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Transducer Response Equalization *

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This paper describes a new technique, Response Equalisation Extreme (REq-X), that enhances the frequency range and accuracy of transducers. This technique, which is implemented in PULSE, the Brüel & Kjær Multi Analysis System Type 3560, allows you to equalize for the frequency response of transducers in real-time. This significantly extends the usable frequency range of transducers. The REq-X technique corrects the time signal of a transducer by the inverse of its calibrated frequency response, and can be added to any device with a frequency response stored in the PULSE Transducer database, e.g. Brüel & Kjær microphones and accelerometers. Brüel & Kjær TEDS transducers are automatically detected. This means for example that you can use he same microphone in any kind of sound field. Furthermore the microphone can be corrected for angle of incidence and for various accessories.

Key Words: **NVH, Transducer Equalisation, Microphone, Accelerometer, Measurement accuracy**

1. INTRODUCTION

Response Equalization is a new technique that allows you to flatten and stretch the frequency response of microphones, accelerometers and couplers in real-time. This extends the frequency range of transducers, it improves the accuracy of the measurement and it expands the use of existing transducers. The principle of REq-X is shown in Figure 1. This means that you can use the same microphone for different sound fields – free-field, pressure-field and diffuse-field independent of type of microphone. What's more, the microphone can be corrected for angle of incidence in steps of 30 degrees, i.e. for 0^0, 30^0, 60^0, 90^0, 120^0, 150^0 and 180^0 angle of incidence, and for various microphone accessories for example, windscreens, microphone grids and nose cones, thereby improving the measurement accuracy by further 5 to 10 dB.

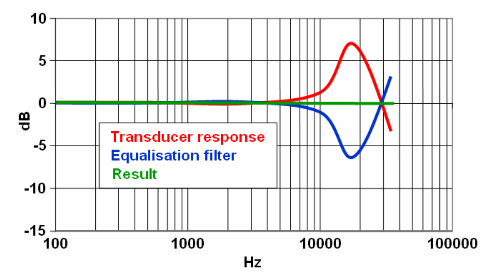

Fig. 1: Transducer response (red/upper), equalization filter (blue/lower), equalized response (green/middle)

For a correctly mounted accelerometer you can expect REq-X to increase the highest recommended usable frequency range from one third of the accelerometer's resonance frequency to ½ of the resonance frequency – an increase of 50%.

This leads to better quality measurements all-round. The bottom line is that if you want the highest possible measurement accuracy result – then you need to use response equalization.

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2. MICROPHONES AND THEIR FREQUENCY RESPONSE

Microphones are divided into three types according to their response in the sound field: free field, pressure field and diffuse field (or random incidence) microphones.

When a microphone is placed in a sound field, it modifies the field, the pressure will rise in front of the microphone caused by local reflections and the microphone will measure too high a sound pressure. This rise in "sensitivity" is frequency dependent, with a maximum at the frequency where the wavelength, λ is equal to the diameter of the microphone, D. If the corresponding frequency axis for a 1/2" microphone is plotted along the D/ λ axis it is seen that the increase starts at 2 kHz with a maximum of approximately 10 dB at 27 kHz.

Free field microphones have uniform frequency response for the sound pressure that existed before the microphone was introduced into the sound field. It is of importance to note that the physical size of the microphone will disturb the sound field as mentioned earlier; the free field microphone is designed to compensate for its own disturbing presence. In Figure 2 the blue curve shows frequency response of free field microphone when used in a diffuse-field.

The red and the green curve show the frequency response of the free field microphone when used in a free field. The red/upper curve is for 0° incidence and the green/lower curve is for 120° incidence. When using a free-field microphone in a diffuse-field or when using the free field microphone in a free-field but not pointing directly against the sound source then the level at high frequencies will be underestimated if Response Equalization is not used. Thus correct use (without REq-X) of a free-field microphone is in a free-field with only one sound source and with the microphone pointing towards the source.

The diffuse field microphone is designed to respond uniformly to signals arriving simultaneously from all angles. It should therefore be used for measurement in all situations where the sound field is a diffuse sound field e.g. in many indoor situations where the sound is being reflected by walls, ceilings, and objects in the room. Typically rooms with hard concrete walls and without carpets on the floor and inside vehicles.

In situations where several sources are contributing to the sound pressure at the measurement position, also a diffuse field microphone should be used. Figure 3 shows its response in various sound fields, but only in a diffuse field it has a flat response.

In Figure 3 the blue/middle curve shows frequency response of a diffuse-field microphone used in a diffuse field. The red or upper and the green/lower curve show the frequency response of the diffuse-field microphone when used in a free field. The red curve is for 0° incidence and the green curve is for 120° incidence. Using the diffuse-field microphone in a free-field without using any Response Equalisation there is a big risk that you over or under estimate the level at high frequencies by more than 5 dB.

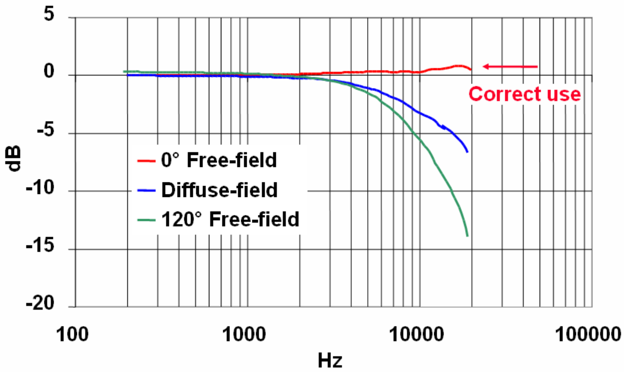


Fig. 2: ½ inch general purpose free field microphone in various sound fields

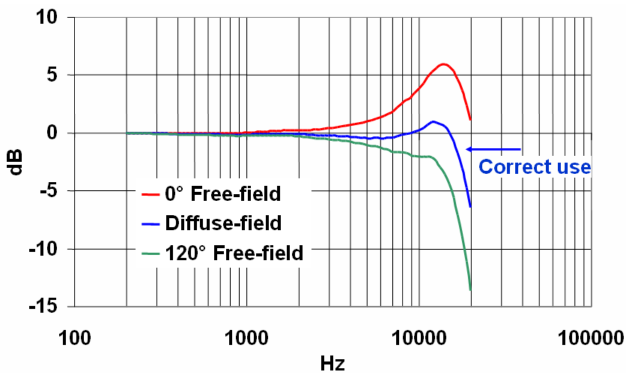


Fig. 3: ½ inch general purpose diffuse field microphone in various sound fields

The main application of the pressure microphone is for measurement in closed cavities e.g. coupler measurement and audiometer calibration where the physical dimensions are comparable or smaller than the wavelengths of the measured sound field, and for measurements at walls or surfaces, where the microphone can be mounted with its diaphragm flush with the surrounding surface.

All Brüel & Kjær microphones are delivered with an individually measured calibration chart on which you can see the microphone's frequency response for the sound field that it is designed for.

Additional frequency responses for other sound fields and accessories are available on the Microphone Data Disk, and can be seen using the Microphone Viewer program on the disk. The frequency response curves can also be viewed using Excel spreadsheet.

The Microphone Data Disk has been delivered with Brüel & Kjær microphones for more than 10 years. These data is used for Response Equalization

3. ACCELEROMETERS AND THEIR FREQUENCY RESPONSE

All accelerometers will give a constant output signal for a constant acceleration, from very low frequencies up to a limit set by the increase in output due to resonance of the accelerometer. Traditionally, the accelerometer is not used close to its resonance as this could result in a big error in the measured signal. As a rule of thumb, the accelerometer can be used without Response Equalization up to one third of its resonance frequency. This will then ensure that the error at that frequency does not exceed approximately 10% or 1 dB. 0.3 times the mounted resonance frequency gives the 10 % limit as shown in Figure 4.

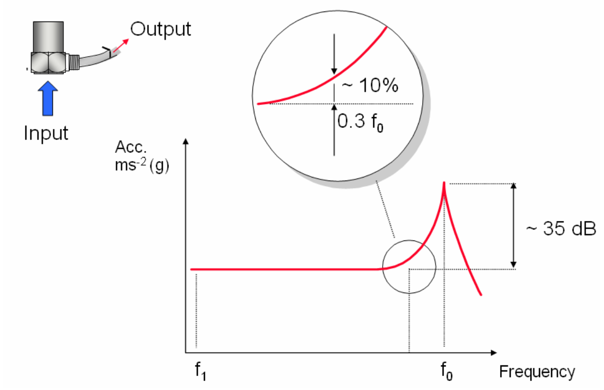


Fig. 4: Useful upper frequency limit for an accelerometer is 0.3 x f_0

The frequency response on the accelerometer calibration chart is equal to the one obtained using stud or metal clip mounting.

Mounting the accelerometer with the aid of a steel stud is the best mounting method and should be used in all applications wherever possible. However Stud Mounting will not always be possible. Using Cementing Stud, Thin double adhesive tape or bees' wax or grease then the resonance frequency and thus the useful frequency range will decrease.

Note that bad mounting of the accelerometer can spoil vibration measurements by severely reducing the usable frequency range. The main requirement is for close mechanical contact between the accelerometer base and the surface to which it is to be attached.

A calibration chart is supplied with each accelerometer. Here you will find 5 parameters (resonance frequency, Q-factor, upper & lower frequency limit and amplitude correction/slope) that define the frequency response for an ideally mounted transducer.

These parameters are given for all Brüel & Kjær accelerometers - and have been for the last 10 years.

Using TEDS accelerometers or if you key these parameter into the Transducer Database then they can be used for Response Equalization. The transducer database also contains the frequency response for various mounting methods – for some selected transducers.

4. HOW DOES REQ-X WORK?

The response equalisation is implemented in the time domain using Iterative Frequency Sampling Method. The advantage of this is that once the time signal has been selected for Response Equalization then the equalisation is done in real-time and applies to all analysis types available.

In Figure 5 the left graph, G(f), shows the frequency response of a transducer. This can be taken from the Transducer Database. Inversing the graph we get the correction spectrum, H(f), which should be multiplied to the input spectrum to give a flat response. Calculating an inverse FFT on the correction spectrum we get the impulse response, h(t) of the correction spectrum.

Implementing the equalization in the time domain, means that the equalized signal is calculated as a convolution between the input signal and the impulse response function of the equalization filter.

The length of the impulse response depends on the low frequency limit. If for instance the signals are analyzed up to 25.6 kHz, a sampling frequency of $Fs = 65536$ Hz is used. If you want the spectrum to be corrected down to 128 Hz then the resolution of the correction filter should be at least $\Delta f = 128$ Hz. We can now calculate that the length of the impulse response to be at least $N = Fs/\Delta f = 65536/128 = 512$ samples.

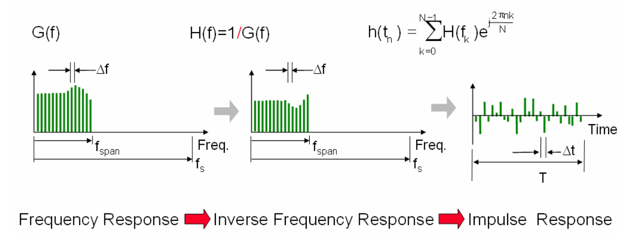
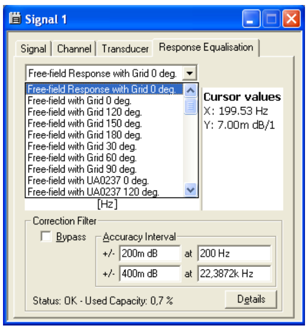


Fig. 5: REq-X is implemented in the time domain using impulse response of the correction filter and convolution techniques

Depending on the shape of the transducer frequency response and how precise a response equalization you want to obtain then it might bee needed to increase the frequency resolution, thus the length of the impulse response, which is done automatically. The maximum length of the impulse response is limited to 4001 samples. A filter like this will cause a time delay, which is automatically corrected for. The amount of processing power needed for the actual equalization is displayed. If phase is available then REq-X also compensates for the phase response.

5. HOW TO USE REQ-X

In the signal property page you apply response equalization. For a microphone typically there are 50 different equalization curves to choose from, i.e. which sound field and which accessory you want to equalize for, see Figure 6.



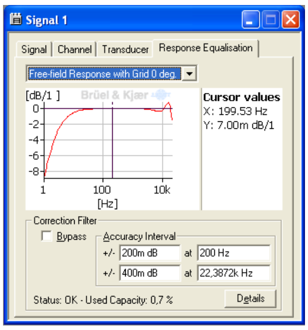


Fig. 6a: Different equalization FRF's

Figure 6b: Chosen equalization FRF

Then the user can choose the low and high frequency accuracy interval in dB and degrees. Status will show whether this equalization can be realized within a 4001 sample long impulse response function, as well as how much of the maximum filter capacity the implementation requires. For microphones the default frequency range is 200 Hz up to the upper frequency in the Transducer Database dataset. For accelerometers the default frequency range is 200 Hz up to half the resonance frequency. The accuracy is set to 0.2 dB at the low frequency and 0.5 dB at the high frequency by default.

Correction Filter Details (see Figure 7) shows the actual transducer response (same as in Figure 6b) together with the realized correction filter as well as the equalized frequency response.

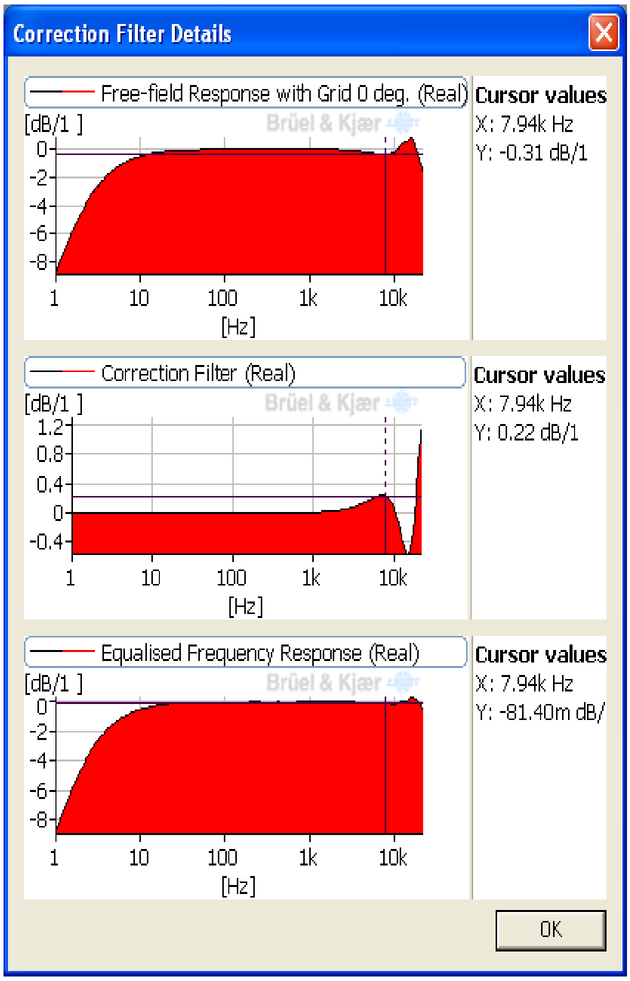


Fig. 7: Correction Filter Details

REq-X will now be added to the selected transducer. As the transducer signal is response equalized before putting it into any analyzer then it is automatically response equalized in any analysis done in the measurement project.

6. SOME EXAMPLES

Figure 8 shows the result of an equalization of a free field microphone type 4190 used in a free field with a windscreen. In this example we have selected very narrow tolerances, 50m dB at both 50 Hz and at the upper frequency limit 22.4 kHz, in order to get a very flat frequency response when the signal is equalized. We can see that the maximum improvement is about 0.7 dB at 2.3 kHz. Even though the frequency response is nearly flat the REq-X can flatten it even further. This is an advantage if you have very high demands of measurement accuracy.

Figure 9 shows the result of an equalization of a free field microphone type 4190 used in a diffuse field. The same tolerances as mentioned above are used. We can see that the in this case the improvement is about 3.7 dB at 10.3 kHz. Thus if you are measuring in a diffuse field and you do not have a diffuse field microphone then you can use a free field microphone in stead.

Brüel & Kjær microphones are made with an optimized frequency response for the sound fields they are designed for. Even though the microphone is well designed, we can effectively enhance the frequency response even further. Using REq-X we can flatten the frequency response further and in this way improve the measurement accuracy by up to 1.5 dB over the specified frequency range.

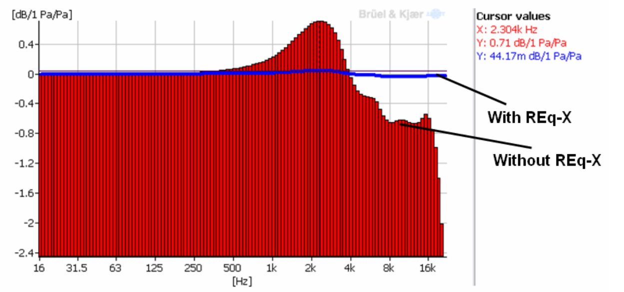


Fig. 8: Type 4190 free-field microphone used with windscreen in free-field

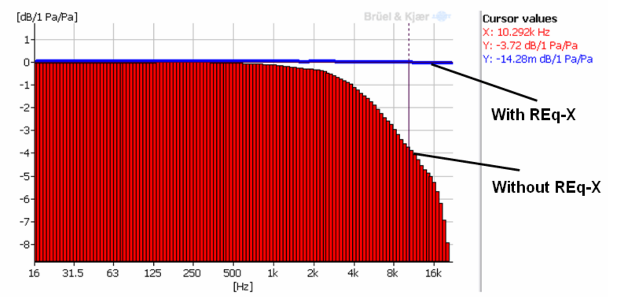


Fig. 9: Type 4190 free-field microphone used in a diffuse sound field

REq-X can also be used to correct for the angle of sound-field incidence and for microphone accessories like windscreens and thereby improving accuracy by a further 5 to 10 dB.

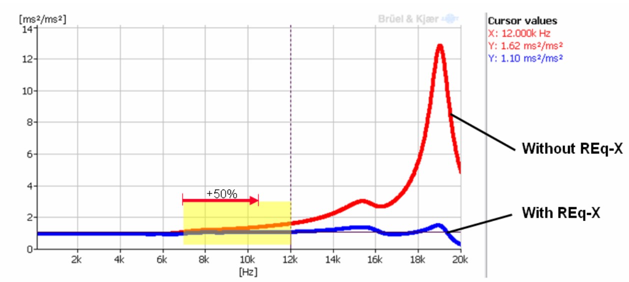


Fig. 10: Accelerometer Type 4507 mounted with a metal clip

Figure 10 shows the measured frequency response of accelerometer Type 4507 mounted with a metal clip. The resonance frequency was measured to be 19 kHz. Without the use of REq-X the upper frequency is 7 kHz. Using REq-X the upper frequency is raised to 12 kHz, which is an increase by more than 50% and the accuracy has been improved dramatically all the way up to the resonance frequency. Brüel & Kjær accelerometers are specified with an upper frequency which is defined by the 10% limit. This is typically up to 0.3 times the resonance frequency. Using REq-X we can now halve the measurement inaccuracy to 5% over the same frequency range. If we instead stick to the 10% limit and use REq-X then we can extend the accelerometer frequency ranges. Using Uni-axial accelerometers the upper frequency can be extended by up to 100%. For other types the upper frequency can typically be extended by up to 50%. This is illustrated in the Fig. 10, where the upper frequency is increased by 70%.

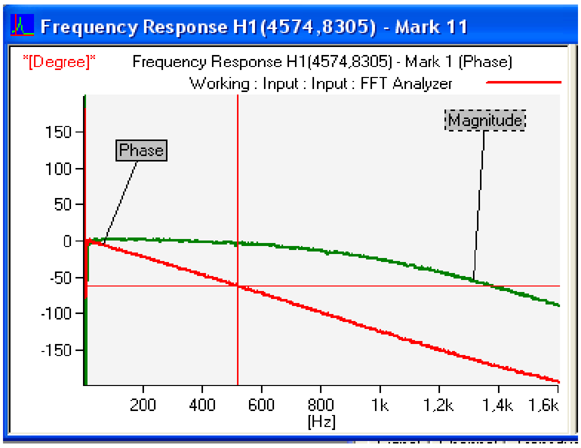


Fig. 11: Type 4574 without REq-X

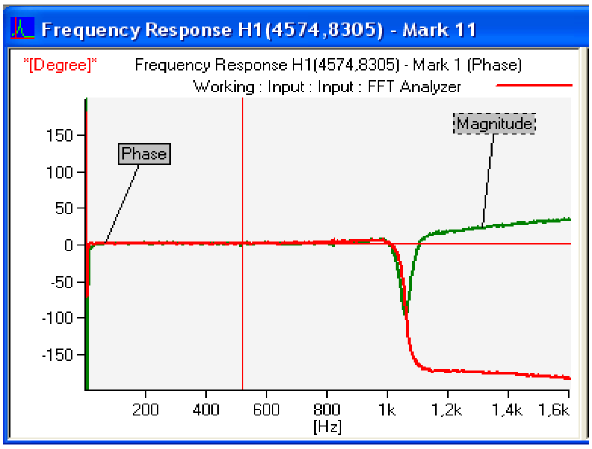


Fig. 12: Type 4574 with REq-X

An example of both amplitude and phase equalization is shown in figures 11 and 12. A DC accelerometer Brüel & Kjær Type 4574 has been equalized up to 1 kHz within a tolerance of 0.2 dB and 1 degree at the lower limit of 1 Hz and a tolerance of 0.5 dB and 1 degree at the upper limit of 1kHz. Figure 11 shows the amplitude and phase response without Response Equalisation and figure 12 shows the the amplitude and phase response with Response Equalisation.

7. CONCLUSION

The benefits of Response Equalisation eXtreme, REq-X, are as follows: it expands the use of new and existing transducers, it improves the accuracy of the measurements and it extends the frequency of transducers. It works in real-time, thus any measurement and analysis will benefit from this. Combined with the Dynamic Range Extension, also called Dyn-X technology, Ref.[1] it expands both frequency and measurement ranges, resulting in even more accurate and reliable measurements.

REFERENCES

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