EE 422G - Signals and Systems Laboratory

Lab 5 Filter Applications

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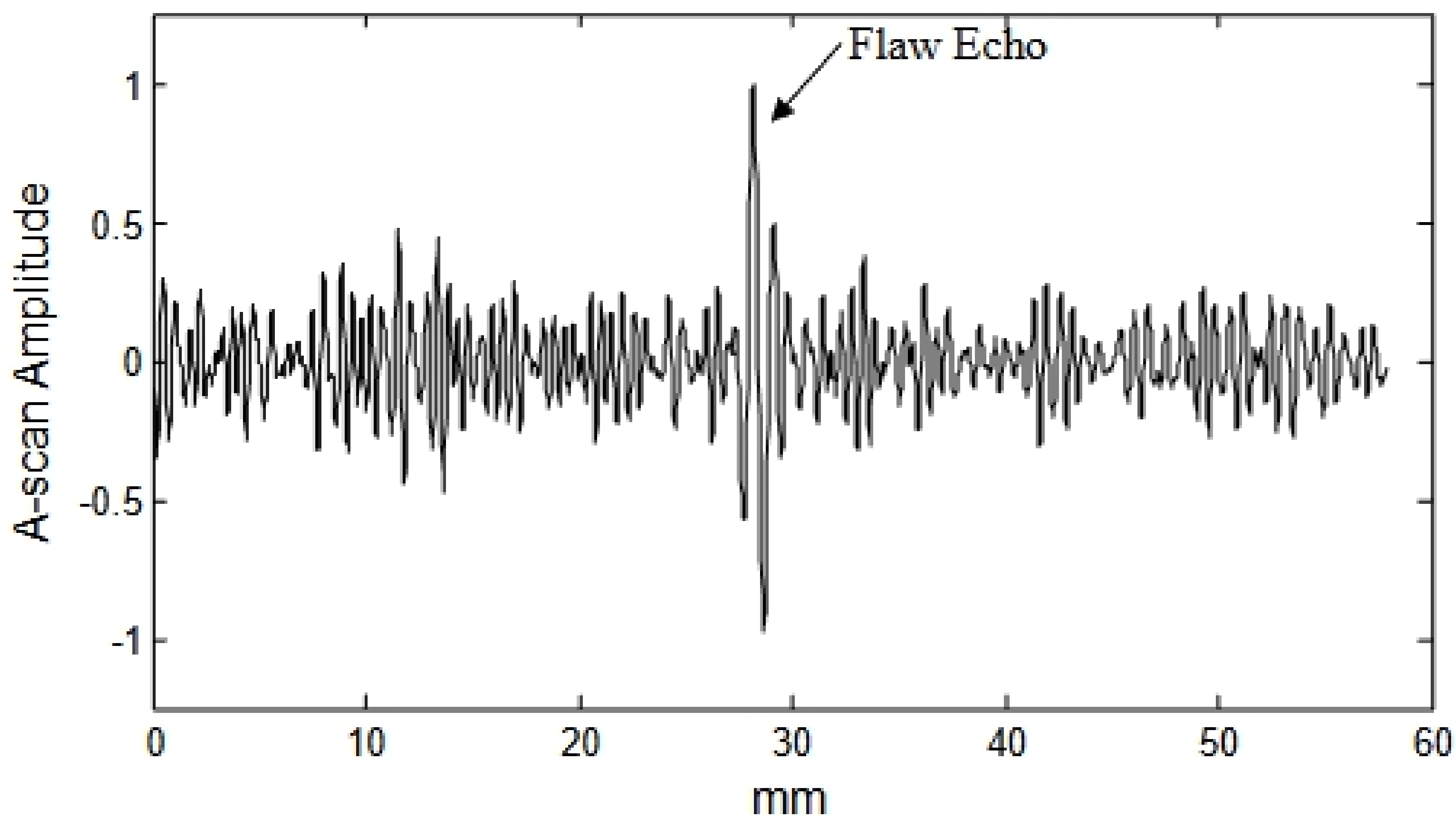
Objectives:

- Apply knowledge of signal and noise properties to design filters to enhance signal detection in noise.
- Apply analysis tools and experimental techniques verify performance of the filter.

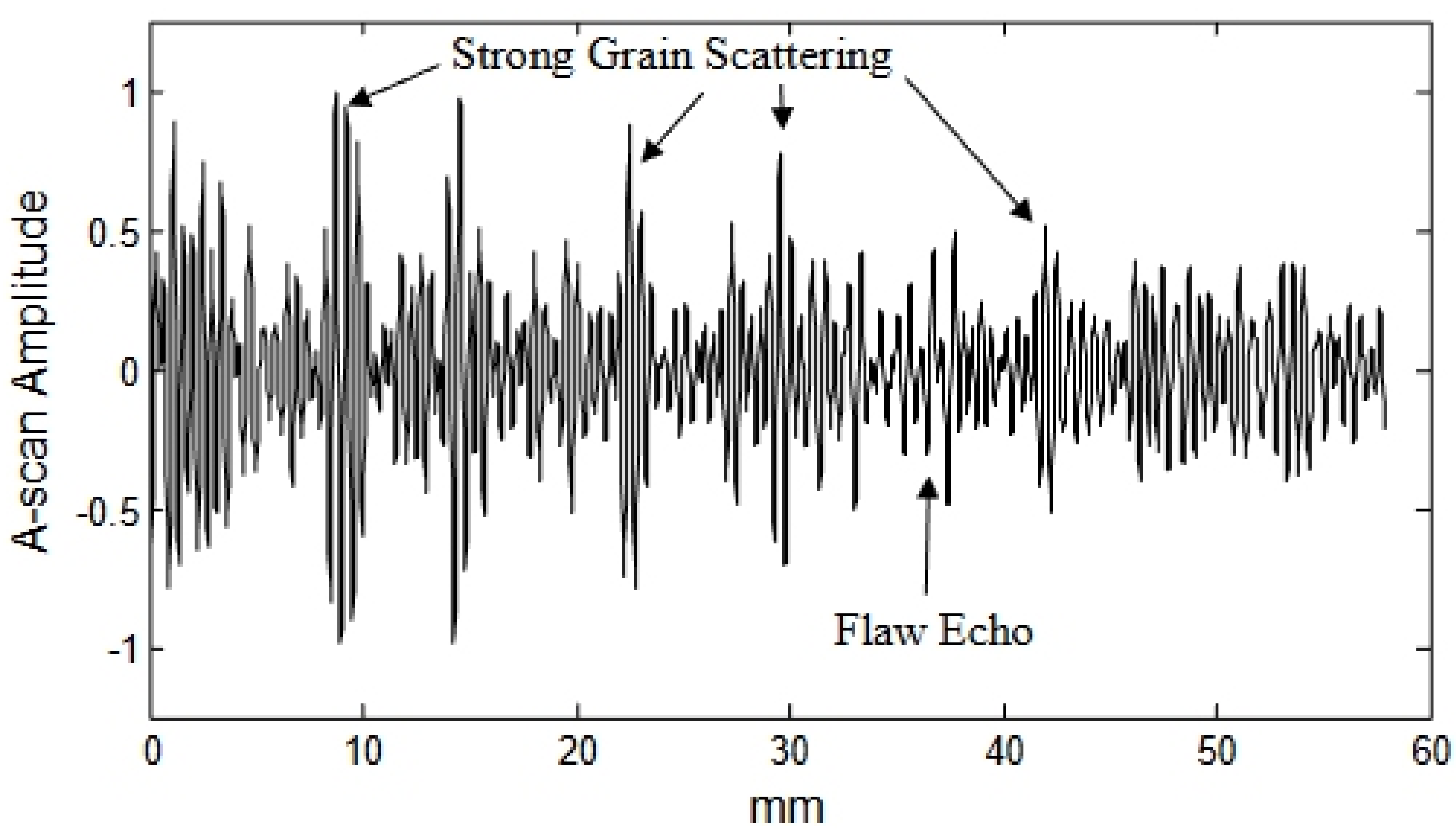
1. Background

An ultrasonic A-scan is a signal created by sending a pulse of high frequency sound into a material and recording back-scattered energy. This pulse-echo principle is similar to what is done in radar or what a bat does to navigate. The timing of the return echoes are used to image or locate the scatterers in the insonified field. In non-destructive evaluation (NDE) this pulse-echo ultrasonic technique is used to scan materials for internal flaws, such as cracks and other defects without having to cut (destroy) the material for inspection. Figure 1 shows examples of A-scans from a stainless rod. Stainless steel is composed of grain-like structures or crystals on the order of 0.1 mm with random distributions of sizes and orientations throughout the material. These microstructures scatter portions of insonifying energy from the propagating ultrasonic pulse back to the receiving element (the piezoelectric properties of ultrasound transducer element allow for the same element to be used as a generator and receiver of ultrasonic energy). The grain-like structures throughout the material result in backscattered energy appearing over the duration of the entire A-scan. Since this *noise* results from a process in the scanned environment (and not from artifacts of the measurement or system noise) it is sometimes referred to as *process noise*.

Figures 1a and 1b show A-scans from insonified flaws simulated by flat-bottom holes 4mm in diameter. Figure 1a shows a case where the flaw echo is stronger than any of the scattered grain amplitudes. Figure 1b shows another A-scan where scattered grain amplitudes are stronger than the flaw echo. While the individual grains echoes are much smaller and weaker than the flaw echo, the large number of grain structures distributed throughout the volume sometimes result in an in-phase (coherent) addition to create strong echoes. The coherent addition of grain scattering results in amplitude variations dependent on the relative positions of the grain scatterers and the wavelength of the illuminating energy. Since the factors contributing to this complex process cannot be practically known, the grain scattering is modeled statistically as a random noise process.



(a)



(b)

Figure 1. Examples of A-scans from stainless-steel samples with flaws simulated by a drilled 4mm flat-bottom hole. A 5 MHz transducer was used to create the insonifying pulse and receive the scattered energy. (a) Case where flaw echo is stronger than surrounding backscattered energy from the grain structures. (b) Case where flaw echo is similar to or weaker than surrounding backscattered energy from grain structures.

Figure 1 illustrates that the echo strength alone is not sufficient to detect a material defect. There are, however, spectral differences between flaw and grain scattered energy that can be exploited through filtering. While scattering strength is directly proportional to difference in density and/or elasticity at material boundaries, there is also a frequency sensitivity related to scatterer size. If the scatterer boundary is large with respect to the wavelength (sometimes referred to as optical scattering), energy at all wavelengths reflect with significant strength resulting in a strong echo. Alternatively, if the scatterer boundary is small with respect to the wavelength, weak scattering occurs (sometimes referred to as Rayleigh scattering). In this case, the long wavelengths (low frequencies) tend to pass through the small scatterers with little energy loss. So low-frequency signal components will exhibit weaker scattering than higher frequency components for smaller scatterers.

In the case of the ultrasound scans in Fig. 1, the insonifying pulse with center frequency of 5 MHz corresponds to a wavelength of 1.2 mm (assuming a sound speed of 5790 m/s in steel), which is smaller than the 4.11mm flaw scatterer. The grain structures, however, are on the order of 0.1 mm, which is an order of magnitude smaller than the center frequency wavelength. This wavelength to scatterer size relationship is in the Rayleigh scattering region, which exhibits significant frequency sensitivity to scatterer size. The insonifying pulse has a bandwidth of about 4MHz, which corresponds to a frequency range from 3 MHz to 7 MHz. This frequency range corresponds to wavelengths ranging from 2mm to 0.8mm. So it is expected that grain echoes will scatter energy from the upper end of the transducer spectrum with greater strength than from frequencies at the lower end. The flaw, one the other hand, scatters energy from the full spectrum of the transducer. Another factor that impacts the frequency distribution of the received energy is the grain scatterers cause the propagating pulse to lose energy for the higher frequencies at a greater rate than the lower frequencies. Therefore, high frequencies in the propagating pulse are attenuated more so than the lower frequencies. So it is expected that the received signal from scatterers at greater depth have a low-pass emphasis due to propagation effects.

Figure 2 illustrates the spectral differences between the grain and the flaw echo. The average spectra or power spectral densities (PSDs) for the A-scans of Figure 1 are plotted. The PSD is computed with the PWLECH function in Matlab, which takes the squared FFT magnitude of small overlapping segments of data from the whole segment and averages them together. This is sometimes called the *hopping-window* approach or Welch's methods for spectral estimation from random processes. The A-scans consist of 2000 samples each, sampled at 100MHz. For the spectra in Fig. 2, a hopping window size of 128 samples was used, with 64 points of overlap between adjacent windows. A tapering window was used (a hamming window) and the FFT length is increase through zero padding to obtain a 256 point FFT (double the actual number of data points). Spectra for the flaw were more tedious to obtain since the flaw echoes occur only at a limited location in the scans. The beginning and ending sample points around the flaw echo were obtained by looking at the plot and extracting out the flaw section only for the FFT, and the magnitudes were averaged together over several A-scans (padding with