ULTRASONIC SIGNAL ENHANCEMENT USING ORDER STATISTIC AND MORPHOLOGICAL FILTERS

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INTRODUCTION

Order statistic and morphological filters belong to a class of nonlinear filters that have recently found many applications in signal analysis and image processing. In this paper, order statistic and morphological filters have been applied to enhance the features of the ultrasonic signal when it has been contaminated by multiple interfering microstructure echoes with random amplitudes and phases. These interfering echoes (i.e., speckles or grain scattering noise) often become significant to the point where detection of flaw echoes becomes very difficult. We have examined frequency diverse order statistic and time domain morphological and recursive median filters for improved ultrasonic flaw detection. In particular, the performance of these filters is evaluated using different ranks of order statistics and different shapes of structuring elements in the application of morphological filters. The processed experimental results in testing steel samples demonstrate that these filters are capable of improving flaw detection in ultrasonic systems.

MORPHOLOGICAL AND ORDER STATISTIC FILTERS

Morphological filters are nonlinear signal transformations that locally modify geometric features of signals. Morphological filters have been known for their robust performance in preserving the shape of a signal while suppressing noise. Morphological filters are based on the principles of mathematical morphology in which signals are represented by sets. These sets are operated on by set transformations in which the signal interacts with another set known as a structuring element. The structuring elements are simpler in nature than the signal under study. The structuring element is similar to the kernel in a convolution operation and is characterized by shape, width and height. By varying the structuring elements, we can extract different types of information from the signal. The basics of morphological operations are dilation, erosion, opening and closing. These morphological operations can be applied to binary or multilevel signals. Since a binary signal is a subset of a multilevel signal, we present a brief discussion of the basic multilevel morphological operators [1] that will be used throughout this paper.

Let x and s denote two discrete functions defined on $X=\{0,1,.......,N-1\}$ and $S=\{0,1,.......,M-1\}$, respectively. It is assumed that $N>M$. The multilevel dilation of signal x by a multilevel structuring element s is denoted by $x \oplus s$, and is defined as:

$$(x \oplus s)(m) = MAX_{n=m-M+1,........,m} \quad [x(n)+s(m-n)],$$

where m= M-1, M, .., N-1.

Dilation is an "expansion" operation in that values of x $\oplus$ s are always greater than those of x.

The multilevel erosion of a signal x by a multilevel structuring element s is denoted by x $\ominus$ s, and is defined as:

$$(x \ominus s)(m) = MIN_{n=0,...,M-1} \quad [x(m+n)-s(n)],$$

where m = 0, ..., N-M.

Erosion is a "shrinking" operation in that values of x $\ominus$ s are always less than those of x.

The multilevel opening of x, by structuring element s, is defined as

$$x \; o \; s = (x \ominus s) \oplus s$$

The multilevel closing of x, by structuring element s, is

$$x \bullet s = (x \oplus s) \ominus s.$$

In general, an opening is used to suppress positive pulses while a closing is used to suppress negative pulses. Cascading opening and closing in tandem yields two more morphological filters: open-closing and clos-opening. These filters smooth the signal similar to that of median filters and result in median roots in a single pass [2].

An order statistic filter is a nonlinear filter in which the input value at a point is replaced by a linear combination of the ordered values in a neighborhood of the point [3]. If {x(.)} and {y_r(.)} are the input and output of the r-th rank order filter with window size M=2N+1, respectively, then y_r(.) is given by

y_r(m) = r-th order statistic of [x(m-N), ..., x(m-1), x(m), x(m+1), ..., x(m+N)]

A median filter is a special case of rank order filter whose output is the median of the samples inside the window ,i.e., (r=N+1). Median filtering is an efficient point estimation technique which has a low-pass effect yet preserves important signal structures such as edges. The recursive median filter is a modification of the standard median filter which results in the output being the median of the last N outputs and the last N+1 inputs. The following definition defines this operation [4].

If {x(.)} and {y(.)} are the input and output of a recursive median filter with window size M=2N+1, respectively, then y(.) is given by

y(m) =median [y(m-N), ..., y(m-2), y(m-1), x(m), x(m+1), ..., x(m+N)]

It important to point out that the recursive operation generates a root with only a single pass through the data, where a root is an invariant signal to the filter.

A connection between order statistic filters and morphological operations with flat structuring elements was made by Maragos [5]. In particular, the maximum (minimum) rank order of any signal of window M coincides with dilation (erosion) by a flat structuring element with a width M and a constant value zero. Also, a signal is a median root if it is the root of both the opening and closing. Moreover, medians and their iterations are bounded below by the opening and above by closing, while the median root is bounded below by the open-closing and above by clos-opening.

EXPERIMENTAL RESULTS

In this section, we present experimental results, which illustrate objectively the performance of morphological filters to detect flaws in the ultrasonic imaging of complex structures resulting in high scattering noise. The strength of morphological filters lies in their natural coupling between the shape of the signal and the structuring element. The structuring element is characterized by its shape, width and height. To illustrate the effectiveness of the parameters of the structuring element in detection, an example of an ultrasonic signal contaminated by microstructure scattering noise has been used. The experimental data is acquired using a broad-band ultrasonic transducer to examine a steel specimen with a constructed flaw embedded within the sample. Ultrasonic measurements were made using the contact technique in the far field, and data was acquired with a 100 MHz sampling frequency. The ultrasonic backscattered signal and its spectrum are shown in Figure 1. This signal was processed using an opening operation followed by a closing operation. A second estimate of the signal is formed by processing the signal using a closing operation followed by an opening operation. Then the output of processed signal, y(n), is the average of the above two estimates i.e.,

$$y(n) = [(x(n) \circ s) \bullet s + (x(n) \bullet s) \circ s]/2.$$

where x(n) and s are the input ultrasonic signal and the structuring element respectively. The average of the two signals is used to minimize the bias caused by the extensiveness properties of opening and closing. The processed results are shown in Figure 2 for a flat structuring element with fixed height (A=0.0) and different widths (M=3, 4, 5, 6, 7, 8 samples). A Comparison between the performance of a flat and sinusoidal structuring element with the same width (M = 5 samples) and height (A=2.0) for a segment of the processed signal, i.e., (1140 - 1300 samples) is shown in Figure 3. Note that the height of the flat structuring element does not effect the processed results when a closing or opening operation is performed. These figures indicate that morphological filters are capable of detecting flaw and enhancing the overall flaw-to-clutter ratio of ultrasonic signals. Also, the sinusoidal structuring element preserves the original shape of the signal better than the flat structuring element because the surface of the processed signal takes the shape

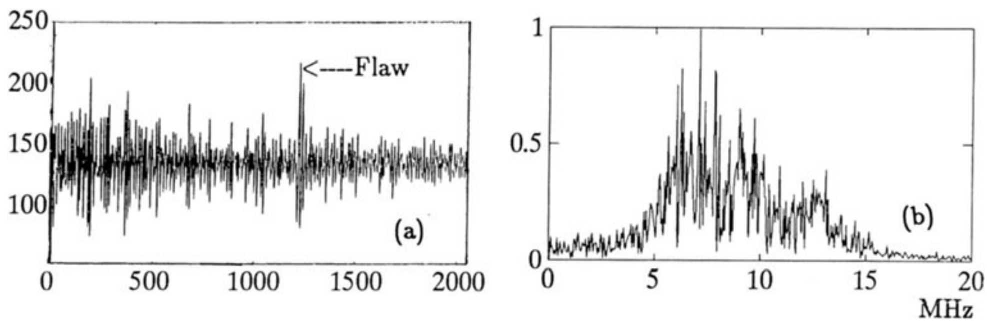

Figure 1a. An ultrasonic backscattered flaw signal.
Figure 1b. Amplitude spectrum of the signal.

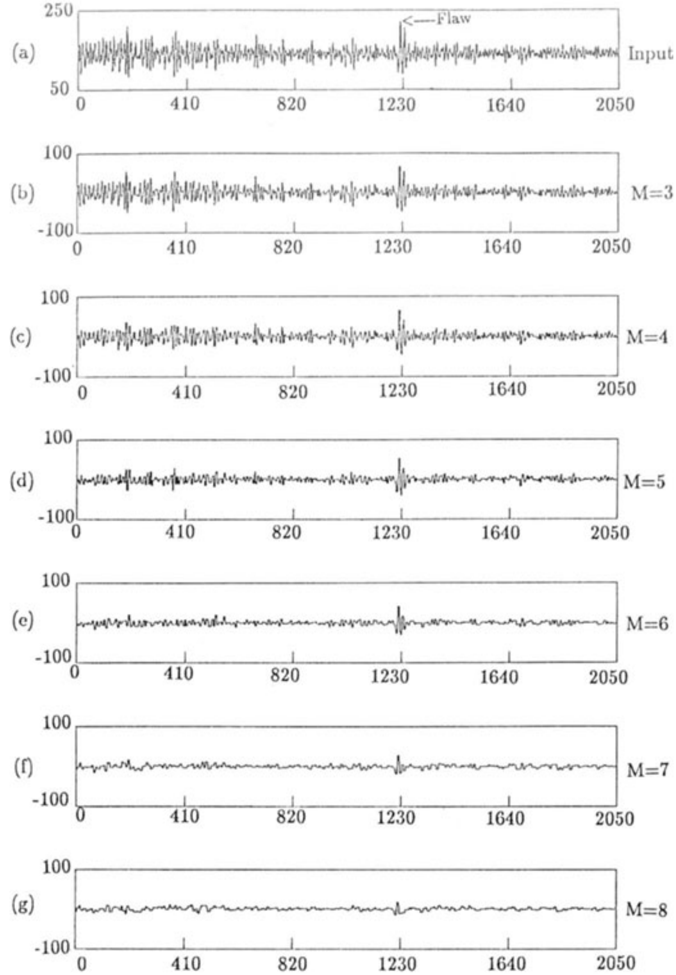

Figure 2. Flaw echo detection and clutter suppression using morphological filters with flat structuring elements. The flat structuring elements have different widths (M). Figure (a) is the original measured signal.

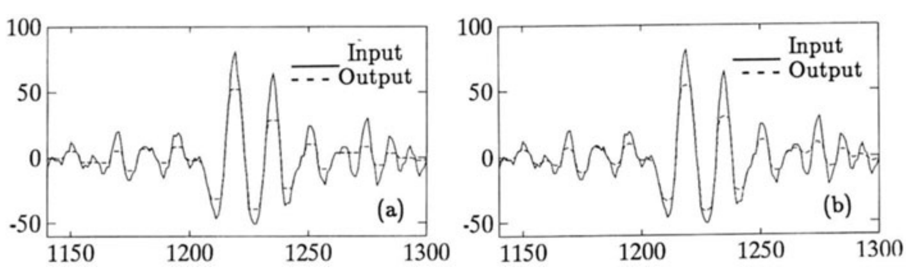

Figure 3. The effect of shape of structuring elements on the processed ultrasonic using
(a) Flat structuring element with a width M=5.
(b) Sinusoidal structuring element with a width M=5 and a height A=2.0.

of the structuring element. However, the flat structuring element smooths the signal more effectively than the sinusoidal structuring element of the same width. A comparison of the flaw-to-clutter ratio between the flat and sinusoidal structuring elements of the processed signal is shown in Figure 4. This figure shows that the flaw-to-clutter ratio increases as the width approaches the optimal value (M_{op}=6 for a flat structuring element and M_{op}=7 for a sinusoidal structuring element). Further improvement of the flaw-to-clutter ratio can be achieved using the band-pass morphological filter [7]. In general, these results indicate that the flat structuring element has better flaw-to-clutter ratio while sinusoidal structuring element has better syntactical performance in preserving the details of the original signal.

The performance of recursive median filters with different widths (M=3, 5, 7, 9, 11, 13, 15 samples) when applied to the same input ultrasonic signal is shown in Figure 5. This figure shows that the recursive median filter can detect flaw echoes and suppress backscattered noise. Note that morphological filters have better syntactical performance in preserving the details of the signal when compared to recursive median filters since they have a flexibility in changing the shape of their structuring elements to match a particular pattern of the original signal.

Both morphological and recursive median filtering have been applied in time domain for flaw detection and flaw-to-clutter ratio enhancement. Frequency analysis is a useful alternative in which certain features hidden in the time domain can be displayed. In particular, the split-spectrum processing combined with rank order statistic filters is used for flaw detection [6]. In split-spectrum processing the backscattered signal is divided into several narrow-band channels. The observations from the output of these channels are normalized with respect to the power in order to obtain the equally-powered output signals. These sets of signals represent uncorrelated microstructure noise. The filtered outputs are passed to a detection processor consisting of a rank order statistic filter for flaw detection. The filtered outputs are ordered with ascending values with respect to their magnitudes. The split-spectrum technique is applied to the input ultrasonic signal (see Figure 1) using 11 bandpass filters with a 3-dB bandwidth of 1.04 MHz, and 1.2 MHz spacing between adjacent filters, covering a frequency range of 0 - 12.8 MHz. The ranked outputs corresponding to each frequency band are shown in Figure 6. The higher

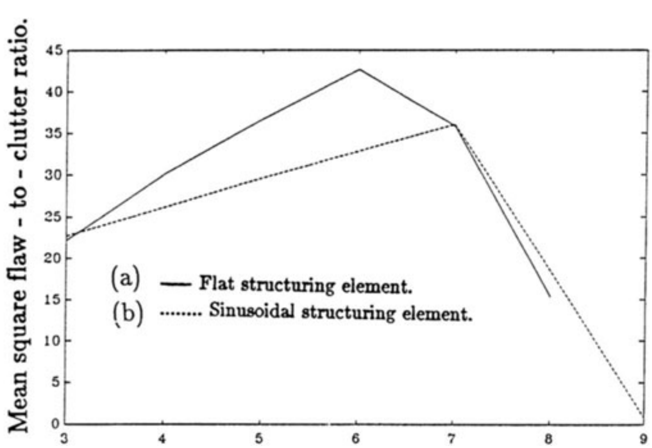

Figure 4. Flaw-to-clutter ratio of the output signal as a function of the width using
(a) Flat structuring element
(b) Sinusoidal structuring element with height A=2.0.

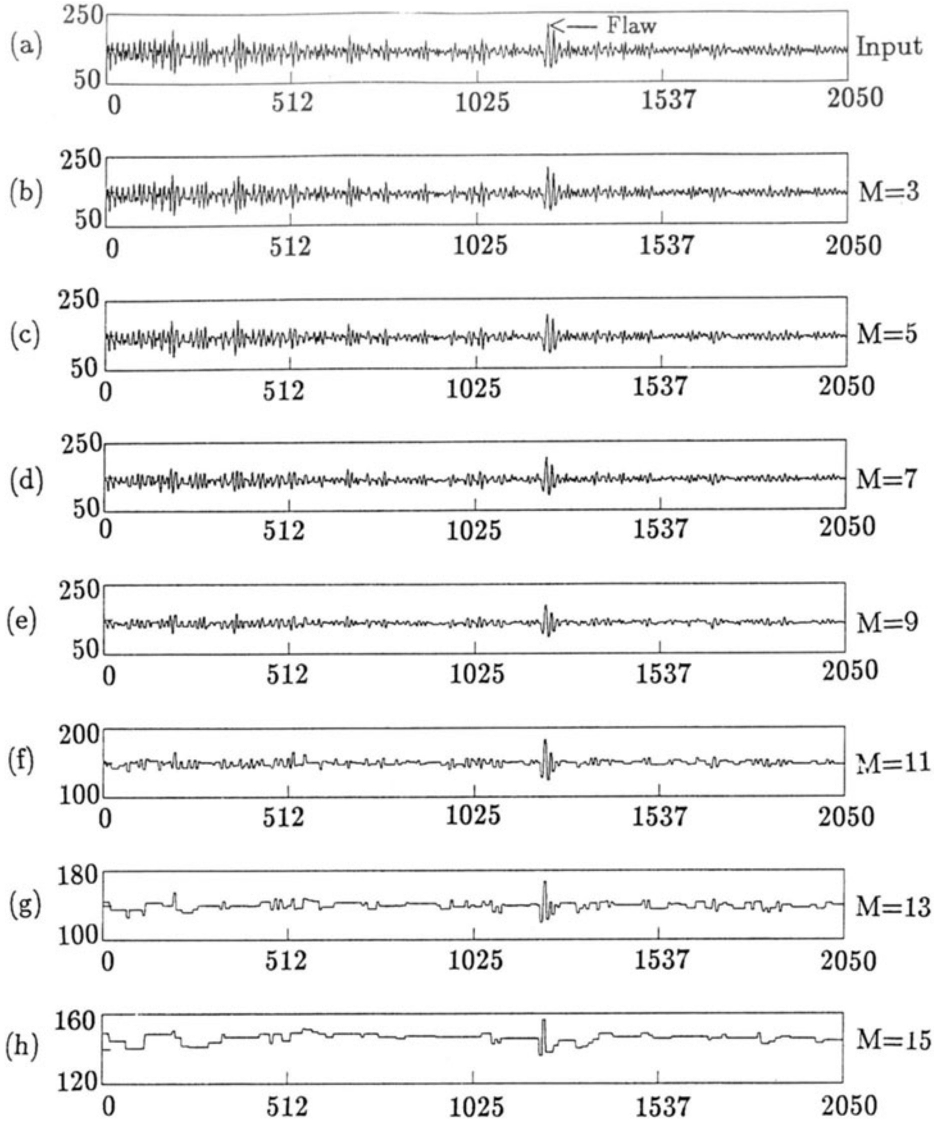

Figure 5. Flaw echo detection and clutter suppression using recursive median filters with different widths. Figure (a) is the original measured signal.

ranked outputs (i.e., ranks 7 - 11) show an improvement in flaw visibility in contrast to the lower ranks (i.e., ranks 1 - 6). Figure 7 is another example of the same broad-band ultrasonic signal processed using eleven filters with a 3-dB bandwidth of 1.2 MHz, and 0.6 MHz spacing between adjacent filters covering a frequency range of 0 - 6.8 MHz. All the ranked outputs show a noticeable improvement in flaw visibility. It must be noted that the performance of split-spectrum processing with rank order statistic filters depends on the number of subbands, correlation between each subband signal and statistical information about the target in each frequency band of the signal.

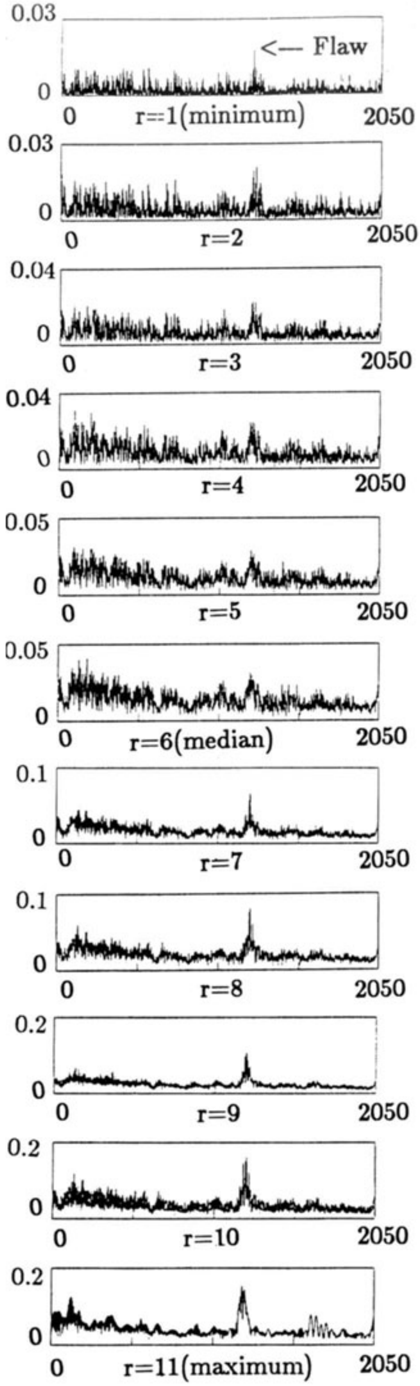

Figure 6. Ranked outputs of order statistic filters using 0-12.8 MHz frequency information.

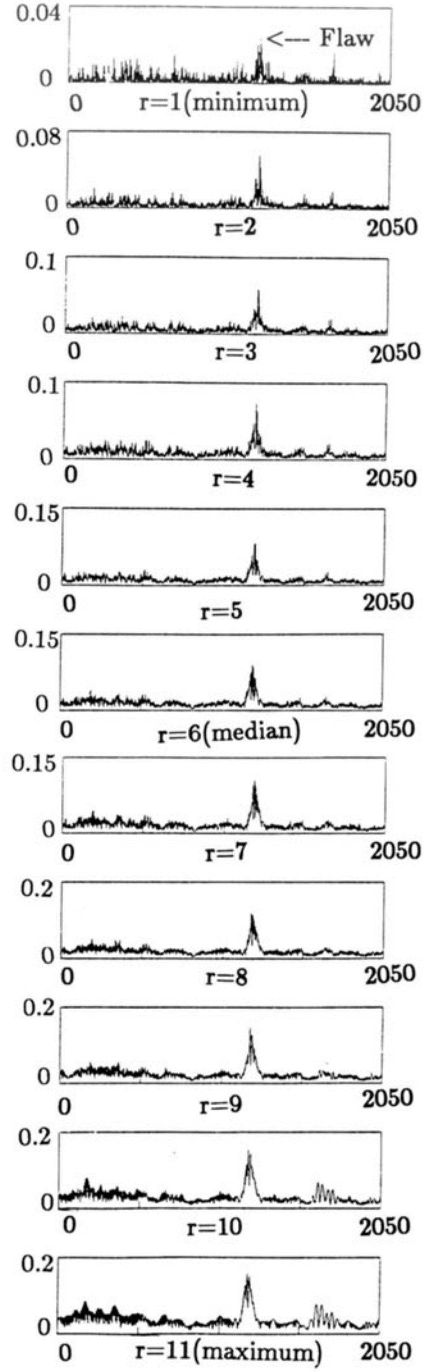

Figure 7. Ranked outputs of order statistic filters using 0-6.8 MHz frequency information.

CONCLUSION

In this paper, morphological and recursive median filters have been introduced as novel time domain processing method to detect flaw and enhance the features of ultrasonic signals. These techniques have been compared with split spectrum technique combined with rank order statistic filters. The results indicate the superior ability of the above techniques in detecting flaw echoes and improving the flaw-to-clutter ratio. However, morphological and recursive median filters have an advantage over split-spectrum processing combined with rank order statistic filters because they are more computationally efficient. Moreover, morphological filters have better performance in preserving the character of the signal because of their flexibility in changing the shape of the structuring elements to preserve certain patterns of the original signal.

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