AN EXAMINATION OF TRAILING ECHOES IN TAPERED RODS

Joannes Pezant, Jennifer E. Michaels and Thomas E. Michaels.
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA 30332-0250

ABSTRACT. Ultrasonic evaluation of complex structures is frequently challenging because of limited physical access to locations of interest. Cylindrical waveguides are an attractive solution for accessing complex structures, particularly at high temperatures, although trailing echoes resulting from mode conversions along the waveguide boundaries often interfere with the ultrasonic measurements. Tapered rod usage has already demonstrated an ability to reduce the impact of trailing echoes, but a clear relationship between taper angle and amplitude of trailing echoes has not been established. The research presented here considers the effect of the taper angle on trailing echoes in a through transmission configuration. Experiments confirm that attenuation of trailing echoes increases with the taper angle, but they also show that above a certain angle, the attenuation tends to be constant. The trailing echoes also spread out in time as the taper angle increases. Thus, a preferred angle may exist that gives the best signal for a particular rod length, diameter and inspection application. Finite difference and ray tracing methods were used to model the effect of the taper angle on trailing echoes using 2D simulations. Comparisons to experiments indicate that a full 3D model may be required to provide a reasonable match to the measurements and allow determination of an optimal taper angle.

Keywords: Ultrasonic, Waveguide, Buffer Rod, Trailing Echoes, Tapered Rod, Ray Tracing

PACS: 43.20.Mv, 43.35.Zc

INTRODUCTION

The nondestructive evaluation of complex structures is sometimes difficult because transducers cannot be mounted where it is necessary to make a measurement. This situation frequently occurs when the temperature of the structure is too high for the transducer to survive, or when the area of interest is not easily accessible. Cylindrical waveguides, or buffer rods, with the transducer mounted to one end and the other end contacting the part, can be a good solution to this problem. However, it is well-known that waves traveling in such waveguides produce undesired echoes called trailing echoes [1].

Several methods have been proposed to minimize or eliminate these echoes, and satisfactory results have been obtained for many situations [2,3]. One of the simplest and least expensive solutions consists of using tapered rods. It has been shown experimentally...
that the introduction of a taper angle considerably reduces the amplitude of the trailing echoes relative to the first echo arrival. The work presented here includes both experiments and modeling to investigate the effect of taper angle on trailing echoes. Both finite difference and ray tracing models are implemented, and model results are compared to measurements. Results are discussed in terms of both understanding wave propagation in tapered rods and selecting the best taper angle, and suggestions are made for future work.

**EXPERIMENTAL OBSERVATIONS**

Published results indicate that trailing echo attenuation can be considered acceptable for taper angles of about one degree [4]. As a result, it was decided to study the effect of taper angle on trailing echoes for taper angles in the range of zero to one degree. Five tapered rods were machined from tool steel as illustrated in Figure 1. Even though eventual use of the rods could be in either pulse-echo or through-transmission mode, this investigation considered through transmission operation only to simplify both modeling and experiments.

Measurements were made using two 10 MHz transducers of 9.5 mm (3/8") diameter (Panametrics model V552-SM), with one clamped to the larger end of the rod and the other hand-held to the smaller end. A total of six through transmission waveforms were acquired for each taper angle. The ratio between the amplitude of the first trailing echo and that of the direct arrival was calculated for each signal to quantify trailing echo attenuation. Figure 2 shows a typical through transmission signal measured from the rod with a 0.5° taper angle. The first trailing echo is about 20 percent of the amplitude of the first wave arrival, and several additional trailing echoes are visible later in time.

![FIGURE 1. Tapered rods used for experiments. (a) Photograph of the rod set, and (b) sketch showing rod dimensions (not to scale).](image-url)
Figure 3(a) shows representative through transmission waveforms for the five taper angles considered, and Figure 3(b) shows the amplitude of the first trailing echo relative to the first arrival as a function of taper angle. As expected, the relative amplitude of the first trailing echo decreases when the taper is introduced. It can also be seen that the trailing echoes tend to split apart and spread out in time as the taper angle increases, which contributes to noise or clutter after the first echo arrival. The limited data shown here indicates that for larger taper angles, the amplitude ratio remains approximately constant or may even increase, but the spreading of the trailing echoes increases the background clutter. For the specific rods and transducers considered here, there appears to be an optimal angle between 0.25° and 0.75° such that the cleanest signal will be obtained, and further improvement will most likely not result from additional increases in the taper angle.

Figure 3. (a) Measured waveforms for different taper angles. (b) Amplitude of the first trailing echo relative to the first arrival versus taper angle. Each data point represents a separate waveform acquisition.
MODELING

The surface conditions of the machined rods and variability of coupling the transducers to the rods both contribute to scatter in the experimental measurements. In addition, trailing echoes are influenced by the specific dimensions of the rod used. Thus, simulations were performed to study the progression of trailing echoes as a function of taper angle, both in terms of their relative attenuation and the build up of background clutter as trailing echoes spread in time.

Finite Difference

The commercially available software package, Wave2000 [5], was used to simulate waves propagating in a tapered rod. This is a finite difference based 2D simulation tool, and thus the circular geometry of the rods could not be modeled. To permit use of this 2D modeling software, the geometry of the waveguide was represented using a two dimensional shape as shown in Figure 4(a), which is a longitudinal section of the 0.5° tapered rod. Taper angles ranging from 0 to 1° in 0.05° increments were simulated, for a total of 21 angles. Note that the vertical tapered edges of the rod were not really straight due to a pixel effect associated with the finite difference grid. The transducer source function is modeled as a 2 cycle, 10 MHz tone burst as shown in Figure 4(b).

Figure 5(a) shows simulated waveforms for the five angles corresponding to the experimental measurements. The attenuation of the amplitude of the trailing echoes is clearly visible in the waveforms, but the trailing echoes are obscured by the noise behind the first arrival as the taper angle increases. This noise appears to be numerical in origin and perhaps exacerbated by the “stair-step” effect of the tapered boundaries. Moreover, the trailing echoes do not appear to spread out in time as they do for the experimental waveforms shown in Figure 3(a).

As before, the attenuation of the trailing echoes is quantified by comparing the amplitude of the first trailing echo to that of the first arrival, and Figure 5(b) shows this relative amplitude for all 21 angles considered. The plot shows an initial drop and then levels off with increasing angle as was observed experimentally, but there is more relative attenuation of the trailing echoes for the simulations than the experiments.

FIGURE 4. (a) Geometry used for finite difference simulation of a 0.5 degree tapered rod. (b) Transducer source function.
Ray Tracing

For the ray tracing model employed here, the transmitter is modeled as a collection of point sources, each emitting rays that are distributed uniformly in angle. All ray paths of interest, including reflections and mode conversions, are computed between the transmitter and the receiver. The waveform at the receiver is then obtained by adding the contribution of each ray. In this approach, there is no drawing of the geometry and no grid for computation; the points of reflection on the boundaries are determined mathematically without any pixel effects. Thus, there is no numerical noise as was the case for the finite difference simulations.

To reduce the number of possible ray paths, the ray tracing was performed in two dimensions using the same 2D cross section as for the finite difference approach. The transmitter was modeled by 30 point sources distributed uniformly across its surface. A 3D correction was made by weighting the contribution from each point source by the annular area corresponding to its radius. Each point source radiates isotropically within the 2D cross sectional plane of the rod, and rays were generated every 0.05° for the subsequent calculations. With this model, curvature effects are not taken into account because the point sources only radiate in this 2D plane. Also, amplitude attenuation along each ray path was ignored.

For each ray path, it is necessary to take into account mode conversions at the rod boundaries. Each time a ray meets a boundary, it splits into two reflected rays, longitudinal and shear, of different amplitudes, angles and wave speeds. Consequently, a single ray originating from the transmitter potentially produces several additional rays that arrive at the receiver at different times and with different amplitudes consistent with the various paths, reflection coefficients and propagation modes. Note that surface waves were not considered.
The calculations were limited to the first three echoes arriving at the receiver for each point source. Specifically, the simulation includes all the rays contributing to the first arrival, the first trailing echo, and the second trailing echo. Thus, the rays experiencing more than four mode conversions were discarded, and rays emitted at large angles were not considered. The exclusion of these rays substantially reduces the computational time without affecting results.

Since all the rays emit simultaneously in time at the source and are initially identical in amplitude, the contribution from each ray is obtained by scaling and shifting the source waveform based upon the computed arrival time and amplitude of each ray. The arrival time is determined from the path calculations and the appropriate wave velocity for each propagating mode. The amplitude is modified at each mode conversion and is determined using theoretical reflection coefficients for plane wave reflection at a planar boundary [6], which is an approximation here since the circular geometry is not taken into account. Once this information is gathered for each ray, the received waveform is created by summing the contributions from all of the rays. For the model to be consistent with experiments, the source waveform was chosen to be a 3 cycle, 10 MHz sinusoid multiplied by a Hanning window.

Figure 6(a) shows five waveforms from the ray tracing simulations out of the 21 taper angles considered. Results show attenuation of the trailing echoes as well as their subsequent spreading in time, which is consistent with experiments. However, it can be seen from Figure 6(b) that the relative amplitude of the first trailing echo is decreasing more rapidly with taper angle than the measurements of Figure 3(b).

The experimental waveform for the straight rod is compared to the corresponding waveform from the ray tracing simulation in Figure 7. The wave shapes are in reasonable agreement, and the differences in time are most likely due to inaccuracies in dimensions and material properties used for the simulations.

![Figure 6](image-url)

**FIGURE 6.** Ray tracing data. (a) Waveforms for five different taper angles. (b) Amplitude of the first trailing echo relative to the first arrival versus taper angle.

1632
A comparative plot of all experimental and simulated amplitude ratios is presented in Figure 8. The ratios obtained through finite difference and ray tracing are in reasonable agreement with each other for angles smaller than 0.4 degrees. After this amount of taper, numerical noise overshadows the trailing echoes for the finite difference simulations and the corresponding ratios can no longer be determined accurately.

The amplitudes of the first arrivals for larger taper angles decrease substantially for the experimental data, but remain constant for both the finite difference and the ray tracing results. This discrepancy is believed to be a result of using 2D models for both simulations that do not take into account off-axis rays that undergo more reflections as they “spiral” down the rod. The overall impact is that for the 2D simulations, the first arrival is larger in amplitude than it should be but trailing echoes are smaller, resulting in relative trailing echo amplitudes that are lower than what is observed experimentally.
SUMMARY AND CONCLUSIONS

According to the experimental results, the increase of the taper angle has three simultaneous effects. First, the amplitude of the first arrival decreases. Second, the amplitude of the trailing echoes relative to the first arrival decreases. Third, the trailing echoes spread out in time. The first effect could be deleterious if the incoherent noise level is high, but may not be a problem if there is sufficient signal-to-noise ratio. The second effect is advantageous since it reduces the relative amplitude of trailing echoes. The third effect, however, may limit the potential improvement of a larger taper angle by increasing the temporal extent of the clutter and perhaps increasing its amplitude as multiple trailing echoes begin to interfere.

For the specific rods and transducers considered here, a small increase in taper angle from the straight rod case causes all the trailing echoes to be reduced in amplitude relative to the first arrival. But after approximately 0.25° to 0.75°, the rate of attenuation levels off with increasing taper angle, after which the major effect is spreading of the echoes. Thus, there appears to be an optimal angle between 0.25° and 0.75° that produces the cleanest signal for the rod geometry used for these studies. It is expected that the length of the rod and the diameter of the transducer will have an impact on the value of this optimal angle for other geometries.

More exact simulations could be performed using 3D models, but at the expense of a substantial increase in computation times. Thus, even if 2D simulation results do not exactly match the experiments, they are useful for determining trends and estimating the range of angles expected to be the best for various rod geometries. Finally, ray tracing is judged to be the best method at this point for the 2D simulations since it realistically captures the spreading in time of the trailing echoes as the taper angle increases.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of James S. Hall. This work is sponsored by the National Science Foundation under grant number IIP-0740663 to Mechanical Integrity, Inc., as a part of the NSF STTR program.

REFERENCES