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EXPERIMENTAL IMPACT-ECHO INVESTIGATIONS OF CONCRETE STRUCTURES

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Summary : *A set of initial investigations were carried out in the Impact Echo frequency and time domain on Nuclear Research Institute Řež (NRI) experimental concrete structures. The measurements were implemented by system TRS developed in NRI with commercial accelerometers and acoustic emission sensors the last ones being developed under NRI and West Bohemian University partnership. First result evaluation and further action recommendations are given.*

1. Introduction

A substantial part of the operated nuclear power plants in the world is nowadays in the state when their large-scale internal concrete structures are demanded to identify intrinsic cracks, flaws, voids and to realize reinforcing bars qualified mapping.

Today already classical standard ASTM 1383 (1998) for measuring primary stress wave speed and concrete plates thickness is based on Impact-Echo (IE) frequency domain utilisation. Less usual but complementing of this standard there is a way how to acquire more details in investigated concrete structures when working in time domain.

Besides others Pečínka and Morávka (2003-2005) studied impact generated stress wave behaviour in inhomogeneous concrete structures by means of analytical and numerical models. In their approach, the broadband transducer time response was generated for cases coming from reality in order to yield a corresponding basement for subsequent experimental follow-up.

The paper deals with experimental verification of numerical approach in both time and frequency domain. At present, the commercial unavailability of suitable broadband transducer was the reason for the use of commercial lightweight shock accelerometer in the beginning of experimental program. It was also necessary to design and integrate the flexible and effective system for advanced Impact-Echo applications mostly done in the time domain. Number of initial experimental investigations with developed system on concrete and brick samples was realized in preparation phase (Stulík, Šípek, 2006) and then followed by NRI concrete large-scale specimen measurements (Stulík, Šípek, 2007). The paper describes results of this effort.

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2. Measurement chains and processing system

Measurement chains

The key elements are sensor and impactor conforming to all demands of IE application. We had for initial disposal the piezoelectric broadband transducer BT-1 used former for steel construction investigation (Fig. **1**, Morávka 2000) and due to its construction could measure only on horizontal surfaces. Therefore, it was not possible to use it later on NRI concrete specimens where almost all investigations are concentrated on vertical surfaces. Transducer BT-1 transfer function has not been determined so far.

From this reason, it was necessary to acquire and apply another sensor. The survey was made and final producer and sensor type was chosen. The selected Bruel & Kjaer shock accelerometer 8309 (Fig. **2**) is otherwise intended for measurement of very high-level, continuous vibration and mechanical shock with not so high charge sensitivity but its sturdy construction of only 3g weight, small dimensions and above all the highest resonance and consequently cut-off frequency on the market, was the primary reason to choose it. Full motion of the test object to the piezoelectric element without distortion and "zero shift" problems is enabled by an integral M5 threaded fixing stud. Integral hard line 40 cm-long output cable was used for reliable connection to the charge preamplifier.

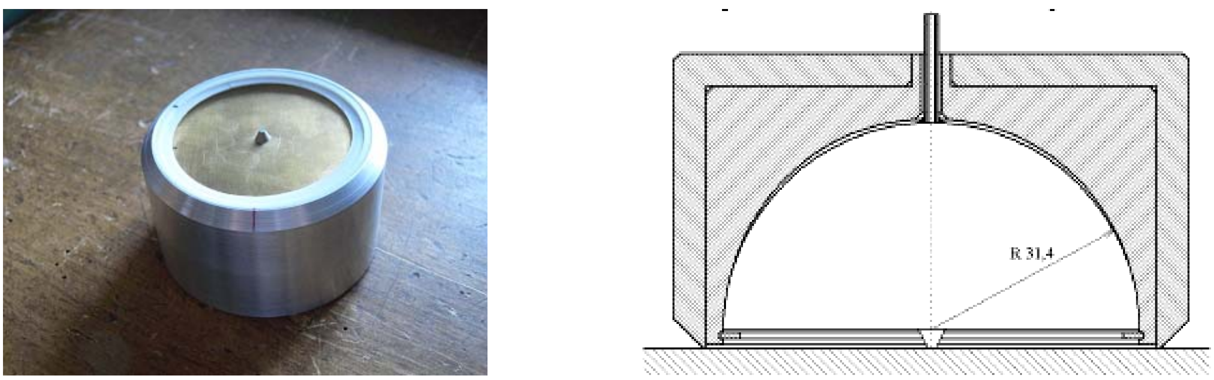

Fig. 1 West Bohemian University broadband transducer BT- 1 for strain waves displacement measurement

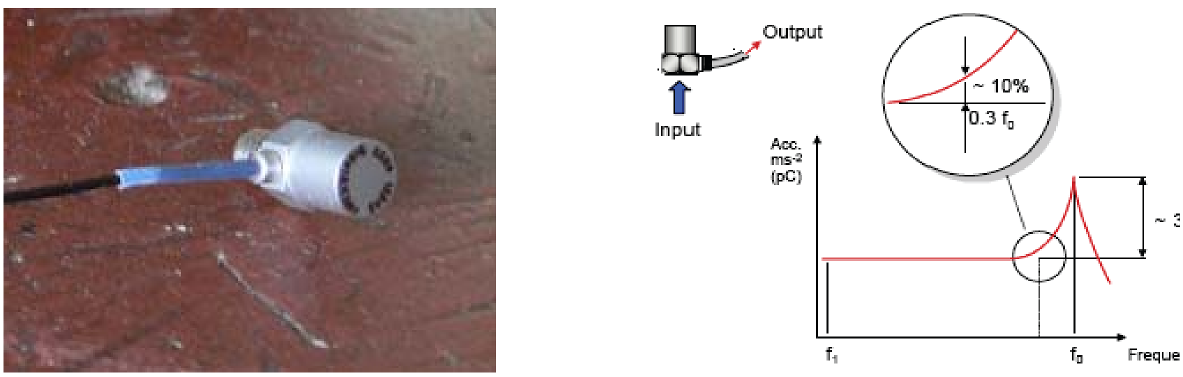

Fig. 2 Bruel & Kjaer Shock Accelerometer Type 8309

Processing system

System conception was based on input demand to acquire data for time and frequency domain processing with the emphasis on time domain evaluation. Basic system configuration, which is evident from Fig. 3 has following main measurement features

- four fast and sensitive simultaneously sampled channels
- sample frequency from 50 - 500 kS/s to 15 MS/s with 24 bit to 16 bit resolution
- ± (500 ppm (0.05%) of Input + 100 µV) for DC, AC coupled range of ± 5V
- Alias-free bandwidth, 8MB Onboard sample memory, Pre and post trigger data points
- fast PCI Express Bus.

With these measurement features, the system is capable to acquire BK 8309 accelerometer signal with the sensitivity better than $1 ms^{-2}$ in frequency band 1 - 54 000 Hz. System structure was designed to enable future integration into transferable version for field measurements.

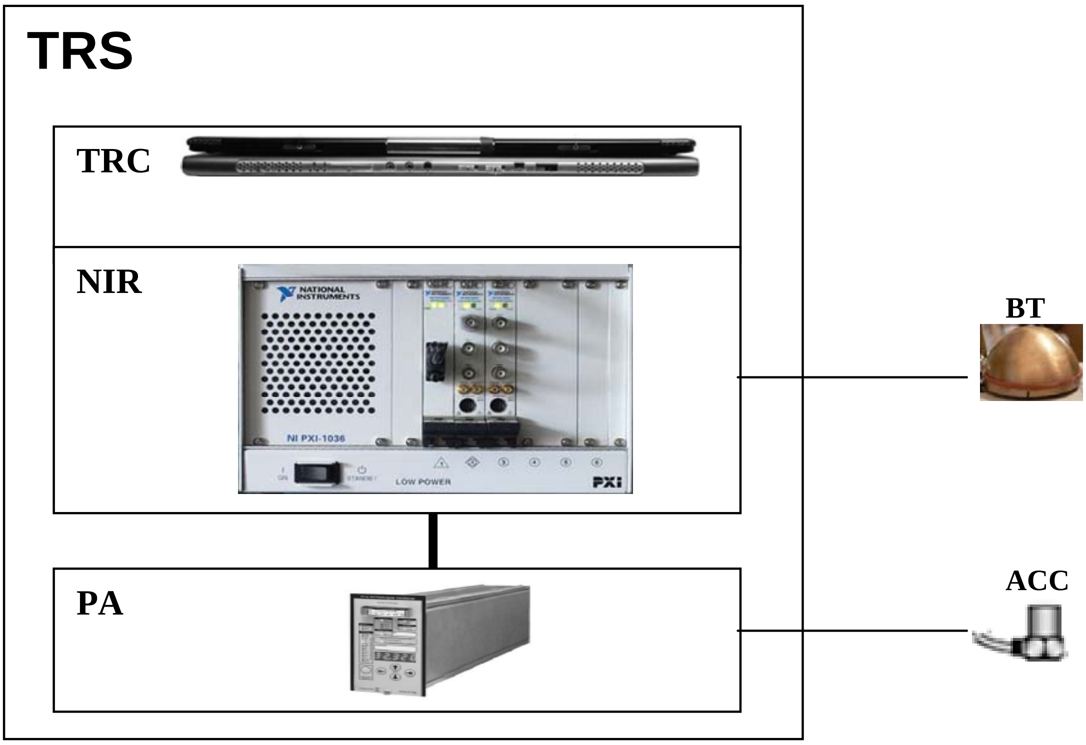

Fig. 3 Basic system TRS configuration

TRS	…	System for Impact-Echo measurement data processing in time and frequency domain
TRC	…	System TRS controller
NIR	…	Four channel measurement subsystem
PA	…	ACC accelerometer signal preamplifier
BT	…	Concrete surface displacement broadband transducer
ACC	…	Accelerometer B&K 8309

Programs Trs_05.vi and Blok01_Deska_xxx-yyy.wbp have been written in National Instruments program platforms LabView and SignalExpress for both measurements with broadband transducer BT-1 or B&K8309 accelerometer. Their user interface windows are shown in Fig. 4 resp. Fig. 5. Programs enable

– input Impact-Echo parameters estimation
– set-up of vertical, horizontal parameters incl. triggering of measurement subsystem NIR
– time domain processing (region choice, statistical description etc.)
– on-line FFT transformation with RMS amplitude or power linear averaging
– result presentation in selectable windows
– storing measurement and processed data in identified files onto system hard disk.

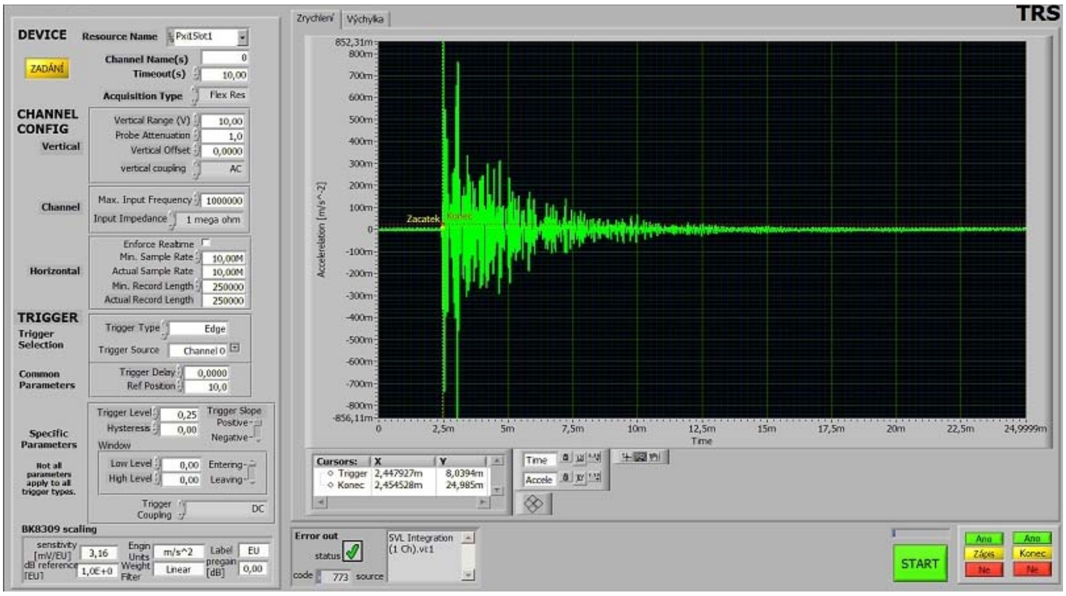

Fig. 4 User program interface in time domain processing in tests with broadband transducer BT-1

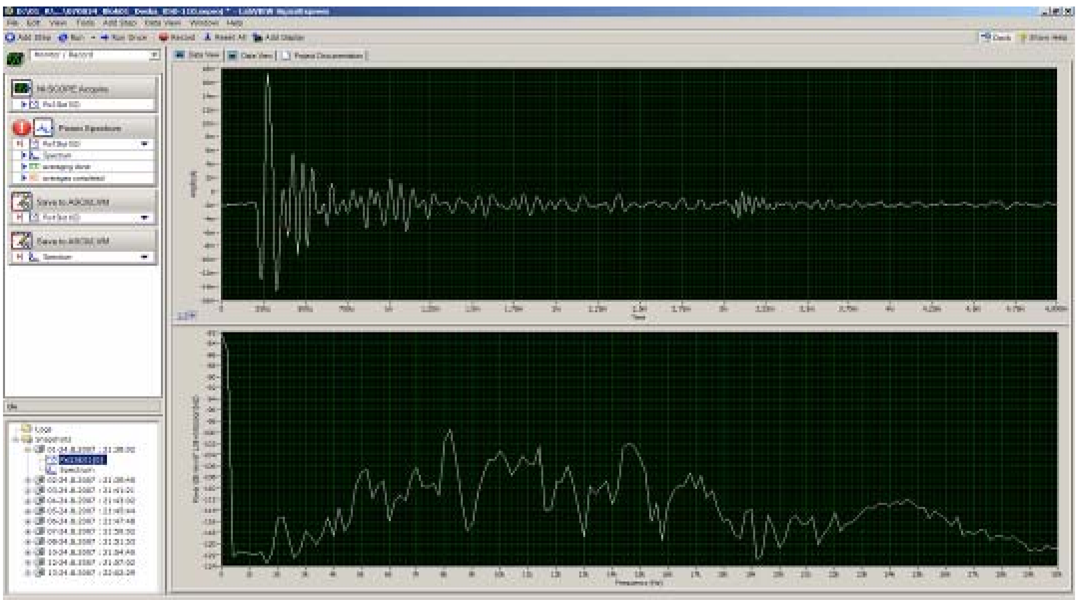

Fig. 5 User program interface in time and frequency domain processing in tests with B&K 8309 accelerometr

3. Time and frequency domain evaluation

Initial time domain investigations with transducer BT-1

Multiple initial tests with both available sensors were done with the aim of

- lesson learning
- to tune-in processes of measurement and processing in both domains
- investigations of sensors fixation and localisation
- tests of stress waves generation
- computed and measured results comparison.

The best results in this phase were obtained with piezoelectric broadband transducer BT-1 on concrete and brick samples with inbuilt test voids, cracks and reinforcing bar. Measurements were done on horizontal sample surfaces with the stress waves generated by so-called pen-test method, which consists in defined thin lead of 0,9 mm diameter breaking.

Crack detection and localisation computed model was presented by Pečínka et al. in Stuttgart 2005. Computed time runs for different mutual distances impact-sensor and deep crack on accessible surface are altogether shown in Fig. 6. The comparison of computed and measured time runs in the same impact-sensor and crack layout is shown in Fig. 7. Computation of time runs was done for concrete wall with dimensions 200 x 200 x 100 cm and measurement was realized on brick with dimensions in approx. 1:15 similarity ratio. Even if the first sight can bring some resemblance, distinct procedures will have to be further elaborated for computation and measurement qualification.

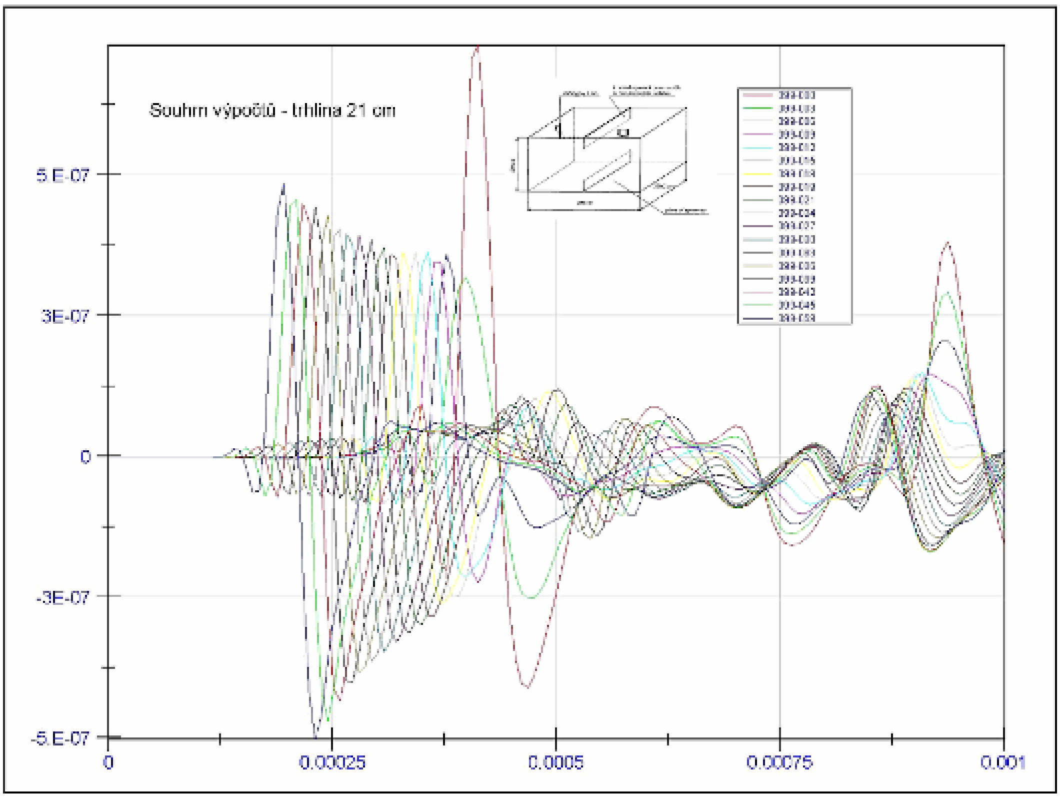

Fig. 6 Computational result base

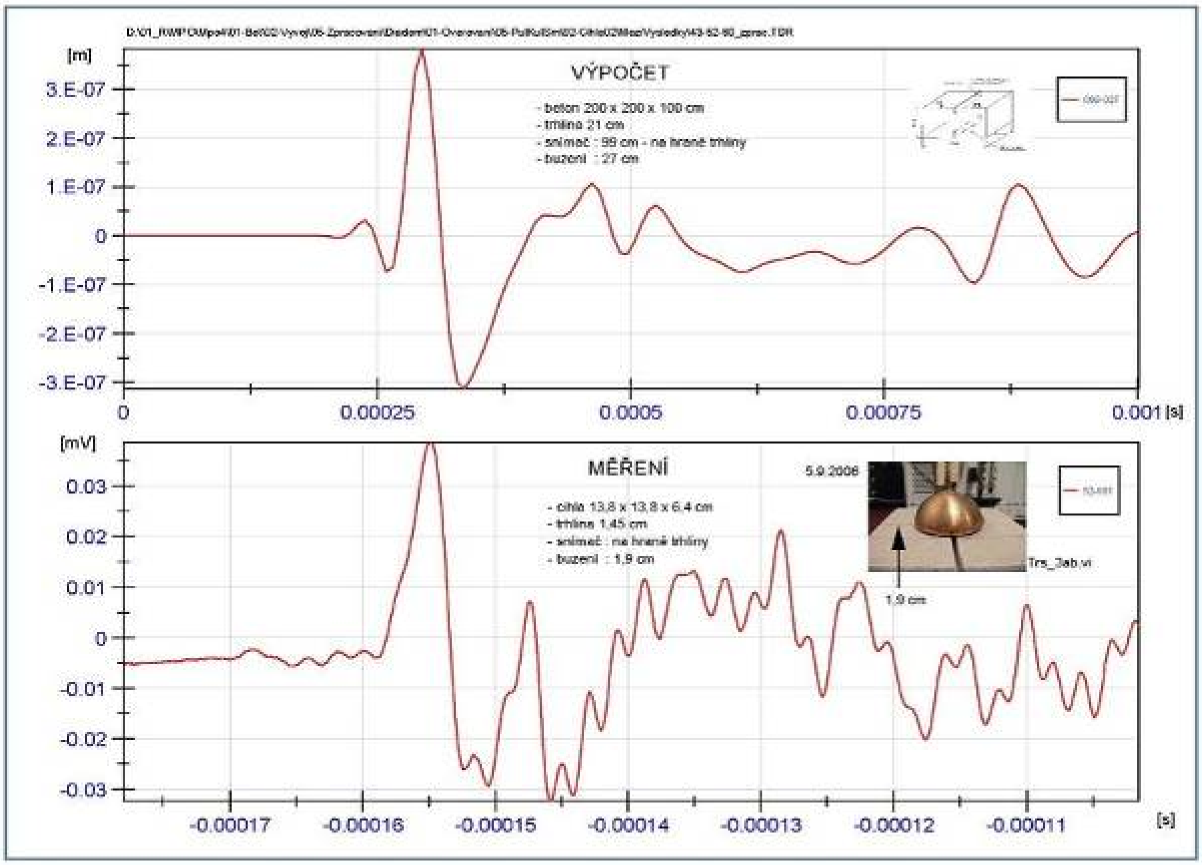

Fig. 7 Computation and measurement comparison

Series of IE measurements with BT-1 transducer were done by pen-test on concrete sample (20x20x20cm) with inbuilt test reinforcing 1cm diameter bar and casted 3 cm under surface. The aim of this investigation ought to confirm a possibility of the time domain rebar detection by means of shear (S) waves reflected from the bar top as presented by Pečínka et al. in Stuttgart 2005.

Consecutive B Scan like measurements were done in perpendicular direction over casted rebar. One set of resulted time runs can be seen in Fig. 8. This representation however does not bring clear view on how S waves can yield the rebar detection information. It becomes more obvious when arranging these time curves into 3D projection as it is shown in Fig. 9. Rebar position with corresponding dimensions is here distinctly shown in 100 µs interval i.e. in the time when S-waves are not so influenced by other waves propagation behaviour.

Even if computed 3D Impact-Echogram of concrete sample with longitudinal volume void (Morávka 2006) in Fig. 10 is not presented in the same view as the previous 3D Impact-Echogram from Fig. 9, one may see that in the interval up to roughly 400 µs the both approaches can complement each other to acquire more information about rebar position and form. In order to qualify fully the rebar diagnostics, the following investigations will have to include among others the refinement of mutual linkage of both approaches.

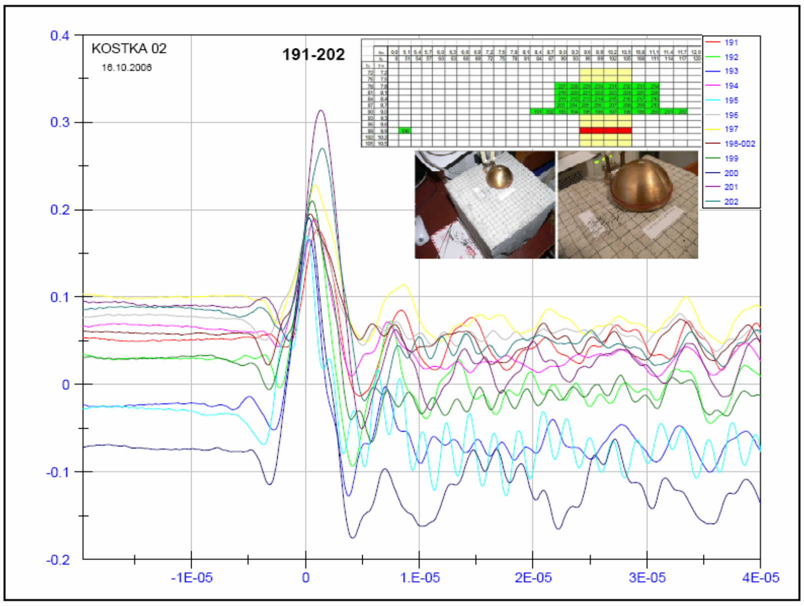

Fig. 8 Set of concrete sample impact echo time runs measured with BT-1

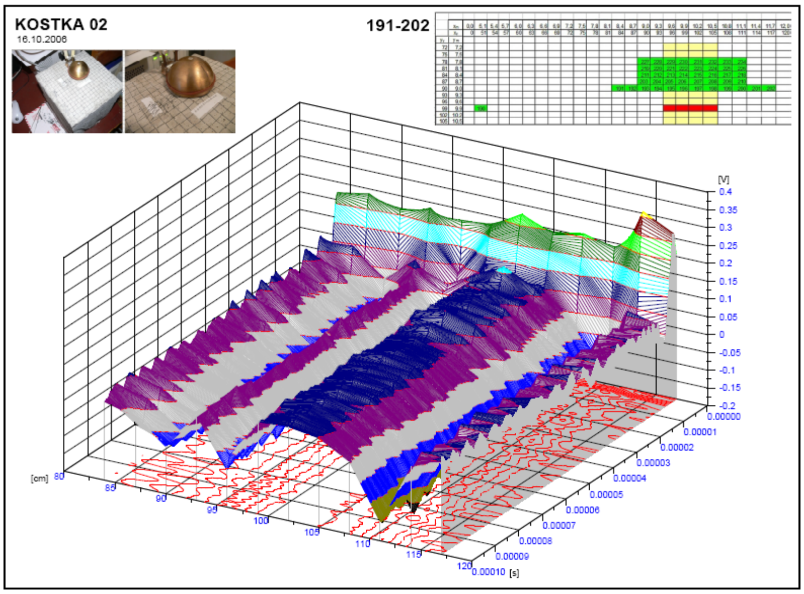

Fig. 9 3D Impact-Echogram of concrete sample with test reinforcing bar with approx. 1 cm diameter

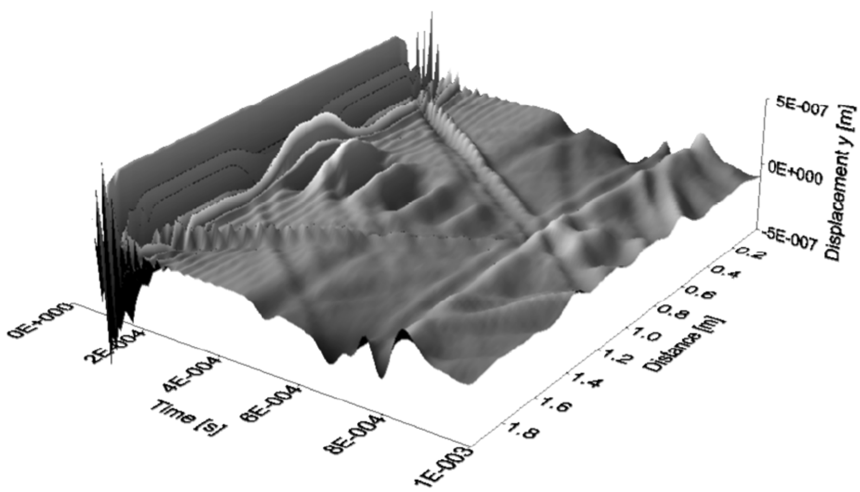

Fig. 10 Computed 3D Impact-Echogram of concrete sample with longitudinal volume void (Morávka 2006)

4. NRI specimens investigations

Time and frequency domain investigations on NRI specimens were carried out with the B&K 8309 accelerometer because it was not possible to use broadband transducer BT-1 on vertical planes.

As the first step it was necessary to verify the use of B&K 8309 accelerometer in the frame constructed for specimen measurements (Fig. 11). Following preparatory tests (Fig. 12) shown that

- designed B&K 8309 accelerometer holder in experimental frame exhibit undesired embedded frequency responses
- it is necessary
  - to fix B&K 8309 accelerometer to concrete surface by both sided SCOTCH adhesive band
  - generate stress waves manually by ball with 15 mm diameter in 8 – 10 cm horizontal distance from accelerometer.

Fig. 11 Experimental fixture frame

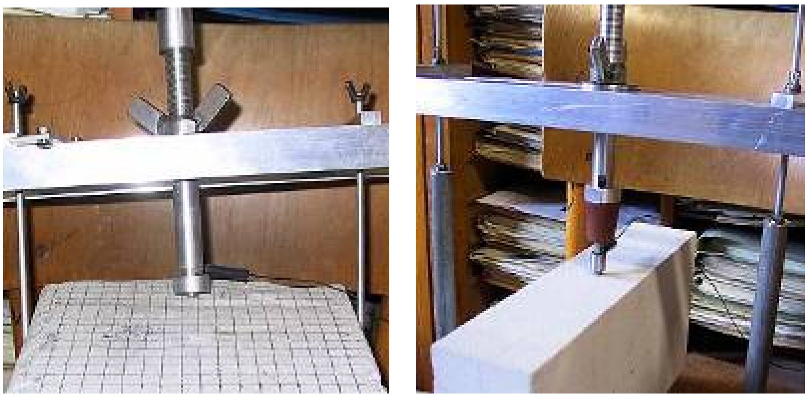

Fig. 12 B&K 8309 accelerometer fixture testing

The measurement set-up is shown in Fig. 13. Measuring chain with fixed accelerometer on concrete specimen Blok01 surface was connected to Endevco 2775B preamplifier, which was further connected to the other part of system TRS located in measuring booth Měřící buňka. In this booth, the subsystem NIR and controller TRC were located. Two-order filter "DP propust", placed on system input, was used to improve signal/noise ratio.

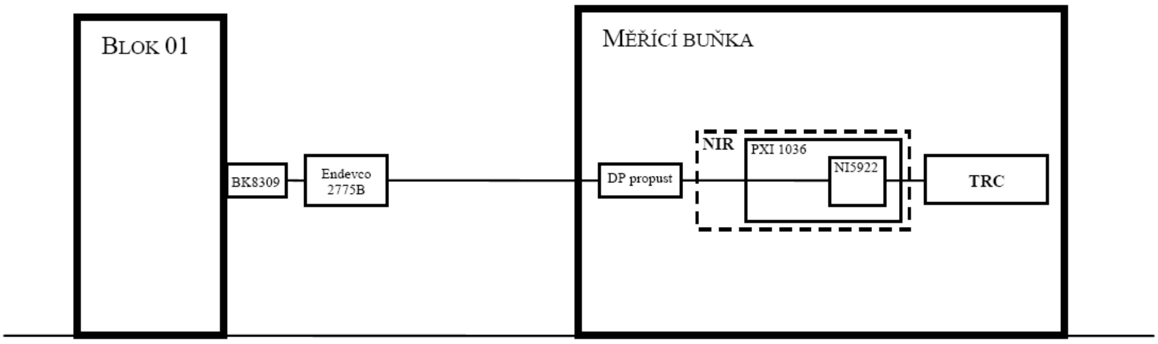

Fig. 13 Measurement setup of NRI BLOK01 specimen

Blok01 specimen (200 x 200 x 100cm) contains central test volume void (40 x 40 x 3cm) in 50 cm depth and two rebar rods (200 x Ø 3cm) in 10 cm depth (Rebar #01) respectively in 50 cm depth (Rebar #02). The multiple void and rebar measurements were realized in series of 7 – 10 for each surface point in 5 x 5cm grid. The typical time and spectral (PSD) runs from one point are shown in Fig. 14. While the similar first wave formations of time runs show that the measurement conditions are preserved then in case of spectral runs such presentation fails to be transparent.

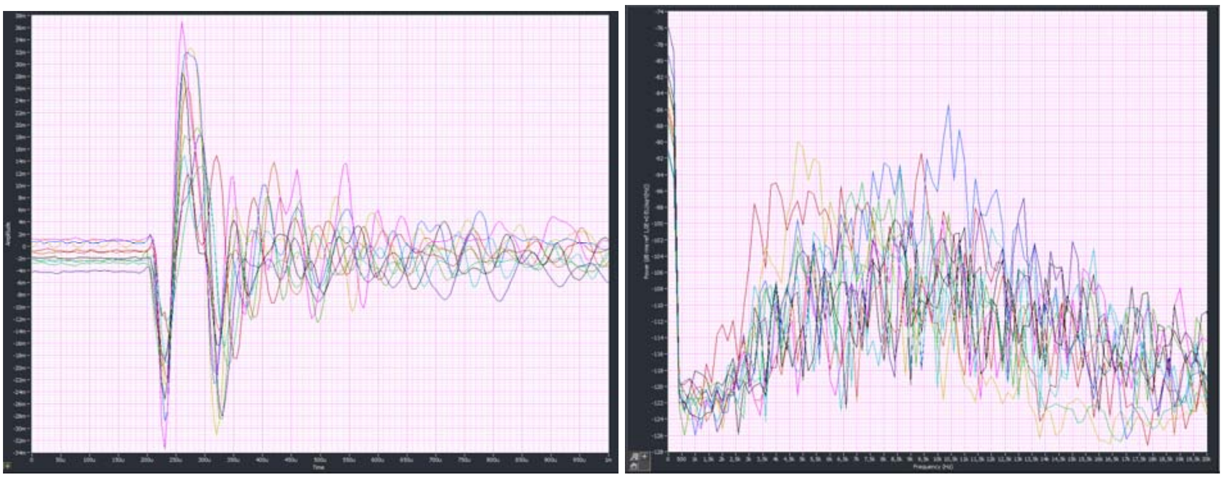

Fig. 14 Time runs and PSD overview

To make results more predictive the all time and spectral runs were transformed into 3D coordinates where time and PSD values became z coordinates of this 3D view. Projecting these z coordinates onto xy plane (x ~ specimen X length coordinate in cm, y ~ frequency in Hz resp. time in µs) we obtain more transparent information. Resulting Impact-Echograms show the frequency domain detection possibilities in Fig. 15 for volume void and in Fig. 16 for rebar and for volume void in Fig. 17 in time domain.

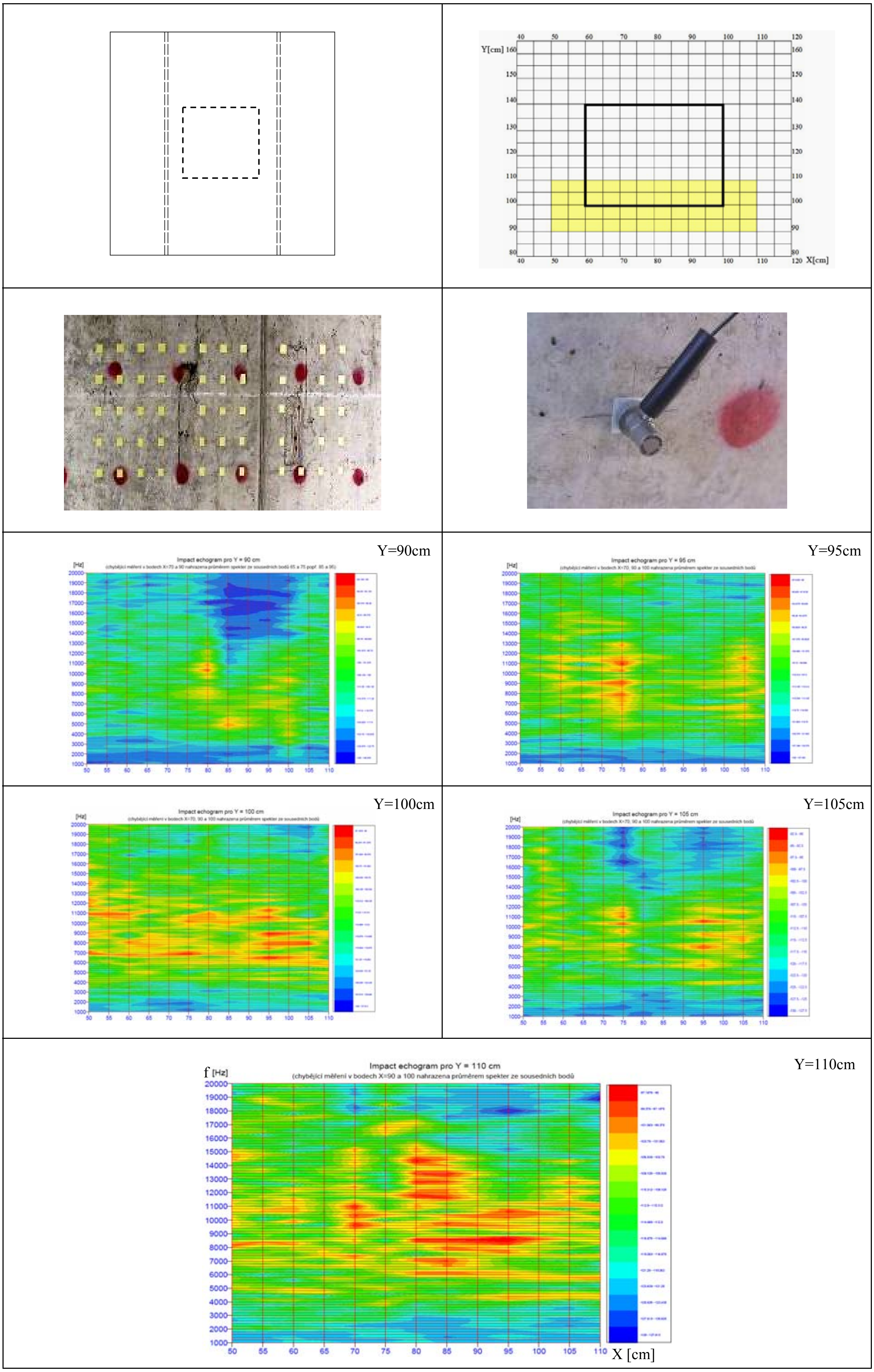

Fig. 15 Concrete test volume void Impact Echograms in frequency domain

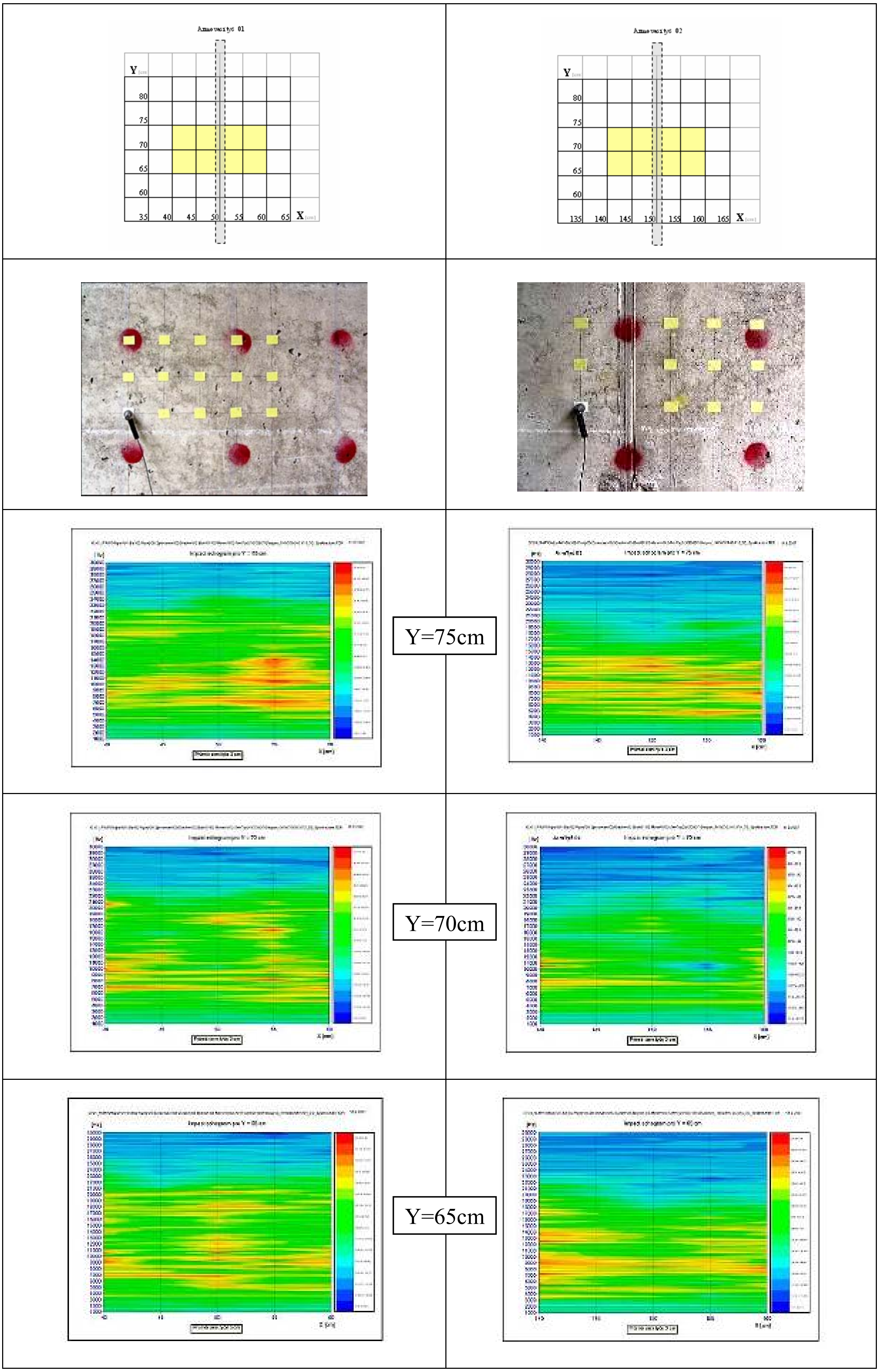

Fig. 16 Test reinforcing bar-Impact Echograms in frequency domain

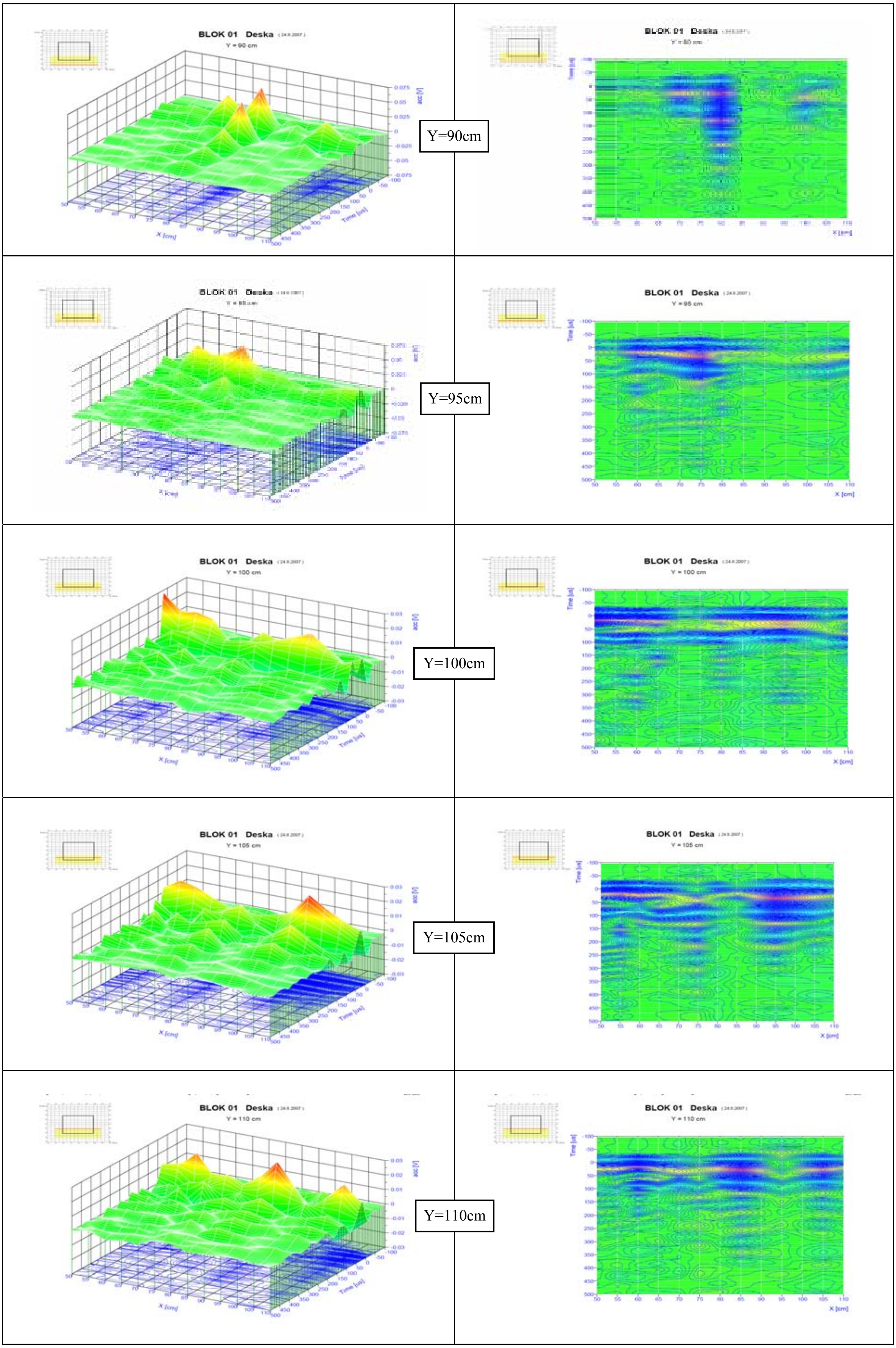

Fig. 17 Concrete test volume void Impact Echograms in time domain

Displayed Impact Echograms (IEG) represents altogether about 1300 realized measurements with manually generated impact in 95 surface points in grid of 5 x 5cm with gradually displaced BK 8309 accelerometer. Results can be shortly commented in the following way

- void detection (Fig. 15) in frequency domain
  - there is obvious difference between IEG for specimen coordinates Y=90 and 95 cm (out of void space) and Y= 100, 105 a 110 cm (space above void), it means that there is possibility of void detection
  - from Y=90 to 110 cm the void peripheral shape is indicated in the range from X=70-75 cm to 100-110 cm with the exception of IEG for Y=105 cm
  - void shape can be detected in frequency band from 4-6 to 12-15 kHz
  - for the first sight it is not possible to find in the above mentioned band distinctly presented void depth frequency f_T = 4,06 kHz computed from formula for P-wave velocity $\mathbf{c_p}$ = 4 230m/s, void depth of T = 50 cm and actual P-wave velocity correction factor 0,96 (Lin et al., 1997)
- rebar detection (Fig. 16) in frequency domain
  - more distinct results were obtained for Rebar #01 (10 cm depth) namely for Y=75 and 70cm
  - Rebar #02 (50 cm depth) was slightly recognised at Y=75cm
  - measurement 5 x 5cm grid was too rough related to 3cm rebar diameter.
- void detection (Fig. 17) in time domain
  - given results provide the most recognizable detection of void edge shapes achieved in the time S-waves range of about 150 μs namely in 2D projection with isolines.

5. Conclusions

The designed and integrated system TRS was found to fulfil the required measurement and processing tasks in time and frequency domain.

Two measurement chains were investigated – one with B&K 8309 shock accelerometer and the second broadband spherical transducer BT-1 prototype. Very hopeful results were obtained for rebar detection in the time domain when using transducer BT-1 prototype. NRI BLOK01 specimen impact echograms of void and rebar detection with accelerometer measurement chain have to be furthermore refined. Nevertheless, it is obvious that owing to time-consuming fixation procedures the use of accelerometer chain is not now too optimal for bulky measurements.

It can be noticed that complicated and large-scale NPP structures will require the development of

- broadband transducer which enables more sensitive measurements also on vertical planes or accelerometer fixation to tune measurement process
- suitable piezoelectric impactor with defined timing and output
- measurement and processing automatization
- qualified database evaluation of computed and processed data in time and frequency domain.

6. Acknowledment

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