A NEW METHOD TO ANALYSE IMPACT-ECHO SIGNALS

NEUE METHODE ZUR ANALYSE VON IMPACT-ECHO SIGNALEN

UNE NOUVELLE METHODE D'ANALYSE DES SIGNAUX IMPACT-ECHO

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SUMMARY

The impact-echo method is a young diagnose for controlling the quality of a construction. In this method, a stress pulse is introduced into an object by mechanical impact on its surface, and this pulse undergoes multiple reflections (echoes) between opposite faces of the object. To determine the frequency of the detected signal usually the Fourier transform is used. In this article we apply the new analysis tool, the wavelet transform, to the echo signal. In an example these two types of signal analyses tools are compared on the basis of measurements on a stairs like specimen.

ZUSAMMENFASSUNG

Die Impakt-Echo Methode gilt als noch recht junges Instrument in der Bauwerksdiagnostik. Aussagen über den Signalinhalt der dabei erzeugten Ultraschallsignale werden bisher nur über die Fourier-Transformation gewonnen. Eine neue bzw. zusätzliche Auswertungsmethode beschreibt die Wavelet-Transformation. Anhand zweier Messungen an einem stufenförmigen Probekörper wurden einmal exemplarisch die beiden Auswertungsarten gegenübergestellt, um die Aussagefähigkeit solcher Signale zu erhöhen.

RESUME

Dans le diagnostic du bâtiment, la méthode impact-echo est considérée comme un instrument encore assez jeune. L'évaluation des signaux ultrasoniques ne se fait jusqu'à présent que par transformation Fourier. La transformation ondelette constitue une nouvelle méthode d'évaluation. Afin d'améliorer l'évaluation de tels signaux, les deux méthodes ont été comparées de façon exemplaire sur la base de mesures effectuées sur un échantillon en forme d'escalier.

1. INTRODUCTION

A relatively new method in the building industry for non-destructive testing on concrete is the impact-echo-method [Carino et al., 1986]. It permits thickness measuring and locating of voids of one side accessible constructions. This method is already used in tunnelling as a quality control. Mechanical vibrations ranging between ultrasonic and audible are initiated by means of a steel sphere. The change of the structure and material causes a reflection of the sound wave (changing the impedance). At the surface the provoked several reflections will be recorded and the signals are evaluated subsequently. For evaluation of those signals, e.g. in the to calculation of the thickness of a plate, the Fourier transform is usually used. In the following a new method for the analyse of impact-echo signals is presented. The aim of this method is a more substantial description of ultrasonic signals.

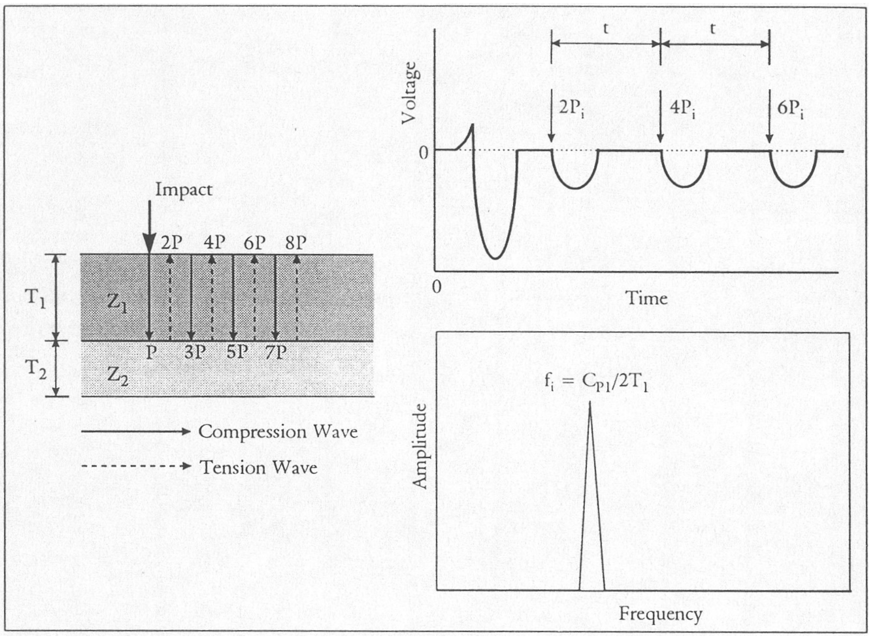

Fig. 1: impact-echo principle

2. WAVELET TRANSFORM

The wavelet transform (WT) is a relatively new topic in signal processing [Goupillaud et al., 1984]. The evolution of the theory continues and the application is expanding to various fields. In our application we use the WT for the time-frequency analysis of impact-echo signals. A brief introduction of WT is given now.

The usual analysis tool for impact-echo signals is the Fourier transform (FT). The FT and its inverse are defined as follows:

$$F(\omega) = \int f(t)\exp(-i\omega t)\,dt \tag{1}$$

$$f(t) = \frac{1}{2\pi}\int f(t)\exp(-i\omega t)\,dt \tag{2}$$

where *F(ω)* is the Fourier transform and *f(t)* is the signal. In these equations we multiplying the original signal with a complex expression which has sines and cosines of frequency *f* and integrate this product. If the result of this integration is a large value, then the signal *f(t)* has a dominant spectral component at frequency *f*.

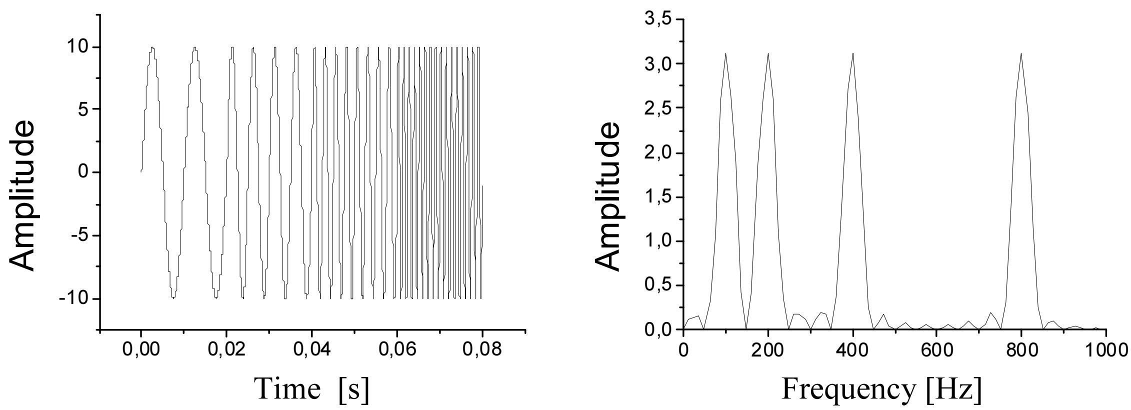

Fig.2: The signal 1 and the Fourier transform.

The integration is from minus infinity to plus infinity over time, so the determination is impossible where in time the component with frequency *f* appears. Therefore the FT is ideal for the analysis of stationary signals, whose statistical properties do not change with time.

To analyse non-stationary or transient signals, another method that transforms a signal into a joint time-frequency domain is necessary. Gabor originated the windowed Fourier transform (WFT) as an extension to the classical FT [Gabor, 1946]. Now *f(t)* is windowed by a window function *g(τ-t)* which is shifted in time by changing *τ* over the whole signal. The WFT of *f(t)* is defined as

$$F(t,\omega) = \int_{-\infty}^{\infty} f(\tau)\, g(\tau - t)\exp(-i\omega t)\,d\tau \tag{3}$$

With the window function one cut out a part of the signal at a particular time range and multiplying this range with the complex expression. The integration of this product describes the dominance of the frequency *f* at the time *t*. The problem with the WFT has to do with the steady width of the window function. A short window width results in a good resolution in time, a wide width in a good resolution in frequency. This is a consequence of the uncertainty principle. If dt is the transform resolution in the time domain and dω is the transform resolution in the frequency domain, the uncertainty principle can be written as

$\Delta t\,\Delta\omega = \frac{1}{2}$. The WFT results in an intensity-graph where the x-axis represents the time, the y-axis the frequency and the amplitude will be pictured by several colours.

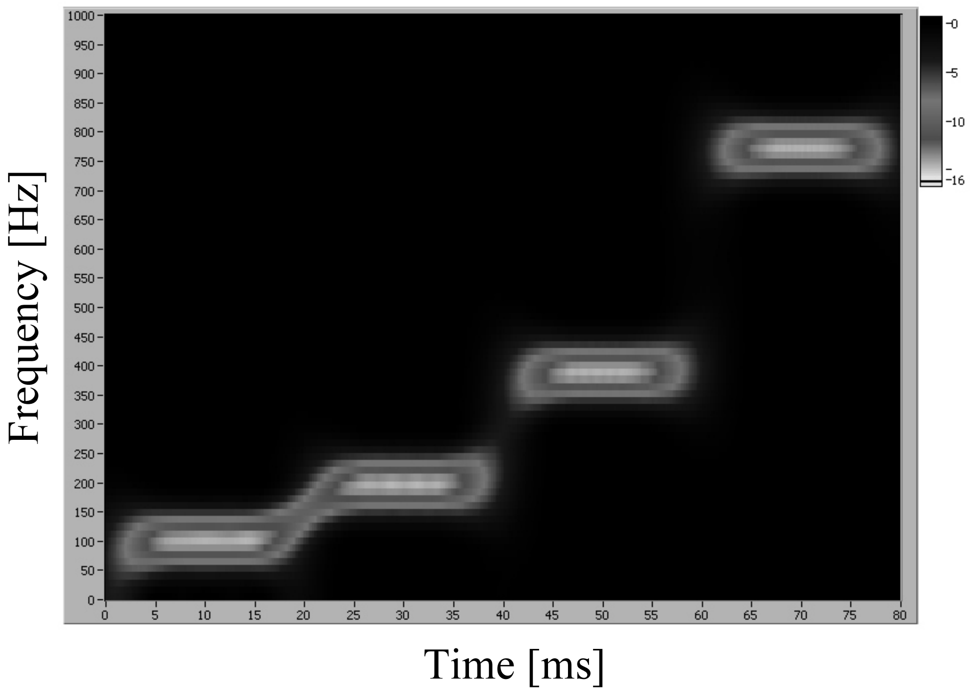

Fig. 3: The WFT from the signal in picture 1. One can see the different frequencies at different times. Light colours mean high amplitudes.

A further extension of the WFT is the wavelet transform (WT) defined by

$$f(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\,\Psi\left(\frac{t-b}{a}\right) dt \qquad (4)$$

with the shift parameter b, determines the position of the window in time and thus defines which part of the signal *f(t)* is being analysed and the scale variable a [Kaiser, 1994, Polkar, 1999]. In this investigation the relation between the scale variable a controlling dilatation and the frequency is $\omega=\omega_0/a$, where ω_0 is a positive constant. The wavelet function $\psi(t)$ differs from the sinusoidal function.

$\psi(t)$ may be considered as a window function both in time and frequency domain. The size of the time window is controlled by the translation, while the length of the frequency band is controlled by the dilation. This property of the WT is called multiresolution. A short window width correlates with a small scale parameter results in a good resolution in time, a wide width in a good resolution in frequency.

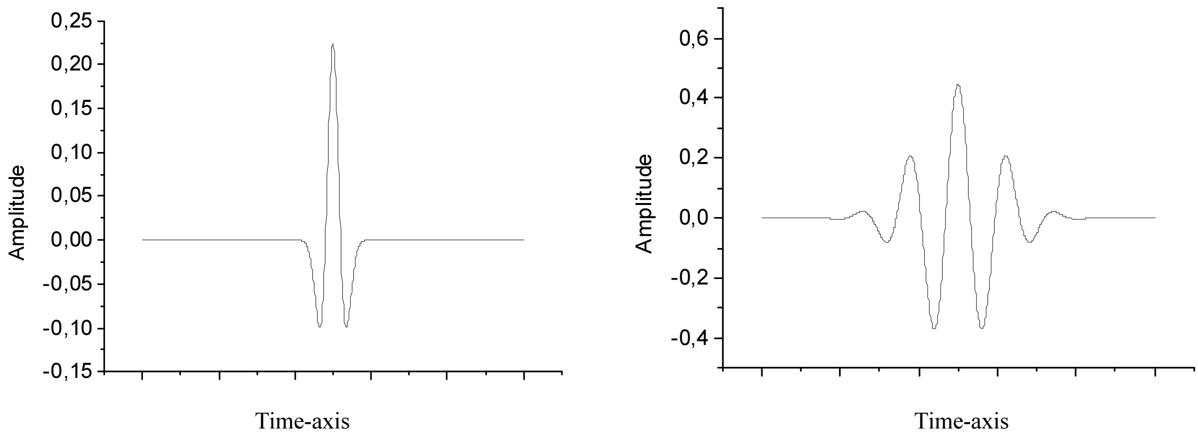

Fig. 4: Two examples of wavelet functions. The Mexican Hat wavelet is placed on the left side, the Morlet wavelet on the right side.

In practice one hold down the scale factor a and vary the shift parameter b. The result shows the dominance of this frequency at every time. By changing the scale factor and repeated scanning by altering b one get a 3-D plot of the signal. The usually presentment is an intensity graph, where the x-axis represents the time, the y-axis the scale and the intensities of the transform at points in the a-b plane representing by a colour plate.

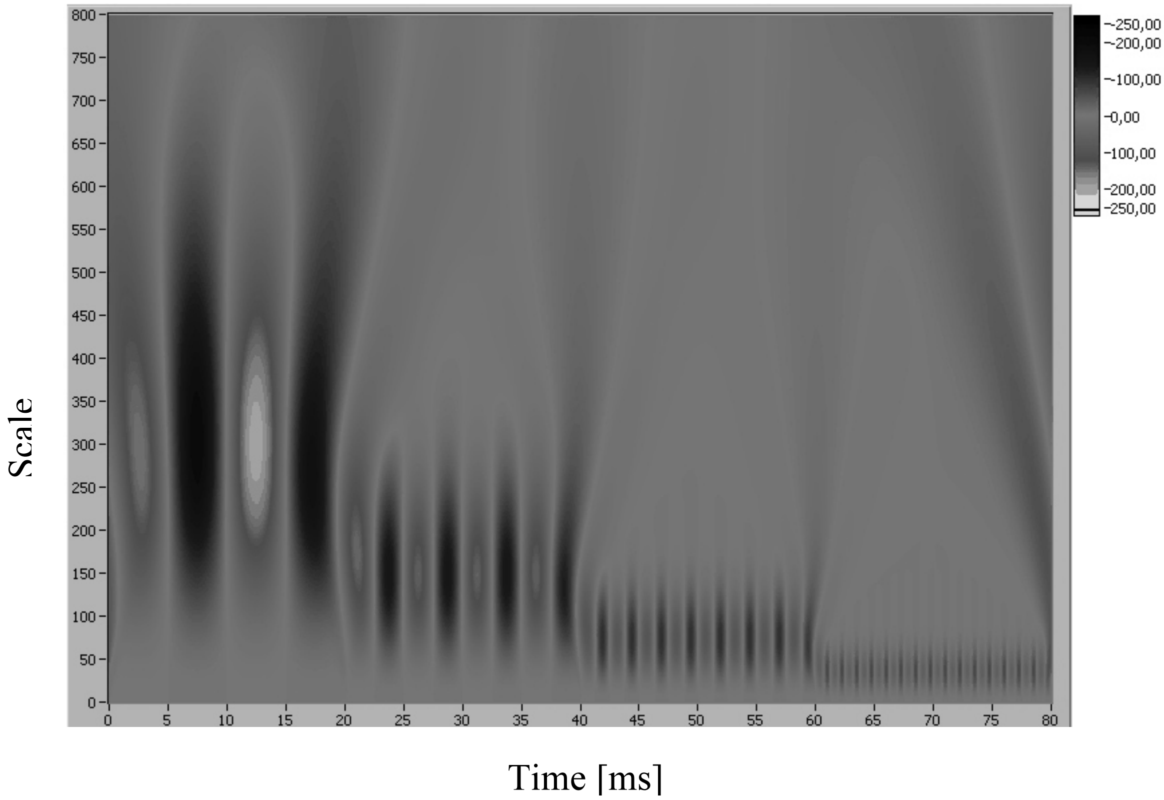

Fig. 5: The wavelet transform of signal 1. The relation between the scale variable a and the frequency is $\omega=\omega_0/a$, where ω_0 is a positive constant, so the lower frequencies are at the head of the picture. Light colours are high positive values, dark colours are high negative values.

3. TESTING PROGRAMM

Within the scope of the research project FOR 384 supported by the DFG, a specimen with voids was made at the university of Stuttgart (*Fig.6*). The composition of the concrete consists of CEM I 32,5 and aggregate of A/B 16. The water-cement ratio amounts 0,47, and the cement content is 404 kg/m³. Within the specimen four voids made of polystyrene particle foam are implemented at different depth.

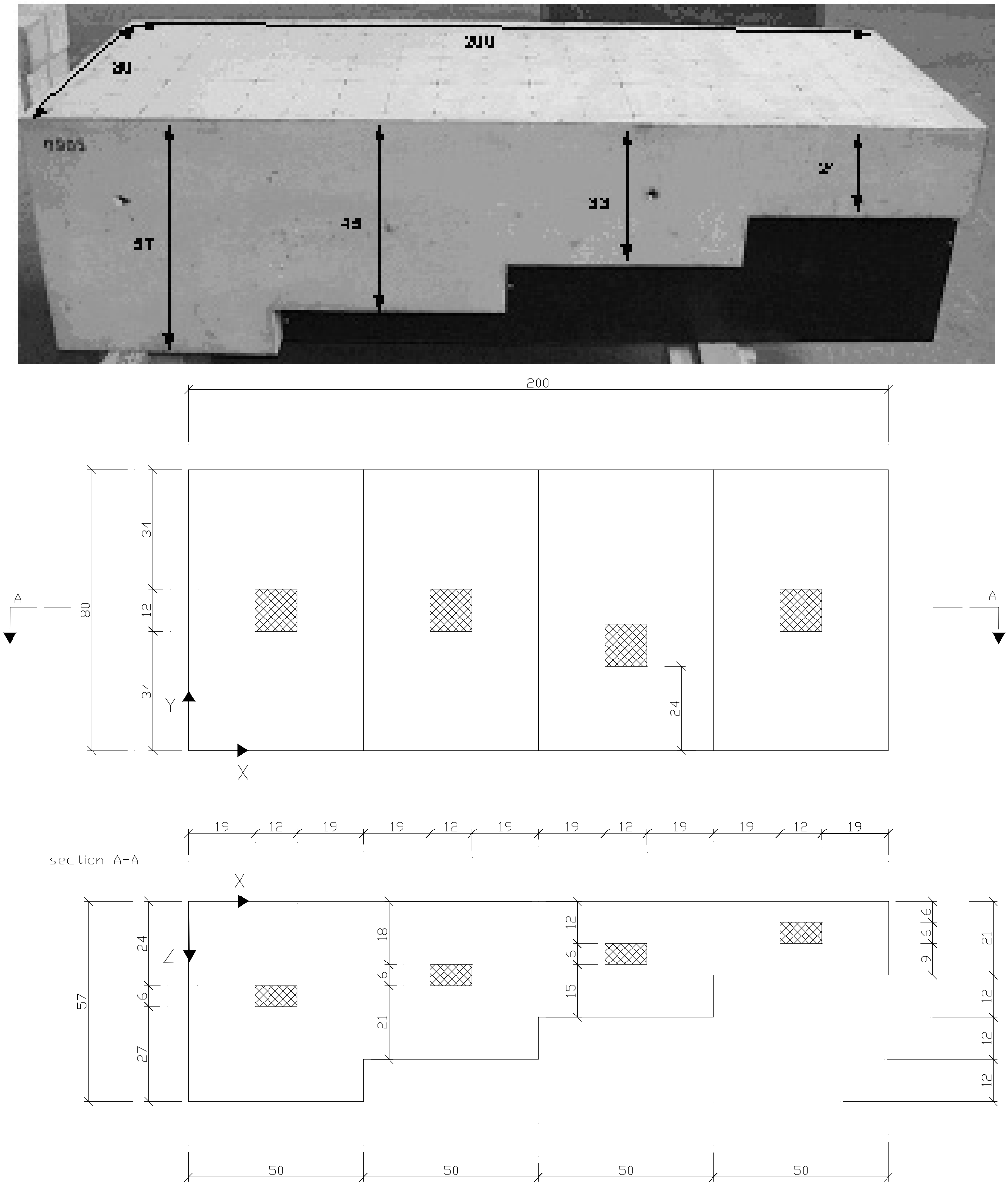

Fig. 6: Sketch of the specimen

A small steel sphere with a diameter of about 16 mm generated the impact. For recording the signals, an acceleration sensor from Kistler (type 8694) was used with a frequency range between 10 Hz and 20 kHz. For this article, two signals were picked out to compare the Fourier transform and the wavelet transform representative:

Point A (x/y/z) = (25/40/0) and Point B (x/y/z) = (75/40/0)

4. TEST RESULTS

The following pictures show the signal form the ultrasonic receiver recorded mounted at two different test points A and B variable thickness. The signals are unfiltrated, unamplified and uncorrected by a sensor compensation curve. Signal a) respective b) is the echo evoked by a 16mm diameter steel sphere at a place where the specimen is 24cm respective 18cm thick. At first glance the signals look like similar. A transformation into the frequency space should be more informative.

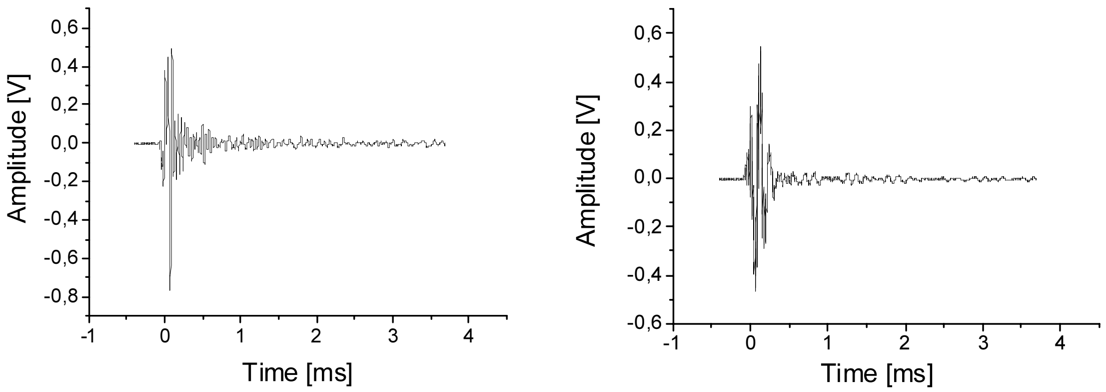

Fig.7: Impact-echo signal obtained from a 24 cm (left) and 18 cm (right) thick specimen.

Fourier transform of these waveforms results in the amplitude spectrum shown in Fig.7. The peaks are attributed to modes of vibration of the specimen excited by the impact. The dominant peak is the frequency of the successive arrivals of the multiply reflected P-wave. The assignment is difficult when the signal disturbed by scattering or interferences like the signal b) transformation pictured on the right side below.

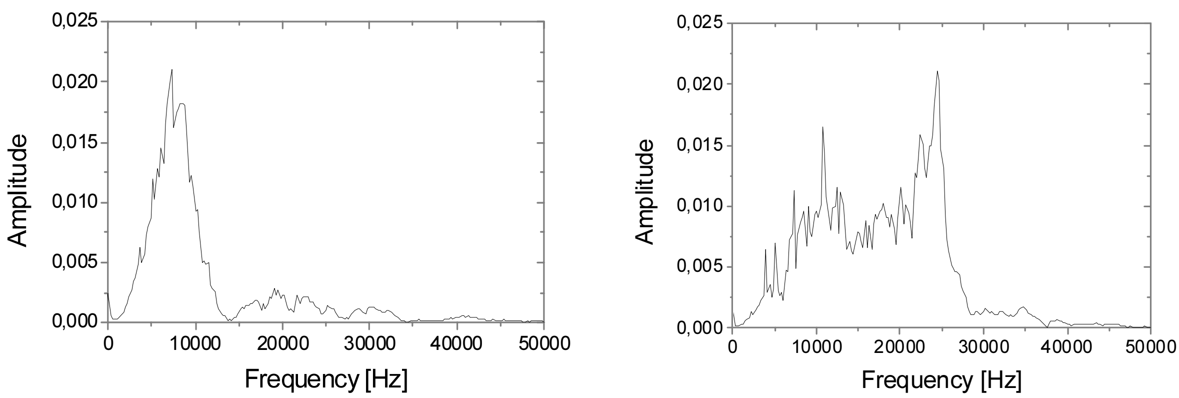

Fig.8: Amplitude spectrum results from the Impact-echo signals above

Now we are interested in the time frequency distribution of the Impact-echo signals and set the wavelet transform on the signals. The results presented in the pictures below. In these intensity graphs high positive values are black coloured, high negative values are grey coloured. The x axis represent the time whereat the data points distance is 1 µs. The relation between the scale variable a arranged in the y-axis and the frequency is $\omega=\omega_0/a$, where ω_0 is a positive constant, so the lower frequencies are at the head. There are three dominant frequencies in signal a) at the scale factors 5, 36 and 102 correlated with 159 kHz, 22,1 kHz and 7,8 kHz. Figure 9 shows the wavelet transform for the Impact-echo signal b). There are resonances at the scale factors 33 and 67 respectively 23,8 kHz and 11,8 kHz. The onset times of the frequencies are equal, so no dispersion occurred in concrete in this frequency range also higher frequencies are more damped than lower ones.

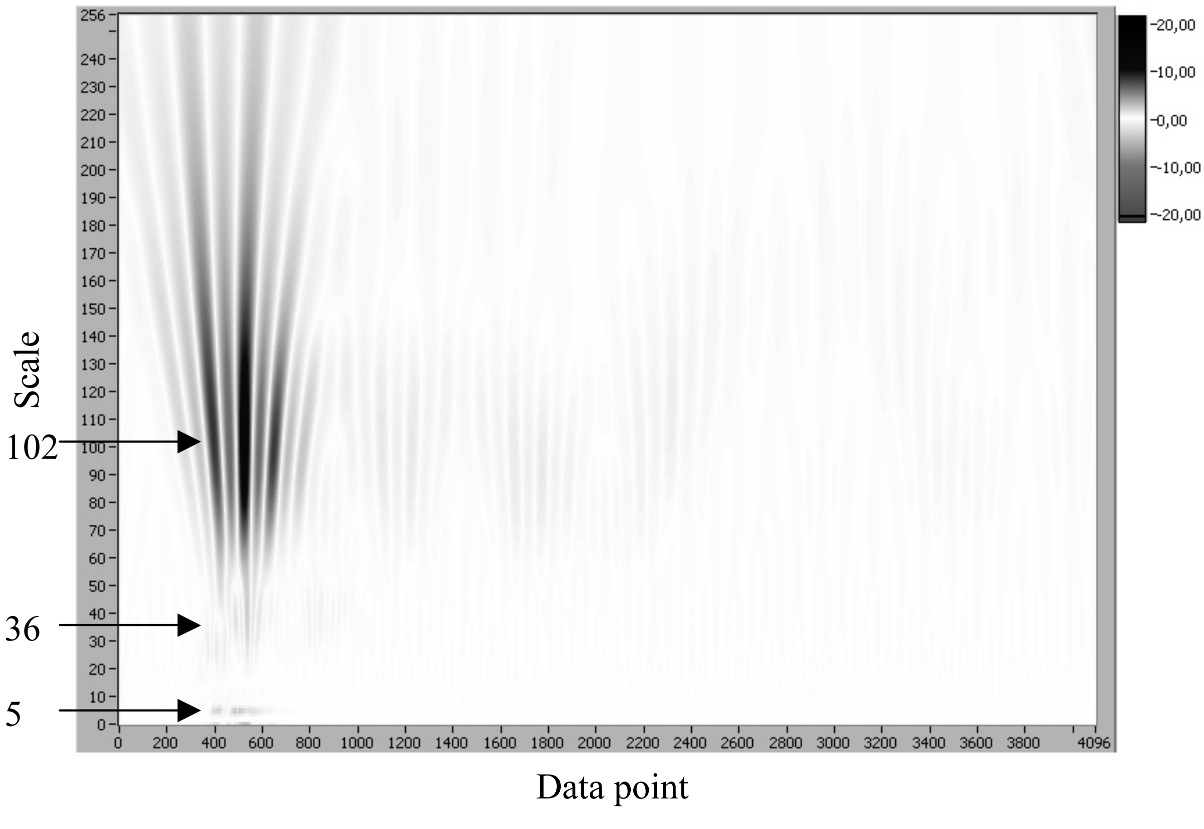

Fig.9: Wavelet transform of signal a). High positive values are black coloured, high negative values are grey coloured. The scale factors 5, 36 and 102 correlate with 159 kHz, 22,1 kHz and 7,8 kHz.

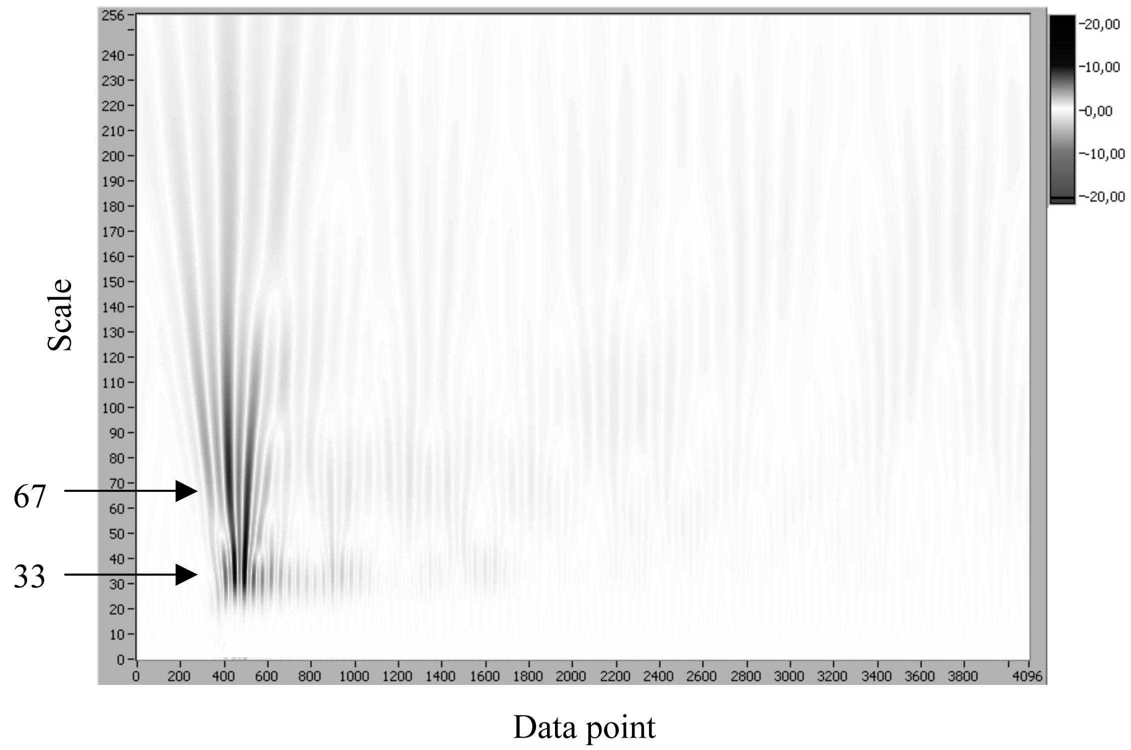

Fig.10: Wavelet transform of signal b). High positive values are black coloured, high negative values are grey coloured. The scale factors 33 and 67 correlated with 23,8 kHz and 11,8 kHz.

Because no dispersion occurred one can cut the signal, in our example at point 600 and set the rest of the points equal zero. Therewith we obtain a signal with the whole frequency information and without distortion by reflections, scattering and interferences in the signal coda. Now we apply the Fourier transform to our signals and get following amplitude spectrums.

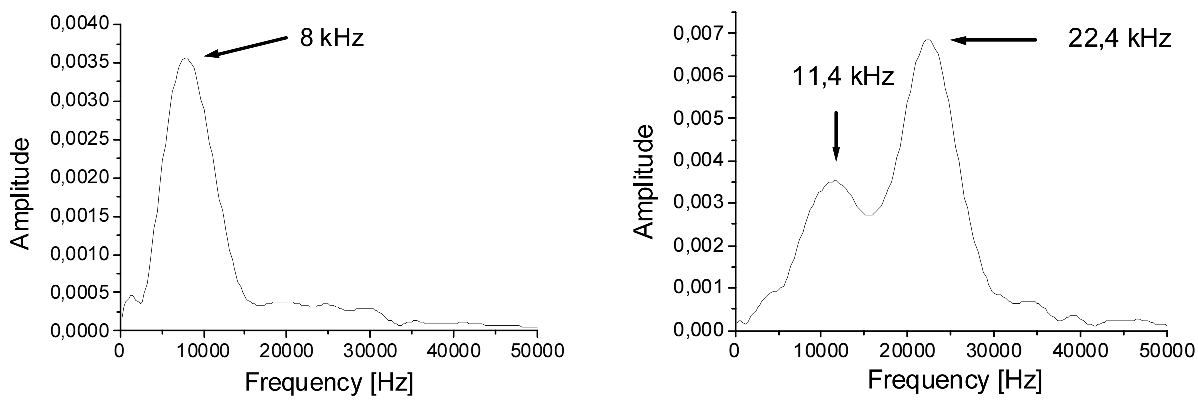

Fig.11: Fourier transform of the Impact-echo signals

The frequency peak in the frequency spectrum of signal a) lies at 8 kHz. The P-wave velocity in the concrete specimen is 4260 m/s, so one gets a thickness of 27 cm. This correspond good with the 24 cm of the specimen at this point. The frequency spectrum of the signal b) shows two peaks at 11,4 kHz and 22,4 kHz respectively 19 cm and 9,5 cm. The real gauge of the specimen at this point is 18 cm what tally good with the first frequency peak. Probably the higher frequency caused by a resonance of the sensor because in the range of 22 kHz both wavelet transforms shows an area of high amplitudes.

5. CONCLUSION

A new analysis method, the wavelet transform, was applied to Impact-echo signals to get more detailed information. In the time frequency range we see that concrete is free from dispersion in this frequency range. The information of the echo lies in the first amplitudes of the signal after the first onset. The Fourier transform of this signal range results in a more non distortion frequency spectrum which makes an assignment of the dominant peak to the resonance of the specimen and because of that the determination of the specimen thickness easier. In further investigations we will also apply the Gabor transform to the impact echo signals.

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