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Ultrasonic soundings of targets by processing of signals from plural receivers

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Introduction

Ultrasonic pulse echo flaw detection systems have been widely used in the field of nondestructive testing for quite long time. Theoretical studies made in the 1970's and early 1980's suggest that ultrasonic NDT using pulse compression technique can overcome some of the drawbacks of classical pulse echography[1-5]. The limitation of currently available ultrasonic instruments hardly lies on the property of hardware but it may lie on the lack of sufficient signal processing techniques[6]. At present, the ultrasonic A-scan instrument is most commonly used, which is in fact the fundamental part of other advanced techniques such as ultrasonic imaging. It is believed that the received A-scan signal may carry a lot of information on material property and defect but the information appears in various guises of noise, which is yet to be deciphered completely. So further research in ultrasonic signal processing techniques is essential to enhance the testing ability of ultrasonic instruments. During the 1990's, a lot of research has been done on ultrasonic signal processing and still now the endeavor is going on in search for more reliable and versatile signal processing techniques[7-14]. Generally the flaw signals measured in ultrasonic NDT include the effects of the measurement system and are corrupted by different kind of noise. The highly complex interaction between the defect geometry and the back-scattered ultrasonic wave inside the test piece may not be assumed as a linear process. So the signal processing techniques, which require a priori knowledge of noise statistics are subject to fail in many situations. Therefore the approach of signal processing should be involving the noisy signal itself in constructing the signal processing method. A study on choice of coding signal demonstrates that M-sequence is the best choice if the medium is subject to motion or movement[15]. So the application of M-sequence approach should get more attention. The use of inverse filter in ultrasonic signal processing has given a significant degree of success over rival methods during the last one decade with different people using it in different ways[16-21]. In these methods, probably the potential of further improvement lies in utilizing the received data itself to design the inverse filter or even cascaded inverse filters.

Conventionally three types of scanning, A-, B-, and C-scan, systems are used for ultrasonic flaw detection or target sensing. In each case of the scans, the transceiver simply transmits a pulse signal in the medium and then receives the echoes from the target. Then the resulting echoes are shown on the display where A-scan works by fixing the transceiver system whereas both B-scan and C-scan necessitate moving it over the test specimen. Here the amplitude of the reflected signal plays an important role for the display mechanism. These traditional methods usually involve single transceiver system, which must use a scanning mechanism in order to detect and locate the target. It would have been a simple and convenient way, if the target could be detected and located by keeping the transmitter and receiver at fixed places, which does not need thorough scanning of the investigating medium. For an instance, it may be useful to locate a school of fish inside shallow water in a bay without sounding by boat. In this paper, we propose a method, which involves a single transmitter at a fixed place, and several receivers, which are also fixed at some predetermined positions, using the correlation method for acoustical diagnosis of targets or flaws. To make the method workable under any noise condition, several noise reduction techniques are devised, which can successfully retrieve very weak signal buried under high noise. In this paper, a new approach of designing an inverse filter (mismatched filter) is introduced, which calculates the parameters based on the part of the system response. So it is able to adjust its parameters according to the system response in minimizing the system noise. In addition, a simple elementary geometrical method has been proposed which can efficiently pinpoint the location of faults. The method is based on the travel time (TT) of the signal from transmitter to the receiver via target. Primarily the air medium between two acrylic plates has been chosen to illustrate the feasibility of the method. The system has been successfully operated to detect artificial flaws consisting of small targets in air.

Theory and basic principle

Suppose a two dimensional system in which a transmitter and plural receivers are set at predetermined points and small target(s) exists. Instead of burst of ultrasonic wave, several full length M-sequences, modulated by ultrasonic wave, are used as the transmitting signal and reflections from the targets are received by the plural receivers at different points. Cross correlating the demodulated received signal with the original M-sequence, the reflections corresponding to the targets can be detected in the form of sharp peaks. Manipulating the received data from the plural receivers, locations of the targets are determined in the investigating medium. With perfect modulation and demodulation in an ideal system, the transceiver system output (one input of the correlator) can be made a replica of the transmitting signal[16)]. In this work, we have performed the amplitude modulation (AM) of the carrier by M-sequence. In the receiving end, the envelope of the AM is detected by quadrature demodulator.

To explain the principle of obtaining the impulse response by correlation process, let's consider *x(t)* be the transmitted sequence, *y(t)* be the received sequence and *h(t)* be the impulse response of the composite system, which includes the test piece, the transceiver system and their associated electronics. As a matter of fact, the scattered ultrasound, that is picked up by the receiver, and the additive system noise *n(t)* constitute the received signal *y(t)*. The output of the correlation filter can be represented by

$$\psi(\tau)=\int x(t+\tau)[x(t)*h(t)+n(t)]dt \tag{1}$$

This is in fact the cross correlation between the transmitted sequence and the received sequence (inside the third bracket). By interchanging convolution and integration, and computing the autocorrelation of the transmitted sequence, the output correlation function representing the signature of the test object is

$$\psi(\tau)=h(\tau)*\psi_{xx}(\tau)+N_y(\tau), \tag{2}$$

where $N_y(\tau)$ is the random noise component given by

$$N_y(\tau)=\int x(t+\tau)n(t)dt \tag{3}$$

and $\psi_{xx}(\tau)$ represents the autocorrelation function of the transmitted sequence. If the autocorrelation function of the transmitted sequence could be made a perfect delta function equation (2) would become

$$\psi(\tau)=h(\tau)+N_y(\tau) \tag{4}$$

and we would have readily got the impulse response corrupted only by additive measurement noise. If the autocorrelation of the transmitted sequence can produce perfect delta function, it is possible to get the impulse response of the system without frequency distortion from the cross-correlation of transmitted and received sequences[15,22)].

It is not possible to get a truly random signal and its mathematically perfect autocorrelation function is practically unrealizable. However, there exist certain classes of deterministic but pseudorandom signals, which can serve the above purpose fairly well. The M-sequence, generated by shift register[23-24)] has been used as a pseudo white-noise input of the system, hence the cross correlation function (CCF) of the transmitted M-sequence and the system output will be proportional to the system impulse response. The transmitter sends a fan beam of the M-sequence towards the sounding area. The reflection from the target goes in all directions around the target and the receivers around the target receive the reflected M-sequence. The detection is accomplished by deriving the impulse response of the system from the CCF of the original M-sequence, and the received echo/reflected sequence. The cross correlation process can be mathematically expressed as

$$\psi_j(\tau)=\lim_{T->\infty}\frac{1}{2T}\int_{-T}^{T}x(t)y_j(t+\tau)dt \tag{5}$$

where *x(t)* is the transmitted sequence from the transmitter and $y_j(t+\tau)$ is the received sequence by *j*th receiver with a delay τ, which is supposed to contain some replicas of the transmitted sequence. $\psi_j(\tau)$ is the cross correlated output which is expected to produce a sharp peak corresponding to each reflection from the target(s). Let us suppose that there is only one target and that the transmitted M-sequence is denoted by *M(t)*. Now the received sequence will consist of (i) a direct sequence from the transmitter to the receiver (ii) reflected sequence(s) and (iii) noise. Ideally, the reflected M-sequence should be the replica of the original M-sequence delayed by a certain amount of time. So the received sequence can be written as

$$y_j(t)=c_{di}M(t-\Delta_{di})+c_{rj}M(t-\Delta t_{rj})+noise\,. \tag{6}$$

Both of the constants c_{dj} and c_{rj} depend on the position of the receiver. Moreover, c_{dj} depends on the characteristics of the medium while c_{rj} depends on the characteristics of the medium and the size of the target as well. The terms Δt_{dj} and Δt_{rj} are the delays corresponding to the direct sequence and the reflected sequence with respect to the original M-sequence. The CCF of $y_j(t)$ and *M(t)* is supposed to give two sharp peaks corresponding to the direct sequence and the reflected sequence at separate positions, according to the delays Δt_{dj} and Δt_{rj}. The position of the target can be determined in the following way.

From the peak position corresponding to the reflected sequence, the delay Δt_{rj} can be easily calculated. Once Δt_{rj} is known, the total distance d_j from the transmitter to the *j*th receiver via the target can be calculated by using the following relation:

$$d_i=v\Delta t_{ri}, \tag{7}$$

where *v* is the speed of sound in the medium under investigation. Then the target can be considered to be located on the ellipsoid whose foci are the transmitter and the jth receiver positions and the major axis length is equal to d_j. The exact location of the target can be determined using simple geometric method of finding the coincident point of the corresponding ellipsoids. The novelty of the method is that it does not require to scan the surface. In any general case it will require only a few receivers and a transmitter irrespective of the number of targets to detect.

Signal processing and noise reduction

If peaks corresponding to reflections from the targets were clearly identified in the CCF, it would be easy to locate the targets. In practice, however, it is quite difficult to identify them because of suspicious peaks in the CCF due to noise from the surroundings and it is essential to cancel out effects of the noise. In order to cancel the effects of surrounding noises as much as possible during transmission and reception, some measures have to be taken so that the original signal is not prone to mixing with the environmental noise of any working condition. The following measures are taken for data manipulation and noise cancellation:

Band modification by moving average:

In our work, data processing is performed on both of the sampled received signals and original M-sequence and the sampling frequency is such that there are 8 samples per unit pulse of the M-sequence. So the expected peak on the CCF is supposed to consist of 16 samples. In order to minimize spurious peaks whose widths are less than 16 samples, the sampled data are made smooth and clean by performing the moving average of the data sequence, expressed by the following equation:

$$data[n] = data[n-1]/4 + data[n]/2 + data[n+1]/4 \,. \quad (8)$$

This is equivalent to operate the Hanning spectral window. It is observed that applying the moving average of the data sequence considerably minimizes the noise peaks of comparatively small width while keeping expected peaks (wider than 16 samples) intact.

Inverse filtering:

The random and clutter type noise remaining after signal averaging can be significantly reduced by passing the signal through an inverse filter with a new approach of design. It is possible to reduce the stationary noise using an inverse filter, which is designed on the noise data (iii). In the present study, major part of the long CCF is to be assumed as a noise except the portion corresponding to (i) direct signal and (ii) reflected signal from the target as described in section 2.1. Those two portions are possible to determine using a priori information about the target and in this regard, we utilize a portion of the response itself (CCF of the received signal), which presumably does not contain any expected peak, for calculating the filter coefficients. Virtually, it means the filter coefficients are calculated using a specimen signature of the noise to be removed. Now if the entire CCF data is passed through this filter, it is possible to make the peaks clear and distinct since the noise will be blocked as it is predictable to the filter and the sharp peaks corresponding to reflections will pass through the filter as unpredictable data. In this way, the spurious peaks and ripples due to noise caused by time invariant system can also be removed from the CCF data.

The inverse filter is designed by linear prediction method[25]. The inverse filtering operation on a signal s (n) is described as:

$$\hat{s}(n) = s(n) - \sum_{k=1}^{P} a_k s(n-k) \quad (9)$$

where $\hat{s}$ is output of the filter and P is prediction or model order. The inverse filter is designed calculating the coefficients $\{a_k\}$ based on the noisy data. We obtained the coefficients $\{a_k\}$ by solving the following equation[26]:

$$\sum_{k=1}^{P} a_k R(i-k) = -R(i), \quad \mathrm{i} = 1,2,\ldots,P \quad (10)$$

where $R(i)$ is the autocorrelation function defined by

$$R(i) = \sum_{k=1}^{N-1} s(k)s(k+i) \quad (11)$$

Here it is to note that this autocorrelation function is constructed with N samples of data from a suitable portion of the received signal, which presumably contains no expected peak. Now the inverse filter representation of the model is shown in Fig.1. Thus by passing a given ultrasonic signal $s(n)$ through the inverse filter, we actually get the output as the prediction error $\hat{s}$. In fact the prediction error filter of Fig.1 can be regarded as the filter that attempts to remove the predictable part of the signal and produce an output, $\hat{s}$, that is completely unpredictable to the filter.

Noise cancellation by subtraction:

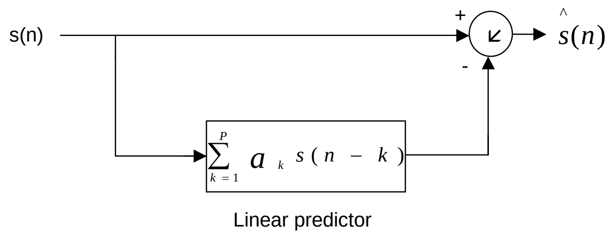


Fig. 1: **Inverse filter**

Some coherent peaks, additive to the expected peak(s), appear on the CCF, which are confusing in regard to the clear distinction of target(s). This is due to the surrounding structure or due to the effect of limitations of the measuring system. It is noticeable that every time the data is taken in the identical condition, these clutter peaks appear irrespective of the presence of any target. To perform the subtraction, first data is taken from the test object without the presence of any target. Then under identical condition, another data is taken after keeping the target in place, which is to be detected. The CCF of second data is supposed to contain all the same coherent peaks as that of the first data excepting the peak corresponding to the target. So it is possible to cancel out those coherent peaks by taking the difference between the CCF of the second data and that of the first data. This helps distinguishing the peaks corresponding to the reflections from the newly developed targets by removing the coherent noise of the system.

Experiments

Set up:

The block diagram of the experimental setup is depicted in Fig. 2. Here the medium is the air space of 5 cm between two acrylic plates with 2x1 m^2 area. The boundary is closed by acoustic absorber so that reflections from the boundary may be reduced. A transmitter of 40 kHz is placed at a predetermined point while a receiver is placed at different points around the target in order to receive the reflections from different directions. M-sequence of 6^{th} order is generated by shift registers, which has the input clock frequency of 625 Hz that determines the basic frequency of the M-sequence signal. The ultrasonic wave of 40 kHz, modulated by the M-sequence, is transmitted from the transmitter inside the medium under investigation. The signal from the receiver which receives the transmitted sequence (acoustic) as well as the reflected sequence is demodulated after amplification in order to retrieve the expected signal, which is then

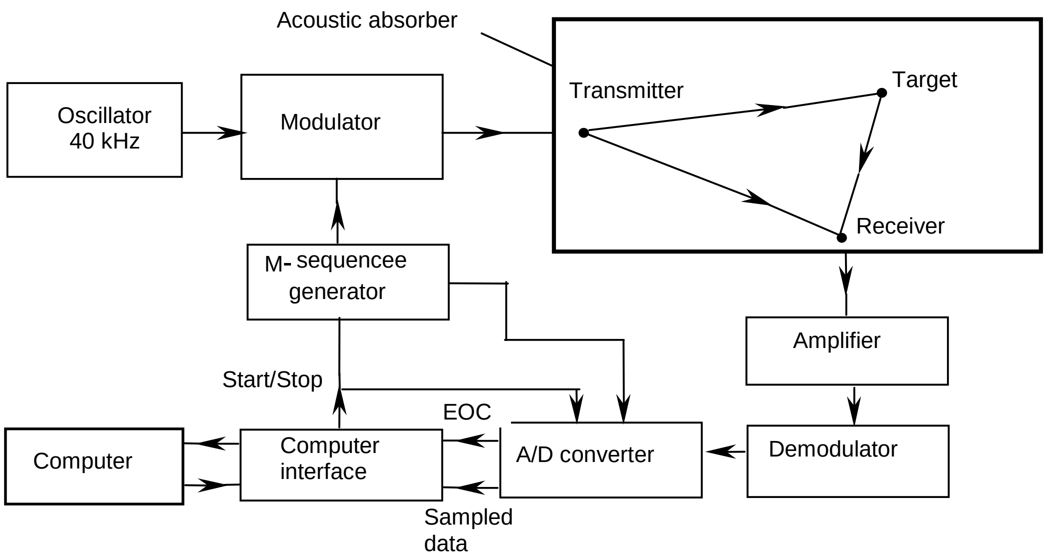


Fig. 2. **Block diagram of the experimental setup**

sampled, and A/D converted at 5 kHz. At the same time, the original M-sequence coming from the M-sequence generator is also sampled at 5 kHz. The sampled data are saved in two separate data files for further processing. For the experiment, narrow band ultrasonic transducers (center frequency- 40 kHz, element size-10.4 mm in diameter) have been used.

Single target detection:

The location of a cylindrical object (target) with diameter 4 mm and placed 1 m away from the transmitter is determined in the two dimensional airspace between the two acrylic plates. The sampled data is cross correlated with the original M-sequence. A portion of the CCF is shown in Fig.3a. As expected, it seems from the figure that there is a sharp large peak marked “B” at a delay time possibly corresponding to the reflection from the target. Also there are several other small peaks, which do not correspond to the target. In the case of a very small object, the peak corresponding to the target may not be so sharp and big enough to be distinguishable from these unexpected peaks. So it is essential to remove these peaks for the clear detection of the peak representing the target. After implementing the noise reduction techniques, as described in the last sections, the final CCF takes the shape of Fig. 3b, where all the noise peaks are significantly reduced while the expected peak is enhanced.

Multi targets detection:

Locations of two targets are determined using signals from plural receivers. This experiment was carried out by keeping the transmitter fixed at the same place while placing the receiver at several positions. Two cylindrical shaped targets of diameters 3 mm and 5 mm were placed at distances 56 cm and 99 cm from the transmitter. For simplicity, we took three readings by placing the receivers at three convenient positions. The final shape of the CCFs (after noise reduction) is shown in Fig.4.

In Fig.5, ‘T’ denotes the transmitter position and ‘A’, ‘B’, ‘C’ denote the receiver positions for three different readings of the experiment. For each position of the receiver,

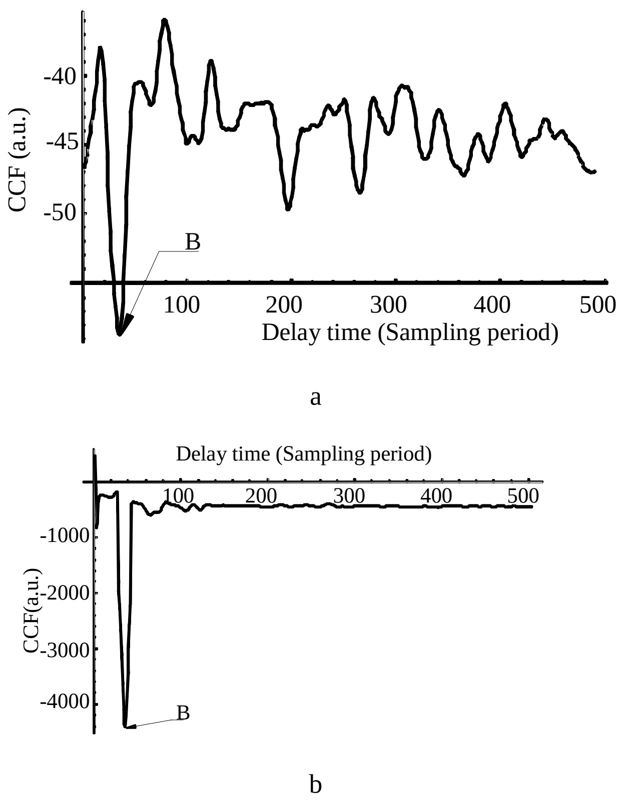
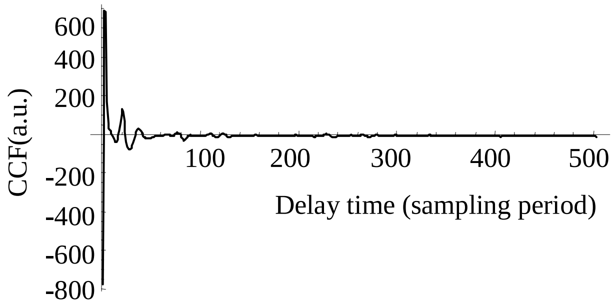
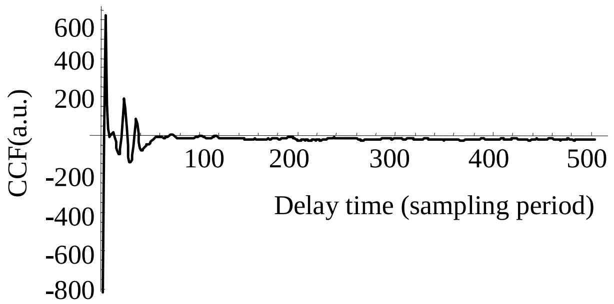


Fig. 3. **Noise reduction and target detection (a) CCF of the received data before noise reduction (b) CCF after implementing the noise reduction techniques**

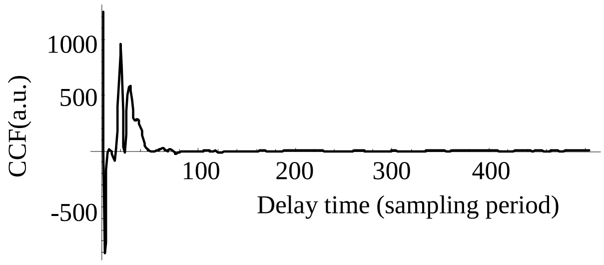
the return trip distances of the signal from the transmitter to the receiver, via targets, are calculated from the peak positions of Fig. 4. Taking ‘T’ as one of the focal points and each of the receiver positions (A,B,C) as the other focal point, three ellipses are drawn on the basis of the return trip distances where the return trip distance is taken as the major axis length of the corresponding ellipse. For each position of the receiver, two elliptical curves are



a



b



c

Fig. 4. **Multi target detection (a) CCF for the first position 'A' of the receiver (b) CCF for the 2nd position 'B' of the receiver (c) CCF for the 3rd position 'C' of the receiver**

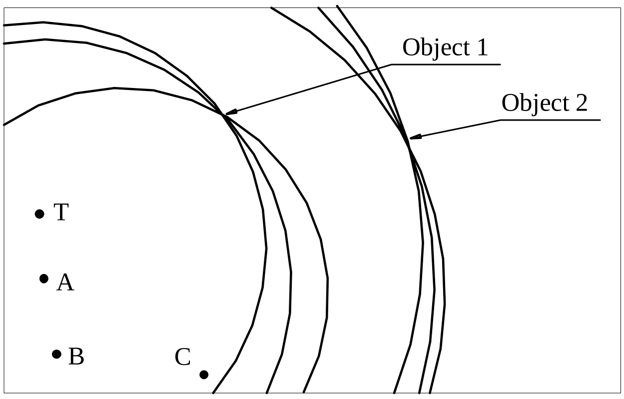
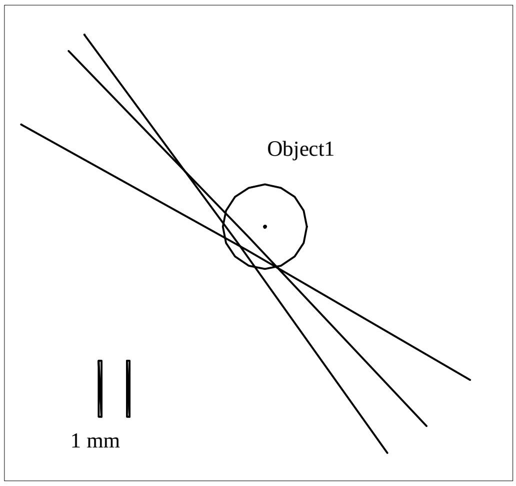
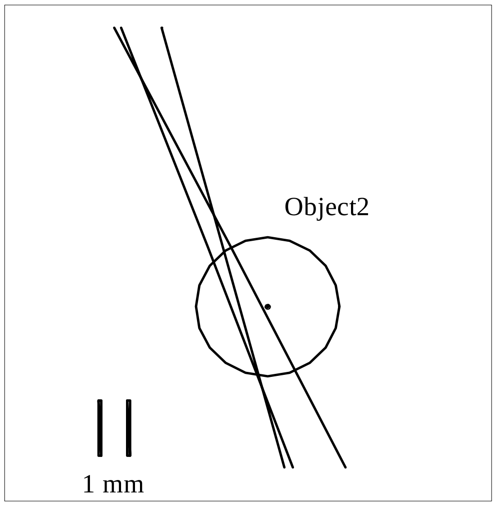


Fig. 5**. Determination of the object location**

drawn corresponding to the two targets. The best possibility of a target's location is the point where most of the curves, corresponding to that target, coincide. In the experiment, we have observed that all the curves, corresponding to a target, coincide at very close points as shown in Fig. 5. The magnified view of the points of coincidence of Fig.5, corresponding to each of the targets, is shown in Fig. 6. The area of triangle formed by points of coincidence is found to be less than 1/3 of the target's area in each case. For an alternative way, some reconstruction algorithms of the topography can also be adopted to locate the targets.



a



b

Fig. 6**. A magnified view of the actual object location and the points of coincidence of the ellipsoids in Fig. 4, (a) Actual location of object 1 (b) Actual location of object 2**

Conclusions

A new way of designing inverse filter has been proposed which is able to adjust its parameters according to response of the system. Based on this method, immersion transducers can be utilised for the detection of fishes or underwater objects. With proper adjustment and modification of the transmitting and receiving system, the method can be applied in acoustical detection of micro-cracks in the metal tanks or plates as well as small holes in pipe-like objects in order for periodical checking. This method is workable under a noisy condition because the noise is poised to be cancelled by the noise itself. It has been observed that the basic frequency (1/unit pulse width) of M-sequence has a significant role in the result of this method. The higher the value of this frequency, the more precise and smaller object can be clearly detected with the proposed method. In order to detect very small objects, the transmitter and the receiver must be of higher frequency, because in order to recover the M-sequence by demodulation, the carrier frequency should be nearly 10 times or more than the basic frequency of the M-sequence. For the time being, we have only used a Trans-receiver system of 40 kHz frequency and the basic frequency of the M-sequence has been taken as 625 Hz. Using this system, we successfully detected from moderate to reasonably small objects in air medium. It may happen that some receivers may fail to detect reflections from some targets due to angular dependence of the reflectivity and the proposed method for such a case can be improved by using multiple transmitters at a time. This method can also be utilized for target sensing and locating in the places where human eye or other means can not be utilized to do so. There is much opportunity to do further work using latest trans-receiver systems with very high resonance frequencies.

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Ultrasonic soundings of targets by processing of signals from plural receivers

Summary

A method for acoustic soundings of targets is proposed. Ultrasonic M-sequence signal is transmitted through the medium under investigation and reflections from the targets are received by plural receivers at different positions. The cross correlation function between the original M-sequence and the reflected signal is adopted to detect any reflection and based on it, a method is presented to find the exact location of the target. In order to detect the expected peaks corresponding to the targets in the cross correlation function, a novel design of inverse filter is proposed so that the system can work under heavy ambient noise condition.

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