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PREVENT TIME-VARIANCE ON ROOM ACOUSTICS MEASUREMENTS USING ULTRASOUND TRANSDUCER ARRAYS

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Abstract
Room impulse response is usually estimated by using synchronous averaging methods for SNR enhance. However, the theoretical increment of 3dB by doubling the number of the test signal frames is only achieved under the assumption that the system is time-invariant. In real situations of auditorium acoustical measurements, this assumption is usually not verified due to air mass movements and temperature gradients caused by the presence of people and/or due to the air conditioned systems. A measurement technique was set up where simultaneous with the test signal a modulated complex signal is sent to the room by using ultrasound transducer arrays. Four ultrasonic devices were used in order to cover a wider audience area and room volume by establishing multi-path sound propagation. This study aims at estimating a number of parameters related to the time variance to control the averaging procedure in order to increase the overall SNR. This procedure has the advantage of avoiding the perception of the probe ultrasonic testing signals by the audience keeping a reasonable SNR. At the reception, each test signal frame is cross-correlated and labelled as valid or not valid according to comparisons with thresholds obtained from the estimated parameters. The performance of this procedure is assessed by the gain of the resulting SNR. Results are presented and discussed.

Keywords: Time-variance, ultrasound loudspeaker, Room acoustical measurement.

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1 Introduction

In real room acoustical measurements time-invariance condition is usually not verified due to the non-ideal electroacoustic measurement chain and the variation of the air medium characteristics [1,2,3]. Although simple methods based on the cross-correlation function [4] are often used to detect time variance phenomena, the results are not accurate, showing a considerable deviation in situations of low SNR. Therefore, a non-intrusive innovative approach, using probe signals out of the audio band [5-7], was developed in order not to conflict with the audio test signals and not to be perceived by an audience. A measurement technique was then set-up with the purpose of monitoring the acoustical media, searching for time variance phenomena, for low SNR conditions.

2 Methodology

A test signal in the ultrasonic band, more precisely at 40 kHz, is applied to the room by using an ultrasound loudspeaker array, with high polar pattern directivity, simultaneous with the test signal frames [8,9,10]. The relevant parameters (features) for establishing time-variance and associated thresholds are then estimated from the acquired ultrasonic sound signal. The valid test signal frames, which pass the thresholds test, are labeled with a weighting factor depending on its significance and sorted. Otherwise, the frames are rejected, and are not considered in the averaging process.

3 Experiments

The measurement of selected acoustical parameters was carried out in a mid-size reverberant chamber with a volume of 150 m3 (5x5x6m), approximately, and reverberation time for the mid-frequencies in the range of 2-2.5 s. Since this enclosure is assumed to be a more controlled environment than a regular auditorium, the time variance occurrence can be better observed.

As a first attempt to relate the effects of the time variance on the test signal (audio band) and on the tone probe (ultrasound band) a multitone signal in the audio band is used as the test signal. Since both signals are of the same type, sinusoids, the effects are better understood.

The multitone test signal consisted of a set of tonal components centered in each octave frequency band centered at 1, 2, 4 and 8 kHz, generated by the sound source, plus a probe tone of 40 kHz, radiated by the loudspeaker ultrasonic array.

A number of features were extracted by signal analysis in the audio and in the ultrasound bands.
The features considered here are related to the magnitude of the tonal components, the residual part of the ultrasound spectrum over a frequency band centered at the ultrasound tone probe and by cross-correlating the tone probe by time segments.

The magnitude of the tonal components is extracted by using peak continuation and parabolic interpolation techniques in order to increase the frequency resolution. The features related with the residual part were estimated by using the sinusoidal plus residual noise model approach. The tonal components are removed more accurately with this approach than by using other filtering techniques such as Constant *Q* filters or adaptive filters due to filter specifications, essentially. In fact, the NLMS algorithm proved to be inappropriate for this purpose. Neither the tonal component is tracked for the needed frequency resolution nor is the bandwidth sufficiently narrow to remove the tonal component only, not degrading the remaining spectrum of the signal.

In this case, the frequency resolution is more important than the time resolution since the signals are quasi-stationary tonal components over time. Therefore, a considerable large sliding Hanning window of 16384 samples with 75% overlapping factor was used.

In order to accommodate the ultrasound tone probe, a sampling rate of 192 kHz was used. However, the different analyses applied to the captured signals were performed at 44.1 kHz by splitting and down-sampling the audio and the ultrasonic frequency bands conveniently. Before down-sampling, a defined frequency band centered in the tone probe is bandpass filtered to select only the ultrasound

(US) part and side bands. This frequency band is afterwards demodulated to remain centered at 5 kHz.

Figure 1 shows analyses of this signal in an anechoic chamber using the fan device for the low speed and in oscillating mode. The period of oscillation is about 10s.

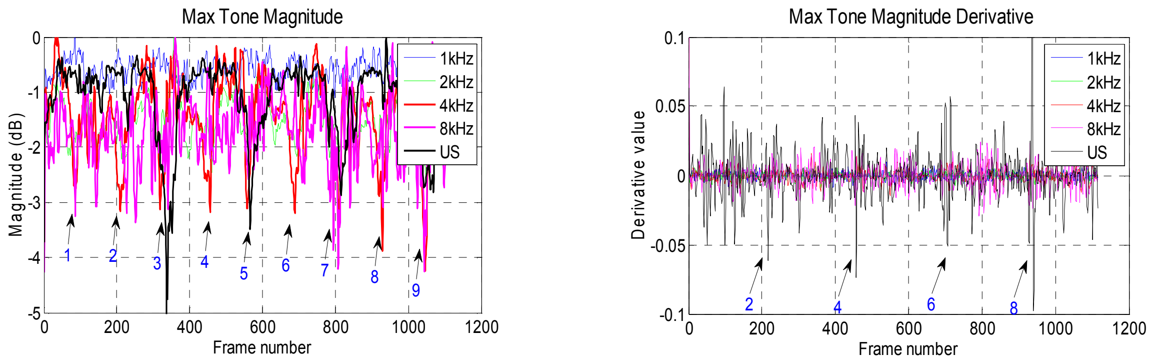


Figure 1. Magnitude and corresponding derivative of the tonal components; the US curve in the Max Magnitude feature is scaled by a factor of 1/10, for better visualization.

The peaks and dips shown in the figures follow a periodical fashion regarding the air movement due to the oscillation movements of the fan device.
The dips in the curves in
Figure 1, corresponding to the cycles of the oscillating fan, are identified by numbers.

The results show a good relationship between the audio and the ultrasounds (US). Although the Max Tone Magnitude curves for the US do not show significant alteration in the locations marked by the even numbers a pronounced peak appears at these locations in the Max Tone Magnitude Derivative feature. This interesting finding shows that these parameters are complementary and should be used together.

The basic list of apparatus used in these experiments consisted of a sound power source, a microphone, a multichannel sound board attached to a personal computer and an ultrasound loudspeaker array [3]. The measurement setup is shown in Figure 2.

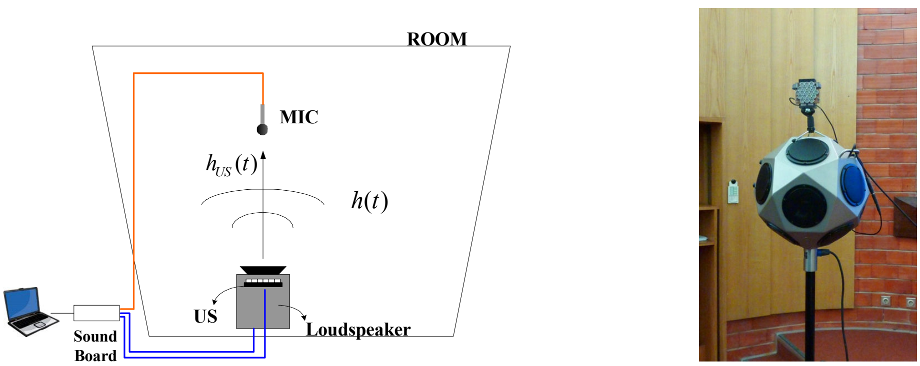


Figure 2. Measurement setup using test signals and ultrasonic test probe simultaneously.

The medium in the enclosure was disturbed by a number of devices such as a heater (H) and a medium size electromechanical fan with three rotating speeds (F). Additionally, the air was disturbed by manually waving with a pad of area 0.6m2 (WP), in an attempt to force significant air masses movements.
The main characteristics of the developed ultrasound array are: (i) polar pattern with a main lobe of about 8 degrees @ -3dB, (ii) more than 15dB attenuation from on axis to secondary lobe of radiation, (iii) centre frequency of 40 kHz, (iv) maximum sound pressure level of 145 dB @ 30cm, and (v) bandwidth of 2.5 kHz (improved to 10 kHz by filtering compensation). The array set-up is shown in Figure 3.

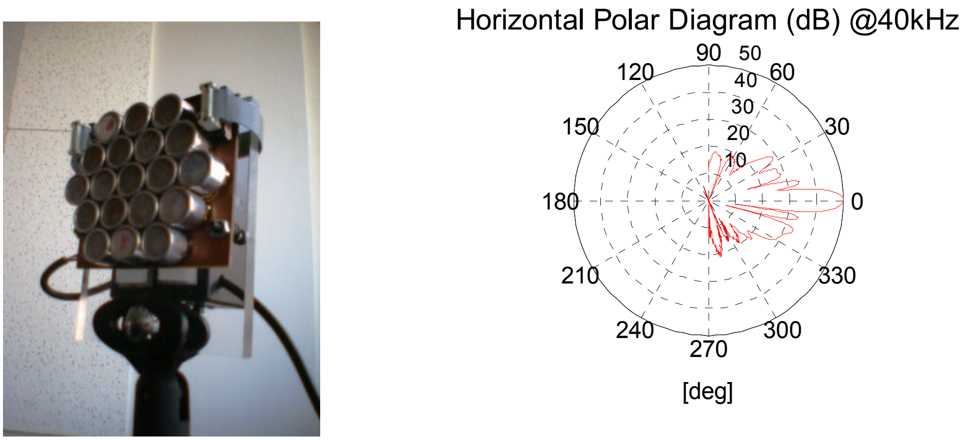
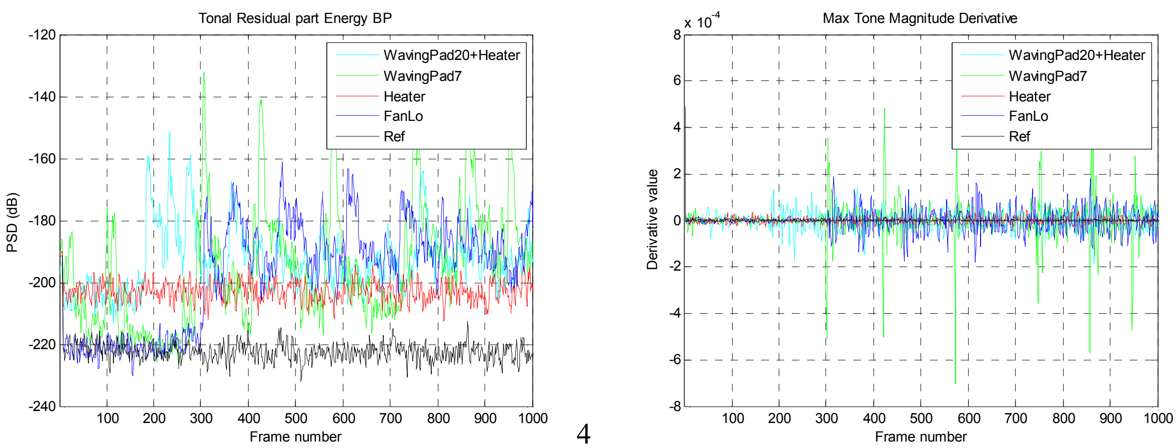


Figure 3. Image and pattern diagram of the ultrasound loudspeaker array.

A simple experiment to validate this method consisted of computing the correlation of the ultrasound tone probe between the corresponding time slots of the reference frame and the remaining frames, extracting a feature similar to the Correlation Energy error used in standard approach, in conjunction with the Frequency Deviation to label and sort the captured test signal frames. A threshold of 1 Hz in the Frequency Deviation feature was used to label the frames as Valid or Not Valid.

4 Results

Preliminary results for wavingPad 20 times during the tests with the heater, wavingPad 7 times, heater, fan low and for the reference are shown in Figure 4.



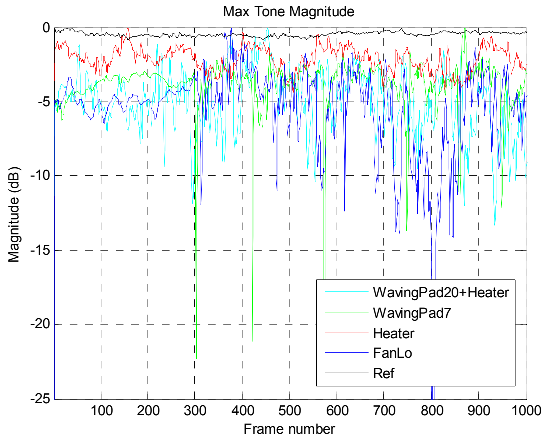


Figure 4. Features Max Tone Magnitude and its derivative, Tonal Residual part Energy BP and Frequency Deviation for the case of WavingPad20 plus Heater, WavingPad7, Heater, FanLo and for the Reference.

In all tests, except for those using the heater, the medium was not disturbed for the first two frames, the Reference frames, in order to calibrate the system and perform the relative analysis.
Based on the results, a number of thresholds were established in order (i) to detect the occurrence of time variance problems in the enclosure under test, and (ii) as a tool of help for the decision to be used on the averaging stage.
The set of features selected were: (1) Time-lag function, (2) Correlation Energy error, (3) Correlation maximum ratio, (4) Relative Error, (5) Frequency Deviation, (6) Max Tone Magnitude, (7) Tone Magnitude Derivative, (8) Tonal Residual part Energy, (9) Tonal Residual part (BR filter). The analysis performed directly to the IR (audio band) uses the first 4 features only.
The experiment was validated by computing the correlation of the ultrasound tone probe between the corresponding time slots of the reference frame and the remaining frames, extracting a feature similar to the Correlation Energy error, in conjunction with the Frequency Deviation to label and sort the captured test signal frames. A threshold of 1 Hz in the Frequency Deviation feature was used to label the frames as Valid or Not Valid.
Table 1 shows results for the SNR (in dB), by using the swept sine technique, for the situations of the waving pad, standard averaging and the procedure implemented, respectively. Only the residual energy analysis was used. To highlight the gain by sorting the frames, the columns for 4 and 8 NAve are shaded.

Table 1 – SNR for the situation of Pad Waving, standard averaging (top most) and the procedure implemented with US (down most).

Band/#Ave	Ref	2	4	8	16	32
0.5	65.1	67.4	55.0	53.7	59.4	63.4
1	62.5	66.5	53.0	54.2	59.8	62.1
2	55.8	59.9	49.6	51.8	57.3	59.3
4	53.6	57.9	48.9	51.4	56.8	57.9
8	60.4	64.5	55.1	58.3	63.5	64.8
AWeight	49.8	54.0	44.0	46.1	51.5	53.3
Full band	49.8	53.7	44.3	45.9	51.3	53.4

Band/#Ave	Ref	2	4	8	16	32
0.5	65.1	67.1	58.8	63.1	62.7	63.3
1	62.5	66.4	56.5	60.5	60.1	61.8
2	55.8	59.7	53.5	56.1	56.5	59.3
4	53.6	57.9	53.0	55.8	55.7	58.2
8	60.4	64.4	60.4	62.3	63.1	65.3
AWeight	49.8	53.9	48.0	50.9	51.0	53.4
Full band	49.8	53.6	48.2	51.2	51.3	53.5

A gain of about 4dB is obtained by using the procedure of weighting and sorting the frames.

Other experiment uses a test signal composed of 32 frames extracted randomly from all the measurements made with the different devices available to produce time variance in the room (a heater, a mid-size electromechanical fan, and a large pad to create strong air movements).

As long as the first two frames in each composed test signal (the reference frames) are not affected by time variance the T20 results are almost the same for the reference (1Ave) and for 2Ave for which an increment of about 3dB is observed for the PNR and the Valid Decay.

The reference and 2Ave analysis provide the right value of T20 and the 32Ave are not changed by sorting the frames, due to the fact that all the frames are included in this set.

The reverberation times decreases by increasing the number of averages [11]. If the frames are sorted, by increasing the number of averages a decrease in the same fashion of the T20 is expected. Otherwise, the decrease of the T20 is not predictable (depends on the order of occurrence of the frames). Therefore, the procedure of sorting the frames can be useful in real situations in order to define a stop criterion for the acoustic measurements.

The Valid Decay and the PNR are improved by about 3 to 5dB for 4 and 8Ave when the frames are sorted. Although a marginal decrease is observed for the PNR in the sorted approach the Valid Decay is increased by about 2dB. This result is important since the Valid Decay is a better measure to guarantee more accurate results for the reverberation time, for the frequency response, etc.. In fact, some deviations are found in IRs between the reference and 16 and 32Ave showing significant audible distortion. Therefore, the procedure adopted to deal with time variance effects should be a balance between the PNR, energy decay and the accuracy of the IR.

Moreover, one can state that better results are achieved for 4Ave if the frames are sorted, at least for this experiment. The sorting procedure leads to a substantial reduction of the measurement times.
The results of the PNR for the analysis of using and not using sorting procedure are shown in Figure 5 for comparison purposes.

The advantage of applying the sorting procedure to the captured frames is confirmed. In fact, the peak-to-noise ratio and the Valid Decay analysis show a significant increase of about 5 and 3dB, respectively, to up to 8NAve. Nevertheless, the results could be improved with the use of more features simultaneously.

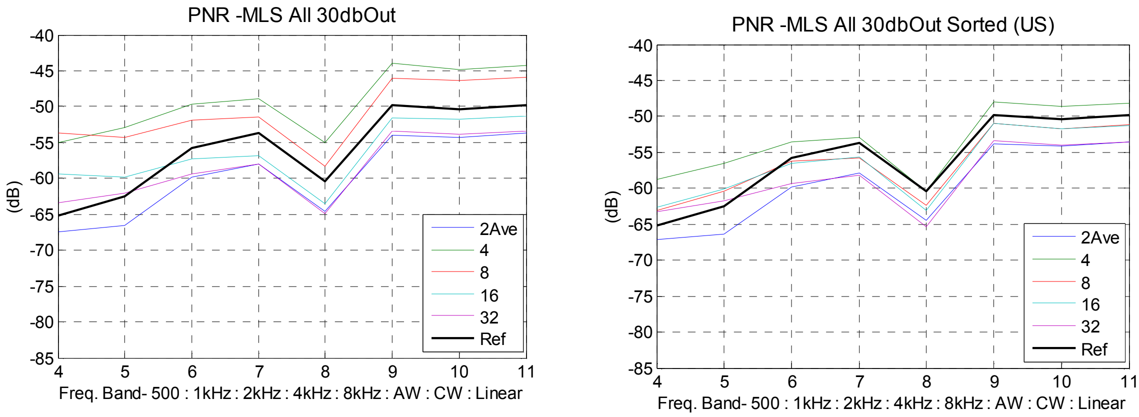


Figure 5 – Peak-to-noise ratio experimental results in frequency octave bands corresponding to the MLS test signals.

The measurement results for the MLS are very poor when compared to the swept sine in situations of time variance. This finding was already mentioned by previous researchers [12,13,14,17].

5 Results

A framework using a new method for identification and attenuation of the time-variance phenomena effects on the acoustic measurements, for situations of low SNR, using an ultrasonic loudspeaker array was developed and implemented. A number of parameters, sound features extracted from an ultrasound tone signal, were used to classify the test signal frames, in the audio band, and to define thresholds in order to improve the SNR and/or increase the accuracy of the estimated IR and consequently the frequency response. The method consists essentially on sorting and weighting each frame before averaging.

Additionally, a similar approach using an extended set of features extracted from the cross-correlation function applied to different IR is used in the case of high SNR. This approach permits to inspect the effect over the audio band and ultrasound band test signals due to time variance and comparing the performance of the swept sine and MLS.

A number of experimental and simulated analysis covering different common acoustical situations in presence of time variance phenomena were carried out. The simulated experiences consisted of using a model of stretching the waveform to create intra-periodic and inter-periodic distortion over the test signal frames. Due to feasibility considerations these experiments were not applied in the ultrasonic approach.

In order to produce time variance phenomena artificially a set of devices comprising a heater, a mid-size electromechanical fan and a large pad, in an attempt to force significant air masses movements, were used.

In a first attempt to verify the performance of the swept sine and the MLS techniques, a set of preliminary analysis to the IR, such as the PNR, Valid decay, T20, and C-Curvature parameter [15], were carried out. In this situation, the framework was not used, i.e. the frames were not sorted.
The results for the simulated analysis using the intra-periodic model (using a sinusoidal stretching factor) show a superiority of the swept sine against MLS technique. In fact, the swept sine is almost

unaffected by this type of distortion. Instead, a decrease of about 6dB for the PNR results is observed for the MLS. Nevertheless, a significant distortion is observed for the high end of the frequency response of the IR in both techniques. Virtually the same results are observed for the case of the Inter-periodic model proving the robustness of the swept sine against the MLS technique.

The results for the parameters analyzed on the ultrasound tone probe show significant drifts from the static values. Amplitude and phase shift variations of about 15dB and 130 degrees, respectively, is observed, mostly due to temperature gradients. The air mass movement with the fan on was less significant. However, a kind of modulation noise was noticed in the upper and lower side bands of the ultrasonic probe test signal spectrum.

The experimental results using the thresholds and sorting procedure were split in two situations: the standard approach (for high SNR) and the ultrasonic method (for low SNR).

Although a number of features were considered in this study for evaluation of the methods, not all the features were used. In fact, the standard approach used the Time Lag function and the Correlation Energy error features and ultrasonic method considered the Correlation Energy error used in standard approach, together with the Frequency Deviation. The remaining features are devoted to future phases of this research.

Similar results were achieved for the standard approach and for the ultrasonic method confirming the advantage of the sorting procedure applied to the captured frames. In fact, up to 8NAve the PNR and the Valid Decay analysis show a significant increase of about 5 and 3dB respectively. Moreover, the distortion over the IR and consequently on the frequency response of the system is reduced by applying this procedure.

As expected, the swept sine technique is much less affected by time variance than MLS. Furthermore, if the frame length is larger than the estimated reverberation time, then the frame segmentation technique [16] can be used to label some frequency bands less affected by a higher weight factor.

The use of an ultrasound loudspeaker array has several advantages yielding implications on the sound wave propagation due to time variance.

In the case of mid to large-size volume auditoriums different loudspeaker ultrasonic array arrangement, using multiple-ultrasonic devices, should be applied in order to cover a wider audience area and room volume by establishing a multi-path direction sound propagation. Notice a single loudspeaker ultrasonic array shows a very directive radiation pattern, though only 16dB of attenuation is measured between the main and the secondary lobe. To overcome this limitation, four new loudspeaker ultrasonic arrays with improved radiation pattern are currently being developed and tested in order to cover different wave propagation paths.

Also, statistical classification procedures will be applied to the frame segments of the test signal on the labeling process.

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