Chirp Generated Acoustic Wavefield Images

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ABSTRACT

Guided waves are being considered for structural health monitoring (SHM) applications, and they can also be used to reduce subsequent inspection times once defects are detected. One proposed SHM method is to use an array of permanently attached piezoelectric transducers to generate and receive guided waves between the various transducer pairs. The interrogation can be done on a continuous or periodic basis to assess the health of the structure. Once defects are suspected in the structure, the traditional approach is to disassemble components for conventional nondestructive evaluation (NDE); however, this is an expensive and time-consuming process. A less expensive alternative to conventional NDE is to record acoustic wavefield images of guided waves generated from the attached transducers. These images clearly show details of guided waves as they propagate outward from the source, reflect from structural discontinuities and specimen boundaries, and scatter from any damage sites within the structure. However, the recorded waves are typically narrowband to enable effective visualization of echoes that are relatively compact in time. In this paper, we consider wavefield images that are recorded from a chirp excitation, which offers the advantage of high quality broadband data from a single excitation. However, responses are not directly useful because the received echoes are too extended in time. Signals are post-processed to obtain multiple narrowband and broadband responses containing echoes that are more compact in time to enable visualization of guided waves interacting with structural features. This technique is demonstrated on an aluminum plate that contains attached stiffeners and glued-on piezoelectric disc transducers. Wavefield data are recorded using an air-coupled transducer scanned over the plate surface while one of the attached transducers acts as a guided wave source. Waves interacting with the stiffener and the inactive discs are analyzed via broadband and narrowband processing at multiple frequencies.

Keywords: Ultrasonics, Lamb Waves, Frequency-Wavenumber Filtering, Structural Health Monitoring

1. INTRODUCTION

Guided waves have been explored for structural health monitoring (SHM) using permanently attached or embedded transducers to identify and locate damage1-7. After the interrogation is done on a continuous or periodic basis, a follow-up inspection is desired if potential structural damage is detected. The usual approach would be to disassemble components and perform conventional nondestructive evaluation (NDE), which is not only an expensive and time-consuming process, but may also introduce new damage. An alternative approach is to use the attached transducers to generate an outward propagating acoustic wavefield that propagates through the structure, and then capture wavefield images via noncontact methods such as a scanned air-coupled transducer or a scanning laser vibrometer8-10. These images contain a wealth of information that enables visualization of the propagating guided waves as they travel outward from the acoustic source, interact with geometrical features of the structure, and scatter from any sites of damage.

Generally, guided wave imaging methods require some degree of mode purity to simplify interpretation. In addition, signals scattered from damage are one or two orders of magnitude smaller in amplitude than the direct arrival. It is also desirable to acquire images from multiple modes, particularly if different wave modes are sensitive to different types of defects. The well-known mode-tuning approach can be employed for generating and receiving different modes by exciting transducers at different frequencies11. However, this process may require acquisition of large amounts of data to obtain needed resolution in the frequency domain and is thus time-consuming, particularly if extensive signal averaging is required to achieve a satisfactory signal-to-noise ratio.

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In this paper, we consider wavefield images that are recorded from a chirp excitation, which offers the advantage of high quality broadband data from a single excitation. Mizutani and Inokawa used chirp signals to generate Lamb waves for thin-walled structure inspection. They applied the continuous wavelet transform to analyze the response to the chirp excitation, but results are not compact in the time domain and are hard to interpret. Kannajosyula et al. applied the well-known chirp-based pulse compression method, which is widely used in radar imaging and medical ultrasound imaging, to noncontact ultrasonic guided wave applications. They utilized a chirp signal modulated with a Hamming window for pulse compression, but did not extract narrowband information from the measured responses. In this study, a chirp excitation is applied to acquire broadband multi-modal data, which can significantly reduce both the quantity of measured data and the measurement time. The chirp response data are not directly useful because the direct, reflected and scattered echoes from various features are too extended in time. Signals are post-processed to obtain multiple narrowband and broadband responses containing more compact echoes in time. This technique is demonstrated on an aluminum plate specimen that contains an attached stiffener and glued-on scatterers (i.e., inactive transducers) to simulate damage. Waves are generated using a single glued-on piezoelectric disc transducer as a source, and wavefield data are recorded by scanning an air-coupled transducer over the plate surface. Waves interacting with the stiffener and the glued-on scatterers are compared after broadband and narrowband processing at multiple frequencies.

2. THEORY

The theory is presented in detail in a companion paper and is reviewed here. Lamb waves in a plate may be generated by a linear chirp source, \( s_c(t) \), where the frequency is swept from a minimum value to a maximum value over a fixed time interval,

\[
s_c(t) = w(t) \sin \left( \omega_0 t + \frac{\pi B t^2}{T} \right).
\]

In this equation \( \omega_0 \) is the starting angular frequency, \( T \) is the duration of the chirp, and \( B \) is the chirp bandwidth in Hz. The function \( w(t) \) is here taken to be a rectangular window of width \( T \). The Fourier transform of \( s_c(t) \) is \( S_c(\omega) \), where \( \omega \) is the angular frequency.

Let \( h(t) \) be the impulse response associated with specific source and receiver locations, which includes both the structural response and all sensor and instrumentation effects. Further, let \( H(\omega) \) be the Fourier transform of \( h(t) \). Since the system is assumed to be linear, the response to the chirp excitation can be expressed in the frequency domain as,

\[
R_\chi(\omega) = H(\omega)S_c(\omega) .
\]

Now consider a different excitation, such as a tone burst, given by \( s_d(t) \). In the frequency domain we have,

\[
R_\delta(\omega) = H(\omega)S_d(\omega) .
\]

The response to the signal \( s_d(t) \) can be readily calculated from the measured chirp response by division in the frequency domain,

\[
R_\delta(\omega) = R_\chi(\omega)G(\omega) \text{ where } G(\omega) = \frac{S_d(\omega)}{S_c(\omega)} .
\]

The filter \( G(\omega) \) is constructed from the known Fourier transforms of the chirp excitation and the desired excitation. If the bandwidth of the desired excitation falls within that of the chirp, then division in the frequency domain is well-posed and \( G(\omega) \) can be readily computed. Finally, \( R_\delta(\omega) \) may be transformed back to the time domain to obtain the tone burst response signal.

3. EXPERIMENTS

An aluminum plate, 915 mm x 610 mm x 3.2 mm, was used for this study. Aluminum stiffeners were attached to the back surface of the plate using a semi-rigid epoxy adhesive. Specifically, a “T” shaped stiffener was attached near the centerline of the plate, and “L” shaped aluminum stiffeners were attached around the edges of the plate. Six glued-on PZT discs were also attached to the back of the plate as shown in Figure 1(a). One of these transducers was used as the
acoustic wave source and the others appear as back surface scatterers, which simulate defects. Figure 1(b) is a front side drawing of the part showing the specific locations of the three transducers attached to the right side of the plate. The area inside the dashed box, shown in Figure 1(b), was scanned to capture the acoustic wavefield by recording full RF waveform data at each pixel location. Coordinates are listed in Table 1 for the three transducers, the center “T” stiffener, and the corners of the data acquisition area.

The propagating acoustic wavefield in the plate was measured using a QMI AS400ARi 400 MHz air-coupled transducer, 50.8 mm focal length, attached to an automated scanner. The acoustic wave source was transducer #1, a 300 kHz, 7 mm diameter piezoelectric disk, which was permanently attached to the back surface using a semi-rigid epoxy adhesive at the location listed in Table 1. It was driven using both tone burst and chirp voltage waveforms from the gated amplifier of a Ritec RAM 5000 system. The waveform source input to the Ritec amplifier was generated using a model 33250A Agilent arbitrary waveform generator. Figure 2 shows output waveforms from the waveform generator and the Ritec gated amplifier for a 0 to 400 kHz chirp with a duration of 160 μs. The position of the chirp was centered between turn on and turn off transients of the gated amplifier as is visible in Figure 2(b).

![Image of aluminum plate with transducers](image)

**Fig. 1.** (a) Photograph of the back side of the aluminum plate showing the stiffeners and six glued on transducers. (b) Diagram relative to the front side of the plate, which shows the data acquisition area (inside the dashed lines) and the location of the three transducers that were mounted on the right side of the plate. Transducer #1 was used as the acoustic wave source.

**Table 1.** Coordinates of interest.

<table>
<thead>
<tr>
<th>Description</th>
<th>$x$ (mm)</th>
<th>$y$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer #1</td>
<td>690</td>
<td>470</td>
</tr>
<tr>
<td>Transducer #2</td>
<td>723</td>
<td>205</td>
</tr>
<tr>
<td>Transducer #3</td>
<td>664</td>
<td>147</td>
</tr>
<tr>
<td>Center of Stiffener</td>
<td>463</td>
<td>305</td>
</tr>
<tr>
<td>Lower Left Corner of Data Area</td>
<td>254</td>
<td>102</td>
</tr>
<tr>
<td>Upper Right Corner of Data Area</td>
<td>761</td>
<td>507</td>
</tr>
</tbody>
</table>
The QMI AS400ARi 400 MHz transducer contains an integral 40 dB amplifier, whose output was input into an Olympus PR5058 pulser receiver for bandpass filtering from 35 kHz to 1 MHz and 10 dB of additional amplification. The plate was raster scanned at a resolution of 1.27 mm, and RF waveforms were digitized over a 2000 μs time window at a sampling frequency of 2.5 MHz and resolution of 8 bits at each pixel location.

4. RESULTS

Measured chirp waveforms were filtered using tone burst waveforms as was discussed in Section 2. Actual waveforms are shown in Figure 3 for the specific tone bursts used in this study.

A validation test was conducted at a measurement position of $x = 635$ mm, $y = 254$ mm on the plate using both chirp and tone burst excitations. The tone burst waveforms are shown in Figures 3(a) for 75 kHz, 5 cycles, and in Figure 3(e) for 300 kHz, 5 cycles. These signals were used both as inputs to the Ritec gated amplifier for tone burst response measurements and as reference waveforms for filtering the chirp response results. The purpose was to compare tone burst filtered signals from the chirp response to the actual responses that resulted from a tone burst excitation.

![Fig. 2. (a) Chirp excitation with a linear sweep from 0 to 400 kHz. (b) Measured chirp response at output of Ritec RAM 5000 gated amplifier.](image)

![Fig. 3. Various tone burst waveforms used in this study: (a) 75 kHz, 5 cycles, (b) 100 kHz, 3 cycles, (c) 250 kHz, 2 cycles, (d) 250 kHz, 5 cycles, (e) 300 kHz, 5 cycles, and (f) 400 kHz, 7 cycles.](image)
Shown in Figure 4 are plots of the time domain signals and frequency spectra for the measured broadband chirp response and the measured tone burst responses at both 75 KHz and 300 kHz. Figure 5 shows waveforms obtained after processing the chirp response with filters calculated as per Eq. (4) using the signals of Figures 3(a) and 3(e). The waveforms derived from the chirp response almost perfectly agree with the measured tone burst responses, which demonstrates the validity of using filtered chirp waveforms to obtain narrowband tone burst results.

Time slice snapshots of the propagating wavefield are shown in Figure 6 for the chirp response after filtering with the 250 kHz, 2 cycle waveform of Figure 3(c). This filter is selected to capture a broadband, impulse-like, response. Waves are visible radiating out from the source transducer at (690, 470) and interacting with the center “T” stiffener, edges of the plate, and impedance discontinuities at the locations of transducers #2 and #3.

Next, the chirp response acoustic wavefield was filtered using tone burst pulses of 100 kHz, 3 cycles, 250 kHz, 5 cycles and 400 kHz, 7 cycles, which correspond to Figures 3(b), 3(d) and 3(f), respectively. The motivation for choosing these tone burst filters is discussed in a companion paper. Figure 7 shows snapshots from the resulting acoustic wavefields after processing.
Fig. 5. Comparison of the measured responses from 5-cycle, Hanning windowed tone burst signals to signals calculated from the chirp response. (a) 75 kHz, and (b) 300 kHz.

Fig. 6. Acoustic wavefield snapshots generated from chirp data for 0 - 400 kHz chirp excitations after filtering with a 250 kHz, 2 cycle tone burst filter. (a) 30 μs, (b) 60 μs, (c) 90 μs, and (d) 120 μs.
Fig. 7. Acoustic wavefield snapshots generated from chirp data for 0 - 400 kHz chirp excitations after filtering with a tone burst filter. (a) 100 kHz, 3 cycles at 90 μs, (b) 100 kHz, 3 cycles at 120 μs, (c) 250 kHz, 5 cycles at 90 μs, and (d) 400 kHz, 7 cycles at 90 μs.

Figures 7(a) and 7(b) show wavefield snapshots after processing with the 100 kHz, 3 cycle filter at two different propagation times. Two distinct modes are visible, a weak leading S0 mode followed by a stronger A0 mode. Referring to Figure 7(a), at a time of 90 μs the S0 wave has propagated well past the stiffener region and the lead edge of the A0 wave is just arriving at the stiffener. Mode converted waves from S0 to A0 are clearly visible “V” patterns radiating out from the stiffeners. Referring to Figure 7(b), at a time of 120 μs the A0 wave group has interacted with the stiffener and additional backscattered A0 waves are visible adjacent to the stiffener boundary. There is some bending of the A0 wavefront as these waves propagate past the stiffener.

The results for the 250 kHz, 5 cycle filter are shown in Figure 7(c). There are still two distinct modes, but now the amplitudes of the S0 and A0 waves are comparable. Mode conversion from the leading S0 waves to A0 waves is clearly visible at the stiffener interface as well as conversion from S0 to A0 at the location of transducer #3, which is glued on to the back of the plate.

The results for the 400 kHz, 7 cycle filter are shown in Figure 7(d), and here the wavefield is mostly composed of a single S0 mode. Note that the S0 wavefronts bend to a greater degree at 400 kHz than at 250 kHz, and that at 400 kHz S0 waves are more clearly backscattered from the stiffener and the edges of the specimen. However, A0 waves mode converted from S0 at transducer #3 are much less pronounced than they were at 250 kHz.
The acoustic wavefield results were filtered in the frequency–wavenumber, or $f-k$, domain to select specific propagation modes. This filtering process involves first transforming coordinates from the original Cartesian scan grid to a radial–angular representation as described in Ref 15. Next, an angle can be specified, and waveforms along this radial angle can be displayed in the $f-k$ domain as is shown in Figure 8(a) for the original chirp response wavefield. The incident wavefield, propagating radially away from the source, is displayed in the right half plane of this plot, and waves backscattered towards the source are displayed in the left half plane. Both forward and backscattered $A_0$ and $S_0$ modes are clearly visible in Figure 8(a).

$A_0$ and $S_0$ waves can be selectively removed by filtering regions in the $f-k$ domain. Figure 8(b) shows the $f-k$ plot after a filter of 250 kHz, 5 cycles is used to process the chirp response wavefield for an angle of 180 degrees. This angle is along a horizontal line from the source transducer to the stiffener boundary and it was chosen to best show waves directly backscattered from the boundary. Figure 8(c) is the resulting $f-k$ plot after $S_0$ waves are removed and Figure 8(d) is after $A_0$ waves are removed.

Fig. 8. Frequency–wavenumber plots derived from acoustic wavefield data after a Cartesian to radial-angle coordinate transformation centered at the source location. (a) $f-k$ plot of chirp response for $\theta = 235^\circ$, (b) $f-k$ plot of 250 kHz, 5 cycle filtered chirp response for $\theta = 180^\circ$, (c) $f-k$ plot of 250 kHz, 5 cycle filtered chirp response for $\theta = 180^\circ$ with $S_0$ waves removed, and (d) $f-k$ plot of 250 kHz, 5 cycle filtered chirp response for $\theta = 180^\circ$ with $A_0$ waves removed.
Finally, the filtered frequency–wavenumber results were transformed back to the time domain. Results are shown in Figure 9 for the 250 kHz, 5 cycle filtered wavefield data, and in Figure 10 for the 400 kHz, 7 cycle filtered wavefield data. Figures 9(a) and 9(b) show the wavefield at 90 and 120 μs after removal of the S₀ mode. At 90 μs the A₀ incident wavefield is just arriving at the stiffener and at 120 μs the leading edge of the A₀ wavefield has propagated past the stiffener. A₀ waves that were mode converted from the leading, incident S₀ waves are also clearly visible on this image. Figures 9(c) and 9(d) show the wavefield after the forward and backwards A₀ waves have been removed after propagation times of 60 and 90 μs, respectively. Note that A₀ waves scattered from the stiffener interface are not effectively removed because the approach used removes only waves propagating along a radial direction from the source transducer. There are also some artifacts represented as weak lines on the images that emerge radially from the source transducer which result from an initial Cartesian to radial–angle transformation followed by a final radial–angle to Cartesian transformation to display the mode filtered waveform results in the time domain. Compared to the 250 kHz, 5 cycle results, the 400 kHz, 7 cycle results shown in Figure 10 exhibit a much weaker A₀ wave and substantially increased interaction of the leading S₀ wave with the stiffener boundary.

**Fig. 9.** Acoustic wavefield snapshots generated from chirp data for 0 - 400 kHz chirp excitations after filtering with a 250 kHz, 5 cycle tone burst filter and selections of wave modes via f–k filtering: (a) A₀ waves at 90 μs, (b) A₀ waves at 120 μs, (c) S₀ waves at 60 μs, and (d) S₀ waves at 90 μs.
Fig. 10. Acoustic wavefield snapshots generated from chirp data for 0 - 400 kHz chirp excitations after filtering with a 400 kHz, 7 cycle tone burst filter and selections of wave modes via \( f-k \) filtering (a) \( A_0 \) waves at 90 \( \mu \text{s} \), (b) \( A_0 \) waves at 120 \( \mu \text{s} \), (c) \( S_0 \) waves at 60 \( \mu \text{s} \), and (d) \( S_0 \) waves at 90 \( \mu \text{s} \).

5. SUMMARY AND CONCLUSIONS

In this paper we have demonstrated that a chirp excitation is a viable option for generating and analyzing acoustic wavefield images as compared to multiple tests at specific frequencies with narrow band tone burst excitations. With the complete acoustic wavefield response recorded via a scan from a single broadband chirp excitation, various tone burst filters may be applied to obtain results that almost perfectly agree with what would have been obtained from separate time-consuming tone burst scans. We have further demonstrated that the chirp excitation may be combined with frequency–wavenumber filtering methods to select specific wave modes for subsequent analysis. The significance is that the proposed chirp-based method can greatly reduce both the measurement time and quantity of data while producing excellent quality results.
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