UTILISATION DU TRADUCTEUR ULTRASONORE A PHASE ALEATOIRE POUR LE CONTROLE NON DESTRUCTIF DES ACIERS A GROS GRAINS

THE RANDOM PHASE TRANSDUCER IN ULTRASONIC NDT OF COARSE GRAIN STAINLESS STEEL

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Novembre 1993

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SYNTHÈSE :

Présentation du principe de fonctionnement des traducteurs ultrasonores à phase aléatoire. On montre l'intérêt de leur utilisation dans les matériaux à gros grains. Les résultats expérimentaux sont comparés avec ceux obtenus à l'aide d'une technique classique de calcul d'une moyenne spatiale. Ces résultats montrent l'intérêt de ce type de traducteur pour caractériser la diffusion multiple qui accompagne la propagation des ultrasons dans ces matériaux.

EXECUTIVE SUMMARY :

Ultrasonic NDT of cast stainless steel is known to be difficult due to a huge loss of focussing of the ultrasonic beam, and to a high level speckle noise generated by the coarse grain structure. In this paper, we describe the principle of the ultrasonic random phase transducer. Experimental results are compared with those obtained with a standard spatial compound technique. We show that the random phase transducer is a good tool to characterize the multiple scattering process generated by these materials.

THE RANDOM PHASE TRANSDUCER IN ULTRASONIC NON DESTRUCTIVE TESTING OF COARSE GRAIN STAINLESS STEEL: AN ORIGINAL TOOL TO CHARACTERIZE MULTIPLE SCATTERING EFFECT

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INTRODUCTION

Until this day, ultrasonic inspection has been very scarcely applied to the cast stainless steel components of the french nuclear pressurised water reactor because of its reduced performances in these coarse grain media. The flaw detection is difficult in these materials because the echographic signal can be masked by a high-level speckle noise due to the backscattered echoes produced by multiple acoustical heterogeneities (grain bounderies, density variations,...) [1-4].
It is well known that ultrasound speckle is a consequence of the stochastic nature of the reflectivity of scattering media and of the coherent nature of piezoelectric transducers. The speckle noise can be reduced by the use of incoherent processing techniques (e.g., spatial compounding, incoherent summation, random phase and phase insensitive transducers).
The problem of the speckle reduction can be approached by the use of incoherent (phase insensitive) transducers. Such tranducers can be made in several different ways. For example, power-sensitive receivers such as the acousto-electric transducers made of CdS, are available. However, these transducers generally exhibit a lack of sensivity. Other solutions consist in sampling the field with small-aperture piezoelectric elements arranged in a two dimensional array or in using random phase transducers.
In a precedent work [5], we have demonstrated, with a linear array, that a multiple scattering process is generated by the cast stainless steel structure. The multiple scattering effect is characterized by an unexpected behavior of the speckle noise with respect to frequency (the frequency increases as the signal propagates) and by a strong distortion of the incident pulsed wave. This effect explains the deterioration of focusing generally observed in these coarse grain structures beyond 2 MHz. Moreover, we have shown that the acoustic fields of the transmitted and reflected signals are spatially incoherent. This behavior allows to obtain a great number of uncorrelated information on the reception transducer.
Besides, in recent papers [6-8], the interest of the random phase ultrasonic transducers has been presented in order to reduce the speckle noise for acoustical imaging in scattering structures. For this method, there is neither need of dividing the aperture into subelements or necessity of scanning the field. This technique requires only one transducer filling the entire receiving aperture. The spatial coherence is controlled by moving a random phase screen (RPS) in front of the aperture. The envelope detection and the spectral analysis are performed for each position of the RPS.
In this paper, we present the incoherent random phase transducer used in nondestructive characterization of coarse grain stainless steel: we compare the results with those ones issued from the spatial compounding technique. From the strong differences obtained after a time-frequency analysis, we emphasize that the random phase technique is a good tool to characterize the multiple scattering effect.

THE RANDOM PHASE TRANSDUCER

Principle: The random phase transducer approach to incoherent processing of pulse-echo signals is illustrated in figure 3: it consists in using a coherent transducer filling the entire receiving aperture. The degree of spatial coherence is controlled by moving a random phase screen (RPS) in front of the receiving tranducer. The envelope detection and the spectral analysis are performed on the echo lines recorded for each RPS position. These data are then averaged over a set of RPS positions.

The RPS generates random phase shifts that depend on the position of the RPS as well as on the coordinates of the receiving aperture. Thus, a random phase jitter is superimposed on the natural phase relationships between different points of the backscattered pressure field. The final effect is to remove the phase information contained in backscattered pressure field.
Using the random phase transducer can lead to an incoherent processing: in these conditions, a deterioration of resolution is observed (the directivity pattern becomes wider) and a removal of diffraction effects and a significant improvement of signal-to-noise ratio are predicted.

The random phase screen: the RPS is a phase shift generating object. it can be viewed as a transparency with transmittance function $T(\vec{X})$. Practically, it can be built as a plane object whose thickness varies with space and whose refraction index differs from the surrounding medium index. The transmittance is related to the local thickness through the relation [9]

$$T(\vec{X}) = exp\left[-j2\pi(n-1)\frac{e(\vec{X})}{\lambda}\right] \qquad (1)$$

where n is the relative refraction index of the screen with respect to the surrounding medium and $e(\vec{X})$ is the thickness of the screen.
The statistical properties of the RPS are characterized by the transmittance autocorrelation function, $R_{TT}(\vec{X})$ [6]. A particular case of the transmittance is obtained when the transmittance autocorrelation function is proportionnal to a Dirac function: then, an infinitesimal displacement of the RPS is sufficient to obtain uncorrelated information. This limiting case corresponds to a totally incoherent RPS.

The incoherent processing in single scattering: when an ultrasonic beam illuminates a scattering medium, a pressure field is backscattered towards the receiving transducer. Each point $\vec{X}$ on the receiving aperture of the transducer senses a pressure signal equal to:

$$p(\vec{X},t) = \sum_{scatterers} p_i(t-t_i) \qquad (2)$$

where $p_i(t)$ corresponds to the elementary pressure wave scattered by scatterer i and t_i to the time of arrival of the elementary pressure wave to $\vec{X}$.
In a monochromatic approach, the backscattered pressure field can be written from its complex amplitude $P(\vec{X})$ and through the relation:

$$p(\vec{X},t) = Re\left\{P(\vec{X})e^{-j\omega t}\right\} \qquad (3)$$

The complex pulse-echo signal E, generated at the receiving surface of the transducer without the RPS is:

$$E = \int d\vec{X} O_r(\vec{X}) P(\vec{X}) \qquad (4)$$

where $O_r(\vec{X})$ is the receiving aperture.
Let's place a RPS on the surface of the transducer; for a position $\vec{\delta}$ of the screen, $P(\vec{X})$ becomes $P(\vec{X})T(\vec{X},\vec{\delta})$ and the pulse-echo signal becomes (the RPS works in receive mode only):

$$E_{\vec{\delta}} = \int d\vec{X} O_r(\vec{X}) P(\vec{X}) T(\vec{X},\vec{\delta}) \qquad (5)$$

With a totally incoherent RPS whose the autocorrelation function is proportional to a Dirac function:

$$R_{TT} = < T(\vec{X}_1,\vec{\delta}), T(\vec{X}_2,\vec{\delta}) > \propto \delta(\vec{X}_1 - \vec{X}_2) \qquad (6)$$

it is demonstrated that the average of its squared magnitudes is proportional to [6]:

$$< \left|E_{\vec{\delta}}\right|^2 > \propto \int d\vec{X} O_r(\vec{X}) \left|P(\vec{X})\right|^2 \qquad (7)$$

It is the equation of a pulse-echo signal produced by an incoherent transducer sensitive to the pressure intensity. Therefore, a totally incoherent random phase transducer is equivalent to a totally incoherent transducer.

Directivity pattern: an interesting interpretation of the random phase transducer can be made using the theory of the diffraction grating. When a monochromatic plane wave comes upon a periodic grating, it is diffracted by an angle that depends on the grating period as well as on the wavelength. Therefore, an energy lobe appears in that direction. Our RPS can be viewed as a random grating, i.e., a superposition of periodic gratings of random period and amplitude. For a given position of the RPS, the transducer sees a particular grating that generates lobes in particular directions. For another position of the RPS, there are lobes in different other directions. The directivity of the random phase transducer is the average directivity and it is easy to understand that it is degraged compared to that of a coherent transducer. It has been shown [6] that the more incoherent the RPS, the larger the directivity pattern.

Diffraction filter: it is well known [9] that the finite size of coherent transducers induces the diffraction effects that determine not only their focusing properties but also bias errors that are to be corrected when quantitative parameters are to be extracted from pulse-echo measurements (e.g., attenuation measurements). The transducer effects are strongly linked to the transducer size and disappear when the transducer is point-like.
For a RPS, the effective size of the random phase transducer is given by its equivalent aperture function; the larger the directivity pattern, the smaller the equivalent aperture of the random phase transducer. Therefore, if the RPS transmittance autocorrelation function is quite narrow, we expect the diffraction effects to disappear, or at least to decrease (if the equivalent aperture function is not infinitly narrow)[8].

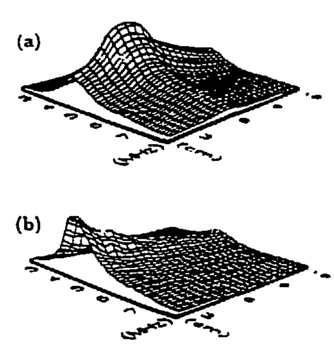

Figure 1 :
(a) coherent and focused transducer
(b) random phase transducer

Noise reduction potential in single scattering: in a classical (coherent) processing, the signal-to-noise ratio (SNR) is rather low: 1.91 or 1.0 respectively for the envelope- and the intensity-detected signals [11]. We derive a general expression for the SNR obtainable in totally incoherent pulse echo processing. After a set of RPS positions, the SNR magnitude is defined as [6]:

$$SNR_{magnitude} = \frac{<<|E|^2>_{RPS}>_{medium}}{[<<|E|^2>^2_{RPS}>_{medium} - <<|E|^2>_{RPS}>^2_{medium}]^{\frac{1}{2}}} \quad (8)$$

It is a complex random process whose statistics depend on those of the scattering medium. The resolution cell is supposed to contain a large number of scatterers, and consequently, the pressure field is zero mean and has Gaussian statistics[11].

It has been shown that the expected SNR of the useful envelope detected signals becomes [6]:

$$SNR_{magnitude} = 1.91\sqrt{N} \quad (9)$$

where N is the number of uncorrelated enveloppe detected. This means that, we have to receive a large amount of uncorrelated information elements in order to increase the SNR. Over a surface of the order of the backscattered field autocorrelation, we can receive only one uncorrelated information element. Therefore, to receive a lot of information elements, we need a receiving surface whose area is many times larger than the field autocorrelation width.

Study of coarse grain stainless steel: we must notice that the theoretical approach of the random phase transducer has been carried out in a single scattering propagation regime. Now a multiple scattering effect is associated with the propagation in the coarse grain stainless steels. The main consequences of this effect are especially [5]:
- that the correlation length of the backscattered field is shorter than this of a single scattering medium,
- and that the beam size increases with the propagation.

The first observation shows that we can receive more uncorrelated information (on receiving apertures) from multiple scattering media than from single scattering ones; therefore, the SNR improvement might be better with coarse grain stainless steels than with other materials where the first Born approximation is verified.

About the second observation, it appears that only a transducer having a large directivity pattern can be sensitive to the multiple scattering effect. Therefore to measure this effect, it is better to use a random phase transducer than a classical coherent transducer.

EXPERIMENTAL RESULTS

The objective of this experimental part is to compare the spatial compounding technique and the random phase transducer technique in coarse grain stainless steel NDT. We have used the same measurement line and the same piezoelectric coherent transducers for the two techniques (we have seen that a random phase transducer is basicly a coherent transducer associated with a RPS). Firstly, we have compared the performances of these both techniques. A time-frequency analysis of echographic lines shows strongly different results. Secondly, we have measured the backscattered signal "attenuation" with respect to frequency, using the random phase transducer technique.

Experimental set-up: five different unfocussed transducers are used in pulse-echo mode (table 1):

Table 1 :

Transducer US	Diameter (mm)	Frequency (MHz)
1	39	1.0
2	20	2.0
3	27.5	2.25
4	37.5	3.5
5	13	5.0

The received information is digitized by a 8 bits, 25 or 50 MHz sampling rate, A/D converter and analysed with a PC-80386 micro-computer.

The experiments are performed in a water tank on a cast stainless steel sample (thickness=80mm). The average grain size is 5 mm.

The spatial compounding technique (figure 2): the transducer is moved one hundred times, step by step (4 mm) facing the front face of the sample. Thus, the covered surface is 40 × 40 mm.

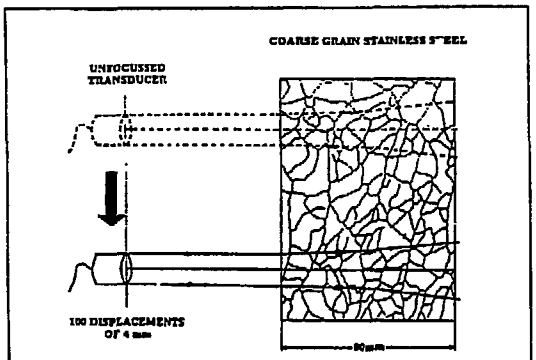

Figure 2 : *experimental set – up –spatial compounding technique–*

The random phase transducer technique (figure 3): here, the coherent transducer stays fixed facing the sample. Uncorrelated information is created by the displacement of the RPS in a plane located in half way between the transducer and the sample. The RPS is moved by stepper motors (step=6 mm). We have selected the roughest RPS (with the narrowest transmittance autocorrelation) to work in totally incoherent processing.

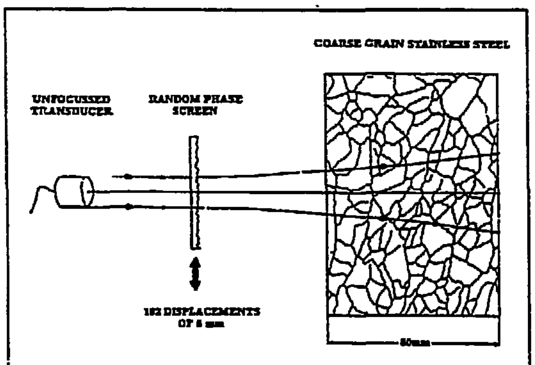

Figure 3 : *experimental set – up –random phase transducer technique–*

Estimation of the backscattered signal "attenuation" with frequency bandwidth analysis (figure 4): first, each A-scan signal is sampled by shifting a time Hanning window of fixed duration $T = 5.12\mu s$. Then, the power spectrum is computed for each sample. The sampled slice of signal corresponds to the sum of several echoes coming from different scatterers, and thus the resulting frequency spectrum appears highly disturbed. These data are averaged over a set of transducer or RPS positions (according to the incoherent processing technique used) to obtain a speckle reduction. The frequency bandwidth analysis consists in following the decreasing amplitude of frequency spectra as a function of time around each frequency. The slope of this temporal decrease supplies an "attenuation" estimation. By considering a signal "attenuation" proportional to $e^{-2\alpha d}$, where d is the average depth of the slice of material selected by the window and $\alpha = a_n f^n$ the "attenuation" coefficient, and in the assumption of a constant celerity c ($d = ct$), the logarithmic temporal decrease of power spectra is $2\alpha c$. By repeating the process over different frequency bandwidths, we obtain a set of "attenuation" coefficients as a function of frequency.

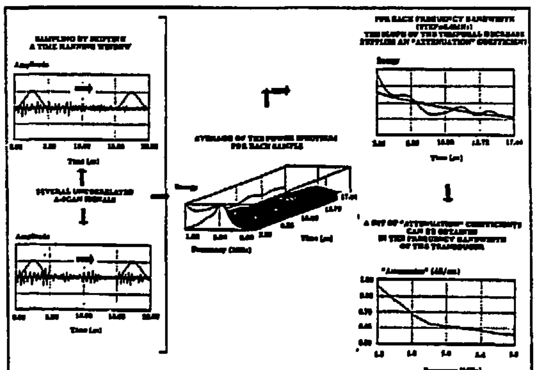

Figure 4 : *estimation of the "attenuation" time – frequency analysis*

Comparison of the results of "attenuation" obtained with both the incoherent processing techniques: first, we have studied how the results could fluctuate depending on the transducer position with respect to the steel sample. For this study, we have worked with the unfocussed transducer (number 2 in table 1).

The spatial compounding technique: the step by step displacement (4 mm) has been carried out upon two different and adjacent areas of the steel sample (40 × 40 mm). The figure 5 shows that the "attenuation" does not depend of the scanned area. For both the graphs, the "attenuation" increases with respect to frequency. Moreover, this growth is under estimated because of the diffraction effect [9].

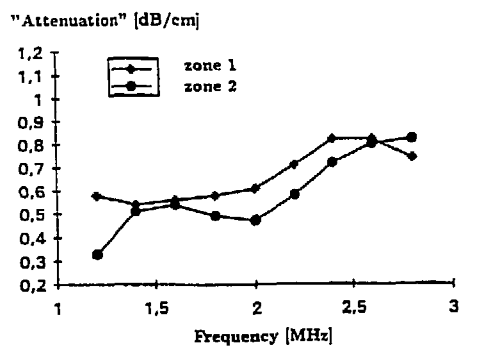

Figure 5 :
"Attenuation" versus frequency
–spatial compounding technique–

The random phase transducer technique: we have carried out four different measurements by moving the transducer as indicated on figure 6. For each position of the transducer, the RPS has been moved step by step (6 mm) 192 times.

The figure 6 clearly shows the likeness of the graphs A-B and C-D; that is to say when the observation points are the closest. In all the cases, from 1.5 MHz, the "attenuation" decreases with respect to frequency. Such a result is quite strange and we shall define in the following this "attenuation" as a "pseudo-attenuation".

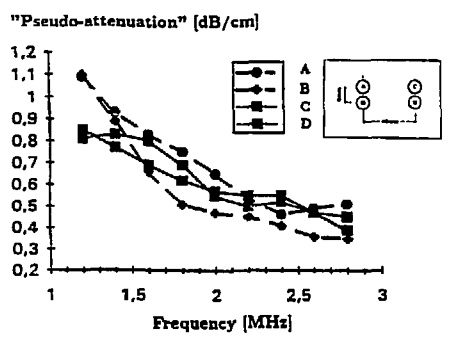

Figure 6 :
"pseudo – attenuation" versus frequency
–random phase transducer technique–

Discussion about "attenuation" and "pseudo-attenuation": the results issued from the spatial compounding technique are homogeneous as expected because the scanned areas are larger than the mean grain size (5mm).

In addition, the random phase transducer technique allows a noise reduction at each observation point. The shape of the evolution of the "pseudo-attenuation" with respect to frequency is quite similar whatever the position of this observation point.

Besides, the frequential evolution of the "attenuation" is at the opposite of the "pseudo-attenuation" one. In the case of the spatial compounding technique, the "attenuation" is an increasing function of frequency; backscattered signals become poorer in higher frequencies during the propagation (the central frequency of the signals decreases with respect to time, because of the absorption caused by the direct conversion of ultrasonic energy into heat), and the "attenuation" is stronger in higher frequencies. When, the random phase transducer behaves exactly like an array made of small omnidirectionnal transducers. Its larger directivity pattern allows to collect the multiple scattering effect created inside the steel sample. Consequently, the central frequency of the signals tends to increase as a function of time and the "pseudo-attenuation" (it includes the classical attenuation measured by a coherent transducer and the multiple scattering effect) is lower at higher frequencies.

Multiple scattering effect characterization: to characterize the multiple scattering effect, we have computed the "pseudo-attenuation" of the backscattered signals with the five unfocussed transducers described in table 1. Thus, we can present the evolution of the "pseudo-attenuation" in a frequency bandwidth included between 0.5 MHz and 6.5 MHz (figure 7).

The concatenation of these 5 graphs introduces imprecisions at the joined points. Nevertheless, a tendancy appears around 1.5 MHz. Up to this characteristic frequency, the "pseudo-attenuation" is an increasing function of frequency; the multiple diffusion effect is negligible and the higher frequencies of the signal vanish during the propagation. Beyond this frequency, the "pseudo-attenuation" is a decreasing function of frequency. This decreasing is fast up to about 2 MHz and then becomes considerably weaker. The multiple scattering effect contributes to amplify the higher frequencies and makes up greatly for attenuation by absorption of the signal

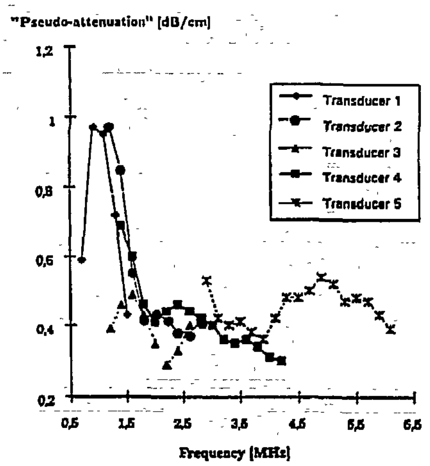

Figure 7 : "pseudo – attenuation" measurement in cast stainless steel

CONCLUSION

We have presented the interest to use random phase transducers in coarse grain stainless steel NDT. These transducers allow a speckle reduction at each local observation point and do not induce any diffraction effect. We have shown that a time frequency analysis allows to measure a "pseudo-attenuation" caracteristic of the cast stainless steel. This "pseudo-attenuation" includes the attenuation by absorption and the multiple scattering effect which amplify the higher frequencies of the signals. The "pseudo-attenuation" appears as an increasing function of frequency up to 1.5 MHz and then, as a decreasing function of frequency. The random phase transducer technique is a good tool to characterize the strong multiple scattering effect beyond 1.5 MHz. Further work is in progress to apply the random phase transducer technique in NDT of coarse grain stainless steel.

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