Invited Paper

inter.noise 2010
noise and sustainability
13-16 June 2010 . Lisbon . Portugal
www.internoise2010.org

Time Selective Response Measurements – Good Practices and uncertainty

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Abstract
Time Selective Response, TSR, is a frequency response measurement method based on linearly swept sine signals. Because TSR can be used for free field measurements in ordinary rooms and is fast, accurate and relatively insensitive to background noise, it is convenient for measurements of microphone and sound level meter free field responses. However, the methods combination of time and frequency weighting can make it complicated to estimate the uncertainty of the measured response. This paper briefly recollects the method and presents some experience with and guidelines for choosing measurement and weighting parameters and considerations on the associated uncertainty on the results. The results are discussed on the basis of practical measurements at Brüel & Kjær of microphone and sound level meter free field responses.

Keywords: Time selective, Frequency response, Free-field, Microphone, Uncertainty

1 Introduction

In 1991, Brüel & Kjær introduced Audio Analyser Type 2012 with its Time Selective Response, TSR, measuring algorithm. With the TSR method, the system response of electroacoustic devices can be measured reliably in ordinary rooms. Type 2012 is not produced anymore, but with the introduction in the PULSE™ 12 Analyzer Platform, TSR is now also available on Bruel & Kjær's present family of sound and vibration analysers.

The TSR method provides a fast and convenient way to perform free field measurements in reflective environments, but the combination of time and frequency weighting in the method can make it complicated to estimate the uncertainty of the measured response.

This paper presents some guidelines for choosing measurement and weighting parameters and considerations on the associated uncertainty on the results.

2 The TSR method

2.1 The signal processing of TSR

Time Selective Response, TSR, is a frequency response measurement method based on linearly swept sine signals. The method is based on Poletti's [1, 2] ideas that solved some issues that could lead to erroneous measurement in earlier methods. The method is based on an underlying assumption on linearity and invariance of the object response. The impulse response of the system is determined by combining the inverted excitation signal with the response signal. Reflections can be excluded from the measurement by selecting the desired part of the impulse response by weighting with a time window.

The excitation signal in TSR is a complex, linear sweep

$$s(t) = e^{j\pi k t^2} \tag{1}$$

The resulting output signal is

$$y(t) = h(t) * s(t) = \int_{-\infty}^{\infty} h(\upsilon)\, e^{j\pi k (t-\upsilon)^2}\, d\upsilon \tag{2}$$

where *h*(*t*) is the impulse response of the object response, the transfer function of the complete measurement setup and the surrounding room. In the analysis, the output signal is combined with the inverse sweep

$$\begin{aligned} u(t) &= e^{-j\pi k t^2} y(t) \\ &= e^{-j\pi k t^2} \int_{-\infty}^{\infty} h(\upsilon)\, e^{j\pi k (t-\upsilon)^2}\, d\upsilon \\ &= e^{-j\pi k t^2} \int_{-\infty}^{\infty} h(\upsilon)\, e^{j\pi k (t^2+\upsilon^2-2t\upsilon)}\, d\upsilon \\ &= \int_{-\infty}^{\infty} \left[h(\upsilon) e^{j\pi k \upsilon^2} \right] e^{-j2\pi k t \upsilon}\, d\upsilon \end{aligned} \tag{3}$$

Inserting $\xi = kt$, this has the form

$$u(\xi) = \int_{-\infty}^{\infty} \left[h(\upsilon) e^{j\pi k \upsilon^2} \right] e^{-j2\pi \xi \upsilon}\, d\upsilon \tag{4}$$

The integral is recognized as the Fourier transform of the product of the system impulse response and the linear sweep, $h(t)e^{j\pi k t^2}$. Hence, using the convolution theorem,

$$\begin{aligned} h(t) &= e^{-j\pi k t^2} F^{-1}\{u(\xi)\} \\ &= e^{-j\pi k t^2} \int_{-\infty}^{\infty} u(\xi)\, e^{j2\pi \xi t}\, d\xi \end{aligned} \tag{5}$$

From this it is seen that $h(t)$ can be calculated for any point in time from the complete response. In particular, the time range including the direct sound from the measurement object can be selected for further calculation. The frequency response function can then be calculated by Fourier transform of $h(t)$.

$$H(f) = F\{h(t)\} \tag{6}$$

Conceptually, TSR can be understood as a combination of the swept sine signal and a tracking filter that follows the signal with a delay so that only the frequencies arriving at a certain delay are included in the measurement. The tracking filter is equivalent to the weighting function that defines the selected time range.

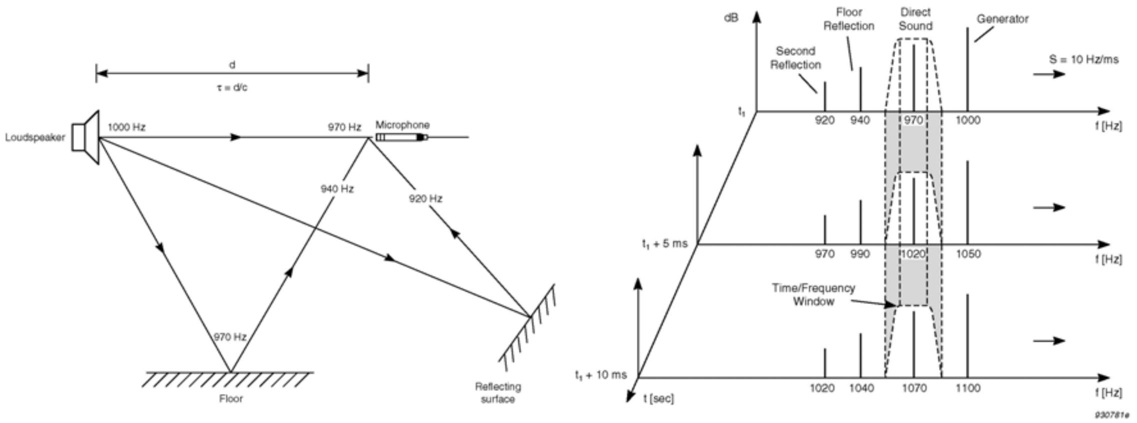

Figure 1. Illustration of the concept of a tracking filter, from [3, 4].

The TSR algorithm effectively works as a zoom FFT around the center of the swept frequency range, i.e. the impulse response that is determined is frequency shifted to the center frequency of the sweep. This property means that the sweep does not need to cover the full frequency range of the target transfer function.

The TSR method requires measurement of the complex response function. If the measured frequency range is limited so that negative frequencies are not included in the full sweep, the complete function can be calculated from a single sine sweep, but if the sweep includes zero or negative frequencies, a cosine and subsequently a sine sweep must be made in order to obtain the complex function.

2.2 Windows in TSR

In addition to the time window that is (can be) deliberately applied to the time response in a TSR measurement, there are two window functions inherently applied to the signal.

The first window inherent to the method is due to the limitation of the frequency sweep to the specified range. This is equivalent to applying a window function to an infinitely long frequency sweep.

$$s(t) = W_1(t)e^{j\pi kt^2} \tag{7}$$

The frequency spectrum of the finite sweep is determined by this weighting function.

The combination with the inverse (unweighted) sweep does not by itself distort the resulting impulse response.

The second window inherent to the method is due to the limitation of the analysis to a certain time range, and this is also effectively an application of a window to the impulse response, the time range mentioned above.

$$h(t) = W_2(t) e^{-j\pi k t^2} \int_{-\infty}^{\infty} u(\xi)\, e^{j2\pi\xi t} d\xi \tag{8}$$

The second window defines the time range that is included in the final Fourier transform so as to obtain the frequency response. Subsequent application of a narrower time window in order to exclude reflections is effectively the same as narrowing the time range, except that the time steps and frequency steps in the analysis are maintained.

The windows that are applied in Brüel & Kjær's TSR analysers are Tukey windows, i.e. rectangular windows tapered with raised cosine functions. The user selectable time window is a generalised form where the width of the two tapers can be selected independently.

In order to minimise the influence of the window applied to the sweep, the actual sweep covers a larger frequency range than that specified for the analysis.

The influence of the windows on the final result does not only depend on the windows themselves, but is a combination of the windows and the response to be measured. Therefore, it is not possible to predict the exact uncertainty based on the measurement parameters alone.

2.3 Applications of TSR

Since the TSR method provides time selectivity and both the time and frequency responses are immediately available, it is convenient for a large range of applications.

The method can be used for accurate and fast comparison calibration of microphones and sound level meters and measurement of the influence of accessories etc. Due to the time selectivity no anechoic chamber is needed for the measurements.

The method can be used for simple absolute frequency response measurements, e.g. of loudspeakers. A procedure for combining far field measurements with the TSR method with traditional near field measurement in a loudspeaker measurement is described in [5].

Another useful application of the TSR method is to use it as an effective means for localising reflections in a measured response. This can be used in optimising devices that shall disturb a sound field as little as possible. In particular this is relevant during the development of sound level meters, microphone holders, loudspeaker enclosures and similar devices.

3 Parameter choice

3.1 Sweep length

As it can be seen from the expressions in 2.1 the sweep rate, and thus the sweep length, only influences the integration time, not the resolution of the measured impulse response. This means that the sweep length only influences the signal to noise ratio of the measurement. Some experimenting should be done with the signal to noise ratio. If lowering the signal level with 10 dB significantly changes the measured response, the signal to noise ratio should be improved. If the noise itself cannot be reduced or the signal level increased, there are two ways to improve the signal to noise ratio in the TSR method. Either the sweep length or the number of averages must be increased. The sweep length does not have other influence on the measurement result, provided that the underlying overall assumption on linearity and invariance of the system is fulfilled.

3.2 Frequency range

The choice of frequency range in the measurement has only minor influence on the measurement. This is due to the mentioned fact that TSR effectively works as a zoom FFT around the center frequency of the sweep. The spectrum of the frequency sweep will be convolved with the object response, but if the weighting function that defines the sweep is reasonably designed, this will only have insignificant influence in the valid (selected) frequency range. This is illustrated in figure 2. Note, that the frequency ranges shown in the figure includes the part that is generated outside the specified frequency range so as to minimise the influence of the limitation of the sweep.

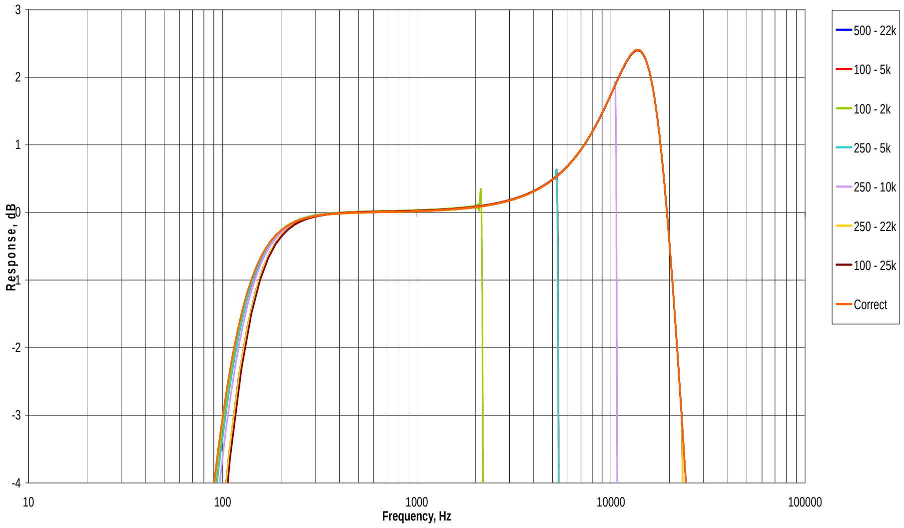

Figure 2. Simulated absolute response measurement with different frequency ranges. The time window is the full time range of the analysis.

3.3 Time window

The time window is a critical parameter in the TSR method (as in any other time selective method). Ideally, the time window should include the complete time response and exclude all other information.

In order to include all the desired information, the time window must at least be sufficiently long so as to include the fluctuations of the object response,

$$T_{\min} = 1 / f_c \tag{9}$$

where f_c is the necessary frequency resolution. If the time window is too short it will behave as a smoothing function on the response. This may be acceptable in some cases at high frequencies, for example in relative measurements where the resolution is not required in the measured ratio, but if the object response rolls off at low frequencies, a too short time window may deteroiate a large part of the object response.

The geometry of the measurement setup should be considered carefully. Simple measurement of the size of the measurement object helps in determining the minimum time window, and geometrical consideration can also help in optimising the path length difference in the setup.

In a normal building, the open height in rooms below lamps etc. is typically around 2.5 m. With a measuring distance of 1 m to 2 m, this leaves a difference between the direct path and the first reflected path of 1.2 m to 1.7 m, corresponding to a time difference between the direct sound and the first reflection of 3.5 ms to 4.9 ms. This limits the low frequency resolution that can be achieved in time selective measurements in normal-sized rooms. If a higher resolution is desired, a room must be used where the distance to any reflecting objects is larger. This may, however, require more bulky mounting devices that again may lead to less stable mounting and be more susceptible to movement in the air in the room. A time window allowing measurement of a 3.5 ms long time response will be sufficient for most applications within the microphone and loudspeaker measurements.

It is important that the time window only cover the part of the object time response that contains significant energy. In other words, if the complete impulse response of the measurement object is included in the time window, no further information can be achieved with a longer time window, and the smoothing properties of the window does not deteriorate the object function. One important aspect of this is that the resolution of the result cannot be improved by extending the time window towards negative time from the impulse. This will only allow more noise to influence the measurement. This is illustrated in figure 3 (note, that the noise level is deliberately exaggerated in the example).

If it is possible within the limitations of the reflections, different measurement distances and time windows should be tried in order to resolve whether the complete impulse is included in the measurement. The necessary length of the time window can be determined experimentally by gradually increasing the length until the shape of the measured response does not change.

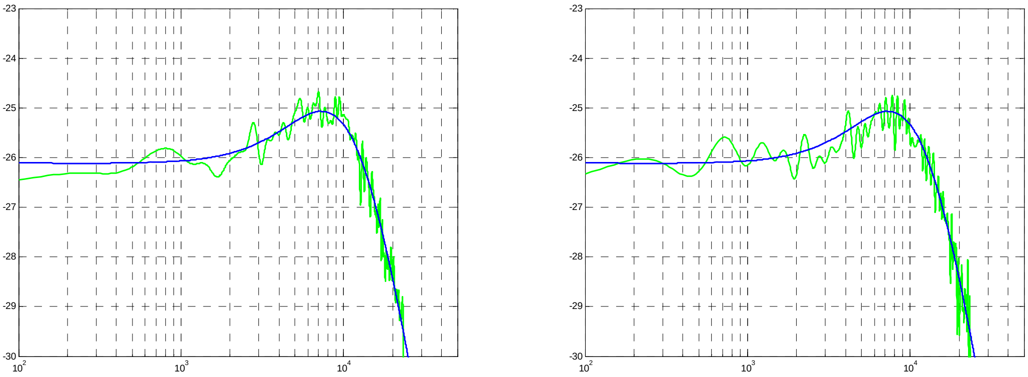

Figure 3. Noise influence. Left: Time window covering the impulse response. Right: time window extended towards negative time.

4 Uncertainty estimation

Uncertainty estimation of frequency response measurements made with the TSR method is of course similar to that of any other frequency response measurement method, except for the aspects that are particular to the method. Here, the aspects related to TSR are discussed. Note, that these aspects to some extent are the same for other time selective methods, because the underlying principle of determining the impulse response and selecting a certain part is common to all these methods.

As mentioned and demonstrated, it is not possible to predict the exact uncertainty based on the measurement parameters alone. Some evaluation can be made on the maximum variation that can be anticipated, but that is likely to lead to overestimation of the uncertainty. Instead, the evaluation should be based on controlled variations or realistic modelling of the actual measurement situation.

In the case of the measurement of a single response, e.g. in a loudspeaker measurement, the influence of the windows on the response contribute directly to the uncertainty of the measurement. If some knowledge is available of the object response, the influence of the parameters can be estimated by modelling. Alternatively, the measurement can be repeated with variations of the parameters. It should, however, be kept in mind that there may be systematic deviations that are not revealed by the possible parameter variations.

In the case of relative measurements where the response of the measurement object is compared with the response of a reference, e.g. in microphone comparison calibration or measurement, some of the deviations due to the windows cancel out because they are present in both measurements. In this case there are also considerable possibilities of making the measurements under different conditions both in the physical measurement setup and in the measurement parameters, thereby achieving knowledge on the uncertainty in the measurements..

In a frequency range where the reference and the object under test have similar and reasonably flat frequency responses, the low frequency resolution does not hinder an accurate determination of the difference between the two, and the uncertainty on the determined frequency response can be relatively small if care is taken to avoid systematic errors.

5 Examples

In this section a couple of examples of these measurements are used for illustration of the issues mentioned above. The TSR method is used intensively at Brüel & Kjær for measurements of free field responses. It is the company’s policy to thoroughly document all electroacoustic devices developed, and the TSR method have worked as an efficient and accurate tool for the purpose in several years.

Microphone free field response measurements

Free field response measurements of microphones at Brüel & Kjær are exclusively made using the TSR method. Absolute free field sensitivities are measured by comparison with reference microphones that are traceable to Danish national standards. Measurements of influence of accessories such as wind screens, protection grids etc. and directional characteristics are relative measurements where only the stability of the measurement object and the measurement setup is relevant. However, the measurements are always relative measurements. The free field measurements with the TSR method are made at frequencies above 500 Hz. Below 500 Hz the free field response of the microphones can reliably be established with other methods that are not the subject of this paper.

In order to ensure high accuracy and reproducibility in the measurements some practices have been developed. Although these are not directly related to the TSR method, they are mentioned here in order to demonstrate how the TSR method is used.

Many of the measurements are carried out in a measurement room situated in a normal office building. Some factors can disturb these measurements. Circulating air, e.g. due to ventilation systems disturb the measurements, small pressure pulses are generated in the building due to opening doors or the like and changing temperature causes changing speed of sound, detectable even when the changes are fractions of a degree. In order to minimise the variations in the measurement results due to these factors, the ventilation system is turned off during each response measurement that consists of six TSR sweeps. The TSR method makes it possible to do this in a minimum of time. The six sweeps allows the identification of occasional (but seldom) variations in the measurements as shown in figure 4. The practice also gives supplementary information to the uncertainty estimation.

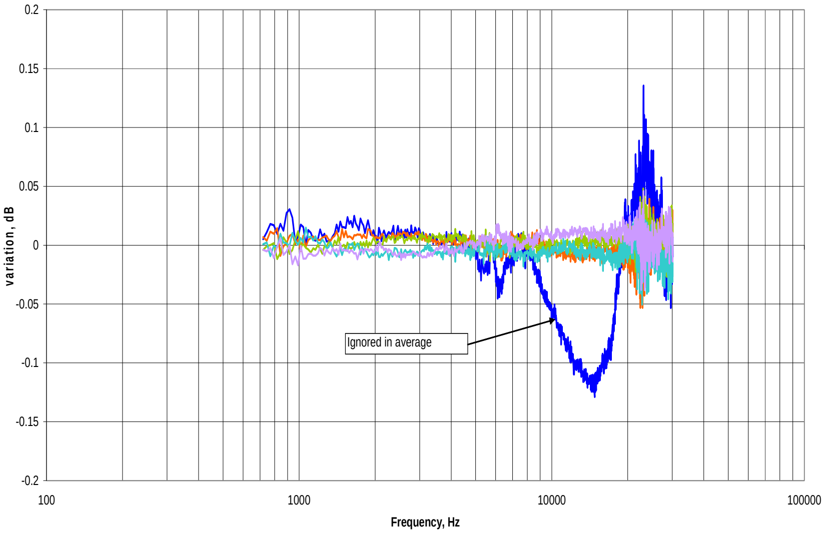

Figure 4. Variation of six consecutive sweeps. One of the sweeps has been disturbed.

Sound level meter free field response

The authors have in recent time worked with TSR measurements of sound level meter free field frequency responses in order to establish well-documented uncertainty estimates on the free field response of sound level meters.

Although the measurements in principle are similar to those of microphone free field responses, the measurement of the free field response of large devices such as sound level meters and outdoor microphones is particularly challenging. The time window must be large in order not to exclude parts of the devices, and it is often difficult to mount the devices for measurement without having reflections from the mounting setup.

The authors' measurements are carried out in different rooms, with different loudspeakers, in different distances and with different frequency ranges. Figure 5 shows the responses of the sound level meter and of the microphone on a long cylinder, and Figure 6 shows the double standard deviation of the responses. As it can be seen from the figures, it is indeed possible to achieve a good reproducibility of these response measurements. Work is still going on in improving the measurement procedure and the data analysis, and has also been a part of the preparation of this paper.

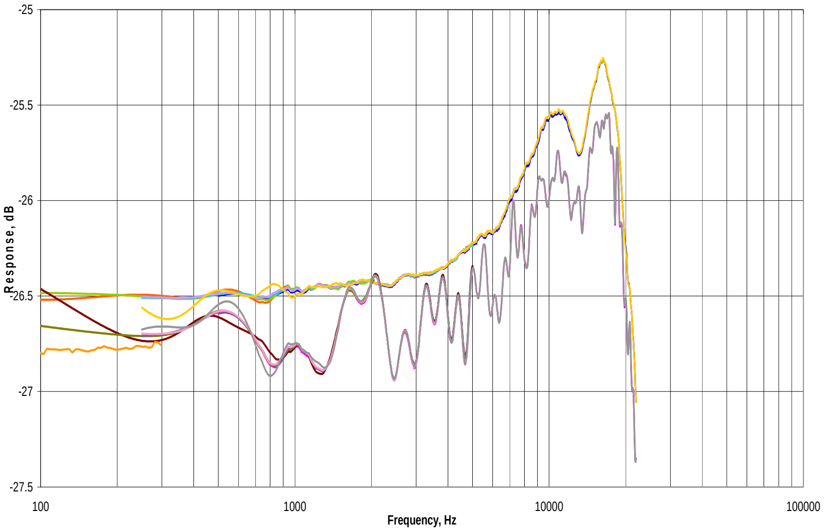

Figure 5. Measured free field responses of a sound level meter and the sound level meter microphone carried out in widely different setups, see text. Upper curves are for the microphone alone. Lower curves are for the microphone mounted on the sound level meter. Orange curve shows the low frequency response in an enclosure.

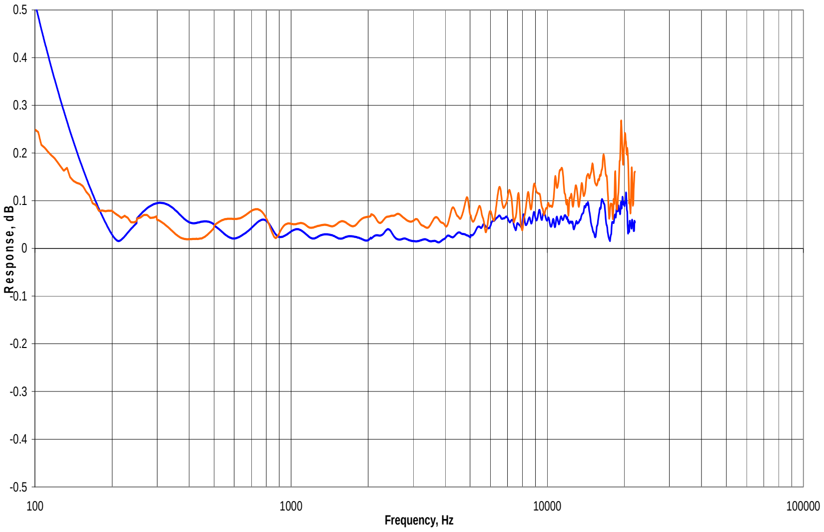

Figure 6. 2σ of measurements carried out in widely different setups, see text. Blue curve is for the microphone alone, red curve is for the microphone mounted on the sound level meter. The results shown are considered valid from 200 Hz.

6 Discussion and recommendations

The purpose of this paper is to give the reader some understanding of the TSR method and to provide guidelines and recommendations to the use of the method.

It should be mentioned that the influence of the windows in the time and frequency domains discussed here are of general nature and exists in all time selective methods. Actually, the influence of the windows in TSR is relatively easy to understand as compared to methods applying non-linear sweeps.

Our recommendations are

- Make the window as long as possible, but not longer than necessary
- Object low frequency behaviour determines necessary window length
- Low frequencies – go closer and increase time window
- Increasing the sweep time increases S/N ratio, not resolution
- Always try with different window sizes
- Always repeat measurements
- Large rooms are preferable, no matter whether they are anechoic or not
- The air must be stable (easier than in anechoic chambers)
- Carefully consider the reflections and which to include in the time window

Routine measurements do of course not need to be verified each time

7 Summary

In this paper the Time Selective Response, TSR, method has been recollected, and the influence of some choices of measurement parameters and their interaction with the object response, has been presented.

The importance of the right selection of time weighting function has been shortly demonstrated. It has also shortly been demonstrated that the actual frequency range of the measurement is of small importance.

Some guidelines on how to evaluate the measurement uncertainty due to the time and frequency limitations in the measurements have also been given

It is the intention of the authors to show more examples i Lisbon than those presented here.

8 References

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