Measurement of the sound absorption coefficient of materials with a new sound intensity technique

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Abstract

The paper presents a completely new measurement technique of the sound absorption properties of materials, based on the measurements of active intensity and sound energy density. It allows one to measure the absorption coefficient with a wide band excitation, to use frequency bands of any width and to make measurements both inside a tube or in situ.

The intensity technique is compared to Transfer Function Method (as defined in the ASTM E-1050 standard), by means of a complete theoretical study and of a large experimental validation.

The results suggest that the new method is at least as accurate and reliable as the ASTM E-1050 standard. It also has many advantages: it is faster, easier, it directly produces results in $^1/_3$ or 1 octave bands, it can be implemented with portable, low cost instrumentation.

1. Absorption coefficient measurement techniques

Absorption coefficient measurements are not easy, especially if one needs to do them in situ, i.e. where materials are placed and having no regard of their shape or extension.

Usually the measurement of absorption coefficient is made in a reverberant room, according to the ISO 354 standard [1], or using the traditional standing wave tube technique, described in the ISO/DIS 10534 standard [2].

Both of these methods do not allow one to make measurements in situ, and the second one requires single frequency measurements, so that a complete test takes a long time. Moreover with the second one small samples have to be used and the tube/sample diameter has a strong influence on the frequency range and measurement limits.

Anyway, in a standing wave tube it is also possible to make just a single, fast measurement, using a wide band signal instead of repeating measurements for each single pure tone.

The use of a wide band signal speeds up the test and also allows one to be sure that collected values at each frequency were obtained in the same environmental conditions, for instance at the same room temperature and wave propagation velocity.

These improvements can be achieved if the Chung & Blaser Transfer Function Method [3,4], described in the ASTM E-1050 standard [5], is chosen. This method requires a two-channel FFT analyzer and two closely spaced microphones, which have to be previously calibrated for phase and gain matching.

As it is well known, the ASTM standard method involves the separation of a stationary, random, broad band signal into its incident and reflected components. It is based on the transfer function between the two sound pressure signals measured by two microphones placed along the tube wall.

These two sound pressure signals are considered ergodic processes. This assumption has to be made in order to use time averages instead of statistical functions. In fact time averages allow one to describe the stochastic process on the base of just one of its realizations, so that it is not necessary to collect many of them to characterize the process in terms of statistical parameters [6].

The more the averaging time is long, the more the averages approach the theoretical value, so that a good accuracy requires a long averaging time.

This standard is applied using a FFT analyzer, which works with narrow band filters and thus constant-percentage bands analysis can not be done directly: furthermore, due to the indetermination principle, the narrower the frequency bands are, the longer the averaging time must be, in order to reduce the error below a fixed threshold [7].

When it is necessary to characterize a material for technical or trading purposes, a few values of the absorption coefficient are required, at the IEC octave or $^1/_3$ octave center-band frequencies.

It is a good practice to get these values from the average absorption coefficient of all the frequencies included in each octave or $^1/_3$ octave band, and not simply from the "local" value of the absorption coefficient at the center-band frequency: thus the results of a narrow-band analysis require a proper post processing to yield the required average absorption coefficients.

In some previous works of one of the authors [8,9] several implementations of the Transfer Function Method were analyzed, in comparison with the ISO/DIS 10354 standard. These works pointed out that a strict implementation of the Transfer Function Method causes many problems, which can be solved only by using a properly designed experimental apparatus, and limiting the analysis to certain kinds of absorbing materials, which do not exhibit strong variations of the absorption coefficient with frequency. Similar results were also obtained by Chu [10].

An alternative extended method to measure the absorption coefficient, that uses a single microphone, subsequently placed in many different positions along the tube, and that computes the transfer function between each pair of positions, has been developed by one of the authors, as reported in the above mentioned works [8,9]. This measurement technique is slower than the original Transfer Function Method, it requires an accurate manual placement of the probe, and it still suffers of the same limitations due to narrow-band analysis and averaging time of the original Transfer Function Method. In the second work [9] an implementation of the new Intensity Method was tested for the first time, but the results were wrong because of an error in the computing formulas.

2. The new sound intensity technique

The new intensity technique was created to make available an easy and quick solution to the above mentioned problems. With the new method it is possible to make measurements in situ because this method is robust and its basic requirements are very simple. It must be clearly stated that the proposed method is completely new, and it is not at all similar to other proposed "intensity methods" for absorption coefficient measurements, as those reported by Fahy [11]

which relies on the use of the intensity meter as an “impedance meter”and in wichthe impedance is obtained by the sound pressure and particle velocity ratio. This new Intensity method uses only of the concepts of Sound Intensity and Energy Density, and thus is much more robust than the other methods in which ratios of complex quantities are involved.

Furthermore, this new method does not rely on the previous knowledge of the incident intensity, obtained by a reference measurement of the same sound source in a free field: a single measurement near the absorbing surface is all that is required to extract the results.

Something is worth to be underlined is that in the intensity technique no hypothesis about stochastic processes need in principle to be made, as the Sound Intensity definitions yield for any kind of sound field, both with deterministic and random signals. Obviously the ergodic assumption should be made if the Intensity Technique has to be compared with the Transfer Function Method, but just because this is required from the latter, or in general from any measurement method which is based on spectral analysis [12].

There are still limits in frequency range, according to sample extensions and placement, being necessary to have plane waves on the sample surface and to avoid border effects, but these limits are significantly broader than those required for the validity of the Transfer Function Method.

With the new technique, the absorption coefficient can be calculated from the measurement of the Sound Intensity I and the sound field Energy Density D, on the base of simple mathematical relationship existing among them. These relationships allow one to know what the reflected and incident sound intensities are, so that the absorption coefficient can be calculated exactly from its definition.

The Sound Intensity I is a vector quantity and it can be measured using a 3-D Sound Intensity probe (which uses 3 phase-matched microphones pairs) or a B-format *Soundfield* microphone, which is a special probe using a 4 microphones tetrahedral array and a proper circuitry to recover the pressure gradients along the three Cartesian axes.

As initially suggested by Chu [13], it is even possible to use a single, omni-directional microphone properly placed in several closely spaced positions, provided that the sound field is excited with a deterministic broad-band signal, as, for instance, the MLS signal.

All these techniques involve the computation of pressure gradient components along the three Cartesian axes (X,Y,Z), then the Cartesian components of the particle velocity u can be derived from these sound pressure gradients using Euler’s equation (usually written with finite-difference approximation, in which the pressure gradient is simply obtained from the difference of the pressure signals measured by the two microphones placed along the measurement axis, divided by the microphone spacing), as clearly explained by Fahy [10] and Rasmussen [14].

The result of particle velocity vector and sound pressure product is the active intensity vector I; the knowledge of sound pressure and particle velocity also allows one to know the sound field energy density D, being

$$D(t) = \frac{1}{2} \cdot \left[\rho \cdot u(t)^2 + \frac{p(t)^2}{\rho \cdot c^2} \right] \tag{1}$$

The above mentioned mathematical computations can be done both in time or frequency domain, employing FFT or real-time, constant percentage band filters analyzers. Usually the RMS values of sound pressure and particle velocity are measured and the energy density average value $\overline{D}$ is used:

$$\overline{D} = \frac{1}{2} \cdot \left[\rho \cdot \overline{u}_{RMS}{}^{2} + \frac{\overline{p}_{RMS}{}^{2}}{\rho \cdot c^{2}} \right] \tag{2}$$

Intensity, instead, has to be linearly averaged over time:

$$\bar{I} = \frac{1}{T} \cdot \int_{0}^{T} p(t) \cdot u(t) \cdot dt \tag{3}$$

For the sake of simplicity, let we assume that all these averaged quantities are time-invariant, being the excitation signal a stationary random noise.

It is necessary to set up the experiment so that a few hypotheses are satisfied.

Sample extension should be large enough to avoid border effects; the source has to be placed in such a way that the incidence angle is known and at a certain distance from the surface, so that making the measurement close to the reflecting surface ensures that the incident wave is a plane wave.

Making no assumption about sample surface (which can be completely flat, producing a specular reflection, or rough enough for producing diffuse scattering of the reflected sound), the absorption coefficient α will be a function of this incidence angle θ :

$$\alpha = \alpha(\vartheta) = 1 - \frac{|I_{ref}|}{|I_{inc}|} \tag{4}$$

In any case, also the reflected wave is locally considered as a plane wave, although it is clear that with diffusing surfaces the reflected intensity vector can be found pointing in another direction and having different modulus if the measurement is repeated in the neighborhood of the point.

The whole test system is assumed to be linear; and thus it is studied by using incident and reflected sound wave effects superposition.

The reference system is chosen so that the XY plane includes the sound source, the impact point and the normal to the surface at the impact point. For further simplification the X axis corresponds to the line connecting the source with the reflection point as in figure n.1, and Y axis will be simply orthogonal to the X axis.

Because of the system linearity, it is possible to say that the energy density average value D is obtained by the sum of the densities produced by the two superposing plane waves due to the incident and reflected fields:

$$D = \frac{|I_{inc}|}{c} + \frac{|I_{ref}|}{c} \tag{5}$$

in which $|I_{inc}|$ and $|I_{ref}|$ are the moduli of the incident and reflected intensities and c is the sound speed.

This energy density refers to a small volume around the measurement point, where incident and reflected waves pass through. At this measurement point, several quantities can be measured, as the intensity value I_x, I_y, I_z (Cartesian components of the total active intensity) which are given by the vector combination of the incident and reflected intensities..

The particular choice made in setting up the reference system ensures that the incident intensity vector has no component along the Y and Z axes ($I_{inc}=I_{incX}$), so that the measured values I_y and I_z provide directly the corresponding components of the reflected intensity vector I_{ref}. On the other hand, the measured value I_x is simply due to the algebraic difference between the X-components of the Incident and Reflected intensities,:

$$I_x = I_{incX} - I_{refX} \tag{6}$$

Also the three Particle Velocity components (u_x, u_y and u_z) and the Sound Pressure value p are measured by the microphone or probe, so that the Energy Density average value D is known by means of equation 2).

Thus the whole problem reduces to the computation of two unknown quantities: I_{incX} and I_{refX}. The two independent equations (5) and (6) are available, so the problem is easily solved.

Once I_{inc} and I_{ref} are available, α can be calculated from its definition

$$\alpha = 1 - \frac{|I_{ref}|}{|I_{inc}|} = 1 - \frac{\sqrt{I_{refX}{}^2 + I_{refY}{}^2 + I_{refZ}{}^2}}{I_{incX}} \tag{7}$$

This particular absorption coefficient could depend on the incidence angle θ: in order to have just one average value it will be necessary to make several measurements at various incidence angles, and then to average the results; however, this average absorption coefficient is not the Sabine's absorption coefficient, as derived by reverberant chamber measurements following the ISO 354 standard. The Sabine's absorption coefficient can easily be greater than unity, while the absorption coefficient obtained using the Intensity Technique can not be greater than 1. It can be concluded that the absorption coefficient measured with the new method is exactly the quantity required as input by Ray Tracing or Image Sources computing programs, and it does not depend on the kind of reverberant sound field which establishes in the room where the tests are made (i.e., a special test room is not required).

If the absorbing material is also (partially) diffusing, in principle measurement results change when measurement point does. In this case, even for a fixed incidence angle, a separate average of the Incident and Reflected Intensity Modulus over various measurement points has to be undertaken to ensure that the total reflected energy is properly taken into account.

The intensity components average made by moving the intensity probe during the measurement would not give the same result, because it causes a systematic reduction of the reflected intensity modulus due to reciprocal cancellation of not-coherent components.

3. Theoretical comparison with the Transfer Function Method

In order to verify if the mathematical relationships on which this new theory is based are reliable, a comparison was made with the well known ASTM E-1050 standard [5], which is based on the Chung & Blaser Transfer Function technique [3,4].

This is the only one similar existing standard, because the Intensity Method uses a broad band signal to excite the field as the ASTM E-1050 does. In the Transfer Function Method, the measurement is possible only under normal incidence conditions (θ = 0), on non diffusing

surfaces, inside a tube of proper diameter and length, to ensure that both the incident and reflected waves are plane and in the same direction.

Two microphones are placed with a proper spacing s along the wall of the tube; the gain and phase matching of the two microphones is obtained with a proper "microphone switching" technique, which is essential for the validity of the Transfer Function Method. Fig. 2 shows a scheme of the measuring apparatus.

In this case, the 3 equations derived for the Intensity Method in the previous paragraph can be collapsed in a single one, which gives directly the absorption coefficient:

$$\alpha = \frac{2 \cdot \left| \frac{I}{c \cdot D} \right|}{1 + \left| \frac{I}{c \cdot D} \right|} \tag{8}$$

In this equation the ratio between the Active Intensity I and the Energy Density D appears explicitly. This ratio, which has the same dimension of a velocity, was called by Schiffrer and Stanzial the "Acoustic Energy Speed" [15], or U-velocity. In general it is a vector, having the same direction as the Active Intensity vector, and with a modulus which is bounded between 0 (completely reactive field, no energy transport) and c (completely active field, as for a plane, progressive wave). Although the work of Schiffrer and Stanzial was completely theoretical (and quite difficult to understand), it is evident from equation 7) that the U-velocity is an important descriptor of the sound field: starting from this a very useful measurement can be done, and probably it can be used also in the measurement of other acoustical quantities.

Before experiments had been done, a complete theory development and check, based on Fourier Transform theory and spectral analysis [7,12,16], confirmed that the expected results of the two methods are supposed to be substantially the same if a narrow-band FFT analyzer is used, if the 2 microphones are perfectly matched both in gain and in phase, and if no "noise" affects the measured quantities (the latter assumption can be satisfied with a proper averaging time)

If sound pressure is considered as an ergodic process, and also particle velocity is (this is the assumption required for making use of the Transfer Function Method), it is possible to study what would happen if an FFT analyzer is used to make the calculations required by the Intensity Method instead of the Transfer Function Method.

The well known Chung & Blaser theory was used to describe the Transfer Function Method, and the Fahy formulation was employed for deriving the Active Intensity, Particle Velocity and Sound Pressure quantities from the 2-microphone probe.

After a quite complex mathematical analysis, it resulted that with both methods the absorption coefficient as a function of frequency can be written as a ratio of Auto and Cross Spectral Densities (G_{AA}, G_{BB} and G_{AB}) of the two microphone signals:

$$\alpha(\omega) = 1 - \frac{\left(\frac{G_{AA}(\omega) + G_{BB}(\omega)}{2} \right) + \mathrm{Re}\left\{ G_{AB}(\omega) \cdot [\Xi(\omega)] \right\}}{\left(\frac{G_{AA}(\omega) + G_{BB}(\omega)}{2} \right) + \mathrm{Re}\left\{ G_{AB}(\omega) \cdot [\Xi(\omega)]^* \right\}} \tag{9}$$

Although the above expression is formally the same for the two methods, the factor Ξ represent a different function of the dimensionless frequency ξ (defined as $\omega \cdot s / c$).This term is a

phasor in the Transfer Function Method and a complex number in the Intensity Method expression:

$$\Xi = \left(-\cos\xi - j\cdot\sin\xi\right) \qquad \text{(Transfer Function Method)}$$
$$\Xi = \left(\frac{\xi^2 - 4}{\xi^2 + 4} - j\frac{4\cdot\xi}{4+\xi^2}\right) \qquad \text{(Intensity Method)} \tag{10}$$

Figures number 3 and 4 report the behavior of the real and imaginary parts of the two expressions (10) for the complex number Ξ when the parameter ξ changes, covering the frequency range for which the tube is built (100 to 1600 Hz), assuming a microphone spacing s of 50 mm and a sound speed c of 340 m/s; it is easy to see that when the frequency increases, the two expressions diverge, due to the approximation introduced by the finite difference implementation of the Euler's equation in the Intensity Method.

However, the absorption coefficient is a ratio (in the denominator the complex conjugate of the factor Ξ appears), and thus there is a kind of adjustment which reduces the effect of this deviation.

It can be concluded that, under very restrictive conditions, fixed by the limits of the Transfer Function Method, the theoretical computations formula are the same except for a complex numerical factor, which anyway exhibits only slight differences between the two methods. It must be noticed again that the restrictive conditions stated above are not necessary for the Intensity Method, which in principle should work also with non-ergodic signals, and that, following the formulation of paragraph 2, it is not required to use the geometrical setup necessary to ensure plane wave superposition, which instead is essential for the Transfer Function Method to work.

4. Experimental comparison with the Transfer Function Method

The Intensity Method was tested in practice using the same tube and equipment of the Transfer Function standard and a real time, constant-percentage bandwidth spectrum analyzer instead of a FFT analyzer. As the Transfer Function Method requires narrow-band analysis, initially a bandwidth of $^1/_{12}$ octave was used for both the methods.

This could seem questionable, as the ASTM standard requirements call explicitly for FFT analysis: but the proper working of the Transfer Function Method with $^1/_{12}$ octave analysis was checked by employing the special calibration sample provided by the tube manufacturer, who specifies its absorption coefficient as a function of frequency.

It resulted that collected data were perfectly equal to those provided for calibration even using $^1/_{12}$ octave bands.

The new method was tested over many samples made of very different materials like foam rubber, open-cell polyurethane foam, building materials such as plasters, vibration insulating pads (Sylomer) and almost everything can be found in a laboratory (mineral wool, glass fiber, Armaflex, and so on). In total, 20 different absorbing materials were used to study the two broad band methods behavior, to make a comparison when they are used in a wide or narrow band analysis and to study their repeatability and reproducibility.

Figures from 5 to 10 show some of the collected experimental results.

In particular it is evident that in some samples the Transfer Function Method shows anomalous peaks for which there is not a reasonable explanation. It was also noticed that the frequency of these peaks depends on the microphone positions, so they are certainly artifacts due to the presence of standing waves inside the tube with nodal planes in correspondence of the microphone positions. The results from the Intensity Technique, on the other hand, are usually smoother, even with those samples having low absorption coefficient.

In the Transfer Function Method it is possible to avoid the phase mismatch error using the microphone switching calibration technique. The problem of the error introduced by the phase mismatch still exists in the Intensity Method, because no correction technique was attempted, and the microphone pair employed is not an Intensity-type, factory-matched pair. This produces a "residual intensity", which is measured also when the probe is inserted in a perfectly reactive field, with no intensity at all, as when the tube is rigidly terminated. Usually this residual intensity increase at low frequencies, and this represents a serious limit when making measurements of the sound absorption coefficient at frequencies below 200 Hz, with the standard microphone spacing of 50mm. In fact, below this frequency, the "residual intensity" produced by the phase mismatch translates in a "dummy absorption", which systematically adds to the real absorption of the sample (usually very low at these frequencies). This fact can easily be seen from the experimental results, as at very low frequency the absorption coefficient measured with the Sound Intensity is always slightly higher than the one measured with the Transfer Function Method.

The phase matching problem, however, can be limited in three different ways: first a phase-matched microphone pair can be used; second, it is possible to increase the microphone spacing for very low frequency measurements; third, well-known techniques already exist for numerically correcting the sound intensity measurement, removing the effect of the phase-mismatch error.

After many tests had been made using both the two methods, a study of their repeatability and reproducibility was also made.

Following the ISO 5725 Standard [17], Repeatability r is defined as the value below which the absolute difference between two single tests results obtained under repeatability conditions may be expected to lie with a probability of 95%.

A test is made under repeatability conditions when it is made by the same person, in the same environmental conditions, using the same procedure, in the same place at almost the same time, without extracting and reintroducing the sample in the tube.

Reproducibility R is the value below which the absolute difference between two single test results obtained under reproducibility conditions may be expected to lie with a probability of 95%.

The Reproducibility conditions refer to different samples of the same material being tested in different instrumental setups. As in this case it was not possible to change the equipment, thus a slightly different coefficient R' was defined, which takes into account only the effect of using a different sample of the same material: this is however the .most significant contribution to R, as another identical equipment, being based on digital instrumentation of high accuracy class, is expected to cause systematic deviations very little compared to those connected with the sample change.

Figure n. 11 and 12 show the two coefficients r and R' referring to the whole set of tests made.

The Repeatability values are lower for the Transfer Function Method, although the values for the Intensity Techniques are only slightly greater, whereas Reproducibility is almost the same for both methods and quite greater.

In particular, reproducibility R' is about one order of magnitude greater than repeatability r, and this means that both these method are mainly affected by reproducibility limitations due to the limited surface of the sample and to cutting problems, and the repeatability error is always negligible compared to the reproducibility one.

Last but not least, a study of the influence of frequency bands width on the analysis results was made.

Figure 13 and 14 show the comparison between the two method results when a $^1/_3$ octave band and 1 octave band were used.

These tests were based on the calibration sample, the same one already shown in figure n. 5 for narrow-band analysis.

As it easy to see, the collected values are still good with the Intensity Method but they tend to be higher than expected with the Transfer Function Method.

In fact this method should not be used with wide band analysis, because the Chung & Blaser formulation requires explicitly that the band-center frequency value appears in the formulas. Thus the error increases as the bandwidth is enlarged: the Transfer Function Method can still be used with good results for $^1/_{12}$ octave bands (as shown by fig. 5), but it can not be used with $^1/_3$ octave or 1 octave bands.

On the other side, the Intensity Method measurements with $^1/_3$ octave or octave bands are easy and quick to perform (the larger the bands, the lower the averaging time required); moreover they are more useful for technical purposes, when it is necessary to characterize a material specifying its absorption coefficient, giving the results according to standard IEC frequencies.

5. Conclusions

From the theoretical and experimental results reported above, it can be concluded that the new Intensity Method for absorption coefficient measurements is simple and reliable, and has some significant advantages over the standard Transfer Function Method, as defined in the ASTM E-1050 test code. The measurement results are more realistic, and no artifact was produced even with samples with very low absorption or very large variation of the absorption coefficient over the frequency range.

The Intensity Method works fine even without using a phase-matched microphone pair, at frequencies above 200 Hz: to extend the measurement range towards lower frequencies a phase-matched microphone pair or a numerical correction of the signals is required.

The new technique main advantage is that it does not require narrow-band (FFT) analysis, but it can be implemented as well with wider frequency bands: this gives more useful results, and reduces the measurement time by reducing the necessary averaging time.

Small, portable instrumentation for Acoustic Intensity measurements in octave or $^1/_3$ octave bands already exists, making it possible to extend the use of the new Intensity Method outside the laboratory for field measurements, employing the complete theory developed in paragraph 2.

This work will prosecute in this direction: a large experimental validation will be undertaken also for field measurements, employing for comparison the AFNOR S-031 standard (impulsive

technique), in the MLS pseudo-impulsive implementation developed by one of the authors and M.Garai [18,19]. This comparison will include also diffusing surfaces, to check the new method capability of measuring the absorption properties of rough materials which can not be measured with the impulsive technique.

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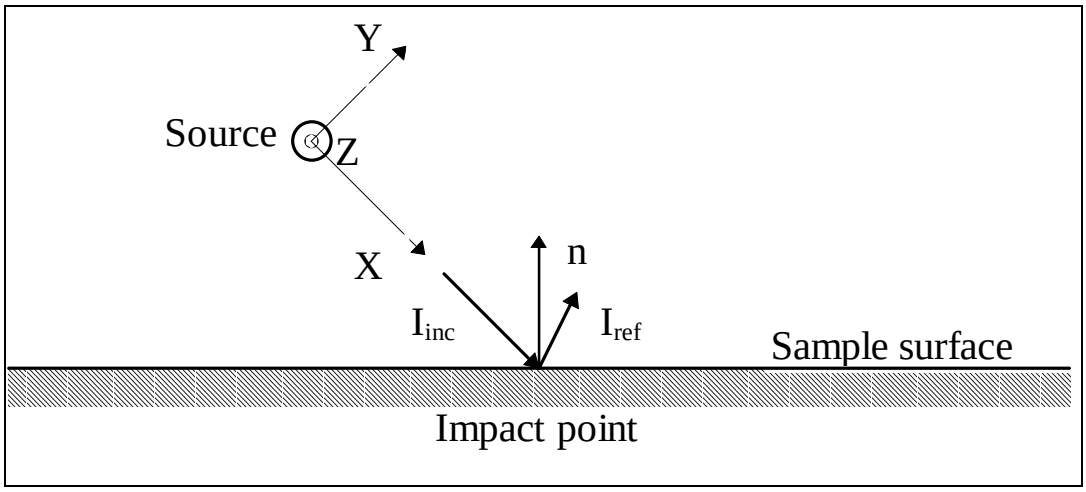

Fig. 1 - Reference system for intensity method measurement

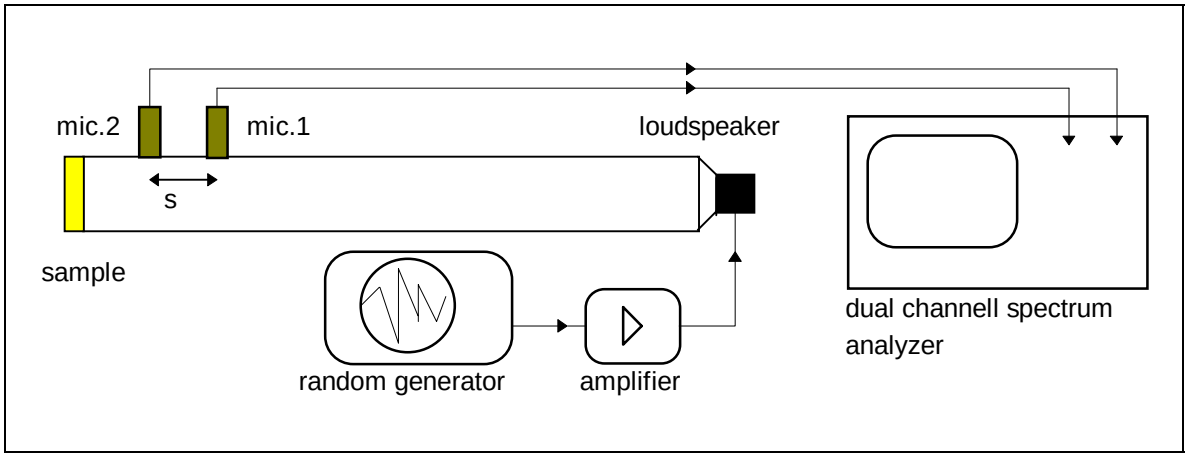

Fig. 2 - Experimental apparatus for in-tube absorption measurements

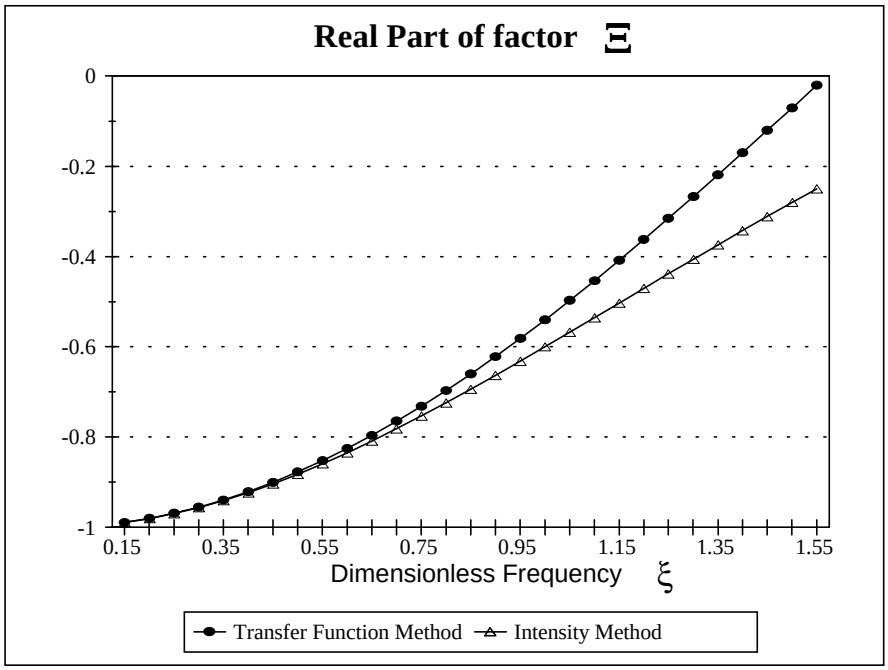

Fig. 3 - Comparison between the real parts of the factor Ξ for the Transfer Function Method and Intensity Method.

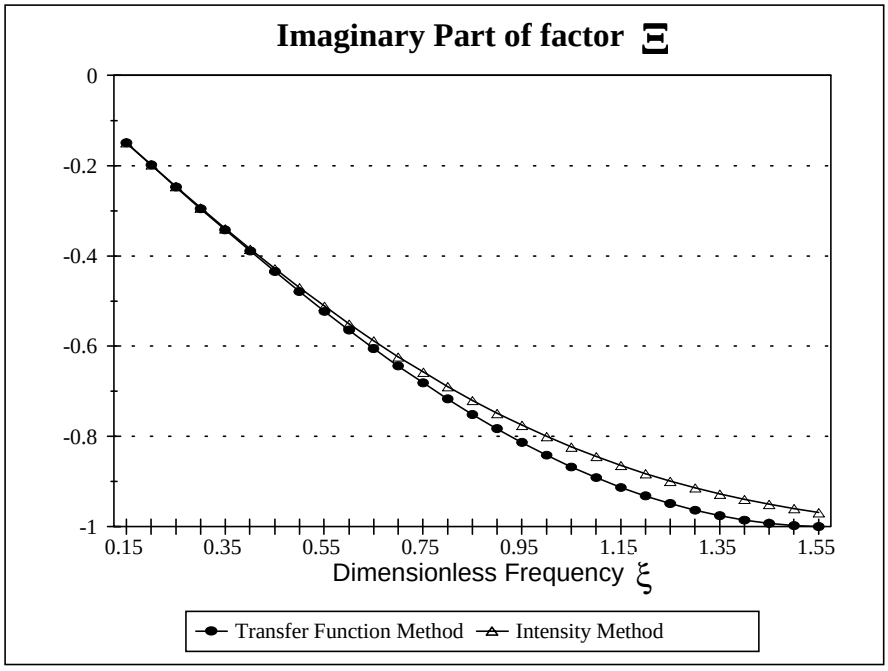

Fig. 4 - Comparison between the imaginary parts of the factor Ξ for the Transfer Function Method and Intensity Method.

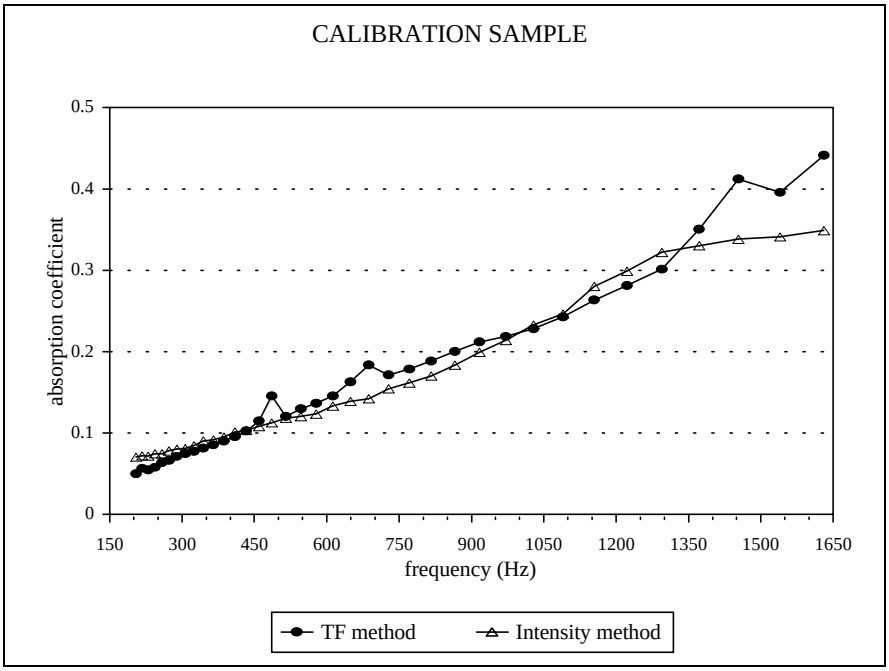

Figure 5 - Calibration sample tested with Transfer Function and Intensity method.

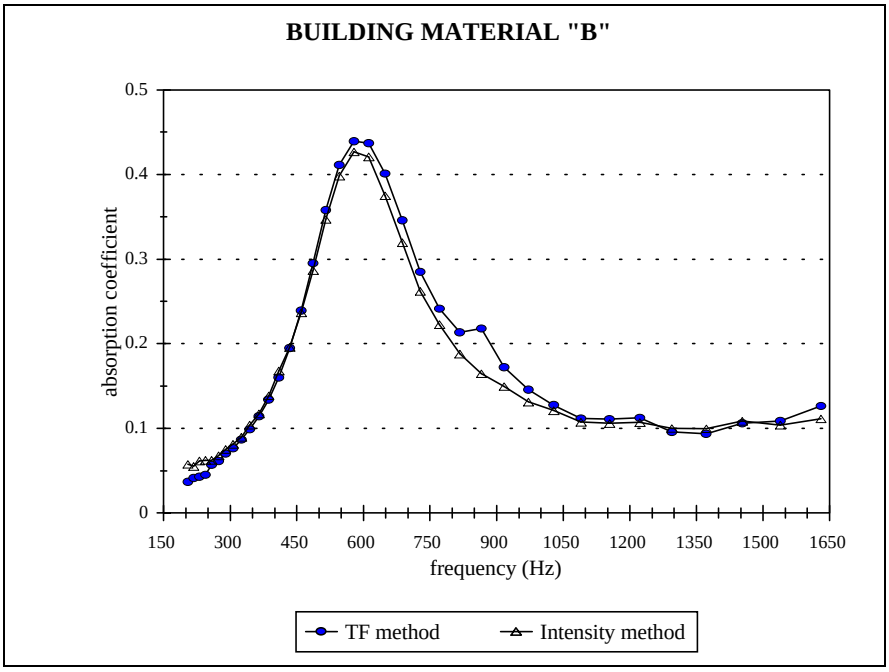

Figure 6 - Building plaster sample, type “B” tested with Transfer Function and Intensity method.

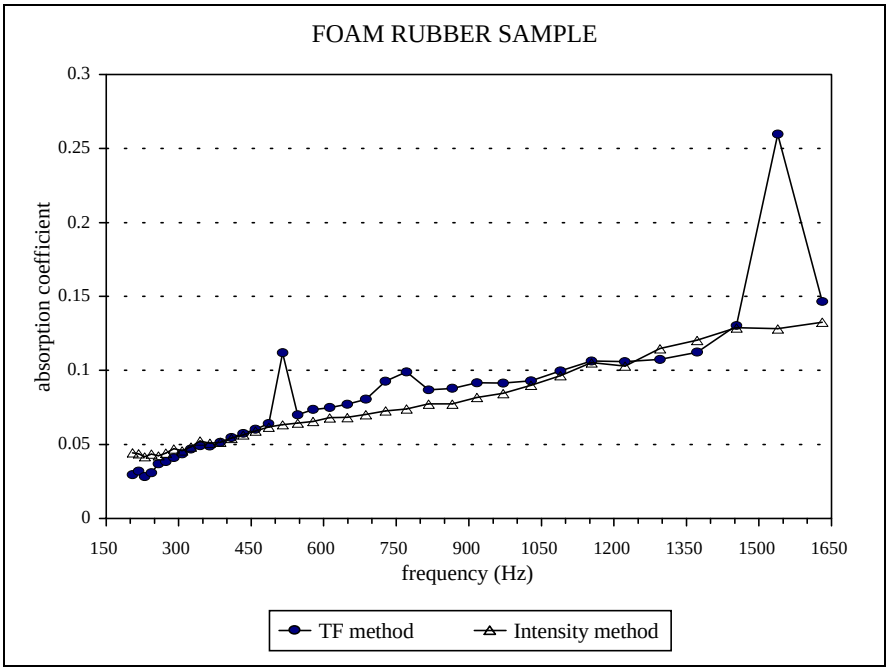

Figure 7 - Foam rubber sample tested with Transfer Function and Intensity method.

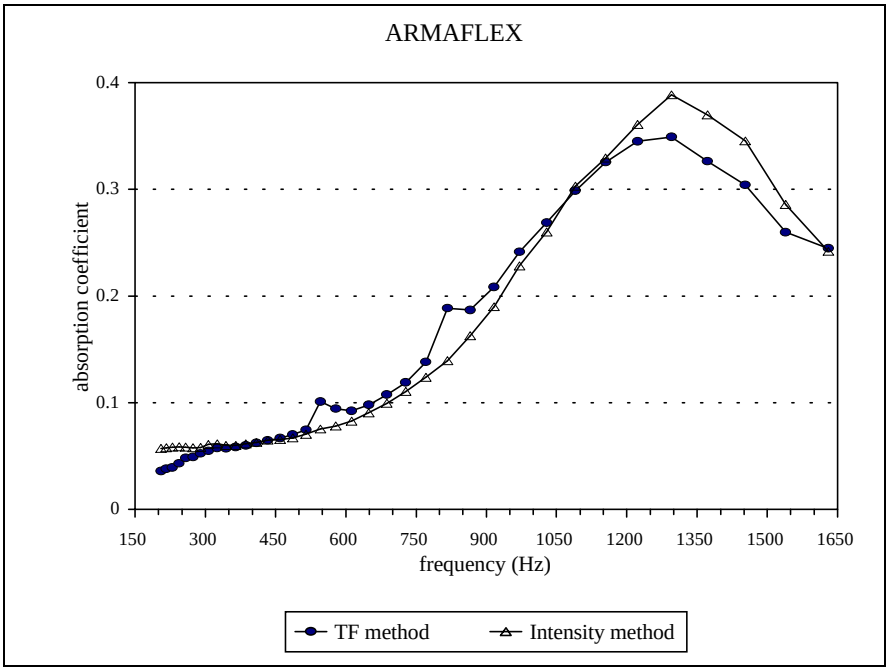

Figure 8 - Armaflex sample tested with Transfer Function and Intensity method.

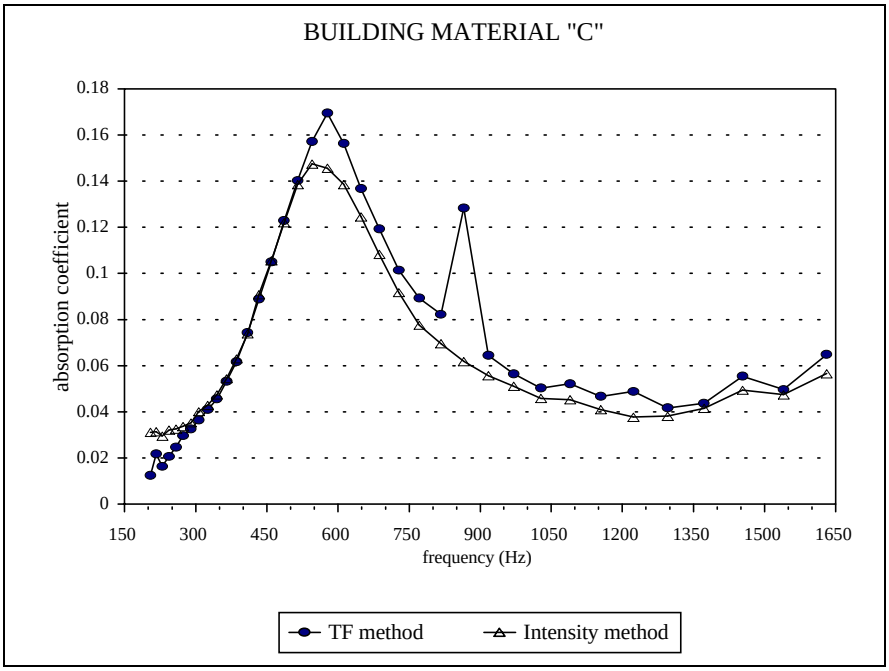

Figure 9 - Building plaster sample, kind “C”, tested with Transfer Function and Intensity method.

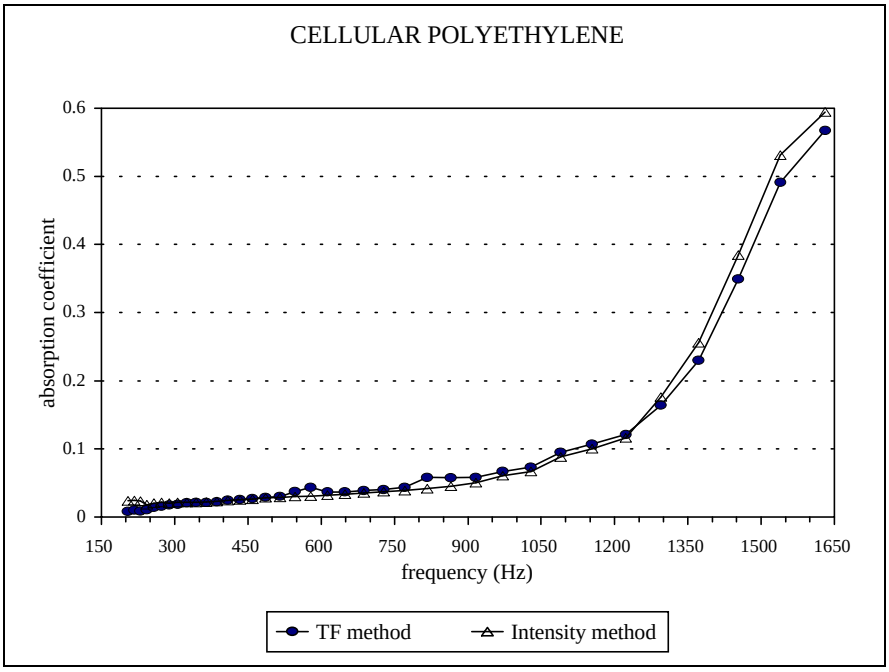

Figure 10 - Polyethylene sample tested with Transfer Function and Intensity method.

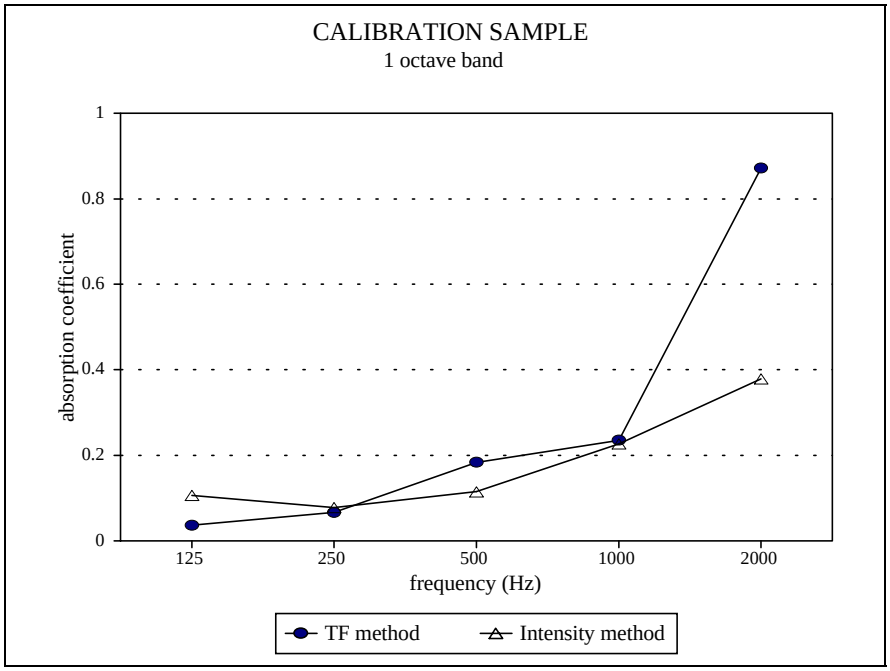

Figure 11 - Calibration sample tested with 1 octave analysis band.

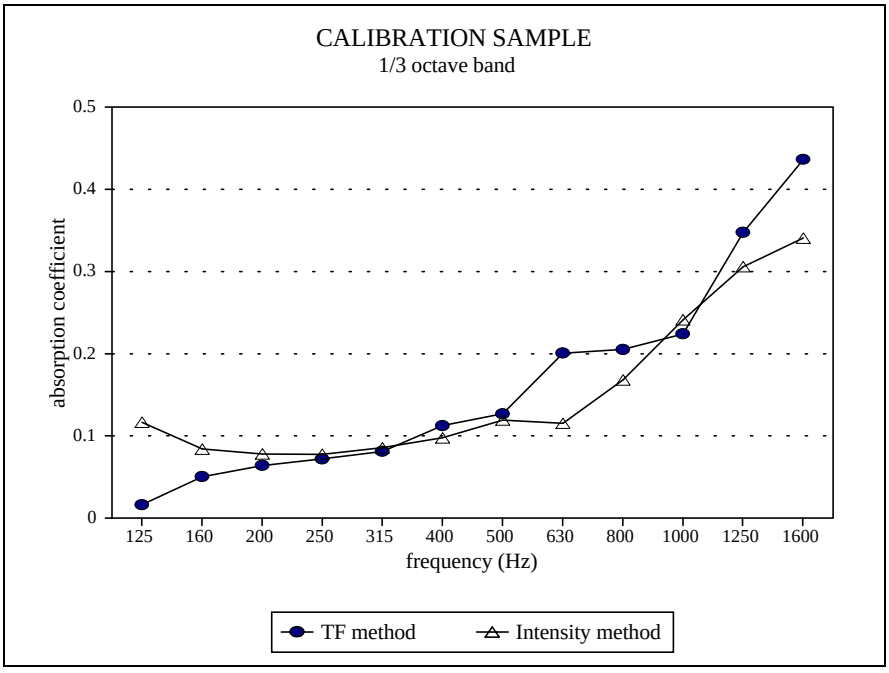

Figure 12 - Calibration sample tested with $^{1}/_{3}$ octave analysis band.

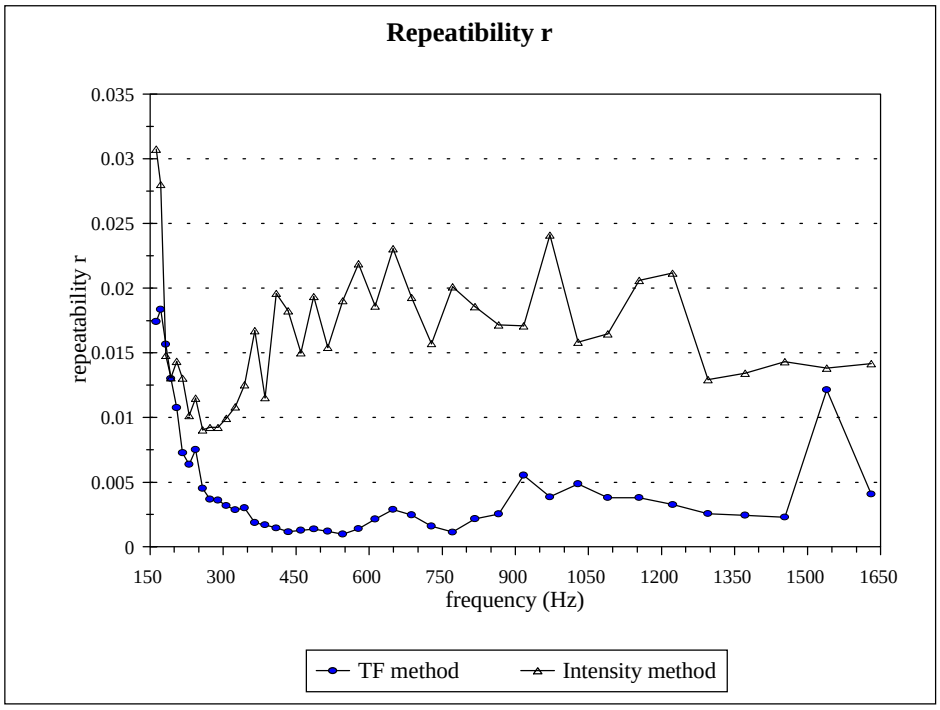

Figure 13 - Repeatability r

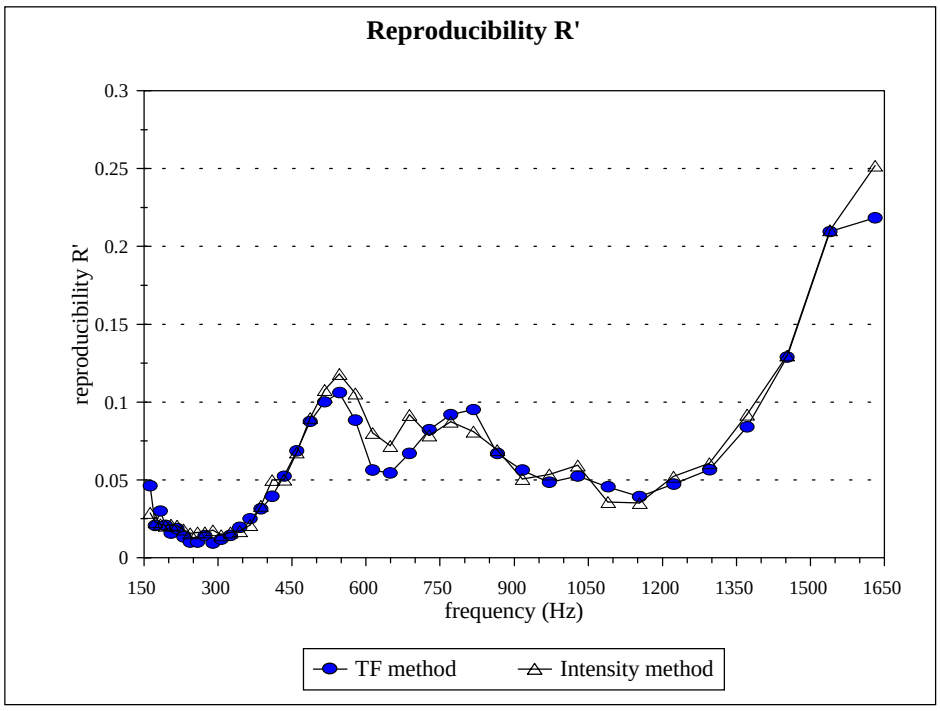

Figure 14 - Reproducibility R