	Rec. 1 – Rec. 2	6.88	5.99
	Rec. 2 – Rec. 3	6.14	3.67
	Rec. 1 – Rec. 3	2.56	4.02
[o]	Rec. 1 – Rec. 2	3.70	2.34
	Rec. 2 – Rec. 3	3.43	1.63
	Rec. 1 – Rec. 3	2.44	3.17

Table VII. Spectral distance between recordings (Rec.) in experiment 1 for each vowel type (3 MFCC coefficients).

	[a]	[ə]	[i]	[o]
Rec.1-Rec.2	1.76	0.77	0.89	0.90
Rec.2-Rec.3	0.69	1.21	0.59	1.48
Rec.1-Rec.3	2.30	1.72	1.27	1.90

two experiments (excepting [ɛ] pilot 1 and [o] in experiment 1). This is the main conclusion about the SD study: a unique decreasing sense of variation is observed with the appearance or the increase in the studied phenomenon. However, the metric analysis alone cannot explain SD values between recordings 1 and 3 compared to the other two. Mean recording MFCC coefficients are a point in a 32 dimensional space and the distances between two points are associated with a direction in the space. Therefore, the fact that SD Rec.1-Rec.3 is not always the highest, the lowest or the intermediate value of the three distances does not make it possible to reach a conclusion because of the impossibility of displaying the space. Additional measurements are made for experiment 1 only (for the second one senses of variation were sometimes different for each vowel type). These consists of calculating three MFCC coefficients by vowel and then of displaying the mean coefficients for each recording and each vowel type in a three dimensional space (Figure 10).

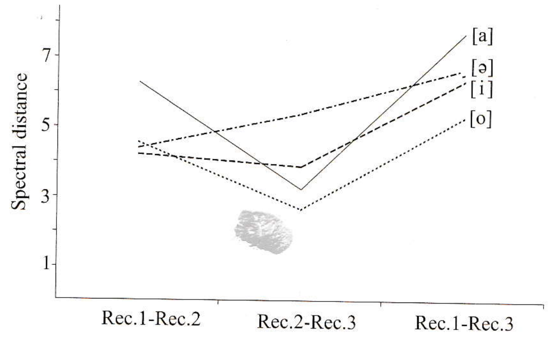

Figure 9. Spectral Distance between Recordings (Rec.) of the experiment 2 for each vowel type (Table V).

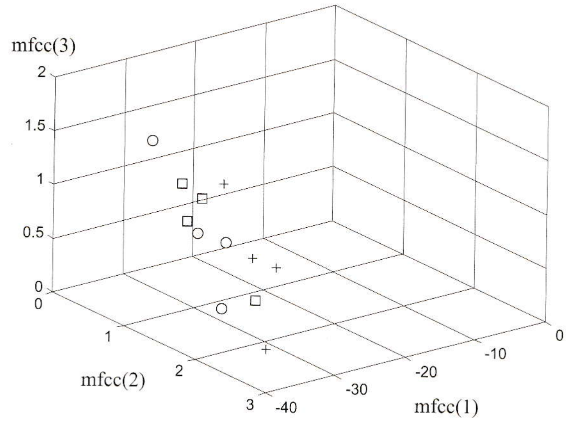

Figure 10. Display of mean MFCC coefficients for each recording of the experiment 1. "o" points are the mean MFCC coefficients for all vowels of recording 1; "□" points of recording 2 and "+" of recording 3.

Distinctive spaces belonging to a recording are not clearly visible. But for future research such a method will always be applied with three MFCC coefficients though computed on different frequency bands in the spectrum.

Because drowsiness seems to be a shorter time phenomenon than long term fatigue, such a spectral study method is not suitable. It would be more appropriated to set spectral distances between consecutive small vowel sets and a rest vowel.

5.5. Maximal Lyapunov exponent (λ)

Figures 11 and 12 respectively show the variations of λ for the first experiment and for pilot 2 in the second one. A linear regression indicates a different sense of variation. However, the comparison between recording 3 vowels and the others is only significant for the first experiment. In the second one, the main observation is that vowels of recording 2 seem to have higher λ values (Figure 12) for pilot 2. A similar phenomenon seems also true for pilot 1 but it is less easily observable. This result has to be compared with the one for mean fundamental frequency (Figure 2).

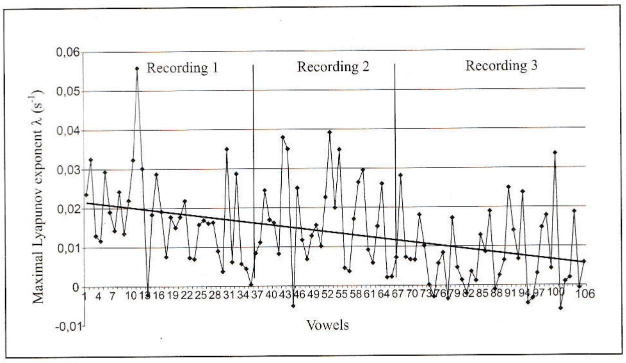

Figure 11. Maximal Lyapunov exponent λ for the vowels of experiment 1 and linear regression.

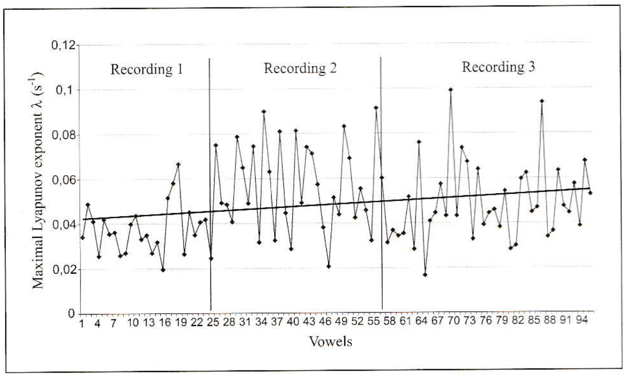

Figure 12. Maximal Lyapunov exponent λ for the vowels of pilot 2 in the experiment 2 and linear regression.

They are probably linked to drowsiness rather than fatigue because of the time of the recording (8 AM).

λ is a dichotomic indicator of presence or absence of chaos in time series data. In previous research, Lyapunov exponent for speech data was qualified as inconsistent [15]. Indeed, some authors found λ to be positive and others calculated a λ of zero for normal vowel production (mentioned in [15]). In [9] a maximum exponent of zero was found for healthy vowel phonation, while disphonic vowels yielded a positive value.

The calculation is highly sensitive to short time series. Here, the benefit of chronological investigation is to allow an interpretation in relative values along the time with identical λ measurement conditions. However, no conclusion on individual values is reached.

5.6. Results for the cockpit voice recorder (CVR)

Ten sentences uttered by pilot 1 of the crew at the end of the last flight (experiment 2) were extracted from the Cockpit Voice Recorder (CVR) tape. Forty vowels were analyzed applying the measurement conditions as described in paragraph 4.4. Comparisons of parameters values between recording 3 (end of the day) and these 40 vowels were carried out.

Time Domain Comparisons: In Table VIII, CVR measurements are compared with those from recording 3.

Table VIII. Mean values of acoustic characteristics of the time domain for CVR analysis and measurements in the cockpit at a stopover (recording 3, experiment 2). Associated standard deviations are in brackets. $DAL_{T0,1} = DAL_{T_0}/T_0$ (amplitude·s^{-1}), $DAL_{T0,2} = DAL_{T_0}/|A_M - A_m|_{T_0}$.

	CVR	In cockpit the ground
$\langle F_0 \rangle$ (Hz)	130.61 (15.44)	117.03 (16.10)
CV (%)	6.41 (8.84)	9.66 (12.64)
$\langle J \rangle$ (Hz)	0.093 (0.14)	0.13 (0.21)
JF (%)	7.41 (11.24)	10.47 (16.60)
S (dB)	1.09 (0.69)	1.16 (0.63)
SF (%)	−62.90 (420.86)	−27.04 (24.47)
$DAL_{T0,1}$	1220.30 (322.35)	653.48 (128.67)
$DAL_{T0,2}$	6.21 (1.57)	3.91 (0.58)

No comparison is statistically significant (t-test) except for the mean fundamental frequency $\langle F_0 \rangle$ and the DAL parameters.

The higher $\langle F_0 \rangle$ value for the CVR recording, in comparison to the one for recording 3 when the plane was on the ground and stopped, is similar to a previous non published research result. In a flight simulator and before any incident occured, $\langle F_0 \rangle$ was higher than a few minutes before the pilots entered the simulator. An explanation would be that the incoming workload induced stress that led to a higher F_0.

The lowest values of succesive periods T_0 in CVR recording (due to the increase of F_0) would induce higher values of DAL_{T_0}/T_0 (Table VIII). The length of signal is greater for CVR than on the ground: $\langle DAL \rangle = 9.32$ ($\sigma = 2.64$) for CVR and $\langle DAL \rangle = 5.73$ ($\sigma = 1.22$) on the ground. The background noise level in the Cockpit Voice Recordings is higher than for recordings made on the ground with the airplane stopped. The additional noise increases DAL. Taking the inverse of $\langle F_0 \rangle$ values in the two cases leads to values of $T_0 = 0.0076$ s (CVR) and 0.0085 s (on the ground). The ratios between each $\langle DAL \rangle$ with the two T_0 values show that $\langle DAL \rangle$ differences gain and explain the higher values of DAL_{T_0}/T_0 with CVR vowels. For the CVR, the amplitude length increases and simultaneously, period durations decreases. Therefore, DAL_{T_0}/T_0 becomes higher than on the ground. The same observations apply for $DAL_{T_0}/|A_{max} - A_{min}|_{T_0}$ parameter.

Spectral Domain Comparisons: Only the [a], [i], [o] vowels were in sufficient numbers in the two corpus.

Formant frequencies are of the same order considering normal intra-speaker variability and the different spectral resolution between bins for the two recording types. For the other parameters, even if deviations are sometimes higher, it appears that they are also of the same order.

Maximal Lyapunov Exponent (λ): $\lambda = 0.0504$ ($\sigma = 0.018$) for recording 3 and $\lambda = 0.043$ ($\sigma = 0.05$) for the vowels of the CVR. The two values are considered equivalent.

The CVR analysis confirms the robustness of calculation routines for current speech in the presence of background airplane noise. Comparisons with a laboratory

Table IX. Mean values of acoustic characteristics of the spectral domain for CVR analysis and measurements in the cockpit at a stopover (recording 3, experiment 2). Associated standard deviations are in brackets.

	[a]	[i]	[o]
SCG on ground	1011.53 (176.07)	1333.09 (548.48)	719.26 (159.38)
SCG CVR	798.63 (118.04)	724.21 (181.47)	609.72 (147.08)
M_2 on ground	537146 (203515)	1984814 (733575)	590290 (238222)
M_2 CVR	136159 (111205)	383858 (254289)	180775 (168451)
Skewness on ground	2.53 (1.12)	1.021 (1.11)	3.27 (1.10)
Skewness CVR	1.90 (0.79)	2.59 (1.42)	3.99 (1.63)
Kurtosis on ground	9.08 (8.17)	0.47 (3.57)	12.09 (8.44)
Kurtosis CVR	9.19 (6.75)	11.79 (16.18)	25.46 (18.68)
SBF on ground	2465.55 (2217.05)	3558.36 (93.65)	3337.65 (881.72)
SBF CVR	200.16 (257.08)	1970.51 (1645.9)	1153.91 (1731.6)
EBF on ground	746.48 (198.60)	936.69 (1284.97)	436.82 (26.99)
EBF CVR	712.03 (157.11)	493.95 (136.67)	466.21 (38.11)
F1 on ground	542.37 (27.24)	263.78 (10.77)	399.30 (34.85)
F1 CVR	588.98 (57.69)	353.91 (190.05)	436.13 (31.86)
F2 on ground	1318.91 (214.47)	1754.96 (106.22)	965.92 (163.72)
F2 CVR	1312.50 (105.49)	1300.78 (420.32)	948.83 (216.50)
F3 on ground	2324.24 (93.78)	2863.92 (220.30)	2307.13 (101.33)
F3 CVR	2401.88 (80.51)	2178.52 (505.04)	2429.49 (53.53)
F4 on ground	3443.97 (89.30)	3741.39 (85.00)	3309.96 (72.19)
F4 CVR	3433.83 (245.25)	2951.37 (570.73)	3527.34 (139.27)

equipment recording in the cockpit show a good correspondence in results.

5.7. Conclusion

The aim of this exploratory study is to test the sensivity of various acoustic parameters in a laboratory context and in real flight situations for two important flying physiological issues which are sleep inertia and drowsiness.

Two experiments were carried out for this purpose. The first one was for an approach of sleep inertia vocal effects in long flight conditions. The aim of the second one was to detect voice effects of fatigue or drowsiness in short daily flights.

Respectively one and two pilots have been recorded and many parameters were measured from the time and spectral domains and the phase space.

Now, from the results obtained, a greater number of speakers will be studied with a focus on sensitive acoustic features and by searching a combination of parameters to derive a new metric. This one could show significant variations.

A lot of acoustic voice parameters are sensitive to sleep inertia. Further research must confirm the variations compared to the state of rest and should try to define some thresholds over which values could be defined as abnormal. Another perspective would be to determine the time taken for the voice to revert to normality.

Only two acoustic features have a sense of variation that could be linked to a manifestation of drowsiness ($\langle F_0 \rangle$ and DAL/T_0) and one to increasing fatigue (λ). This has been observed for one of the crew members. Many reasons can explain this result. Fatigue and drowsiness are individual states that are difficult to evaluate when they are not as important as in experiment two. For the speakers themselves, it is not easy to say if they are more or less tired. Drowsiness manifestations can be short and the pilot does not necessarily speak. For the future, a greater sampling of vowels in speech appears necessary. The good correspondence with CVR analysis results makes it possible to work directly on current speech taken from the CVR or VHF communications. With such recordings a more regular and systematic sampling of vowels can be undertaken.

This approach to these unknown vocal manifestations provides knowledge that should be used to develop further research on the topic.

All vowels are equally affected by sleep inertia and drowsiness for time and phase space measurements. In the spectral domain, the variations of the spectral center of gravity and the moments are dependant on the vowel studied. For spectral distances, this dependance also exists, but the results are more homogeneous - leading to interesting perspectives for this parameter.

The new *DAL* parameter introduced is, with the Lyapunov exponent, the only one for which variations could be linked to causes in the two experiments. It is applicable for any signal, whether quasi-periodic or not, but also after filtering through frequency bands. Perspectives and applications may be numerous. Other investigations are also possible for the spectral distance. By doing Mel cepstral analysis with three coefficients for different frequency bands, distances could be displayed in a three-dimensional space in order to search neighbourhoods proper to different speaker states. Chaos analysis can also be pursued. The research field is wide and probably needs additional measurements such as those of the harmonic-to-noise ratio or those of vocal microtremors. Nevertheless, the panel of acoustic characteristics selected for this study, together with the results, seems to be wide enough to conclude that vocal modifications exist for sleep inertia and fatigue or drowsiness in flight situations.

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Sound Quality Assessment of Internal Automotive Road Noise Using Sensory Science

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Summary

This paper presents a technique to describe the perception of internal automotive road noise. As the acoustic sources on a car reach lower sound levels, special attention is granted to acoustical comfort. While the knowledge of mechanisms behind road noise is growing, its perception by the driver remains relatively unexplored. In this study, a sensory science technique – the classical sensory profile – is applied to obtain a description of the internal road noise by quantitative perceptual criteria. Seven consumer cars (from Renault, Fiat, Peugeot, and Toyota) were driven under four well-defined conditions varying in speed and road surface. Twenty-one typical road noise recordings were presented to a panel of five experts in acoustics. Twelve listening sessions of three hours, individually and in group, led to a list of 15 relevant perceptual descriptors, such as "rough aspect". The performance of the listeners was tested statistically: their repeatability, their ability to discriminate the sounds and the inter-subject agreement. Sufficient agreement was observed across the listeners for 10 of the 15 descriptors, which would constitute the perceptual basis for internal automotive road noise. Through multiple linear regression, strong correlations were found between the associated perceptual dimensions and psychoacoustic properties of the sound samples. The findings from this study are summarized in a sensory grid to assist the test drivers in the evaluation of road noise sound character, and a predictive tool for sound quality evaluation based on correlations between perceptual dimensions and calculated sound metrics.

PACS no. 43.66.Lj, 43.50.Lj

1. Introduction

Sound quality in the automotive industry has attracted considerable interest over the last decades. The impact of a car's acoustics – whether from the engine, road or other components – is known to influence the perceived overall quality from a customer's point of view. Along with the advent of electric cars, internal noise due to engine and powertrain has decreased drastically, accentuating the perception of other noise sources such as road-tyre interaction. It is now common knowledge that customers pay great attention to sound quality even when the sound is only a side effect of the product's operation [1] and that the overall interior sound pressure level is no longer sufficient to assess appreciation [2]. Noise sources must therefore be identified and characterized independently from a perceptive point of view. The prediction and control of the perceived internal road noise is thus a crucial step for manufacturers in order to reach a marketing value which meets the customer's expectations.

Generation of external road noise has been explored by U. Sandberg [3] and divided into low and high frequency ranges. It has been proposed that the low-frequency portion of road noise is due to the impact of tyre thread elements on road chippings, or vice-versa. On the other hand, the high-frequency mechanism is believed to be some air-pumping or air-resonant mechanism perhaps excited by stick-slip motions in the tyre-road interface. To summarize the extreme complexity of the physics of road noise, Sandberg even states that the simplicity and apprehensiveness of presented relations are in proportion to either the limitations of data, or the author's ignorance [3]. Still in this paper, profilometry is suggested as a method to characterize road surfaces regarding the generated road noise. Typically, a laser-beam profilometer is used to record the road's longitudinal profile, whose spectral analysis leads to normalized "texture levels" in four wavelength (λ) bands: microtexture ($\lambda < 0.5$ mm), macrotexture ($0.5\,\text{mm} \leq \lambda < 50$ mm), megatexture ($50\,\text{mm} \leq \lambda < 500$ mm) and unevenness ($\lambda \geq 500$ mm). Relationships linking spectral components of road noise to the profile texture have been established and are used as an ISO standard for the characterization of pavement texture regarding vehicle noise [4]. In another study, three mechanisms behind the generation of road noise inside the passenger cavity have been proposed by Lalor and Priebsch [5]: direct transmission from the outside through small holes in the cabin walls, mass

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