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DIPARTIMENTO DI INGEGNERIA ELETTRONICA

RECONSTRUCTION SYSTEM BASED ON ULTRASONIC TIME OF FLIGHT DIFFRACTION FOR NDT APPLICATIONS.

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Introduction.

This report regards a research work carried out within a scholarship of the COMETT program of the E.E.C. and managed by U.E.T.P. Toscana, in cooperation with the National Non Destructive Center, Harwell Laboratory, Didcot Oxfordshire OX11 0RA, in the period 1/7/90-9/12/90.

This research work, referred as project N° QH80533 and supervised by Dr. M.G. Silk, here is reported in two different sections.

The aim of the first phase of this project was the application in the field of Non Destructive Testing of a technique based on ultrasonic time of flight diffraction. This method was already applied in the medical field in transmission mode.

In this part of the research work a software simulator and an image reconstruction program has been carried out. With these software tools several simulations with different input parameters gave promising results that suggested to continue the project with the second experimental part.

In the second phase of the project a complete laboratory system was carried out and an efficient isotropic ultrasonic transmitter was designed and manufactured.

Preliminary observations on the measurements performed on this laboratory system are reported.

Section 1.

a) Summary of the basic ideas of this method.

The aim of this project is the application of a reconstruction algorithm for the defects inspection inside metals (flaws sizing,inclusions etc.).
The expected characteristics of this advanced inspection technique are the high resolution image and direct interpretation of the results. The high resolution is achievable thanks to the complete data set method applied in backscattering mode with wide angle beam transducer and large aperture.
Moreover the overall spatial resolution should be constant on each point of the image if a 90 degree inspection is carried out.
For practical reasons the synthetic aperture might be sampled with a reduced number of positions so that the inspection and reconstruction time is bounded within reasonable limit (speaking within a standard acquisition system and computers 1 hour seems to be acceptable limit).

b) The computer simulation of the diffracted signals from inclusion.

The preliminary work has been the simulation of the diffracted ultrasonic field from inclusions in metals with a broadband incident field.
A suitable Fortran program has been developed for this purpose.
In this software a model of the diffracted field from different shape inclusions is employed. The model is an improved version of the first order Born approximation for the diffracted field. Shear waves are also being considered to take into account mode conversion phenomena. In spite of the reconstruction is being based only on longitudinal waves it's important to see if for a certain defect's depths the shear and longitudinal waves are separable.
The simulated data obtained with this program are stored in a ZIPSCAN format data file for subsequent reconstruction.

*** Parameters description for the ultrasonic signal simulator :

1) Synthetic aperture length and number of probe positions

2) Physical characteristics of the host material and the inclusions.
The diffraction coefficients depend on this set of parameters.

3) Shape of the inclusion : sphere or cylinder like.
The latter approximated with a stretched ellipsoid.

4) X,Y coordinates for each inclusion center, multiple inclusions are simulated with a superposition principle approach on the received ultrasonic signals

5) The FFT of a "standard" transmitted pulse must be provided to the program with an ASCII file called SAMPLE.FFT. In this way different frequencies and bandwidth can be tested.

6) Sampling time of the transmitted pulse (Assumed of 512 samples)

7) Time delay. This parameter represents the delay time applied as phase lag to each signal. Can be regarded as the Time Base Delay of the digital sampling oscilloscope used in the experimental case. With this parameter the shear waves can be kept outside the acquisition time slot.

8) Transducer aperture : Circular or Rectangular shaped.
As mentioned before wide angle beam transducer are expected to increase the performance because the defects are illuminated by the transmitted field also from the furthest position of the aperture. For this purpose smaller diameter transducer (3-5mm) should be an effective solution but a reduced energy is delivered into the object. However bigger diameter transducer (10 mm) can be adopted with a properly design mask

with a rectangular aperture. The smaller side (1.5-3 mm) of the aperture of the mask is along the scan direction.
The longer one (length = Trans. diameter) is perpendicular to the scan direction. The choice between spherical and cylindrical aperture selects different directivity functions for the transducer (the same for TX and RX).

c) The reconstruction algorithm.

The reconstruction process is performed by a Fortran program called ARANS,(Automatic Reconstruction Algorithm for Non destructive testing Speed up version) that accept as input a data file with ZIPSCAN format with the signals obtained with the simulator (see para. b)) or from experimental measurements.
In both case the signals must be acquired according to the complete data set method. This reconstruction algorithm comes from a previous version which was developed for a transmission mode operation. At this time all the parametric coefficients of the backprojection scalar function has been derived in a new and simpler form exploiting a remarkable gain in the execution time : about a 46% less than the former version.
The input parameters of this program are reported below :

1) One side dimension of the reconstructed square image centered on the scanned area

2) Number of pixel for the reconstructed image

3) Syntethic aperture length (same of the input data file)

4) Longitudinal velocity host material

5) Time delay applied to each ultrasound scan

6) Sampling time of the input data file

Notes.

In the reconstruction process with experimental data some distortions on the final image can be observed due to the uncertainty of some input parameters value. In fact in experimental measurements all the parameters are known within a certain accuracy. The lower accuracy are usually for the time delay and the host material velocity.

d) A proposal for a transducer mask design.

An important factor for the success of this inspection technique is the transducer directivity function. As previously mentioned we are looking a compromise between a wide angle beam transducer and energy loss. The masking technique allows to be effective without leading to
a cumbersome design. The final assembly of the mask on the transducer should be easy to use in almost the practical measurements condition.
Generally a mask is built up with a high attenuation material like resins or sponge, and the aperture is machined directly on the mask by a cutting tool. Ideally we would like a mask which produce a negligible ultrasonic field in the immediate shadow of the mask, but enables most of the available ultrasonic energy to pass through the aperture.
The latter condition is satisfied if the thickness of the mask is very small compared to the wavelength while high attenuation outside the aperture asks for a larger thickness value.
With larger thickness values and small rectangular aperture the mask works like an acoustic wave guide so that most of the energy is trapped inside the mask aperture.
Generally a compromise between these two opposite features is chosen.

Another approach is proposed to overcome the disadvantages of the previous mask design.
A layer at a quarter of the wavelength has the property that the monochromatic incident field is canceled outside the layer (With the approximation of 0 attenuation coefficient). This features can be useful with layers thin in comparison with the wavelength (F0= 5 mhz).Using a simulation software for probe modelling, the field outside a quarter of the wavelength layer has been calculated. However in this application broadband signals are employed rather than monochromatic and at one mhz far away from the frequency for which the quarter wavelength (plate layer) was designed, the attenuation becomes less about 20 dB.
To achieve high attenuation also outside of the probe's center frequency we can invoke the following theoretical formula for the field cancellation:

$$Fn = F0 \, (2 n + 1) \qquad n = 0,1,2,3,.....$$

Where Fn is the frequency where the cancellation occur and F0 is the fundamental frequency with which the quarter of the wavelength plate has been designed.
So at odd multiple frequencies of F0 peaks on the attenuation are expected.
Two consequent peak are separated by 2*F0, and even if F0 is quite lower than the transducer's center frequency the thick layer correspondent to F0 exhibits high attenuation also at higher frequency inside the transducer bandwidth.
This allow the introduce another thick layer among the quarter of wavelength to combine the attenuation effects of this two layers. This thick layer could be simply the water used to match the transducer and the metal specimen.
With a 0.301 mm steel layer and a 1.3 mm water layer a minimum attenuation of 50 dB is obtained in the transducer bandwidth.
Suitable materials for the front layer are metals with acoustic impedance near the probe one and much higher than

water. Simulations with different materials silver,brass,steel lead to the same attenuation values.

e) Preliminary observations on the reconstructed images with simulated data.

To test the performance of this imaging system several simulations are carried out. Since the aim of this project is the inclusions sizing within an acceptable accuracy, two different diameter sulphide inclusion spheres has been reconstructed. The first step of this test procedure consist in computer simulation of the ultrasonic signals received along the 100 mm aperture with the spheres centered at 51 mm depth. The diameters are 1.5 mm and 3 mm respectively. Then the RF reconstruction is applied to this two different data file. A 32*32 pixel, 10 mm side image around the object has been selected to avoid spatial undersampling aliasing. The final step is the PSF calculation of the system with a small object for the subsequent application of the inverse Wiener to these images. The two images show the elevation of the spheres with diameter 1.25 and 2.5 mm, so an under estimation of the diameter of 0.25 mm and 0.5 mm respectively. This promising result requires further investigation with different inverse Wiener filter parameters, errors due to the uncertainty of the delay time, and different shape inclusions and voids.

Section 2.

The second phase of the project regards the experimental validation of the results obtained with the computer simulations.
The aim of the experimental work is the characterization of the ultrasonic field transmitted by the rectangular aperture on the quarter of the wavelength metal foil and the design of a two probes system for the implementation of the complete data set method.

a) Design of a prototype of transducer masking system for high efficiency masking technique.

The design of this prototype has been based on the results obtained with computer simulations by a Probe Modelling Software developed by the National NDT Center, Harwell Laboratory.

The selection criterium of the metal plate layer that we have adopted is the high acoustic impedance and high longitudinal velocity of the material.

Several simulations with different materials as steel, tungsten, tantalum, molybdenum are carried out. The acoustic properties are summarized in the following table :

Material	Z [g/cm²s] x100000	Thickness quarter of wavelength at F= 5MHz [μm]	V long. [m/s]
Steel 402 CRES	45.4	283	5660
Steel 4340	51.0	292	5850
Molybdenum	64.2	314	6290
Nickel	50.0	281	5630
Tantalum	54.8	205	4100
Tungsten	99.8	259	5180

In Fig.1A is shown the simulated attenuation plot of a tantalum layer with thickness 0.2 mm at a distance 1.3 mm from the transducer immersed in water. The simulation consider the double signal's path of the ultrasonic pulse received from an ideal infinite plane reflector.

The maximum attenuation is 96 dB and minimum attenuation is 52 dB in the -6 dB transducer bandwidth.

The results of the experimental measurements carried out in transmission mode on a 0.2 mm thick. tantalum layer are shown in Fig 1B. In this case the distance of the tantalum plate layer from the transducer is assumed 4 mm.

The measured attenuation plot in Fig. 1B shows a max attenuation of 33 dB and the minimum equal 24 dB. Since in the experiment we consider only one way travel these figures must be doubled to be compared with the simulation ones.

In this way we obtain a maximum attenuation of 66 dB and 48 dB respectively. The lower attenuation obtained in the experimental case with the metal layer is due to the repetition of the first signal in the acquisition time slot that increase the amplitude of the frequency spectrum.

The scalloping of the attenuation spectrum is mainly dependent on the distance between the metal layer and the transducer. With a distance of 4 mm the attenuation peaks in the frequency spectrum is expected to be equal 0.185 MHz. On the attenuation plot can be measured a frequency separation of about 0.146 MHz.

A mechanical system has been designed to adjust the inclination and the distance of the transmitting probe on the metal layer with a three screws system. Different transducer holders have been built to fit 5 MHz probes in the range 10 - 12.5 mm diameter. A rectangular aperture 3X10 mm has been made to obtain a wide main lobe in the scan line direction. With this masking system the directivity function has been measured employing the backscattered signal from a 2 mm side drilled hole in a steel specimen and then for the purpose of a comparison it is repeated with a 6.3 mm diameter, 5MHz, standard ultrasonic probe.

The measured value of FWHM is about 4 times greater with the

3X10 mm against the standard probes so the expected effect of the metal layer mask has been confirmed.

b) Acquisition system for broadband signals diffracted by large defects in metal specimens.

An immersion system with two independent mechanical movements is built up for the acquisition of the ultrasonic signals. Two probes are independently moved by computer control, with a resolution of 63 μm and an accuracy of ±126 μm.

All the acquisitions have been repeated twice : one with the masked transducer and one with the standard probe as transmitter.

In this way is possible to evaluate the effectiveness of the proposed solution with the masking system.

Several complete data set have been acquired with a 2 mm side drilled hole at a depth of 35 mm in the steel specimen and an aperture of 70 mm spatially sampled by 30 RX-TX probes positions.

The side drilled hole in some cases works as a void since was filled with air by blocking up the extremities with plasticine.

A reduced set of signals correspondent to the central TX position (in front of the void) are shown in Fig.2A-2B. Each scan consist in 512 samples acquired at F sampl.= 20 MHz.

Two preliminary observations can be made on these signals :

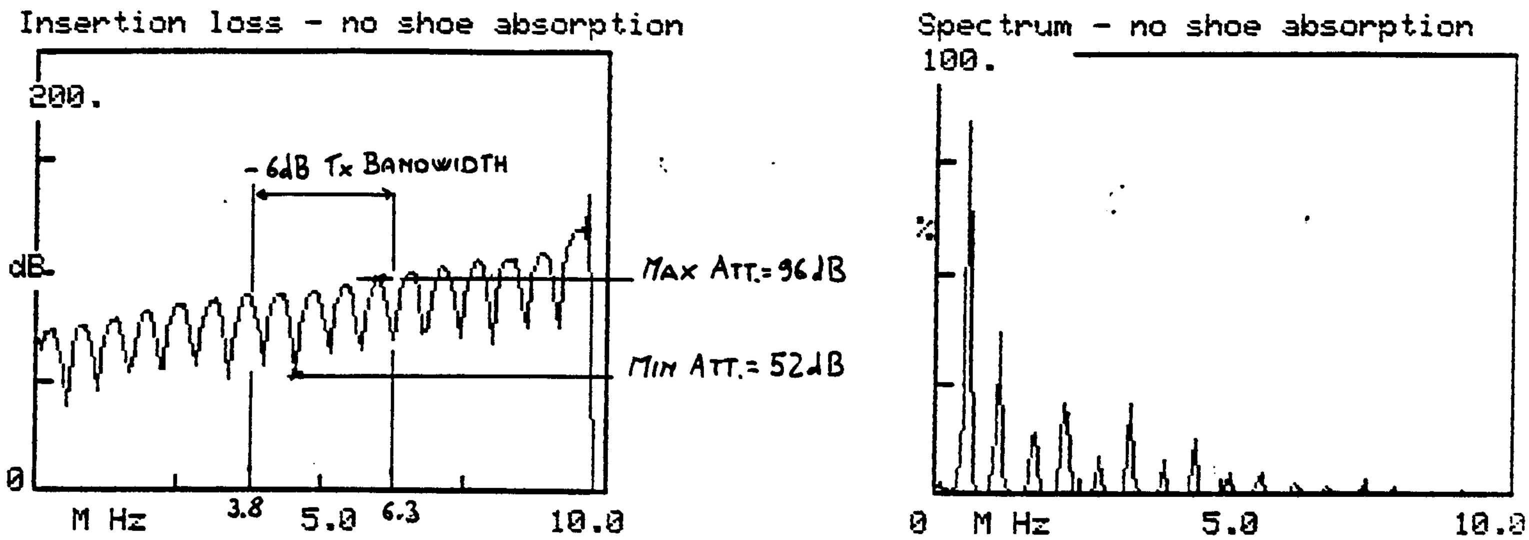
1) The relative amplitude between the reflected signal at the water-steel interface and the backscattered signal from the side drilled hole depends on the inclination adopted for the RX and TX probes, because a different quota of the incident energy propagates into the metal specimen.

Nevertheless in the case of the masked transducer the reflected signal from the first interface has a lower amplitude due to wider range of incident angles of the transmitter beam, so that almost of the transmitted energy reaches the defects instead to be reflected from the metal surface.

2) From the above considerations the S/N ratio achieved with this masking technique is comparable with the standard probes one, with the advantages of a wider main lobe.

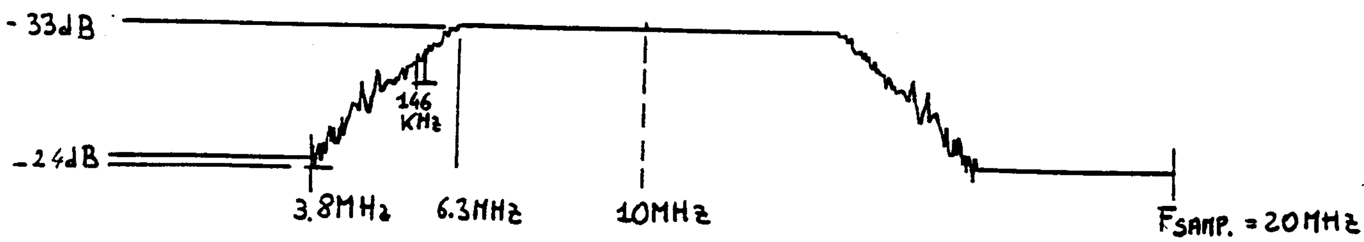
The next and the final step of this work will be the attempt of a reconstruction with these sets of experimental signals for the evaluation of the performances of this method taking into account all the errors introduced during the acquisition process as the alignment errors, phase errors, limited number of TX-RX on the aperture.

Moreover the acquired signal will be compared with the generated signal by the software simulator with the same parameters of the experiments to test the range of validity of the software simulator, which is potentially a powerful tool for NDT applications to study the diffraction of ultrasonic pulses from different large defects inside metal specimen.



- Fig. 1A -

Simulation of the attenuation of a 0.2 mm thick tantalum plate layer at a distance from the transducer 1.3 mm.



- Fig. 1B -

Experimental attenuation plot vs frequency.

Distance of the tantalum plate layer from the transducer 4 mm.

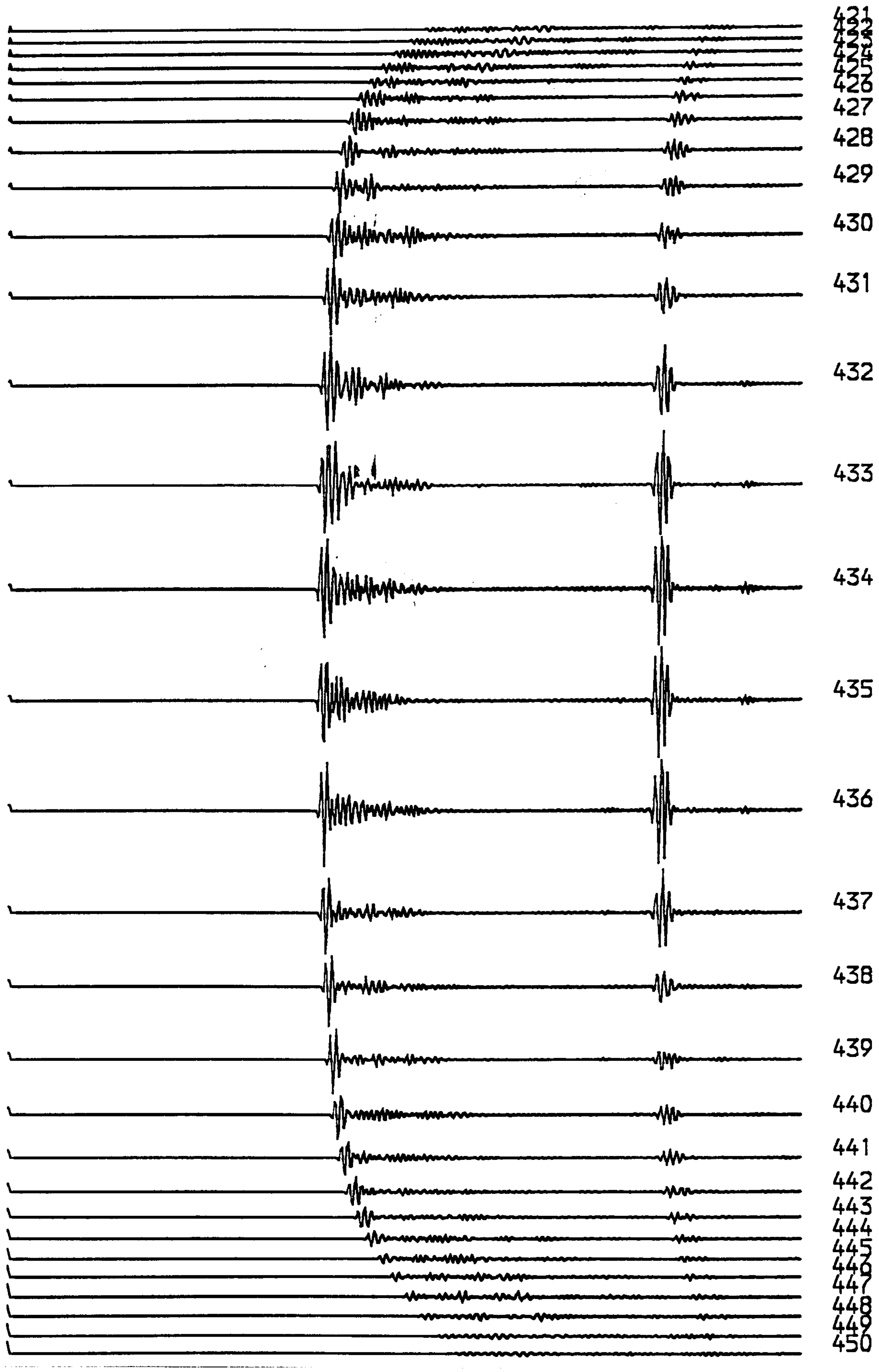


Fig.2A Complete data set scans with the TX in front of the side drilled hole : standard probe KB AEROTECH Alpha F=5MHz/.25" as transmitter .

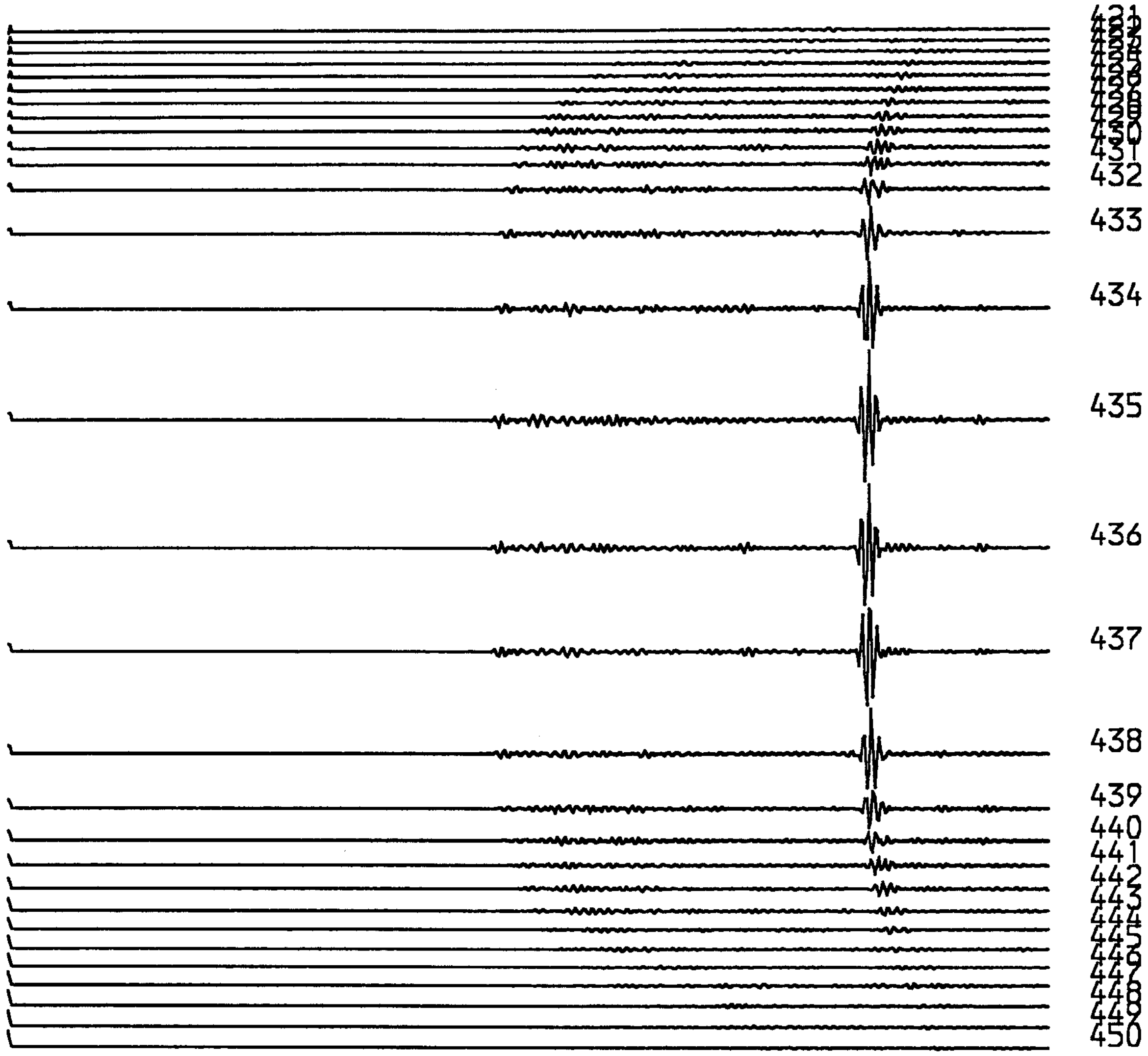


Fig.2B Complete data set scans with the TX in front of the side drilled hole : masked transducer aperture 3X10 mm on tungsten plate layer thick. = 250 μm, F=5MHz as transmitter.