WCNDT '85

ULTRASONICS

ULTRASONIC TESTING AND EVALUATION. SELECTED TOPICS

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INTRODUCTION

Some introductory remarks will be given at the beginning. They are of a general character and concern to all ndt methods. They find perhaps special attention in ultrasonic methods as they create at present a very powerful branch being widely used and developed in science and industry. The confirmation of this statement can be found when one looks at the number of papers published on ultrasonics as well as on the number of papers presented during the last four world conferences on nondestructive testing.

There are four main branches which determine the possibilities and the needs for the application and development of ndt. These are:

* Physical fields which can be used for the investigation of material state
* Signals which arise due to the interaction of physical fields with the macrostructure amd microstructure of materials to be tested
* Materials with their imperfections which causes the decrease in their properties and behaviour, e.g. the decrease in strength, fracture toughness, resistance to temperature, wear, etc.
* Structures which needs monitoring of their integrity, loss of ability to perform its duty due to the ageing caused by stress, fatigue, creep, corrosion, irradiation and similar factors.

The need for ndt is justified mainly by economical reasons and the trend to make best use of the material without influencing the safety and the reliability of the component. To fulfil the tasks, which arise from the demand of the modern industry and the necessity in material conservation, the activity in ndt is being developed in following directions:

* Selection of the phenomenon which can be used to supply the information about the material state, i.e., the material macrostructure and microstructure
* Understanding the interactions of physical fields with material structure and describing the phenomena arising in order to create the basis for the development of a specific technique or precedure of testing
* Elaborating and developing the methods for testing materials, for measuring material properties and for condition monitoring
* Elaborating the means (hardware) to realize the goals standing before the ndt methods
* Elaborating the methods of data acquisition, their treatment and presentation.

The various directions outlined above bring their contribution to the extention of phenomena oriented research and industry oriented research.

A convenient starting point to further discussion is to make some cross sections through the needs, through the phenomena used to get the information we are looking for, and through the hardware and software being developed. The needs for ndt arise from four main domains. These are:

* Production
* Maintenance
* Materials science and engineering
* Condition monitoring which may also be regarded as being in direct connection with the maintenance.

More specifically, there is a need to supply the information about:

* the presence of the flaws, * their intensity, * distribution, * location, * kind, * and finally about the size and orientation.

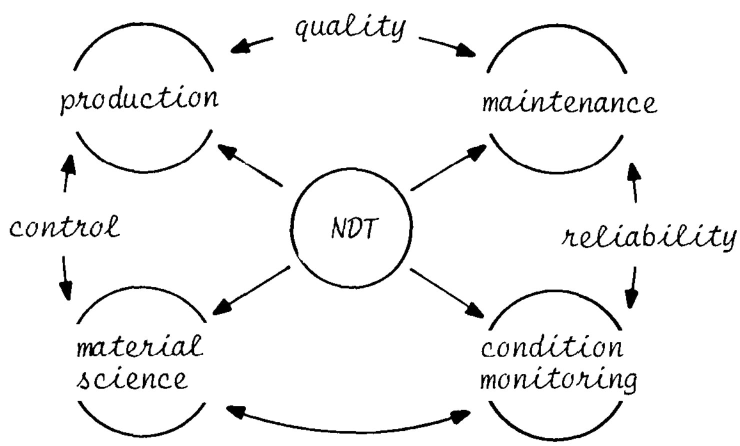


Fig. 1. Nondestructive testing serves as the source of pertinent information in design, production, maintenance, condition monitoring and sciense

These last two information have perhaps an extremaly important value. They supply the quantitative information which can be used for various estimations concerning, in the firts place, the flaw significance, i.e., their influence on strength, endurance, risk of fracture, resistance to temperature, corrosion wear, etc.

Further, there is a need to get information which serves to monitor the condition of the structure and components. Let us mention here the level of stresses arising with static and dynamic loading, early detection of incipient changes in the material during the incubation period in fatigue, changes in material which are developing in the material subjected to the creep conditions, the changes in the material state in corrosive environment, and changes in the surface layers due to the wear.

MATERIAL BEHAVIOUR, RISK OF FRACTURE AND DESIGN PHILOSOPHIES

The major cause of material degradation are: * fatigue, * corrosion, * creep, * shocks (mechanical, thermal).
The above mentioned influences of alternating straining, environment attack, temperature and way of the loading may bring to the formation of cracks, loss of cohesion between the grain boundaries, brittleness of the material and also to final fracture at a single application of the load.

Material subjected to the influence of mechanical stresses may behave in a brittle or a ductile manner. This behaviour depends on: * material structure, * temperature, * state of stresses (also flaws which change the state of stresses in the vicinity of the flaw), * loading condition (static, dynamic, shocks).
The combination of the above mentioned factors effects the material behaviour in such a way that the same material may behave in a brittle or ductile manner. In a qualitative way it was demonstrated since a longer time (2).

Quantitatively, the risk of rapid fracture, which is connected with the brittle behaviour of material, can be assesed using fracture mechanics approach. Two principal equations of fracture mechanics describe the fracture conditions and the crack propagation law. The condition for fracture is shown in Figure 2a.

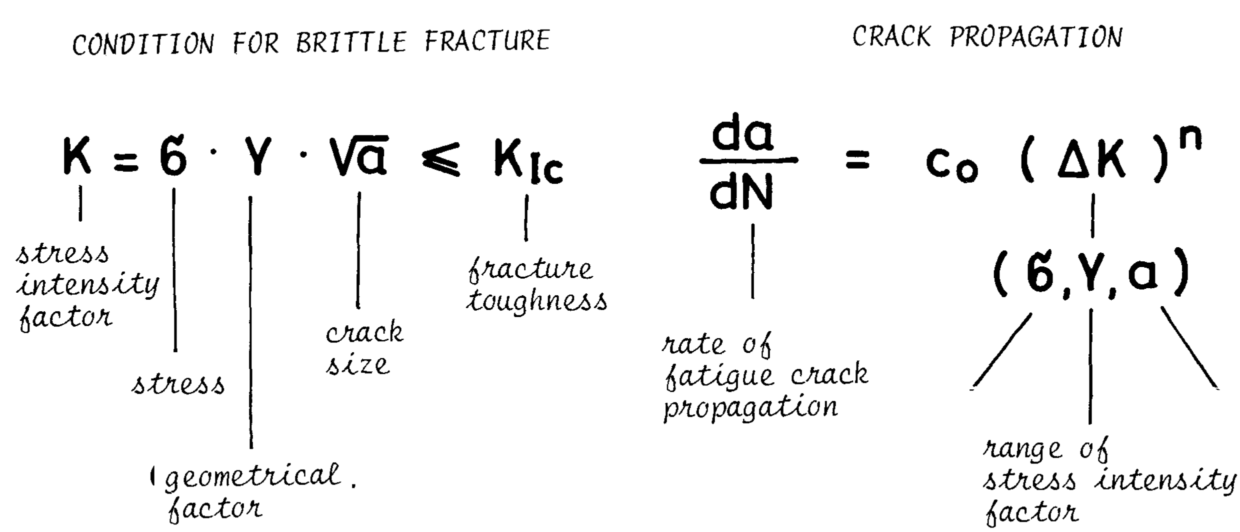
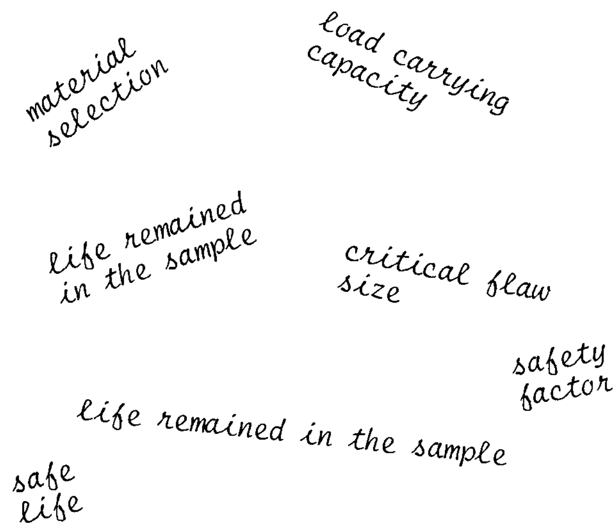


Fig. 2. Equation for estimating brittle fracture condition and fatigue crack propagation

In the case when fully plane state of strain in the vicinity of the crack tip exists the linear elastic fracture mechanics approach, LEFM, can be applied. However, when the conditions for plane state of strain are not fulfilled, at the crack tip there may grow a plastic zone and in this case the elasto-plastic fracture mechanics approach EPFM, has to be used.

Figure 3 shows in a descriptive way various possibilities which exists when fracture mechanics equations are used. Knowing the quantities appearing in equations (Fig. 2) one is able:

* to select the material which gives the best assurance against risk of fracture
* to determine the loading capacity of the sample containing flaws
* to determine the risk of fracture, i.e. to estimate the critical crack size for given conditions of loading and for known material flaws which may exist in the material
* to estimate the life still remained in the sample when fatigue conditions exists
* to estimate the factors of safety against brittle fracture, or for safe life in fatigue.



K	σ	Y	$\sqrt{a}$	K_{Ic}	ΔK	C_0	n
	•	•	a_{cr}	•	critical flaw size		
	σ	•	•	•	loading capacity		
safe life					•	•	•
•	•	•	•		•	safety factor	

* KNOWN VALUES

Fig. 3. Various possible estimations when using the fracture mechanics approach

Knowing material properties, loading condtions, environment, state of stresses, one can define some strength criteria, e.g., conditions for rigidity, or for strength from general theory of elasticity and strength analysis, as well as conditions for brittle fracture and fatigue life from fracture mechanics approach, LEFM or EPFM. Criteria for design of a structure which is safe against brittle fracture at static loadings requires the use of equations from Figure 2a, with the modifications depending on the plastic contribution to the crack propagation (1,3,4).

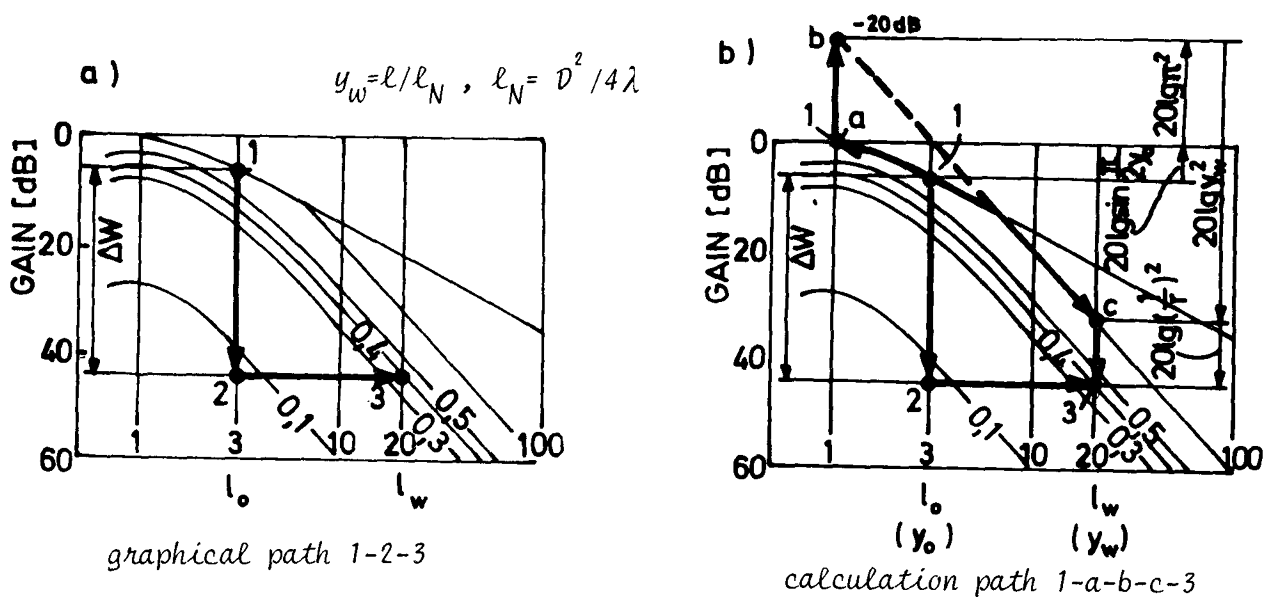
For fatigue there are several design criteria. Some of them require the application of ndt methods:

* Infinite life design. The design stresses has to be lower than the fatigue limit.
* Safe-life design. It denotes the designing for a finite life. The design stresses may be greater than the fatigue limit, because many structures suffer during their service only a limited number of fatigue cycles. The calculations are based, in such cases, on the stress-life curves, strain-life curves and crack growth relations. The application of crack growth relation is a necessity, as some degree of probability must be considered that there exist flaws in the material.
* Fail-safe design. It recognizes that fatigue crack may occur or material flaws are present, however, the structure due to the crack stoppers and multiple load paths will not suffer a final failure before the defects are earlier detected with nondestructive testing.
* Damage tolerant design. It is assumed that crack caused in fabrication, or as a fatigue failure, exists. The fracture mechanics based analysis has to check wether crack will grow large enough before it could be detected during periodic inspections with nondestructive testing techniques. As an example of such design of pressure vessel, the concept "leak bef re break" is being applied. It means that the critical depth of the flaw is greater than the wall thickness and there will a leak before condition for brittle fracute occurs. The arising leak can be quite easly detected with ndt methods.

QUALITATIVE AND QUANTITATIVE TESTING

From the previous general considerations it results that the information about material flaws and structure must be of a qualitative character. It must supply the details about * location, * orientation, length and height of the flaw. Thus, the future development of the procedures of ultrasonic testing have go in the direction of a quantitative evaluation. This imposes strong requirements on procedures which must be strictly followed in order to avoid errors which sometimes may be larger than the measured parameter. For this reason the sensitivity setting and resolution of the instrumentation must be exactly specified.

Meanwhile ultrasonic testing still has mainly a qualitative character. Most information we get from conventional and routine testing is connected with the detection of flaws, their intensity and location. It cannot be used in the analysis of strength or fracture. However, being of a qualitative character it contributes significantly to ensure the reliability. It can be used in service, e.g., to find out if the detected flaws remain unactive in service conditions.
To make the results of ultrasonic testing more quantitative, there have been attempts in the past to apply methods allowing to arrive at good reproducibility of results, to maintain the reliability of testing and to present the results in a qualitative and not in a descriptive manner. This approach is based mainly on the known DGS-diagram (distance-gain-size). (Fig. 4-5). The DGS diagram may be used as a diagram for a specified probe-head, or as a universal or standardized diagram. Parts of such a diagram may be transferred on the oscillloscope screen of the ultrasonic instrument as the so called DAC curve (distance-amplitude-correction). An another possibility is to get the DAC curves directly from the experiment using samples or references blocks containing artificial reflectors, like discs, cylindrical holes or cuts having a defined reflection area and situated perpendicularly to the incident ultrasonic beam.

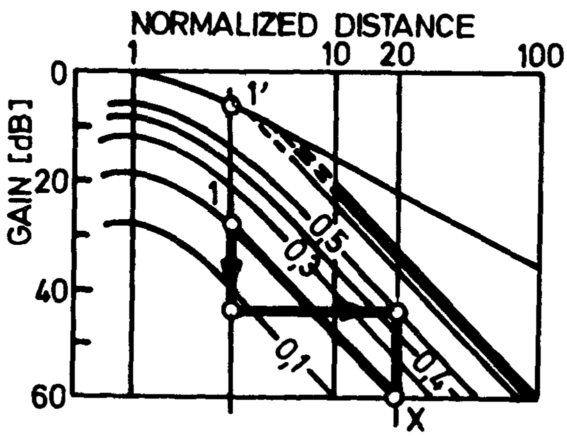


$y_0 = 3$ $y_w = 20$ $\Delta w = 38$ dB $k_{38} = 79,4$ $\quad r = \sqrt{\frac{y_w^2}{2\pi y_0} \cdot \frac{1}{k_{\Delta w}}}$ *in far field*

Fig. 4. Estimating the size of equivalent flaw (flat-bottom hole) using:
a - graphical path, b - calculation path

When the reference conditions, i.e., the reference reflector, the sensitivity setting and the reference points are exactly specified it is also possible to calculate relative sizes of the flaws.

The relative or equivalent flaw size means that the reflection from the real flaw is the same as the reflection from a reference reflectors of known disc diameter. More strictly speaking this denotes not the sizing of the flaws but only a way of qualitative classification of ultrasonic indication.



$$r = r_0 \sqrt{\frac{y_w^2}{y_0^2} \cdot \frac{1}{k_{\Delta w}}}$$

$r_0 = 0,2$ $y_0 = 3,15$ $y_w = 20$

$\Delta w = 16$ dB $k_{16} = 6,3$

$r = 0,506$

Fig. 5. Estimating the size of equivalent flaw (flat-bottomed hole) using calculation path when small reference reflector is given

Figures 4-5 show normalized DGS diagrams with the graphical path showing how to estimate the size of an equivalent reflector (flat bottomed hole). The starting point is the reference point, i.e. the reflection from a known reflector of known size. The difference in gain needed to bring the indication (echo) from the real flaw and from the ideal (disc shape, or flat bottomed hole) to the same height on the screen of the ultrasonic instrument, represents the path 1-2. The path 2-3 bring us to the point through which goes the line which corresponds to the size of the ideal reflector, search for.

As mentioned earlier, with known initial settings of the ultrasonic instrument, there exist the possibility of estimation the size of an equivalent ideal reflector (disc shape) by a simple calculation. This is shown in Figures 4-5. The formula given in these Figures are valid only in the far field. For distances being smaller or not much greater than the near field length, some corrections are needed.

Two examples presented in this Figure present two cases. The first is when large reflectors serves as the reference reflector, the other when the starting point is a small reflector.

The DAC curves can be transferred from DGS Diagram or determined experimentally. They are shown in Figure 6. In this case when the reference point on the screen is specified, i.e. the size of the reference reflector d_O, and the reference height h_O, are known one can calculate the sizes of equivalent ideal reflectors from the equation shown in the Figure 6. The restrictions imposed on this equation are that the flaw must be in the far field and the Y characteristics of the oscilloscope screen is linear.

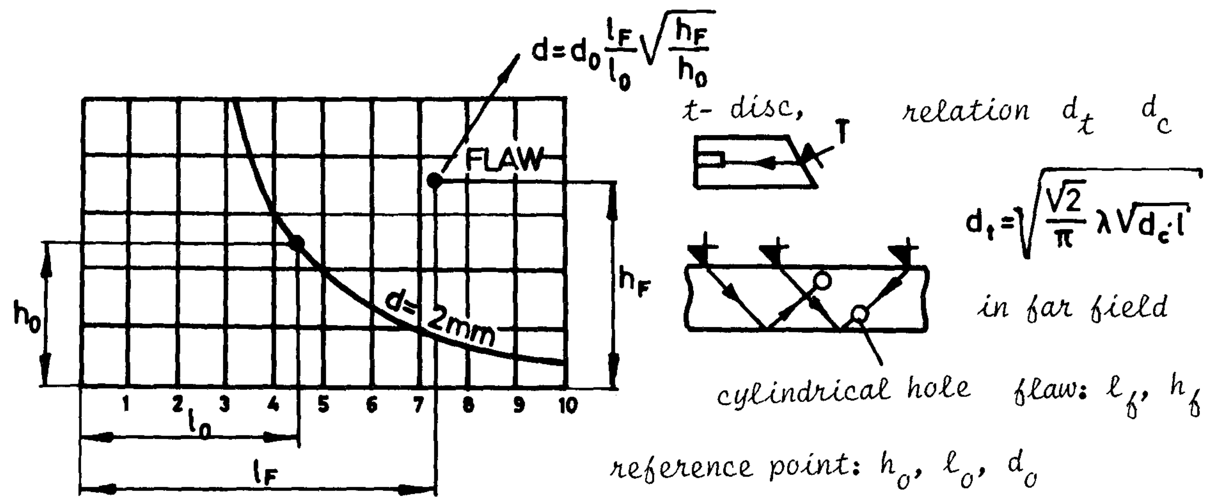


Fig. 6. DAC curve and formula to calculate the size of equivalent flaw in far field at linear Y-characteristic of the screen

When as a reference reflector serves the horizontal cylindrical reflector the size of an equivalent disc is calculated from the other formula shown in the picture.

To the quantitative approach in ultrasonic testing belongs the determination of crack or flaw height, flaw length, and flaw orientation. Also the determination of residual stresses or caused by the applied load, belongs to the quantitative methods. The same may be said about the correlation between material properties and any kind of ultrasonic indications. The determination of the flaw height will be discussed in a special subhead later, the same concerns the stress determination. The correlation between ultrasonic indications and other material properties will be, however, omitted as the corresponding procedure, mainly for concrete, are a well established and normalized routine testing. To this end a short notice on the reject acceptance criteria is given. There are, principally, two kinds of reject/acceptance criteria to be distinguished, namely the manufacture quality or attainable workmanship quality and fittness-for-purpose quality. The manufacture reject/acceptance standards are based on the quality of a product which can be achieved in routine practice, and the ability of the inspection method to detect the discontinuity. The fittness-for-purpose is a more thorough investigation based on the analysis of strength, brittle fracture and the sizes of existing or detected flaws. The fittness-for-purpose serves as a substitute for the manufacturing quality requirements. In the fittness-for-purposes quality, some loss in performance is justified not only from economical but also from technical reasons. This relates to expensive repairs against marginal improvements, and to cases when the risk exists that the repair made under less favourable conditions, than during the fabrication, can lead to flaws hardly to detect or being worse than the original repaired flaw. There exist also the danger, e.g., during weld repair of introducing the internal stresses hardly to remove and even to measure their level.

With problems presented shortly above is connected the risk/benefit analysis, where it is to weight the costs of false acceptance against the costs of false rejection. Considering must here be given to the problem of allowing a component to be used reliable for the greatest possible time instead of being withdrawn from the service.

The considerations presented above are indicative for the fact that the fitness-for-purpose approach is less conservative than the manufacture quality approach and requires exact characterization of material discontinuities.

DETECTION, REGISTRATION AND ANALYSIS

With the large flexibility of ultrasonic methods and exceptionally large variety of possible applications, it is quite difficult to give a comprehensive and general outline of the present state and trends in this technique. It results from the very great versatility of the method and on the other hand on the necessity of adopting the technique to geometrical configurations of the parts to be tested. Thus, the incidence angle, the phenomenon used, the distance travelled to the flaw, the accessability to the probes depend to a great extent on the geometrical condition of the parts or components.

The process of ultrasonic testing can be devided into three phases: * detection, * registration, * analysis. The detection of flaws and other inhomogeneities is carried out with simple portable equipment and more or less sophisticated automatic set-up. The conventional probe heads are able to fulfil the main taks, the detection. For more complicated cases an arrangement of fixed or moving probes are used. The difficulties for securing an appropriate acoustic coupling, is being now avoided by the application of contactless probes, known as ema or emat transducers.

In some cases, especially in immersion technique, focussed probes allows to achieve the desired detectability of the flaws. It was several times demonstrated that the phased transducers offer new possibilities in location and in flaw size estimation. Electronic sytems allow to form the ultrasonic beam, and to change the refraction angle.

To get more complete information about material discontinuities there is a need for acquiring many indications in a short time. This can be obtained using various data acquisition techniques for automatic ultrasonic testing. The system applied use digital signal acquisition and a further fast signal processing which allows data reduction to be applied in a real time. We arrive in this way to the computer aided ultrasonic systems and to the various algorithms used to interpret a great amount of data sometimes in real time. A further step are the ultrasonic systems. They become now a growing attention, as they can be applied for testing components unaccessible for the men due to the healthy security.

Two points more are to be considered in connection with the flaw detection. Analitycal studies of direct and inverse propagation problems show a direct links to experimental investigations od crack detection and residula stress evaluation. Pattern recognition is playing an increasing role in automated systems to interpret and analyse large quantities of data. It is used for signal recognition in real time radar/sonar signals machine vision including industrial robot vision and automated inspection systems. The phases of applying this technique are: * the preparation of raw data, * the techniques used to key pattern recognition, * designing and implementing real time pattern recognition technique.

Special attention draws at present the detection of flaws in ceramic materials, applied as design materials. They posses in general a comparatively low fracture toughness. Due to this the critical flaw size is very low, thus there arise the requirements for the application of high frequency ultrasonics to get desired detectability of fine flaws.

Great attention is being know devoted to the application of electronic means for detection, registration and analysis of a great collection of data. The application of vatious methods of acquiring the information makes it possible to improve the objectivity and to discriminate the influence of subjective factors. The trend in automation and real time analysis claims for more attention. Without the progress in this direction it would be impossible to make the analysis not only on the basis of static pictures, but also the dynamic pictures.

The static presentation rests on the results of measurements of signal amplitude and the time-of-flight of ultrasonic pulse. This quite poor information is broadened by the use of dynamic response of the flaws which presents the envelope of large amounts of single relfections, taken from various positions flaw-probe head or through the irradiation of flaws with the beam at various refraction angles. An excellant example is the use of phased arrays probes. With their help it becomes possible to form the ultrasonic beam, i.e., to change the refraction angle, and to realize the dynamic focussing of the beam. Even if some developments did not found their place in routine industrial practice, it shows the increasing possibilities in testing to supply the information which can be used in further assessment of material quality, its reliability and in the estimation of safe life of components, or structures.

CHARACTERISATION, CLASSIFICATION AND RECONSTRUCTION OF FLAWS

Characterisation and classification of material flaws serve to supply the information needed for an exact estimation of material quality or material state. When use is made from the classification into groups of quality, the experience plays the most important role in the dividing into the proper classes. However, as it was said such classification is hardly to be used for quantitative estimation. It gives rather a general overview of the material state. An example of such classification is the application of DGS-diagrams, and curves like DAC determined experimentally, transferred from the DGS diagram or calculated theoretically. More advanced methods for defect reconstruction and classification use the flexible and fast electronic data collecting with phased arrays, monostatic or bistatic arrangements. (probes fixed at one or at two positions).

For reconstruction purposes algorithms were developed for synthesized aperture. Let us mention some of them:

* for monostatic or bistatic probe arrangements: STP - Sattelite Pulse Technique, SEM - Singularity Expansion Method, SPEK - Spectroscopy
* algorithms valid for synthetic aperture and geometrical optics: EIS - Exact Inverse Scattering, SAFT - Synthetic Aperture Focussing Technique, LSAFT - linear version of SAFT, MHF - Multifrequency Holography, ALOK - Amplituden-Laufzeit-Orst-Kurven, PHAR - Phased Arrays, HOLOSAFT - combination of holography and LSAFT
* algorithms valid for physical optics: RS-HOL - Rayleigh-Sommerfeld Holography, POFFIS - Physical Optics Far-Field Inverse Scattering, PONFIS - Physical Optics Near Field Inverse Scattering
* algorithms for low frequency approximation: INV BORN - Inverse Born Approximation
* algorithms valid in the frequency independent range: FIFFIS - Frequency-Independent Far-Field Inverse Scattering, FINFIS - Frequency Independent Near-Field Inverse Scattering.

These various algorithms are given here as the indication to demonstrate the direction for improved measurement accuracy and reliability.

FLAW SIZING

The methods of sizing materials flaws developed at present may be characterised according to the phenomena used. There may be distinguished methods where use is made from:

* the amplitude of the reflected signal
* the echo envolope of reflected signals
* the interaction of ultrasonic waves with the tip of the crack or with the surface flaw surface.

Graphical presentation of the main concepts of flaw sizing is presented in Figure 7.

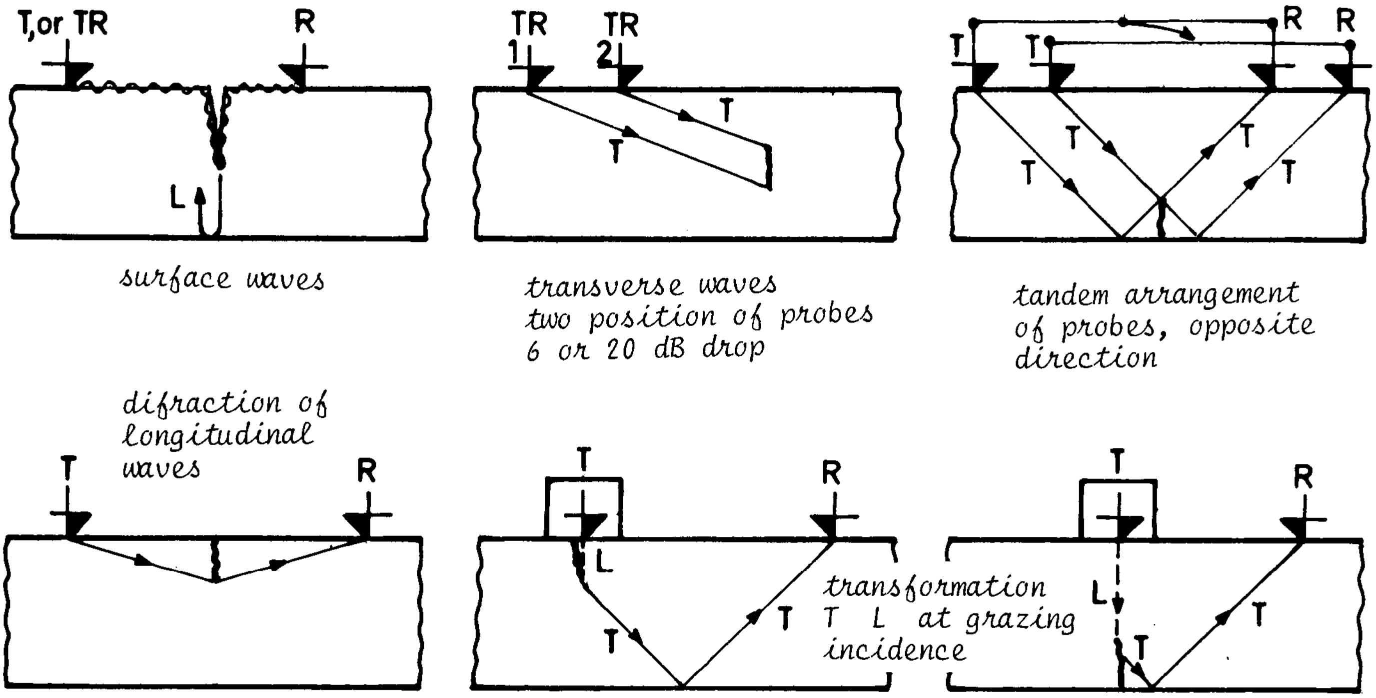


Fig. 7. Various methods of crack depth measurement

The detection of surface breaking cracks with a single probe using subsurface waves, surface waves or transverse wave does not give the desired accuracy. Using the surface wave the amplitude or the time-of-flight of ultrasonic waves can be used too. The amplitude of the reflected surface wave signal depends on the condition of the crack, its width, inclination, and the material which is filling the gap between the crack surfaces. Using the transverse waves, the proportionality between the reflected amplitude and the crack height shows a saturation beginning from several milimeter height. The height of larger cracks can be assessed with two probes in tandem directed one against the other. Here, the resolution of several tenth of milimeter can be achieved. Another possibility exists when use in made from the refraction of longitudinal wave at grazing incidente of longitudinal waves on the crack surface.

For surface breaking cracks the best resolution was obtained with the diffraction method. Using an appropiate refraction angle of longitudinal waves, in the range between 50 and 60 degrees, comparatively high precision could be obtained. It was reported that in ceratin cases the accuracy of 0.1 mm could be achieved for the crack depth range beginning from about 2 mm to about 40 mm.

When measuring deep real cracks the effect of crack closure could be observed. The were signals visible, which could be transmitted through the crack. However, adopting after some trials, the distance between the transmitting and receiving probes the estimation was close to the real depth of 45 mm.

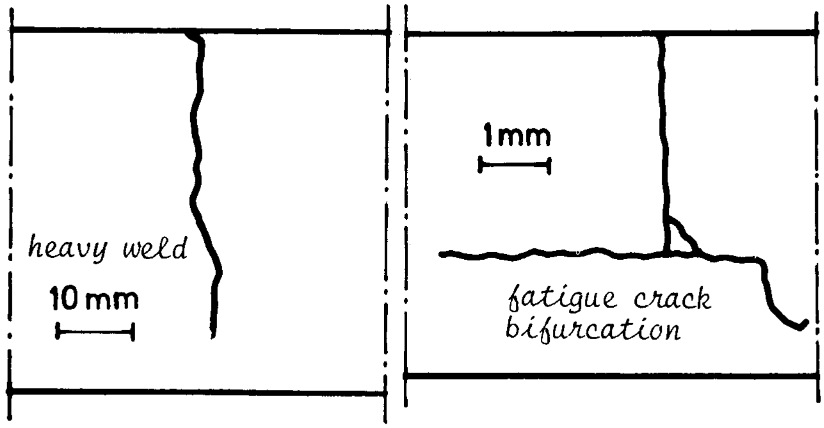


Fig. 8. Two examples showing the depth of real cracks which have been measured with time-of-flight technique

An another example of the application the diffraction methods to crack depth estimation was a bifurcated crack. In spite of this bifurcation the estimations agreed quite well with the real crack depth (Figure 8). It is to notice, that also a wide-band laser generated surface acoustic waves were applied for crack depth estimations.

MATERIAL STATE ASSESSMENT

The possibilities created with the development of ultrasonic technique are not restricted to the testing for flaws and inhomogeneities. There is a large field of material properties and changes in material state which can be assessed when using advanced ultrasonic technique. Except grain size determination, and estimation of concrete compressive strength, as well as tensile strength of grey cast iron, there is now little progress to be noted in the assessment of material properties, especially for materials behaving in a ductile manner.

The principal parameters used for indirect estimation of material properties are the velocity and attenuation. This limited information can be extended on other parameters characterizing the ultrasonic signals when use is made of transform, e.g. the Fourier transform from the time domain to the frequency domain. The parameters obtained in this way can be used in pattern recognition techniques. Such problems where use of pattern recognition technique seems to successful are high attenuated materials like carbon reinforced plastics. Material with high attenuation can be inspected only in through transmission technique and the signals transmitted depend on the distribution of material properties which can change from one place to another, and on the imperfection causing the decrease in material properties. In this case the pattern recognition technique may be applied with success when a model is established with which the detected signals could be compared.

The ultrasonic method which are used for quality control during manufacture can be applied as a prevention technique for safety during service. In this case the whole volume of the part or only selected zones are of interest. The cases when material is subjected to the influence of heat or corrosion are examples when large volumes of material have to be tested. The cases when only local zones are of prime interest is material fatigue which starts at the zones of large stress concentrations. One of the most sensitive parameter which can be used to make estimation on life to failure is ultrasonic wave attenuation. There may be used longitudinal and surface waves as well. An example of such estimation is shown in Figure 9a.

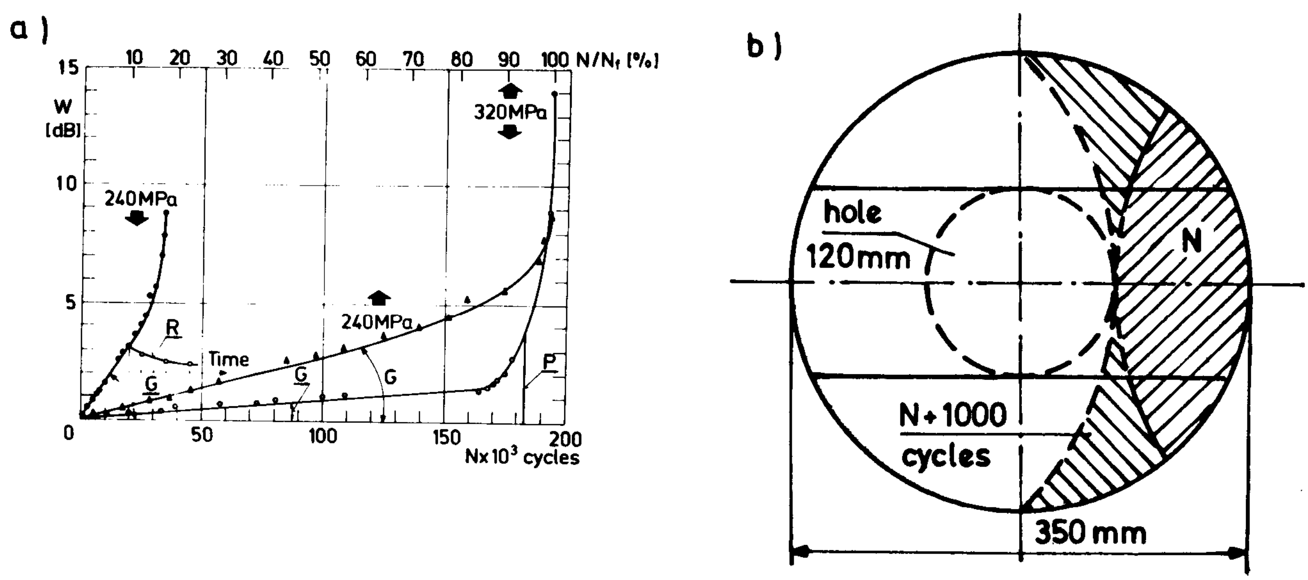


Fig. 9. Using the attenuation measurement for fatigue life estimation (a), and crack growth monitoring to ensure a reliable ramp life (b)

The increase in attenuation is presented against the number of cycles of alternating straining. Two curves are shown for two samples with different loading. The sample subjected to lower loading level 240 MPa showed unexpectadly shorter life than an another sample subjected to bending stresses 320 MPa. One can see from the Figure that the gradient of increase in attenuation is larger for the sample having shorter life than for that with longer life. Similar examples have been demonstrated when using the surface waves. These examples illustrate great possibilities of ultrasonics in prediction the fatigue life. The approach can be greatly enhanced when an advanced analysis to such problems could be applied.

Additional example in Figure 9b presents crack growth monitoring of a big ram in a hydraulic press. During service a crack of the size shown in the picture was found afterwards due to the monitoring in short time intervals it was possible to allow it to work safely for about 1000 cycles (3 weeks).

STRESS ESTIMATION

The factors which may play very important role in the material behaviour are the residual stresses and stresses induced by loading. The approaches to detect the presence of stresses, their spatial distribution as well as their level, are based on theoretical considerations presented about thirty years ago. It appears from the nonlinear theory of elasticity that the change in ultrasonic wave velocity is related with the stress level through the third order elastic constants. To determine the stress level longitudinal, horizontally and vertically polarized transverse wave and surface wave can be used. The changes in ultrasonic wave velocities are very samll, of the order of 1-3 m/s when the stress level changes by about 10 MPa. To detect such changes, very fine resolution in measuring the time-of-flight of the order of a nanosecondand or better is needed.

There are several factors which disturb the measurements. The temperature, the anisotropy, the variation in material structure, the changes in the path travelled by ultrasonic waves when the sample is deformed and the stress distribution along the path of ultrasonic waves, are contributing significantly to the changes in time-of-flight. The changes in ultrasonic wave velocity may be caused by the distribution of stresses along the path travelled by the ultrasonic waves too. Such situation exists e.g. in bolts of varying cross section subjected to tensile loading. An appropriate correction must then be determined experimentally or by calculations based on theoretical considerations.

The temperature dependence of ultrasonic wave velocities can be used for stress estimation too. In this case the slope of the dependence is stress dependent by independent of texture. Also the application of birefringence dispersion methods seems to be very promising in stress determination.

CONCLUSIONS

Some selected directions in ultrasonic testing presented after outlining general problems connected with nondestructive testing, indicate that improving the ultrasonic quality testing and control during manufacturing and in service would ensure that

* material properties are more consistant
* hidden flaw are less common
* reliability of inspection technique is contained in know tolerances
* the changes in materials being exploited can be detected with sufficient degree of confidence
* the prediction about risk of fracture and life to failure will become more precise.

For this purpose the ndt reliability should be enhanced. There are two important strands running through all consideration devotoed to gaining a quantitative appreciation of the factors which govern the reliability of inspection methods. These are the probabilistic consequences of imperfections in inspections methods and factors contributing to the probability of defect detection. As the inspection tells us very little about the defect severity and less about the life to failure, attempts are necessary to extend the understanding about failure modes, and possible changes which preced the crack propagative state in material.

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CONCEPTS OF NDT SYSTEM FAMILIES
FOR INDUSTRIAL APPLICATIONS

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1. Introduction

In the beginning of the 60th, the increasing utilization of nuclear energy for electrical power generation was the most important research and development project in the Federal Republic of Germany. New technologies had to be developed and safety standards to be defined. In the field of NDT, there rose the necessity to inspect cladding tubes for nuclear fuel rods according to rather tight specifications. This was the starting point for the development of a series of NDT system families. The first result was a system called "Rohr-Prüf-Anlage (RPA)", to be simply translated as tube testing system, characterized by immersion tank technique with the tubes to be tested passing the transducers in spinning movement. Rather soon after the industrial realization of this testing technology the application of NDT techniques, especially UT techniques, has been expanding into different directions:

- Advanced application needs
  - . higher inspection speeds,
  - . larger dimensions,
  - . different geometries of pieces to be tested,
  - . different materials
- Utilization of advanced measuring techniques
  - . combination of different materials and geometries,
  - . substitution of water coupling,
  - . combination of different measuring techniques
- Automatization of operation and data acquisition

The following briefly describes how an industrial manufacturer of NDT equipment can reach a sufficient standard of product variety, reliability, and quality by a systematic way of diversification. The different steps of the development are shown in Fig. 1.

2. Application needs

2.1 Higher inspection speed

The first RPAs mentioned above were able to rotate the tubes to be tested at 900 r.p.m. In order to increase the testing speed essentially a family of rotating systems (ROTA) was created with a rotary