MORPHOLOGICAL FILTERS: STATISTICAL EVALUATION AND APPLICATIONS IN ULTRASONIC NDE

M. A. Mohamed and J. Saniie
Department of Electrical and Computer Engineering
Illinois Institute of Technology
Chicago, IL 60616

INTRODUCTION

In this paper, morphological filters [1-4] have been applied to detect flaw echoes in ultrasonic signals contaminated by grain scattering noise (i.e., clutters or speckles). In particular, the statistical properties of morphological operations (i.e., dilation, closing, clos-erosion and clos-opening) are examined using Monte Carlo simulation when applied to signals with uniform and Rayleigh distributions. The simulated results and their statistics (mean and variance) present an interpretation of the noise suppression capability of morphological filters and their biasing effects. This information has been utilized to design a suitable structuring element to enhance flaw-to-clutter ratio in ultrasonic testing. The processed experimental results (A-Scans and B-Scans) show that morphological filters can improve flaw visibility by suppressing grain scattering noise.

STATISTICAL EVALUATION OF MORPHOLOGICAL FILTERS

To sufficiently understand the performance of morphological operations and capitalize on their applications, statistical analysis is needed. In this study, the statistical properties of sequential morphological operations are examined using flat structuring elements with different widths applied to signals with different density functions. Using Monte Carlo simulation, we present the output density functions at different stages of morphological operations when input signals have uniform and Rayleigh distributions. Also, the mean and normalized variance (i.e., the ratio of output variance over input variance) are estimated for each of these density functions.

To demonstrate the above objectives, simulation has been used to process 300 input data sequences, each with a length of N=10000 samples. These simulated signals have been applied to a sequence of morphological operations, i.e., dilation, closing, clos-erosion and clos-opening using a flat structuring element.

The dilation, closing, clos-erosion, and clos-opening density functions when

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inputs are independent and identically distributed (iid), with uniform density functions (ranging between zero and one) and using a flat structuring element with a width M=7 are shown in Figure 1. Their statistics (i.e., mean and normalized variance) are shown in Figure 2 using flat structuring elements with different widths. These figures indicate that dilation shifts the input signal toward the maximum values and the signal variance is reduced, resulting in a smooth operation. The closing operation (i.e., dilation followed by erosion) is a processing step toward recovering the original signal. Overall, the closing operation tunes down the bias caused by the dilation operation, and slightly increases the signal variance with respect to the dilation operation. The clos-opening operation results in further smoothing of the signal, where the signal mean and variance are less than those of the closing signal. The mean of dilation, closing, clos-erosion and clos-opening is shifted to the right (see Figure 2) due to the effect of dilation as a first operation in the sequence of the above operations. Note that the height of the flat structuring element has no effect on the closing and clos-opening density function, but it shifts the dilation density function to the right and the clos-erosion density function to the left by a predictable value depending on the height. In general, the above figures indicate that by increasing the width of the flat structuring element the mean (bias) is increased and the variances of dilation, closing, clos-erosion and clos-opening output density functions is decreased. Furthermore, dilation has been found to be the most effective step in the smoothing operation. The effect of the other operations following dilation is rather small, especially when the width is increased.

In this study, the statistical evaluation of morphological operations has been extended for input signals having Rayleigh density functions. Monte Carlo simulation is used to process the data sequence using the same procedure applied to the uniform density function. Figure 3 shows the effect of a flat structuring element with a width M=7 on dilation, closing, clos-erosion and clos-opening density functions when inputs are iid with a Rayleigh density function (with mean equal to $\sqrt{\pi}/2$ and variance $2(1 - \pi/4)$). Figure 4 shows the mean and variance of dilation, closing, clos-erosion and clos-opening density functions versus the width of the flat structuring element, M, for the Rayleigh density function.

Inspection of Figure 3 and Figure 4 suggests that the overall smoothing capability of the morphological filter applied to an input signal with a Rayleigh density function is similar to the results obtained for input signals with uniform distribution, although some differences can be noted.

The dilation density function has the least variance when input signals are uniformly distributed, although the clos-erosion density function has the smallest variance when input signals are Rayleigh distributed. The differences in the variance among dilation, closing, clos-erosion and clos-opening decrease as the width of the flat structuring element is increased when applied to input signals with a uniform density function. Contrary to this, the differences among dilation, closing, and clos-opening remain significant when the input signals have Rayleigh distributions. Therefore, the results describing the statistics of morphological filters applied to uniform density function can not be used to predict the performance associated with other types of density functions.

MORPHOLOGICAL FILTERS FOR ULTRASONIC FLAW DETECTION

Ultrasonic flaw detection is an important application of morphological filters. The goal in detection is to isolate the flaw echo from its background noise (e.g., speckles or microstructure scattering echoes) and to estimate its exact location. A

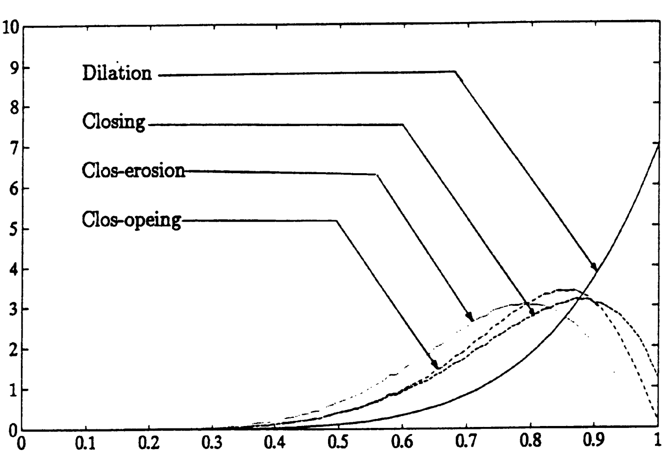

Figure 1. A comparison between dilation, closing, clos-erosion and clos-opening for a flat structuring element with a width M=7 when the input signal has a uniform density function.

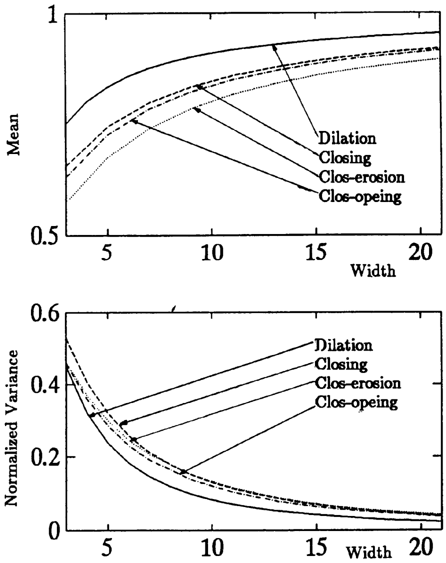

Figure 2. Mean and normalized variance of dilation, closing, clos-erosion and clos-opening when the input signal has a uniform density function.

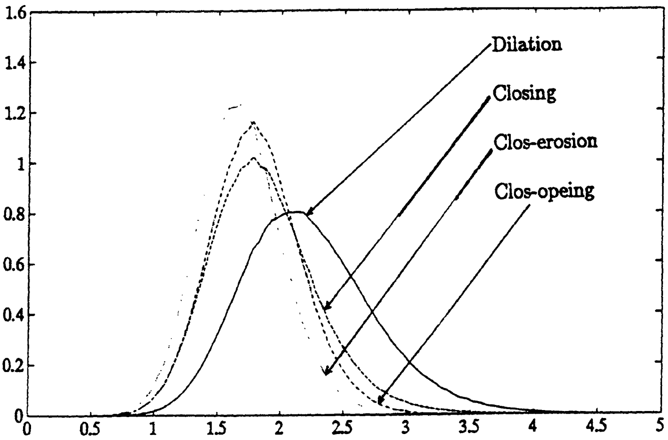

Figure 3. A comparison between dilation, closing, clos-erosion and clos-opening for a flat structuring element with a width M=7 when the input has a Rayleigh density function.

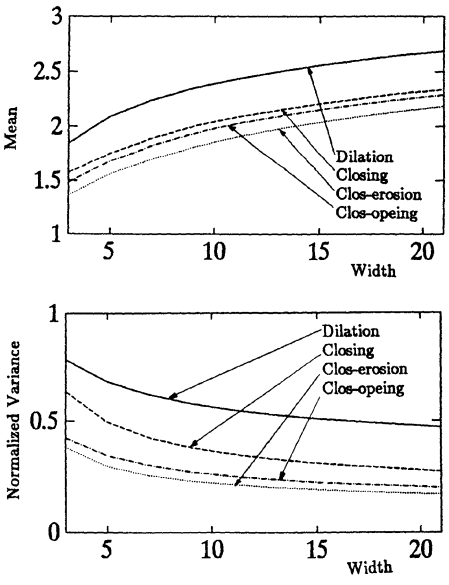

Figure 4. Mean and normalized variance of dilation, closing, clos-erosion and clos-opening when the input signal has a Rayleigh density function.

broadband ultrasonic transducer was used to test a simulated flaw embedded within a steel block. Measurements were accomplished using the contact technique and data was acquired with a 100 MHz sampling frequency. An experimental measurement of a broadband signal is shown in Figure 5. This signal was processed by a sequence of opening and closing operations to improve the flaw-to-clutter ratio. An estimate of the input signal, x(n), is obtained by processing the input signal using an opening followed by a closing operation. A second estimate of the signal is formed by processing the input signal using a closing followed by an opening operation. Then the output signal, y(n), is the average of these two estimates, i.e.,

$$y(n) = [(x(n)\ o\ s_1) \bullet s_1 + (x(n) \bullet s_1)\ o\ s_1]/2 \qquad (1)$$

where "s_1 " is the structuring element, "o" denotes opening and "•" denotes closing. The average of the two signals is used to minimize the bias caused by the extensiveness properties of opening and closing. Equation (1) has characteristics of a lowpass filter.

To achieve an optimal selection of morphological filters, the number of zero crossings of the processed output signal is calculated as a function of the width of the flat structuring element. The result indicates that the number of zero crossings decreases when the width of a flat structuring element is increased. This simply implies that the smoothing process becomes more effective when the width of the structuring element is increased, although excessive smoothing may eliminate flaw echoes. Therefore, an evaluation of a zero crossing and flaw-to-clutter ratio can lead to an estimation of the optimal width of the structuring element. Since microstructure echoes represent the dominating information, properly removing them requires a structuring element with a width larger than the duration of zero crossing of the measured signal. The average width estimated with a zero crossing for the measured signal is 5.14 which leads to the selection of M=6 for removing microstructure noise without excessive smoothing of flaw echo. The processed signal (see Figure 6) indicates that morphological filters are capable of detecting flaw echo while suppressing clutter (microstructure noise).

To further improve the resolution for flaw detection, it is effective to estimate the background echoes (clutter) and then subtract this estimate from the preprocessed signal. This technique is a bandpass filtering operation and can be represented as

$$\hat{y}(n)=y(n)-[(y(n) o s_2) \bullet s_2 + (y(n) \bullet s_2) o s_2]/2 \qquad (2)$$

where y(n) is given by Equation (1), x(n) is the input signal, and s_1 and s_2 are flat structuring elements with lengths of 8 and 10 respectively. The bandpass processed result is shown in Figure 7. This result shows that the background noise is tremendously reduced, while the resolution is enhanced.

A B-Scan experimental measurement is shown in Figure 8. A 5 MHz broadband transducer was used to test a flat bottom hole (0.067") embedded within a steel block as a simulated flaw. This image is processed using Equation (1) with a flat structuring element. The information content of the image has been used to design a suitable flat structuring element with an optimal performance. The average duration of the zero crossing of the B-Scan image is 8.08. Therefore, the flat structuring element with a width of 9 samples was chosen for noise removal. The result of the processed image is shown in Figure 9, indicating that morphological filters are capable of reducing noise and improving resolution. Further

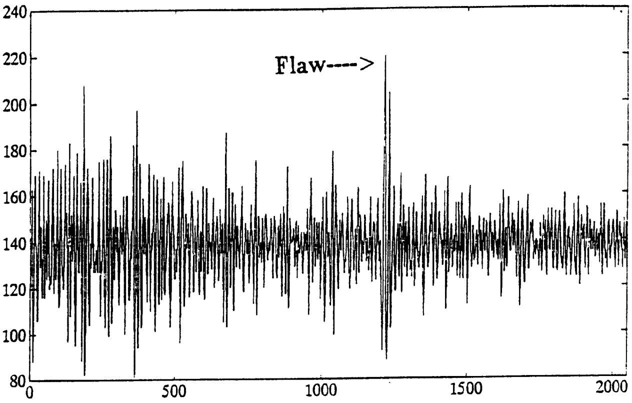

Figure 5. An ultrasonic backscattered flaw signal contaminated by high intensity microstructure echoes.

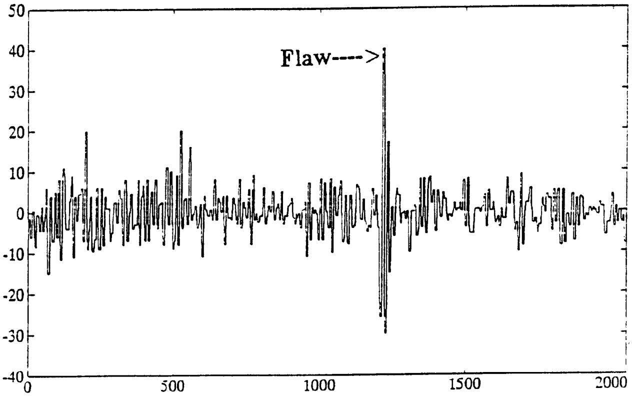

Figure 6. Processed backscattered flaw signal using a lowpass morphological filter.

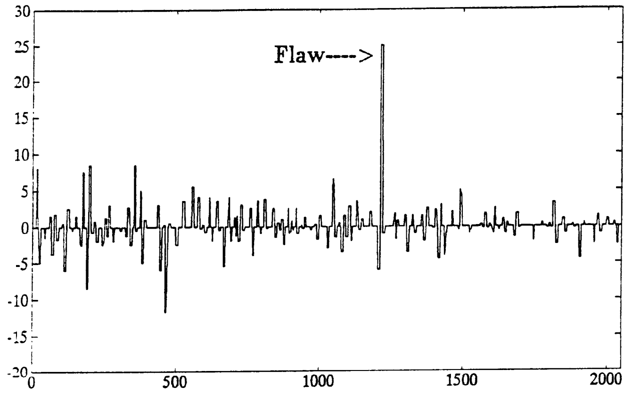

Figure 7. Processed backscattered flaw signal using a bandpass morphological filter.

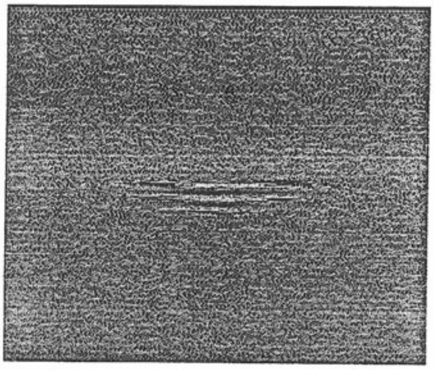

Figure 8. An experimental B-Scan image of a flat bottom hole in a steel block.

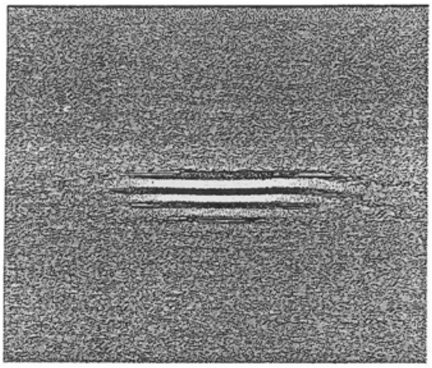

Figure 9. The processed B-Scan image using a lowpass morphological filter.

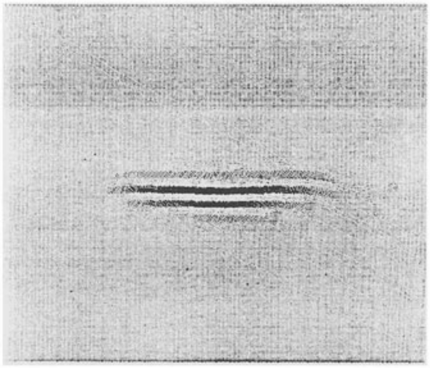

Figure 10. The processed B-Scan image using a bandpass morphological filter.

improvement in detection resolution is obtained using the bandpass morphological filter (see Figure 10).

CONCLUSION

In this study, it has been shown that by increasing the width of the flat structuring element the variance of dilation, closing, clos-erosion and clos-opening density functions are decreased while their expected values are increased. Also, dilation is the most effective step in the smoothing operation. The effect of other operations following dilation is rather small, especially when the width of the structuring element is increased.

Morphological filters have been introduced as a new method for enhancing the quality of ultrasonic signals and images. The experimental results indicate the effectiveness of morphological filters to reduce grain echoes and improve resolution. It has been shown that a bandpass morphological filter provides the best performance in regard to resolution and noise suppression.

ACKNOWLEDGEMENTS

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