Improving Ultrasonic Imaging of Aluminum Plates Using Phase Modulation

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Abstract—Conventional techniques for ultrasonic image beamforming use amplitude information to produce the images. Although amplitude images can be obtained with high quality, they can also present limitations regarding dead zone, artifacts and detection of far reflectors. Coherence techniques based on signal phase result in images that can be used to identify the presence of a defect or reflector, with improvements over those limitations. This work proposes the use of phase modulation in the excitation signal and the application of the Pearson correlation to the instantaneous phase image. Simulations and experimental tests in an aluminum plate with artificial defects using Lamb waves and a linear piezoelectric array were conducted. The frequency response of the transducers-plate system was considered, leading to images with reduced artifacts and dead zone, and improvement in lateral resolution when compared to amplitude and instantaneous phase images without modulation.

Index Terms—Phase modulation; Instantaneous Phase; Ultrasonic imaging; Pearson correlation coefficient.

I. INTRODUCTION

Ultrasonic arrays have several applications in medical and industrial fields, for example in non-destructive testing and imaging of plates and tubes, which are widely used in aeronautics, automotive and petrochemical industries [1]. An array is a set of transducers, geometrically disposed according to a pattern, in general in a linear way (1-D) or in a matrix (2-D). One significant advantage of using arrays and guided waves in the inspection of plate-like structures is that the array can remain fixed at a position, being able to inspect a relatively large area [2].

Image quality depends on several factors, which are primarily related to geometrical characteristics of the array: aperture size and spacing between elements (pitch), which, in turn, define the radiation pattern of the array, basically described by a main lobe and side lobes. Some important characteristics are the lateral resolution, the relation between the main lobe and side lobe amplitudes, and the presence of grating lobes [3]. Lateral resolution depends on the width of the main lobe, which is inversely proportional to the array aperture size, while side lobes amplitudes can be changed by the use of apodization functions. Grating lobes are present when pitch is larger than half-wavelength (λ/2), and consequently artifacts can be produced in the image.

Conventional images can be obtained by using synthetic aperture techniques, where the instantaneous amplitude of the transmitted-received signals are delayed and summed in phase at each image position, in the Total Focusing Method (TFM) [4]. Advances have been also made using the instantaneous phase (IP) of the signals [3, 5], in order to improve defect detection. In these cases, the IP of each signal is coherently summed instead of the amplitude in the beamformer. When compared to conventional TFM amplitude, IP images are more likely to detect defects far from the array, while artifacts and dead zone are reduced. However, the final images have lower contrast due to high intensity of background noise [5], and it can be used as a reflector indication or as a coherence factor to improve the amplitude image.

The use of modulated signals have been proposed to improve SNR (signal-to-noise ratio) and contrast in ultrasonic systems. Frequency modulation [6], chirp signals [7], and codification [8, 9] have been proposed in the excitation of ultrasonic signals. In previous work the authors proposed the use of phase modulation (PM) associated with the Pearson correlation coefficient to improve lateral resolution [10]. The PM has been tested only in simulations and considering ideal conditions, showing good potential to be applied in practice. However, no experimental tests have been made.

In this work the experimental validation of the PM method is made, showing that it can complement information obtained from conventional TFM amplitude and IP images. Non-ideal characteristics of the practical systems, such as the finite bandwidth and frequency response of the system, are also addressed.

Section II presents a brief review of the ultrasonic beamforming techniques. Section III shows simulations and experimental results using the proposed methods, and the conclusions are presented in Section IV.

II. THEORETICAL BACKGROUND

This section presents a brief review on ultrasonic imaging using the TFM amplitude, phase and phase-modulated images.

A. Total Focusing Method

The Total Focusing Method (TFM) is a synthetic aperture focusing technique (SAFT), which employs all possible combinations of emitter-receiver pairs from the array. TFM achieves the best lateral resolution for an array, similar to the one obtained with phased-array techniques, but requires less electronic complexity [2]. On the other hand, by considering a linear array with N elements, it needs more processing power and memory, because all N² possible signals must be stored and processed [4]. The TFM amplitude image can be calculated from:

\[ I_A(r, \theta) = \frac{1}{N^2} \sum_{i,j=0}^{N-1} v_i(\tau_{ij}), \]

where \( v_i(t) \) is the amplitude signal emitted by element \( i \) and received by element \( j \), while \( \tau_{ij} \) is the calculated delay between the position of the emitter \( i \), the imaging point at
It is possible to calculate the TFM using the instantaneous phase (IP) instead of the instantaneous amplitude signals, which results in the IP image [5]. The IP $\phi_j(t)$ of a signal $v_j(t)$ can be evaluated by [11]:

$$
\phi_j(t) = \tan^{-1}\left(\frac{\dot{v}_j(t)}{v_j(t)}\right),
$$

where $\dot{v}_j(t)$ is the Hilbert transform of $v_j(t)$. The IP image is obtained by substituting $v_j(t)$ by $\phi_j(t)$ in (1) [5]. The IP image is a coherent image that improves reflector detection in comparison with the amplitude image, reducing artifacts and is less influenced by distance than amplitude images.

### B. Phase modulation and Pearson correlation

Prado et al. [10] proposed the use of phase modulation in the excitation signals and IP images, improving lateral resolution for a single point reflector when compared to the non-phase modulated signal. Consider a phase-modulated signal $s(t) = A(t)\sin(\omega_0 t + m(t))$, where $A(t)$ is the signal envelope, which depends on both the excitation signal and the frequency response of the transducer, $\omega_0$ is the carrier frequency and $m(t)$ is the message or modulating signal. The signal $s(t)$ will be used as excitation function and $m(t)$ is the information that should be demodulated in image formation.

Prado et al. [5] observed that a line in the TFM amplitude image at a fixed angle $\theta$, starting at the center of the array and passing by a reflector, contains the shape of the excitation signal at the reflector position. In the case of an IP image, the same line in the image passing by the defect will also have the format of the instantaneous phase of the excitation signal. This line is then demodulated, resulting the signal $d(r)$, which has a direct relationship with the time domain modulating signal $m(t)$ [10].

The Pearson correlation $\rho(r)$ is then calculated between the modulating signal $m(t)$ and each phase demodulated line in the image $d(r)$ [10]:

$$
\rho(r) = \frac{\text{cov}[m(t), d(r)]}{\sqrt{\text{var}[m(t)] \cdot \text{var}[d(r)]}},
$$

where $\text{var}$ is signal variance and $\text{cov}$ is covariance. The value of $\rho(r)$ lies in the range $[-1, 1]$. The smaller the value of $\rho(r)$, in modulus, the smaller the similarity between $d(r)$ and $m(t)$. The higher the value, the greater the similarity between them. The algebraic signal is related to the inversion or not of phase between the signals [10].

The domains $r$ and $t$ must be discretized accordingly, with the relation $dr = c.dt/2$, where $dr$ is the pixel resolution in the image, $dt$ is the sample period, and $c$ is propagation velocity. The Pearson coefficient is calculated for every line in the image, producing a Pearson coefficient image (PC image), which will have higher values at regions where the demodulated signal and $m(t)$ are similar, that is, at reflector positions.

### III. RESULTS

To verify the applicability of the phase modulation in ultrasound imaging, simulations and experiments have been conducted. An 8-element piezoelectric linear array was mounted on an aluminum plate and several images were produced in order to validate the method using Lamb waves.

#### A. Simulations

Point spread function (PSF) simulations were conducted considering an 8-element linear array, 9 mm pitch, operating at 360 kHz and propagation velocity 5450 m/s, corresponding to the experimental setup described later. Although the pitch (0.59λ) is greater than $\lambda/2$, it will not produce significant grating lobes, due to the finite element aperture and pulsed excitation.

The transmitted signals with and without modulation were generated considering 4 cycles sinusoidal signals with Gaussian envelope. White Gaussian noise was added to the signals, producing signal-to-noise ration (SNR) of 20 dB. For the modulated case, the message signal used in the PM was a triangular-shaped signal with phase deviation between 0 and $\pi/2$ rad. A point reflector was simulated at $\theta = \pi/2$ rad and $r = 0.2$ m.

Since the modulation procedure changes the amplitude information of the excitation signal, and consequently the resulting image, the proposed method using PM is compared to the conventional TFM amplitude and IP images without modulation.

Fig. 1(a) and 1(b) show the TFM amplitude image and IP image without PM, respectively, while Fig. 1(c) illustrates the PC image obtained with the proposed method. An improvement in defect sizing in the lateral direction is observed, with reduction in artifacts. However, axial resolution is a bit worse, due to the correlation operation.

Fig. 2(a) presents a line of the IP image for $\theta = \pi/2$ rad, passing by the reflector and the instantaneous phase of
Fig. 2 (a) A line in the IP image passing by the defect (solid line) and instantaneous phase of the excitation signal (dashed line). (b) Demodulated signal $d(r)$ (solid line) and the triangular function $m(t)$ (dashed line). (c) Pearson correlation coefficient calculated in the line passing by the defect before (dashed) and after (solid) moving average filtering. (d) Pearson correlation calculated in a line without defect.

Fig. 3 Frequency response of the transducer-plate system for the A0 and S0 modes, and spectrum of the excitation signal, $S(f)$, with phase modulation $m(t)$.

B. Experimental validation

An 8-element linear array with 9 mm pitch was mounted on a 1 mm-thick aluminum plate using piezoceramics (Ferroperm PZ-26, 7 x 7 mm, 0.5 mm thickness). The array was excited in a multiplexed way using a waveform generator (Tektronix AFG 3101, 14 bits) and a power amplifier (E&I 240L, 40 W), and the signals were digitized by an oscilloscope (Agilent MSO7041, 8 bits) using 32 averaging, sampling rate of 2.5 MSa/s and processed in the computer. Three ceramic elements and one rectangular plastic piece (20 x 20 mm, 1 mm thickness) were bonded to the plate to simulate surface defects.

B.1. Frequency response of the system: By exciting a pair of emitter-receiver with sinusoidal bursts, the frequency responses of the first symmetric (S0) and anti-symmetric (A0) modes that are coupled to the plate were obtained, and shown in Fig. 3. The S0 mode was used due to the low dispersion, higher response and wider bandwidth, which could benefit from the phase modulation operation. The A0 mode is more dispersive in this frequency range, and its application under phase modulation techniques will be analyzed in future works.

For the imaging results, the array elements were excited with Gaussian envelope burst excitation at 360 kHz with phase modulation and the triangular modulating signal $m(t)$ used in the simulations. In Fig. 3, the spectrum of the excitation signal $s(t)$ is shown in solid line, and it is within the S0 response bandwidth.

In the simulations, in section III.A and in [10], no assumptions were made about the frequency response of the excitation signal, showing a good similarity between them, while Fig. 2(b) shows the demodulated signal and the triangular message signal used in the modulation (dashed line). The demodulated signal is not an exact version of the message signal due to noise, but they have similar shape.

Fig. 2(c) shows the Pearson correlation in the line passing by the defect. The correlation coefficient between two triangular functions result in the shape shown in dashed line in Fig. 2(c). For a better reflector representation, a moving average filter with the same size of the excitation signal was applied. In order to keep the peak value of correlation close to one, the filter has a gain that is related to the length of the impulse response. As result the PC image in the line passing by the defect is presented in solid line in Fig. 2(c). In Fig. 2(d), a line that do not pass by the defect is shown, as expected, with values close to zero. Therefore, the amplitude of the Pearson coefficient clearly indicates the presence of the defect at 0.2 m, with values close to 1. Furthermore, defect location is approximately centered in the PC result, while in the IP (and in the amplitude), the signal $m(t)$ starts at defect position, at 0.2 m. However, due to the correlation operation, defect representation in the axial direction is larger.

Fig. 3 Frequency response of the transducer-plate system for the A0 and S0 modes, and spectrum of the excitation signal, $S(f)$, with phase modulation $m(t)$.
Fig. 6 PC image without frequency response compensation in dB.

Fig. 5 Normalized IP image without PM in dB.

Fig. 4 TFM amplitude image without PM in dB.

the system. Although the magnitude response of the S0 mode is not flat, it is very similar to \( S(f) \) and do not impose strong bandwidth limitations, in this case. Other modulating functions or higher modulation indexes could produce larger bandwidths, and in these cases the system would impose a stronger modification in the signals, and this effect can be compensated for better results.

B.2. TFM images: Fig. 4 shows the TFM amplitude image of the plate obtained without phase modulation, where reflector locations are represented by black squares in real sizes and indicated by roman numbers from I to IV. In the images shown hereafter, envelope is extracted, then a normalization is made and the images are displayed in dB scale, from -35 to 0 dB. Although all defects can be detected, there is a dead zone close to the array, several artifacts, and background noise with relatively high intensity, which may be caused by mode conversion, multiple reflections and noise.

Fig. 5 shows the IP image without phase modulation. Dead zone and artifacts are significantly reduced, but contrast is also reduced. The IP image using PM signals is very similar to the one illustrated in Fig. 5 with respect to dead zone, artifacts and background.

Fig. 6 shows the PC image without frequency response compensation. There is a clear artifacts reduction even in comparison with the IP image, but defect IV shows a smaller intensity. Lateral resolution is also improved, as will be shown later in more detail.

The S0 frequency response was compensated by dividing the spectrum of the acquired signal by the magnitude of the system frequency response. The phase was considered linear, in the case of propagation of the non-dispersive S0 mode. Fig. 7 shows the resulting PC image after applying the frequency response compensation. As the S0 frequency response is very similar to the spectrum of the excitation signal \( S(f) \), as observed in Fig. 3, in this case there is a small effect on the signals, and consequently the image is not so influenced. However, defect IV is better visualized in the PC image after compensation.

Lines in the PC image passing by defect III are shown in Fig. 8(a) and 8(b), for the non-compensated and compensated case, respectively. There is the expected result that was shown in the PSF simulations, where the coefficient \( \rho(r) \) assumes negative and positive values (dashed lines). For better visualization, the lines are rectified and filtered, resulting in the solid lines. Although the peak PC coefficient values for this defect did not vary considerably in both cases, for the whole image there was a positive effect after frequency response compensation.

Fig. 9 shows detail of defect III for: (a) Amplitude image without PM, (b) IP image without PM, and (c) PC image. Lateral resolution is improved in the PC image, but radial resolution is worse, due to the correlation operation, as already observed in the simulations. Improvement in axial resolution can be obtained with the use of other modulating functions which produce autocorrelation functions that are more localized in time. However, system bandwidth must be taken into account.

As observed in the simulations, the indication of defects in the PC images are more centered in the real position...
Fig. 8 Line passing by defect III in the PC images: (a) without frequency response compensation, and (b) with frequency response compensation. Solid lines are obtained after rectifying and filtering the dashed line results \( \rho(r) \).

Fig. 9 Detail of defect III. (a) Amplitude image without PM. (b) IP image without PM. (c) PC image.

Table I presents the defects sizes for each image in axial and lateral directions. PC results show better lateral resolution with defects that are more centered in the real defect position. As defect IV was not well represented in the PC image, this defect width resulted much smaller than it should be. When considering axial resolution, PC results are a bit worse than the obtained with the other methods due to correlation operation. Amplitude and IP images show similar results. This information is not sufficient to establish real defect sizes, that are smaller than wavelength in this case, but should be used to defect detection and localization purposes.

### IV. CONCLUSION

The use of phase modulated signals and instantaneous phase was experimentally verified in this work, corroborating simulations made in a previous work. System frequency response was measured and compensated, and resulted in images with better defect representation. The PC image reduces artifacts and dead zone, which are characteristics of the IP image, improving defect detection. Amplitude, IP and PC images can be used together to add information to increase probability of defect detection in NDT.

The use of wider band transducers can improve the results, allowing the use of other modulating signals that result in increased correlation.

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### REFERENCES


