Pulse echo flaw detection systems have found extensive use in industry for quality control of many types of metal and ceramic components. The random signal flaw detection system described in this paper provides an increase in sensitivity of several orders of magnitude compared to conventional pulse echo systems.

Following a review of the theory of system operation, we present some recently obtained results of our system on materials which are strongly sound absorbing, including ceramics, plastics and metals as well as materials which have large grains. In addition to detecting flaws in strongly absorbing materials we feel that this system might also be utilized as a way of estimating grain size, inclusion size or porosity.

Conventional pulse echo systems transmit a pulse and display the reflection from the target on an oscilloscope. To avoid problems of range ambiguity the time between pulses must be maintained long enough so that all the echoes are received before transmitting another pulse. The range resolution, the smallest distance by which the two targets can be separated for the system to resolve them, is proportional to the width of the transmitted burst. This in turn is inversely proportional to the bandwidth of the transmitted signal.

As a result of the above conditions, the on/off time of the transmitted signal is extremely small. The peak to average power ratio is proportional to the ratio of the range to the resolution, which is on the order of 1000. Therefore, conventional pulse echo systems may be characterized by the following equation:

\[
\frac{\text{Maximum Range}}{\text{Range Resolution}} = \frac{\text{Burst Interval}}{\text{Burst Width}} = \frac{\text{Peak Power}}{\text{Average Power}}
\]  

(1)

This means that the pulse echo systems must put out power in bursts of great intensity, which may damage the transducer.

The other great limitation of existing pulse echo systems is that they have no signal-to-noise ratio enhancement. Since the thermal noise power of amplifiers is proportional to their bandwidths, the signal-to-noise ratio enhancement at the output of a system is defined in the following way

\[
\frac{\text{SNR}_{\text{out}}}{\text{SNR}_{\text{in}}} = \frac{B_{\text{in}}}{B_{\text{out}}}
\]

(2)

In pulse echo systems, the bandwidth of the output signal at the detector is approximately the same as the bandwidth of the signal at the receiver. Therefore, these systems are unable to achieve signal-to-noise ratio enhancement.
Signal averaging systems have been used for quite some time to produce signal-to-noise ratio enhancement. Dr. Woodmansee of Boeing has applied signal averaging techniques in ultrasonics to improve the input signal-to-noise ratio using commercially available systems. The system described here can provide even greater signal-to-noise ratio enhancement for a given operating speed, and can operate with a lower peak-to-average power ratio.

System Description and Theory

The experimental random signal system is shown in Fig. 1. The noise source produces signals which are transmitted to the sample through the transducer. The reflection of the transmitted signal from the sample is received after a delay of $\tau_s$ by either the same transducer or by a separate transducer. The transmitted signal, after being delayed by $\tau_d$ in the delay line, is compared in the correlator with the reflection from the sample. The correlator output, $R_x(\tau_s - \tau_d)$, corresponds to the time average of these two signals and is known as the autocorrelation function of the transmitted signal $x(t)$. The output of the correlator goes through a low-pass filter, which performs the time integration, and is then displayed by a pen recorder.

Figure 2 shows the time average of the correlator output for a bell-shaped transmitted noise spectrum.

\[
S_x(f) = \frac{(B/2)^2}{(B/2)^2 + (f - f_0)^2}
\]  

where $f_0$ is the center frequency and $B$ is the bandwidth. The correlator output is the inverse Fourier transform of $S_x(f)$ and may be written as

\[
R_x(\tau_s - \tau_d) = \frac{B}{2} e^{-\pi B|\tau_d - \tau_s|} \cos 2\pi f_0(\tau_d - \tau_s)
\]

This output reaches maximum when $\tau_s = \tau_d$ and falls to 1/e of its maximum value when $\tau_d - \tau_s = 1/\pi B$. From eq. 1 it follows that the range resolution of the system is

\[
\Delta R \sim \frac{c}{2\pi B}
\]

Equation 5 is an important result since it demonstrates that the resolving power of the random signal system depends purely on the bandwidth and not the width of the transmitted pulse as in pulse echo systems.

Since the noise signal changes from instant to instant at a rate determined by the bandwidth, high resolution can be obtained in the system without having to transmit the signal in the form of short bursts. The random signal system shown in Fig. 1 can use either noise or RF as the transmitted signal. Therefore, it may also be used as a pulse echo system employing time integration to give increased sensitivity.
Fig. 1. Experimental random signal flaw detection system.
Fig. 2. System waveforms
(a) Spectrum of transmitted noise signal
(b) Correlator output
Signal-to-Noise Ratio Enhancement

If a random process with a mean value \( \bar{x} \) and a standard deviation \( \sigma_x \) is averaged over \( n \) samples, then the new average has a standard deviation which is \( n \) times smaller than its original value. Therefore, by taking \( n \) samples of a random process, the ratio of the mean squared value to the variance is improved by the factor \( n \). It can be shown in an analogous manner that by taking \( n \) samples of an electrical process the signal-to-noise ratio can be improved by the same factor \( n \). The signal-to-noise ratio enhancement in the random signal system is thus given by

\[
\frac{\text{SNR}_{\text{out}}}{\text{SNR}_{\text{lin}}} = \int \frac{\text{Integration time}}{\text{Signal coherence length}} = n
\]

(6)

It was shown earlier that when two targets are moved apart by \( \frac{1}{B} \), the signals become uncorrelated. Therefore, the signal coherence length is \( \frac{1}{B} \) and the signal-to-noise ratio enhancement of the random signal system \( B \) becomes

\[
\frac{\text{SNR}_{\text{out}}}{\text{SNR}_{\text{lin}}} = BT
\]

(7)

where \( B \) is the bandwidth and \( T \) is the effective integration time.

For a given integration time the signal averaging system has only one sample per period, but in the random signal system, when the transmission is continuous, the whole signal period can be filled with samples. Therefore, the signal-to-noise ratio enhancement in the random signal system is larger than that of the signal averaging system by the number of samples that can be fitted into one period. This means that the random signal system could be 1000 times more effective in signal-to-noise ratio enhancement than the conventional signal averaging system, when the noise signal is transmitted continuously.*

The Correlator Output Waveform

The system output can be related to the impulse response of the flaw being observed by the following analysis. Figure 3 shows the usual linear electrical representation of the system. The transmit transducer and its impulse response are shown in the upper half of the figure. The impulse response of the medium \( m_\tau(t) \), has frequency dependent absorption. The flaw is represented by an impulse response \( g(t) \). The receive transducer impulse response \( h_\tau(t) \) may be different from the transmit transducer response \( h_\tau(t) \) if two transducers are used. The receive transducer outputs are fed into the correlator, where the two signals are compared and the resulting output is displayed on the x-y recorder. The y deflection corresponds to the correlator

*It is found that in an environment containing a high density of reflectors, noise transmission must be in bursts for optimum signal-to-noise ratio. In this case the effectiveness of the signal averaging system approaches that of the random signal system.
Transmit Transducer $h_1(t)$
Medium $m_R(t)$
Flaw $g(t)$
Receiver Transducer $h_2(t)$

Echo Signal $e(t)$
Reference Signal $r(t)$
Correlator

Signal $x(t)$
Reference Trans. Transducer $h_3(t)$
Delay Line
Reference Receive Transducer $h_4(t)$

x-y Recorder

Fig. 3. System model.
output and the x deflection corresponds to the length of the delay line. It is then possible to express the correlator output in the following way

\[ y(t) = g(t) \ast m_r(t) \ast R_f(t) \]  \hspace{1cm} (8)

where

\[ R_f(t) = \{ x(t) \ast h_1(t) \ast h_2(t) \} \ast \{ x(t) \ast h_3(t) \ast h_4(t) \} \]  \hspace{1cm} (9)

To illustrate the meaning of these relations we will assume that the target impulse response is a simple delta function delayed by \( \tau_r \) and that the bandwidth of the system is not limited by the transducers. Under these conditions the transducer response \( h(t) \) can be set equal to unity. If the medium absorption is ignored, then the medium response can also be set equal to unity. The correlator output under the above conditions simplifies to

\[ y(t) = R_x(t - \tau_r) \]  \hspace{1cm} (10)

which is simply the autocorrelation function of the transmitted signal.

**Experimental Results:**

Figure 4 shows the detection of a 1 mil wire in the water tank. This demonstrates clearly that the system can detect targets that are much smaller than it can resolve. It is also clear from this plot that the signal-to-noise ratio enhancement is very good. Due to the high sensitivity of the system we did not attempt to measure the upper limit of the signal-to-noise ratio enhancement. However, we did obtain enhancement on the order of 10,000.

Figure 5 is a comparison of system outputs when long RF bursts are used, with the output when noise bursts of the same duration are used. Clearly, the noise signal resolves the target when the RF system is unable to. The output of the noise system remains the same when the pulse width is varied which shows that the resolution of the random signal system is independent of the noise burst width.

Figure 6 is the output for a silicon nitride (Si₃N₄) sample which is a strongly absorbing material containing laser drilled 16 mil holes. It is clear that the system can easily detect these holes.

Figure 7 is an example of a plexiglass sample, which also absorbs sound very strongly but has no grains. The pattern of holes drilled in the rear surface can be detected very easily by the random signal system, even though it would be quite difficult to see with ordinary pulse echo techniques.

Figure 8 is the output for a 12 cm long piece of alumina rod, which absorbs sound too strongly to be examined by pulse echo systems. The output shows that when a long pulse is transmitted, the front echo tends to suppress the echoes from grains near the front surface. In Fig. 9 the pulse width is increased to 25μs, which results in the suppression of the echoes throughout the sample. When the pulse width is decreased to 2μs as shown in Fig. 10, the grain echoes are enhanced until they are as large as the echo from the front surface. This is because the signal-to-noise ratio enhancement of this
Fig. 4. Detection of one mil wire in water.
Fig. 5. Comparison of system operation using periodic 4 usec bursts of RF and noise as transmitted signal. Target is a 40 mil diameter wire.
Fig. 6. Detection of 16 mil laser bored hole in a block of Si₃N₄. Total scan distance is 855 mil in water.
Fig. 7. (a) Plexiglass sample with concentric holes. (b) System output for the plexiglass sample.
Fig. 8. Scan of aluminum rod sample with 15usec pulse. (Note the suppression of grain echoes near the front surface of the sample.)
Fig. 9. Scan of alumina rod sample with 25usec pulse designed to cover the whole sample, which results in suppression of grain echos throughout the sample.
Fig. 10. Scan of alumina rod sample with 2μsec pulse. Note the increase in SNR enhancement of grain echoes due to reduction in pulse length.
system is non-linear when the signal becomes larger than the noise, resulting in a type of an enhancement compression effect. Systems using clipping only in the delay line channel avoid this effect.

Figure 11 shows the output for a piece of pure copper which has been treated to increase the grain size to 1.6 mm. There is a noticeable increase in the grain echoes when the sample is treated further to increase the grain size to .19 mm as seen in Fig. 12. Further treatment of the sample increases the grain size to .3 mm, which results in still larger grain echoes as seen on Fig. 13. These results show that the system could serve as a means of estimating grain size or inclusions under circumstances where the echoes are too weak to be seen by a pulse echo system.

Clutter Avoidance

We have mentioned that the random signal system cannot transmit long bursts without suffering a loss of sensitivity if a high density of reflectors are present. However, shortening the transmitted burst length worsens the peak-to-average power ratio and the signal-to-noise ratio enhancement. However, the transmitting and the receiving transducers can be adjusted at an angle to each other such that their beams are tightly focused as shown in Fig. 14, thereby avoiding echoes from outside the flaw region. This procedure allows the noise signal to be transmitted continuously, while maintaining system performance at maximum efficiency.

Conclusion

To summarize, we have demonstrated a random signal system which has a signal-to-noise ratio enhancement on the order of 10,000. This means that strongly sound absorbing samples which could not be handled previously can now be examined. Also porosity and grain size can be estimated in finer grain materials than was heretofore possible. Finally the large available sensitivity allows the use of higher frequencies, which are absorbed too strongly to be used in conventional pulse echo systems, thus making greatly improved resolution possible.

Finally, we are building systems which aim at one mil resolution. If anybody has any samples which they would like us to test to try out our system, we'd be happy to cooperate.

References

Fig. 11. Output for 5-9 copper sample after cold work and 1 hour of heat treatment to encourage grain growth.
Sample Length: 5 cm avg. Grain size: 1.6 microns.
Fig. 12. Output for 5-9 copper sample after a further heat treatment of 1 hour at 1900°F. Note increase in grain echoes.
Sample Length: 4.3 cm avg. Grain size: 0.19 mm
Fig. 13. Output for 5-9 copper sample after 3rd heat treatment of 2 hours at 1900°F. Pulse length decreased to 2 μsec to decrease front surface signal suppression effect.

Avg. grain size: 0.32 mm
Fig. 14. Clutter avoidance system.
DISCUSSION

MR. GARY DAU (Electric Power Research Institute): You mentioned samples and I'd like to see you try some centrifugally gapped stainless steel pipe.

DR. NEWHOUSE: Well, that sounds as though there must be something terrible about it, but we'll certainly try it.

MR. DAU: Yes, I think there is and a lot of people will agree. And if you have trouble with the samples, perhaps I can help you get some.

DR. NEWHOUSE: Thank you. I'd be grateful if you would do that.

DR. CRIST: Gordon?

DR. GORDON KINO (Stanford University): I was intrigued by the whole deconvolution process vis-a-vis Dick White's suggestions. What happens if you have a transducer with a fair response, nothing wonderful. Then you are basically taking correlation rather than an inverse transformer as he's doing. What happens when you have a poor response on the transducer? Does this get rid of this? Essentially you still get a correlation if you can get rid of the side wave because you are using noise?

DR. NEWHOUSE: Yes, you should.

MR. PHIL HODGETTS (Rockwell International): I would like to know what you think this particular system would do on, say, a number 3 hole like 3/64 of an inch in diameter 6 inches down in a piece of titanium where the entry width is about half an inch. And if you can do something with that, I have got some samples for you.

DR. NEWHOUSE: As I said, the only time we have problems is if the echoes from grain boundaries dominate the echoes from the flaw. And also, I'm not sure about what would happen if we had a lot of reflecting surfaces between us and the thing we are trying to look at. Even though we can penetrate stuff and get a marvelous signal-to-noise ratio enhancement of what comes back, if the signals sort of reverberate around, we might get in trouble. Apart from that, we should have no trouble at all in making things visible. We want to find out what we can do and what we can't do. We're also interested in defects which are very close to the front surface so as to see how close we can recognize things close to a strong reflecting surface.

MR. HODGETTS: Okay. Thanks a lot.