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Published in:
Akustiikkapäivät 2023

Published: 15/11/2023

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Prawda, K., Schlecht, S., & Välimäki, V. (2023). Rule of two: methods to detect and localize non-stationary noise in sweep measurements. In T. Lokki (Ed.), *Akustiikkapäivät 2023* (pp. 135-140). Akustinen Seura ry. https://www.akustinenseura.fi/wp-content/uploads/2023/11/akustiikkapaivat_2023_s135.pdf

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RULE OF TWO: METHODS TO DETECT AND LOCALIZE NON-STATIONARY NOISE IN SWEEP MEASUREMENTS

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Abstract

Exponential swept-sines are currently one of the most popular excitation signals in acoustic measurements, being praised for their favorable signal-to-noise ratio and ease in rejecting harmonic distortion artifacts. However, they are notoriously susceptible to non-stationary noise, such as randomly occurring transients or noise bursts. Such disturbances cannot be mitigated in the deconvolution process, leading to low quality of obtained impulse responses and errors in acoustic parameter estimation. In this paper, we present our work on non-stationary noise detection and localization in measured sweeps, methods we named Rule of Two (Ro2) and Short-term Rule of Two, respectively. In both techniques, we employ correlation to evaluate the similarity of measured signals, while considering expected contamination: background noise and time variance. Comparing correlation coefficients of a series of measurements allows the selection of a clean pair, devoid of non-stationary noise in Ro2. If a sweep contains a disturbance, we can pinpoint the contaminated region by computing its windowed cross-correlation in Short-term Ro2. Validation on a large set of sweep measurements proves the reliability and robustness of both methods. The Ro2 and Short-term Ro2 methods enable robust and efficient acoustic impulse-response measurements in noisy places.

1 INTRODUCTION

The exponentially swept-sine (ESS) is a popular excitation signal used in room impulse response (RIR) measurements since the year 2000 [1]. It offers numeral advantages, such as a high signal-to-noise ratio (SNR) [2], ease in rejecting the harmonic distortion artifacts [2, 3, 4], and increased robustness of measurements compared to previous methods [2, 5].

Copyright ©2023 Karolina Prawda, Sebastian J. Schlecht ja Vesa Välimäki. Tämä on avoimesti julkaistu teos, joka noudattaa Creative Commons NIMEÄ 4.0 Kansainvälinen –lisenssiä (CC BY 4.0). Teosta saa kopioida, levittää, näyttää ja esittää julkisesti ja siitä saa luoda johdannaisteoksia, kunhan tekijän nimi ja lähde mainitaan asianmukaisesti.

The ESS is, however, notoriously susceptible to non-stationary noise, which is a sound event that changes its spectral-temporal properties within the duration of one measurement. Common examples of non-stationary noise are transients, noise bursts, and sound dropouts, i.e., errors in measurement hardware or software leading to a portion of samples in the signal not being recorded. When encountered during measurement, such events lead to artifacts in the obtained RIRs [2, 6, 7, 8].

The SNR increases proportionally to the ESS length and the risk of non-stationary noise occurrence grows simultaneously. This leads to a compromise between lengthening the ESS to increase the SNR and shortening it to minimize the risk of the non-stationary noise [4, 6]. This paper presents a solution to this problem, which is a method called the rule of two, or Ro2. It can detect and localize non-stationary noise events in repeated ESS measurements. The Ro2 method has been previously presented in a journal paper [8].

2 NEW METHODS

In the following, we describe the non-stationary noise detection and localization methods, and threshold estimation procedure used in the Ro2 method.

2.1 Rule of Two

The signal y_i recorded during the i^{th} measurement is

$$y_i = x_i + u_i = s * h_i + u_i, \tag{1}$$

where x_i is the signal including the ESS s convolved with the RIR h_i, and u_i is the stationary noise term. The proposed noise detection method inspects the correlation between two consecutive measurements, y_i and y_j, is [8, 9, 10, 11]:

$$\rho_{y_i,y_j} = \frac{\sum_n^N (x_i(n) + u_i(n))(x_j(n) + u_j(n))}{\sqrt{\sum_n^N (x_i(n) + u_i(n))^2 \sum_n^N (x_j(n) + u_j(n))^2}} \tag{2}$$

where N is the total length of the signal in samples and n is the discrete time index.

The Rule of Two (Ro2) method selects ESS measurements free from non-stationary noise from a series of sweep recordings based on the criterion [8]:

$$\text{if } \rho_{y_i,y_j} > \widehat{\rho}_{y_i,y_j} \text{ then } y_i \text{ and } y_j \text{ are a clean pair,} \tag{3}$$

where $\widehat{\rho}_{y_i,y_j}$ is a selection threshold, which is determined based on the knowledge of the noise level in the measurement environment, such as the stationary background noise level. The correlation is a comparative measure, and thus, the Ro2 requires at least two clean ESSs to reliably separate contaminated and clean sweeps [8]. The measurements should be repeated until a clean pair is obtained. This way, the Ro2 method helps to automatize acoustic ESS measurements.

2.2 Selection Threshold Estimation

To establish the selection threshold $\widehat{\rho}_{y_i,y_j}$ appropriate for the current measurement session, two sources of expected contamination need to be considered—the stationary background noise and the transfer-function variation.

We assume that the background noise terms u_i and u_j are random and uncorrelated with the ESS signals, leading to $\sum_n^N xu_i = 0$ and $\sum_n^N xu_j = 0$. Furthermore, we assume that the energy of the ESS signals is equal across the measurements, i.e., $E[x_i] = E[x_j]$. Additionally, we treat the background noise as a stationary signal during the entire measurement series, meaning that its energy is approximately constant, $E[u_i] = E[u_j] = E[u]$. Making appropriate modifications to Eq. (2) and expressing the correlation in terms of signal energies, we arrive at the selection threshold [8, 11]:

$$\frac{E[x] + \zeta E[u]}{E[x] + E[u]} \leq \widehat{\rho}_{y_i,y_j,\zeta}, \tag{4}$$

where $\zeta = \rho_{u_i,u_j}$ is the correlation of the stationary noise terms. The scenario in which noise terms are not perfectly uncorrelated, i.e., $\zeta \neq 0$, is possible when they include, e.g., electric humming [8]. In the following, we adapt $\zeta = -1$, considering an extreme case of noise terms being anticorrelated, to relax the strict detection threshold posed by $\zeta = 0$.

We accommodate the time-variance related drop in correlation between consecutive RIRs, h_i and h_j, by using the transfer-function variation factor τ. τ can be determined from the difference between two measurements. Thus, Eq. (4) [8] is modified:

$$\widehat{\rho}_{y_i,y_j,\zeta,\tau} = \frac{\widehat{\rho}_{y_i,y_j,\zeta}}{1 + \tau/2}\ . \tag{5}$$

The values of τ strongly depend on the measurement environment and the length of ESSs. For short sweeps in a controlled laboratory setting, $\tau \ll 1$ is expected. In our research, we used $\tau = 0.00019$.

2.3 Short-Term Rule of Two

Having established the presence of the non-stationary noise in an acoustic measurement signal using Ro2, we can determine the time of occurrence of the contamination. We accomplish this by using a procedure similar to the Ro2, but evaluated on short windows of the signal, rather than the entire duration of the measured ESS. We term the procedure Short-term Ro2.

We start by defining the short-term signal x_i at time n

$$\tilde{x}_i^n(m) = w(m-n)\, x_i(m) \tag{6}$$

where w is a Hanning window of length M samples, normalized so that $\sum_{m=0}^{M} w(m) = 1$.

Therefore, the detection threshold from Eq. (4) becomes

$$\frac{E[\tilde{x}^n] + \zeta E[u]}{E[\tilde{x}^n] + E[u]} \leq \widehat{\rho}_{y_i,y_j,\zeta}(n), \tag{7}$$

while Eq. (5) is transformed to

$$\widehat{\rho}_{y_i,y_j,\zeta,\tau}(n) = \frac{\widehat{\rho}_{y_i,y_j,\zeta}(n)}{1 + \tau/2}\ . \tag{8}$$

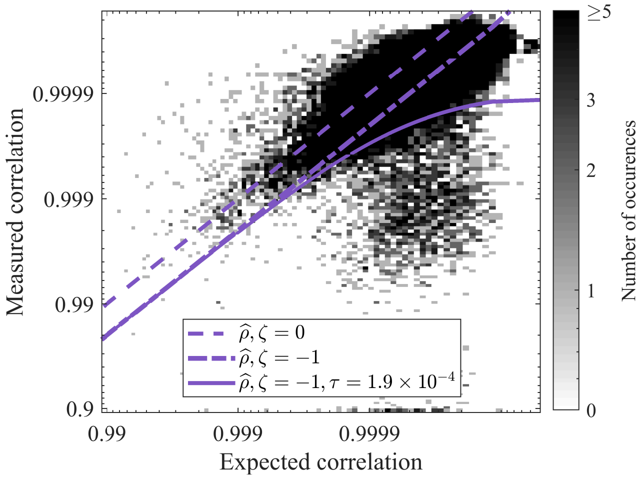


Figure 1: Expected and measured correlation of ESSs, and different thresholds for non-stationary noise detection with Ro2.

Here, the stationary noise correlation (ζ) and transfer-function variation factor (τ) are evaluated for the entire signal, instead of short windows. This is due to the sensitivity of τ to all changes in the signal, also those that are not related to time variance, and the difficulty of estimating stationary noise energy, and thus ζ, when ESS is being played [12].

3 RESULTS

This section presents the results of non-stationary detection using Ro2 and examples of non-stationary noise location with Short-term Ro2. The implemetation of both techniques is available online [13].

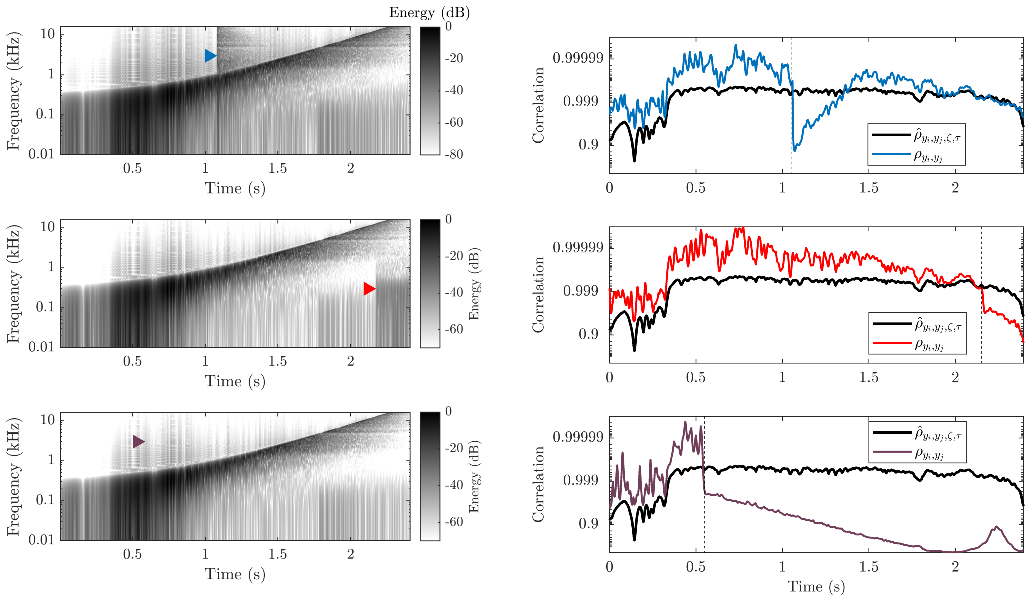
3.1 Non-Stationary Noise Detection

The Ro2 was validated on a dataset of over 20 000 ESS signals measured in the variable acoustic laboratory *Arni* at Aalto University [8]. The measured correlation values are compared against the expected correlation determined based on the knowledge of the system, i.e., the background noise level and time variance.

Fig. 1 shows that different assumptions about the noise terms correlation ζ result in more strict or more relaxed detection thresholds, which can be further modified using the time-variance factor τ. In each case, the examples of weakly correlated signals when a strong correlation is expected are correctly identified as contaminated with non-stationary noise (data points lower than the solid purple line in Fig. 1).

3.2 Non-Stationary Noise Localization

The ESS signals marked as contaminated by the Ro2 were analyzed using the Short-term Ro2 to localize the non-stationary noise events. Fig. 2(a) presents measured sweeps each



(a) (b)

Figure 2: (a) Spectrograms of ESS signals contaminated with non-stationary noise. An arrow points to the onset time of the contamination in each case. (b) Localization of non-stationary noise using Short-term Ro2 at the point of the vertical dashed line.

containing one of the three types of non-stationary noise contamination: transient noise (top), low-frequency noise (middle), and sound dropout (bottom).

Fig. 2(b) shows the calculated short-term running cross-correlation of the measured signals compared with the threshold from Eq. (8). The drop of the measured correlation with regard to the expected values marks to onset of the contaminating event, accurately matching the onset times marked in Fig. 2(a) (dashed lines). This proves that the Short-term Ro2 is capable of precisely locating the non-stationary noise in measured sweeps.

Additionally, the behavior of the calculated short-term running cross-correlation indicates the type of non-stationary noise observed in measured sweeps, as can be seen in Fig. 2(b). The correlation drop due to transients disappears together with the energy decay of the contaminating event. When a noise burst occurs, the correlation stays below the threshold at a relatively constant offset from $\widehat{\rho}_{y_i,y_j,\zeta,\tau}(n)$ for the whole duration of the contamination. After a sound dropout, the ESS correlation never returns to high values.

4 CONCLUSION

In this paper, we present two methods for conducting more robust acoustic measurements: Rule of Two (Ro2), which detects the presence of non-stationary noise in ESSs, and Short-term Ro2, which localizes the contamination within the measurement. Both methods consider the properties of the system under test, such as background noise level and time variance, when establishing the detection threshold. In the evaluation, the accuracy of both tools is shown on a big data set of ESS signals and with different types of non-stationary noise.

Ro2 and Short-term Ro2 improve acoustic measurements by lowering the risk of obtaining erroneous results. They also increase the efficiency and robustness of measurement procedures and allow automatizing acoustic data collection.

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