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## Theme: Radiata Management

**Task No: F10205**
**Milestone Number: 2.5.1**

**Report No. FFR- R045**
(no. allocated by FFR on final copy)

# A Technique for Non-damaging Measurement of Sound Speed in Seedlings

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Date: September 2009

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# EXECUTIVE SUMMARY

There is a need to determine stiffness at an early stage in order to identify candidates for future breeding programs and select clones with superior wood stiffness. Acoustics properties are closely related to the mechanical properties of wood, hence they have proved to be a quick and relatively cheap means of studying mechanical properties of wood. In a previous FFR report (F10202 Q2 2009), we described a method for measuring ultrasonic time-of-flight in seedlings. These measurements proved to be destructive or unacceptably intrusive to the seedling because they required that a probe be inserted through the cambium layer and into the xylem of the seedling. It was therefore proposed that a new method be developed to measure the acoustic speed. The method should be accurate and non-damaging to the seedling, and not require that the cambium be penetrated.

This report describes a new time-of-flight method (dubbed cross-correlation time-of-flight) which can measure the longitudinal vibration speed of sound in a seedling in a non-destructive and non-damaging way. The method uses two miniature accelerometers (weighing 0.2 grams) coupled to the seedling stem to obtain the necessary acoustic signals, and a pin to generate the acoustic pulse. The method measures the sound speed of the seedling stem as a whole and does not selectively measure the fastest path.

The method was tested on nine 1- and 2-year-old seedling clones. Comparing the results of the method to a destructive resonance test showed that the results are unbiased with a mean square error difference of 2%. Repeatability tests show an uncertainty standard deviation of less than 2%.

**The method shows good promise as a rapid and cost-effective tool for screening of wood quality in clonal trials.**

The method developed will be used in various FFR research projects, and potentially could be used by breeding companies to screen clones for stiffness.

# INTRODUCTION

## Background

For many years acoustics has been used to determine wood properties (Bucur, 1995). Sound speed in a material is related to stiffness, and it is for this reason that the measurement of sound speed in wood still receives much attention by researchers, ( e.g., Lindstrom, Reale, & Grekin, 2009). Sound speed is also used widely in the forestry industry at all stages, from determining the properties of standing trees to assessment of the state of in-service timber.

In general one can divide the measurement of sound speed into two groups: time-of-flight techniques, and resonance techniques.

Time-of-flight techniques require two transducers, and basically measure the time taken for the sound wave to travel between them. In some cases one transducer is used to generate the sound and the other to pick up the sound. In other cases the sound is generated at a third point and both transducers are used to pick it up as the wave passes by them (Wielinga, Raymond, James, & Matheson, 2009). Time-of-flight techniques are generally not so accurate, because they are based on starting and stopping a timer when the acoustic wave amplitude reaches a certain threshold. The amplitude of the wave can be dependent on a number of other factors which have nothing to do with wood properties, producing variable results, particularly so when used over short distances as will be the case with seedlings. The advantage of time-of-flight techniques lies in the ability to measure across a part of an irregular specimen without needing to cut out the section.

Resonance techniques generally require only one measurement transducer and some means of generating acoustic waves (Andews, 2002). They are regarded as being a very accurate way to determine sound speed if the specimen is long and slender. However, a sample with well-defined ends is needed, and hence it is not used to measure sound speed in standing trees.

In this report we mainly focus on measuring the speed of acoustic waves in young seedling stems. We also consider the measurement of acoustic damping.

In the past the common method of measuring the properties of a seedling was to use ultrasonic acoustic stress timers; for example, the Fakopp ultrasonic timer can be used for this purpose. Generally, however, one needs to equip the ultrasonic timer with sharp tips in order to penetrate into the xylem of the stem (Huang & Lambeth, 2007). In a previous FFR report (F10202 Q2 2009) we tried to see if we could reliably measure the sound speed of a seedling using some ultrasonic probes. In all cases we found that we could not reliably transmit the ultrasonic wave through the bark/cambium layer and into the stem, and needed to pierce through the cambium and into the xylem. This was therefore damaging to the seedling, and unacceptable for monitoring the growth of the same seedling over time.

## Current development

In order to overcome the limitations of existing time-of-flight techniques applied to seedlings, a new time-of-flight technique was developed. This new technique has the following important differences from the usual spike-probe ultrasonic measurements:

- **The transducers are gently attached to the bark of the seedling. To the best of our knowledge this technique is <u>non-damaging</u> to the seedling.** The transducers used are miniature accelerometers, and equivalents can be obtained from a number of manufacturers. The sound wave is generated by simply flicking the head of a sewing pin on the surface of the stem.
- **The longitudinal wave travelling along the stem is measured. This means the whole cross-section of the stem is influencing the wavespeed**, not just some fastest acoustic

speed (as you might get with spike-probe time-of-flight measurements). This means that the overall total results for a stem should be the same as resonance measurements. It also means that the cambium layer and bark will influence the result.

- **A relatively large section of the longitudinal wave pulse is used (> 100 microsecond) to generate the time-of-flight measurement, giving much greater accuracy, repeatability and insensitivity to the acoustic wave amplitude.** This is a much better technique than the basic threshold idea used in most time-of-flight systems, which basically compare one measurement point and are sensitive to the strength of the pin strike.

# METHODS

## Cross-correlation Time-of-flight Technique

The non-damaging aim is achieved by attaching two miniature accelerometers to the bark layer of the seedling using a layer of beeswax and some foam-lined clips (as shown in Figure 1). The two accelerometers are spaced by a known distance. Each end of the stem is gently flicked using a pin head to generate an acoustic pulse (as shown in Figure 2). The accelerometers measure the vibrations travelling along the stem caused by the pin hit on an end. The vibrations from the two accelerometers are compared for waves travelling in one direction, and the time difference is extracted, giving the speed of sound over that particular section of the stem.

The accelerometers are mounted so that their axis of sensitivity is in the same direction as the stem. Strikes to generate acoustic pulses are made on both ends of the stem for each accelerometer measurement (shown in Figure 3). Averaging the results of a strike from the base of the stem and a strike from the top essentially calibrates the measurement system by removing unequal time delays in the two signals caused by the mounting of the accelerometers, the accelerometers themselves, and the electronics. Geometrically averaging the gains measured from sound pulses travelling in both directions calibrates for unequal gains in the measurement system.

Strikes should not be too close to the accelerometer because the waveform takes some time to form into the desired longitudinal wave type. Measurements on 1-year-old seedlings show that 100 mm appears to be a good limit.

It is possible that, without due caution, the pin hit can be of such force as to damage the cambium. If this is a concern then a small, thin piece of hard plastic can be stuck to the stem with beeswax and the plastic struck directly with the pin head.

The spacing between the accelerometers is a compromise between the available material in the stem (i.e., stem length), the region that needs to be examined, the loss of signal in the stem and the accuracy that is required. The measurements showed that 100 mm is a good spacing.


**Figure 1.** Accelerometers attached to seedling using beeswax (clips are not shown for clarity).

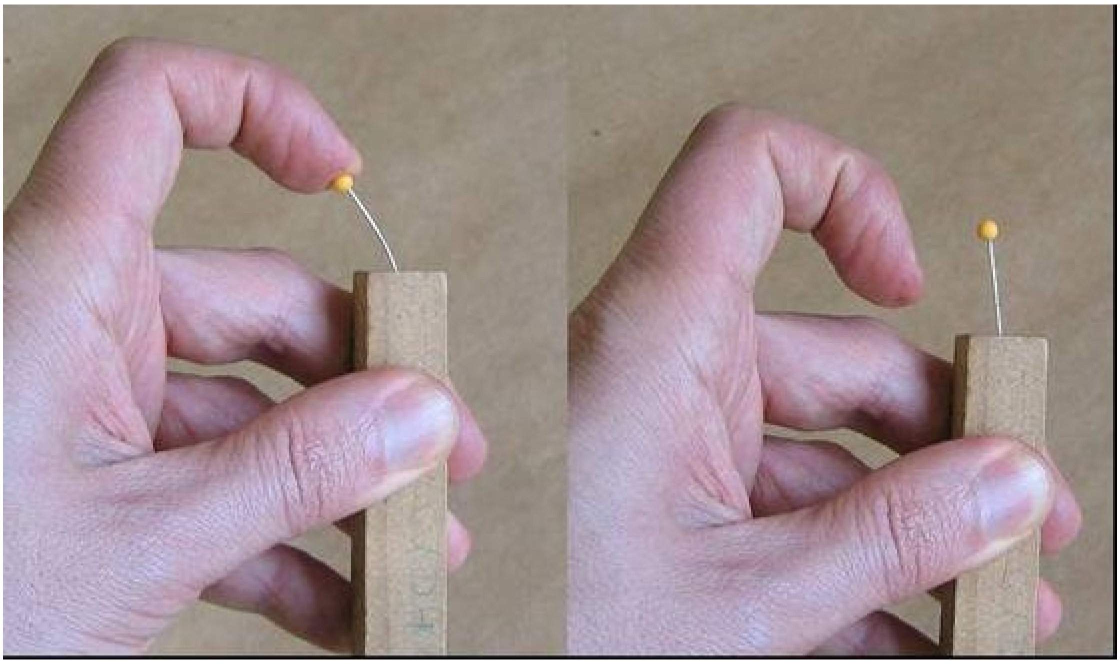


**Figure 2.** Pin striker (plastic-headed sewing pin pushed into wooden handle) and illustration of pin flicking technique.

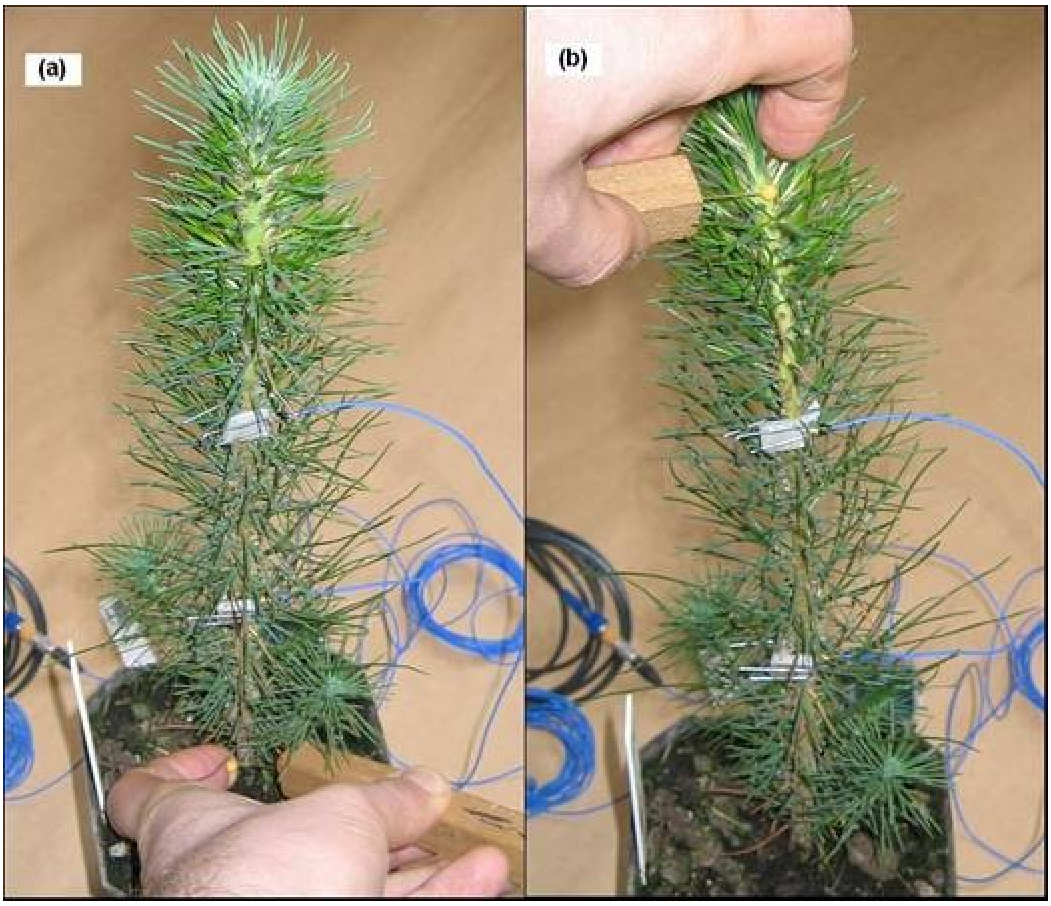



**Figure 3.** Illustration of pin flicking technique on seedling base (a) and seedling top (b).

## Equipment

The equipment used is shown in Figure 4 and Figure 5, and consists of the following components:

1. Two miniature accelerometers. Peizotronics PCB 352C23. Weight 0.2 grams.
2. 2 ICP power supplies and signal conditioners to power accelerometers. Peizotronics PCB 480C02.
3. Digital Oscilloscope connected to PC. (Picoscope 212/3 – 1.5MHz sampling rate).
4. PC to process signals from oscilloscope to produce velocity result.
5. Beeswax to stick accelerometers to stem.
6. Foam-lined clips to hold accelerometers in place. (See Figure 6).
7. Sewing pin with round plastic head inserted into wooden handle. Used as a flicker to generate acoustic pulse in stem by flicking against stem. (See Figure 2).

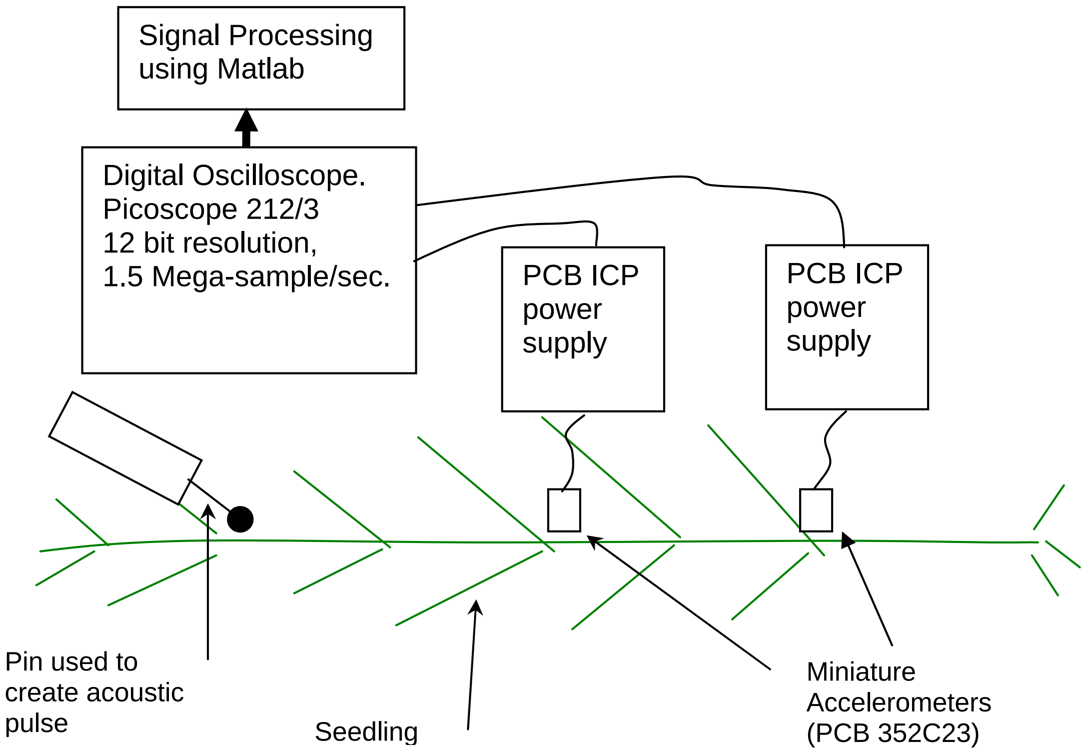



**Figure 4.** Schematic overview of the equipment setup to measure sound speed.

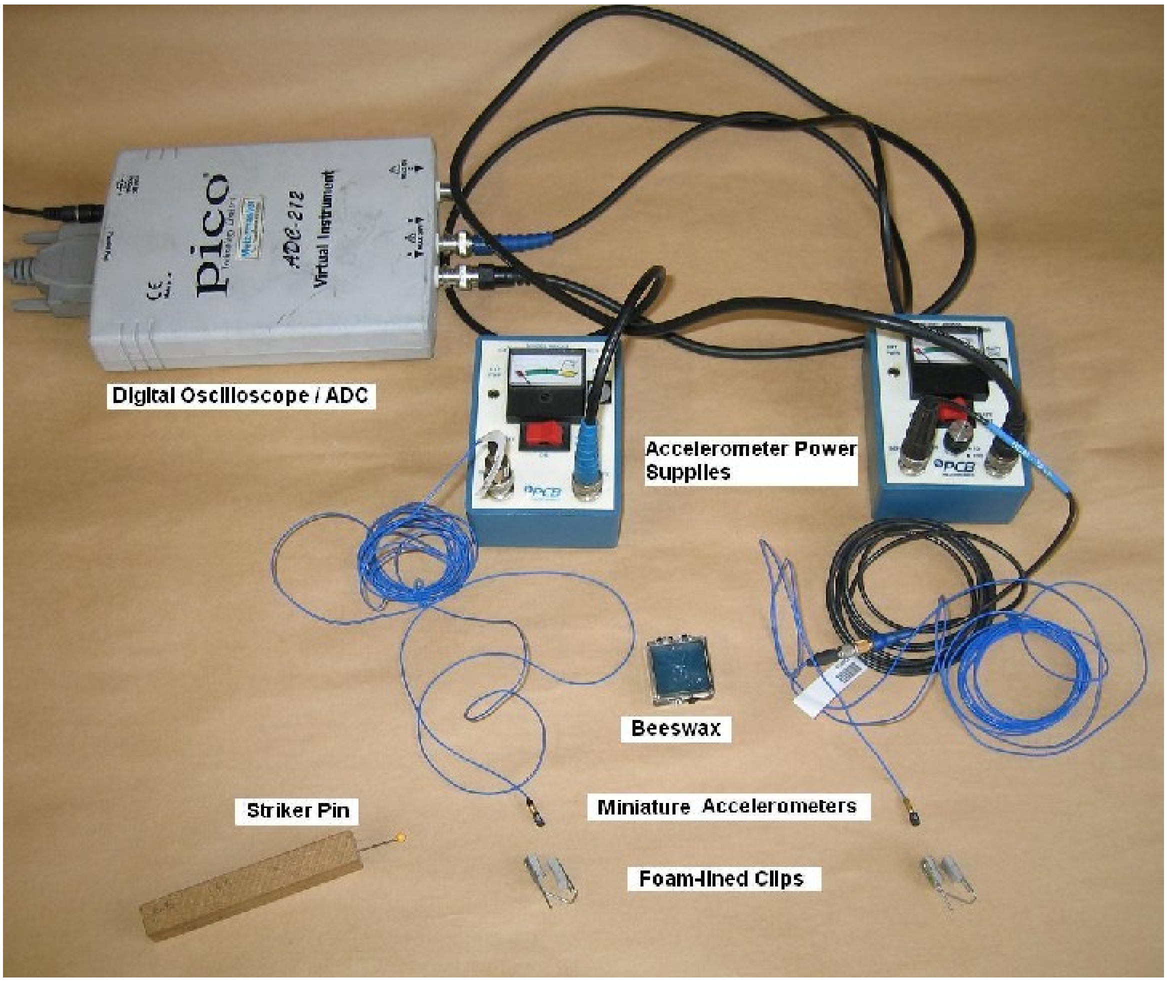



**Figure 5.** Photographic layout of the equipment used to measure sound speed in seedlings.

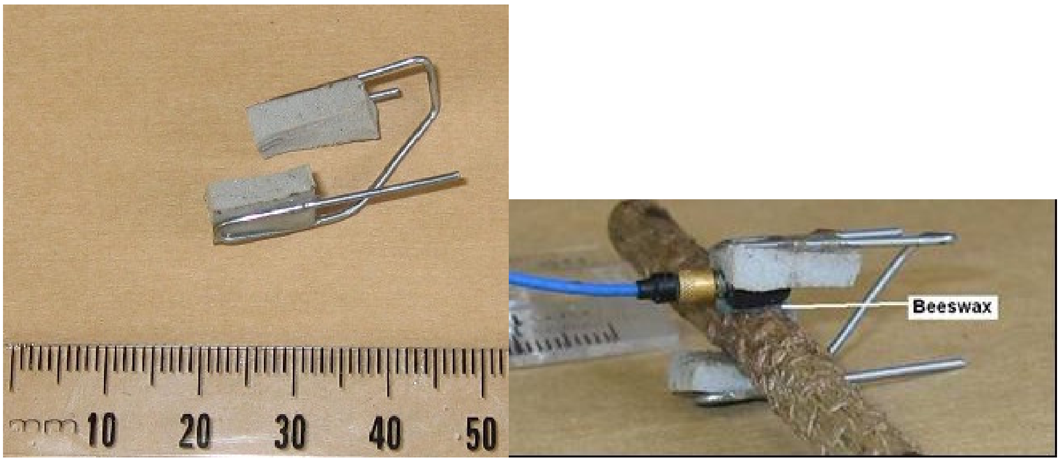




**Figure 6.** [Left] Close-up of open-cell-foam-lined clip used to secure an accelerometer onto the seedling stem (in conjunction with beeswax). [Right] Illustration of mounting of accelerometer on stem using beeswax between accelerometer and stem. The beeswax bonds the accelerometer to the stem and the clip stops the accelerometer from falling off. The foam on the clip acts as a vibration isolator stopping the clip from interfering with the sound waves propagating in the stem.

## The Measurement Algorithm (cross-correlation time-of-flight)

At this stage of development the signal values are copied into a spreadsheet and a Matlab programme is used to extract the signals from the spreadsheet and analyse the signals. This algorithm could be automated and streamlined. The signal analysis algorithm (called the **cross-correlation time-of-flight** algorithm) follows these steps:

1. The signals from the accelerometers are digitised using a digital oscilloscope (we used a Picoscope 212/3 with a sampling rate of 1.5 MHz).
2. The start of the signal is indicated by achieving a certain threshold (for these accelerometers a 15 millivolt threshold works well).
3. Within a prescribed search range (60 microseconds), a signal pulse peak is found for each signal. The signals are then windowed about this found peak using a hanning window with a set half-width (60 microseconds). This window length seems to be a good compromise between sufficient signal length for accuracy, picking out the primary, longitudinal wave, and not picking up reflections for measurement points near the ends of the stem. In general this would change for the length of stem being measured.
4. The signal time-base resolution is increased by using Fourier interpolation (i.e., zero padding in Fourier space).
5. The cross-correlation between the two windowed signals is calculated and the location of the peak is deemed to be the time delay between the acoustic signals, giving a sound speed.
6. A Hilbert transform is taken of the windowed signals (step 3). The amplitude of the Hilbert transformed signals is then integrated, and the gain change between the two accelerometers determined from the ratio of the two signals. This gain is then used to determine a loss factor.
7. Repeat the above. Compare the two sound speed results. If they are different by more than 10% then presume there was a measurement error and discard the results.
8. Compare the two loss factor results. If they are different by more than 20% then presume a measurement error and discard the results.
9. Average the retained results to produce an answer.

## Resonance Technique

The resonance technique for determining sound speed is an accurate way to obtain the sound speed of longitudinal waves and their damping factor, if used on appropriate samples. This method requires that the sample be long and thin and fairly uniform in property and width. For seedlings it is therefore a destructive method because a section of seedling stem has to be cut from the stem.

In this experiment it was used as a base-line comparison for the cross-correlation time-of-flight technique.

The resonance technique has been commonly employed over many years to determine the sound speed and acoustic damping of a slender piece of material and, using the density, the Young's modulus (Cremer, Heckl, & Ungar, 1988). In particular, this technique has frequently been applied to the measurement of sound speed in wood samples ranging from logs and stems (Andews, 2002) down to samples the size of match sticks.

Figure 7 shows the principle of the resonance technique. Determination of the resonant frequencies enables the sound speed to be determined from the formula.

**Sound Speed = 2 x Sample Length x Fundamental Frequency**

The widths of the resonance peaks enable determination of the acoustic damping from the formula.

**Acoustic Damping (loss factor) = Half-power Bandwidth / Resonant Frequency**

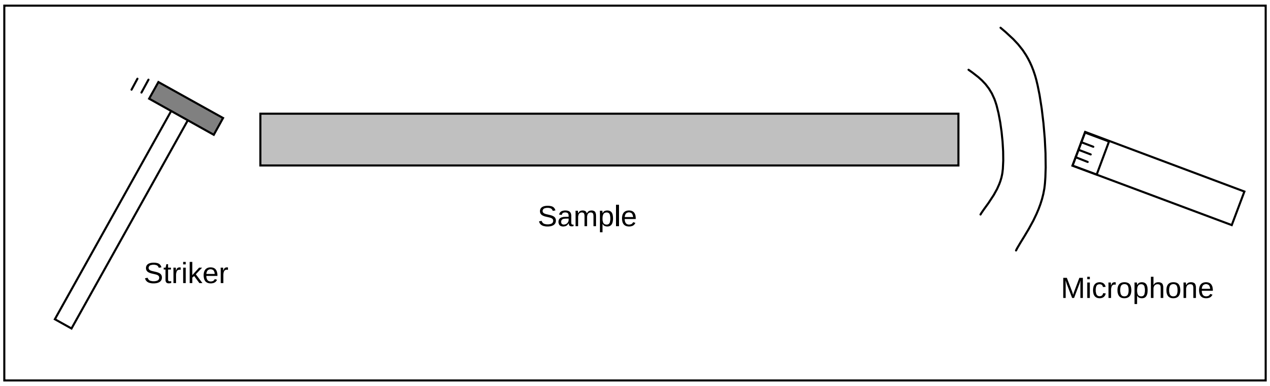



**Figure 7.** Illustration of the resonance technique. The striker hits the sample inducing vibrations, which in turn radiate sound. This sound is picked up by a microphone and is analysed to determine the resonant frequencies.

# RESULTS

## Initial Test – Acetal Rod

For the purposes of initially testing the procedure, measurements were performed on an acetal plastic rod 420 mm long and with a diameter of 20.5 mm. The sound of speed of this rod was measured by longitudinal wave resonance to be 1520 m/s at 14 kHz, and the loss factor was determined to be 0.023.

In Figure 8 and Figure 9 the signals measured by the accelerometers are shown, before and after the first pulse extraction respectively.

In Figure 10 we see the results of sound speed measurement and calculation for a number of different locations along the acetal rod, and for three different accelerometer separations. A greater separation of the accelerometers improves accuracy: The relative accuracy of the accelerometer location is improved and the first pulse separation is increased. A separation of 100 mm provides a reasonable amount of accuracy.

For the purposes of comparison, in Figure 11 time-of-flight calculations using only a threshold on the accelerometer signal are used (i.e., step 2 of the algorithm) – no cross-correlation is used. We can see that this method (which is commonly employed in a lot of acoustic time-of-flight systems, such as the Fakopp), results in biased results with a greater uncertainty.

We can also use the cross-correlation method to determine signal magnitude change and hence the material loss factor. The loss factor is a measure of energy lost per cycle, and hence measuring magnitude change over a distance is frequency-dependent. Our signals contain many frequencies, so we remove the frequency dependence of the loss factor by dividing by the wavelength. In Figure 12 we plot the loss factor results for different points up the acetal rod, and compare them to the loss factor obtained from resonance measurements. We can see that the loss factor results are quite variable, possibly limiting its application.

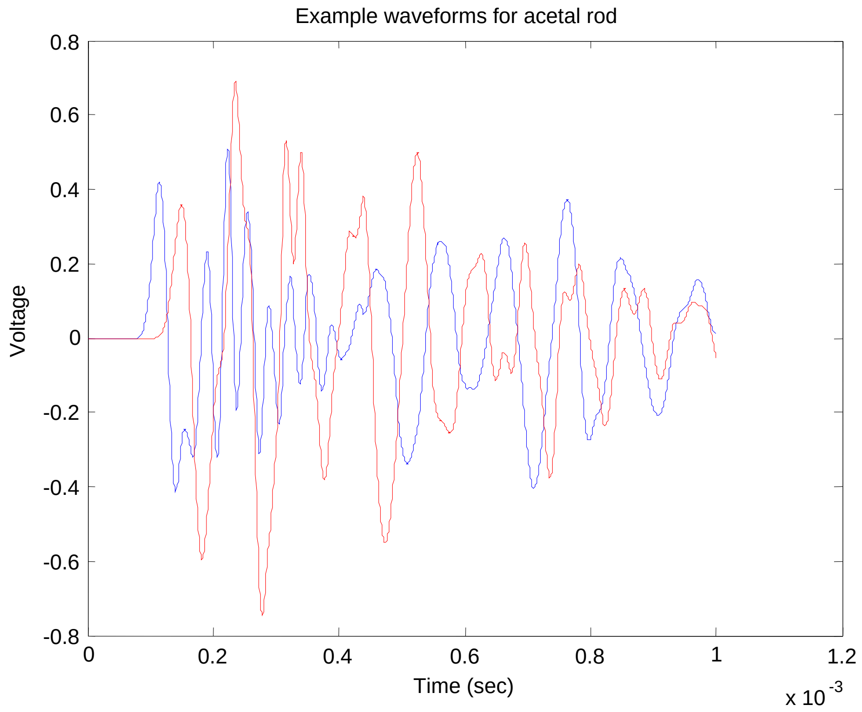



**Figure 8.** Example of raw accelerometer waveforms for an acetal rod.

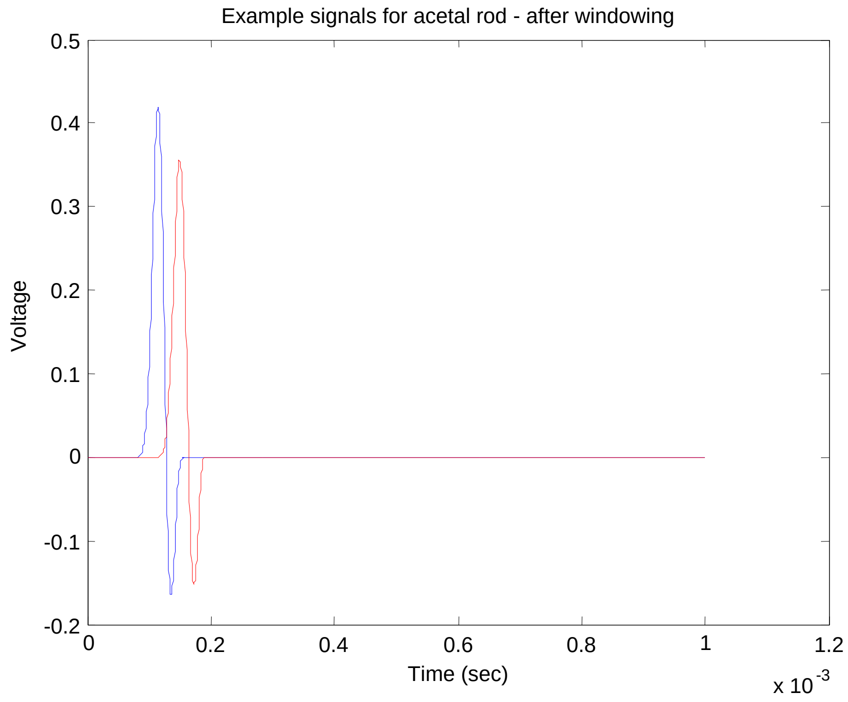



**Figure 9.** Example of accelerometer waveforms for an acetal rod after windowing to select the first pulse.

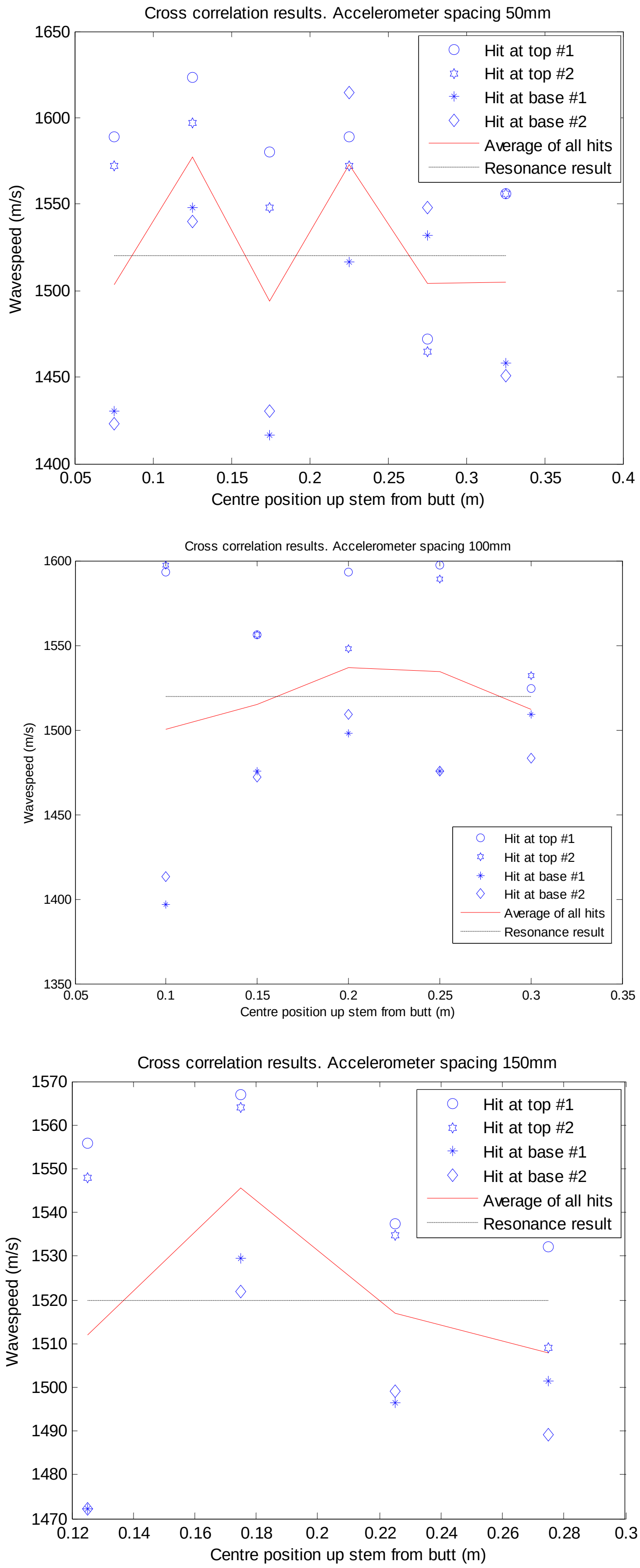



**Figure 10.** Sound speed of acetal rod measured using the cross-correlation time-of-flight method for different accelerometer spacings. Comparison is made with sound speed determined using longitudinal resonance (1520 m/s).

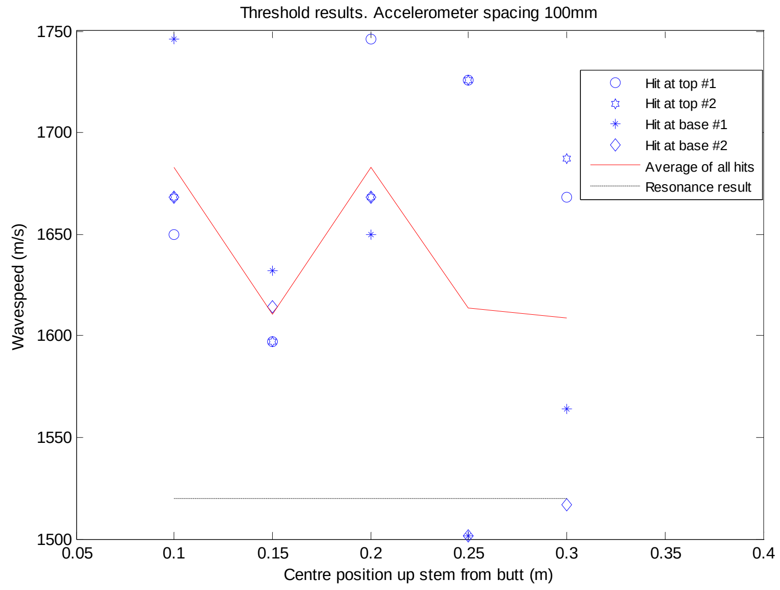



**Figure 11.** Sound speed of acetal rod measured using time-of-flight derived purely from a threshold. Comparison is made with sound speed determined using longitudinal resonance (1520 m/s). This proves to give a much more biased result with greater variability than using the cross-correlation TOF method.

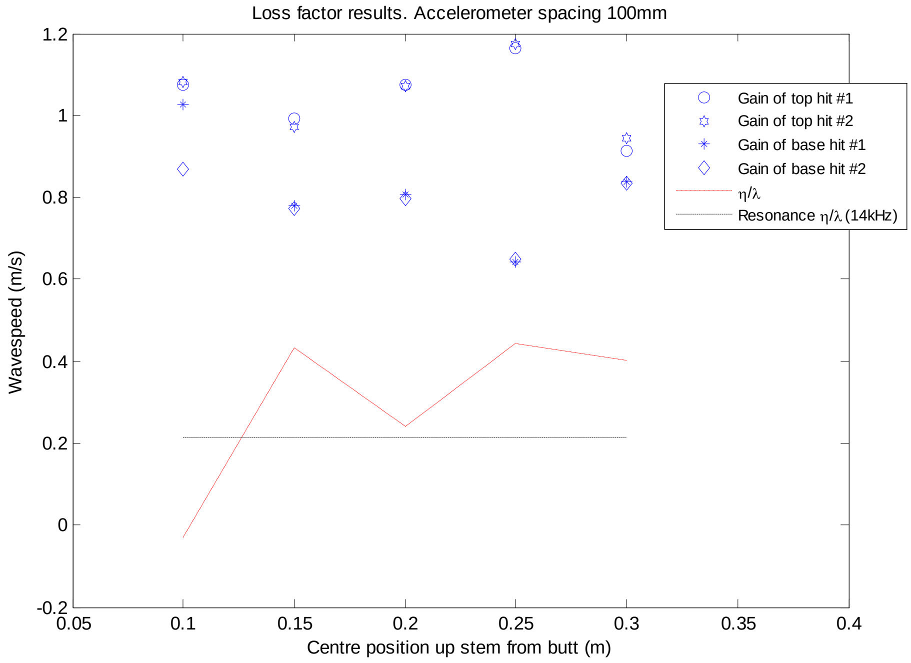



**Figure 12.** Loss factor measurement (normalised by the wavelength) for acetal rod. Comparison with loss-factor determined using longitudinal resonance (0.21 $m^{-1}$).

## Initial Measurements on a Seedling

As an initial trial on a seedling, the cross correlation time-of-flight method was used to determine the sound speed at 50-mm steps up the seedling. The seedling is shown in Figure 13 with accelerometers attached. The seedling was then cut up into 50-mm sections and the speed of sound measured using a resonance technique (as depicted in Figure 14 and Figure 15) with the needles on the stem, and with the needles removed.

Figure 18 shows the results of the sound speed calculations from the cross-correlation time-of-flight measurements compared to the resonance measurement results for the 50-mm sections with the needles on the stem. There is a good comparison, as long as the accelerometers are not too close to the base of the seedling – 100 mm seems to be a good distance.

Figure 19 shows the results of the loss factor calculations from the cross-correlation time-of-flight measurements compared to the resonance measurement results for the 50-mm sections with the needles on the stem. The results seem to be quite different and variable – there appears to be a lot of error.

Figure 20 shows the results of the resonance measurements of the 50-mm stem sections when the stem has its original needles and branching, and after such material has been removed. The sound speed is little affected by this material (especially near the stiffer base). However, the loss factor is greatly influenced by the presence of the needles and branches.

**Figure 13.** Photograph of initial trial seedling. The accelerometers were attached using beeswax (clips were not used in this case).

**Figure 14.** 50mm section of seedling with needles next to microphone ready for resonance measurement.

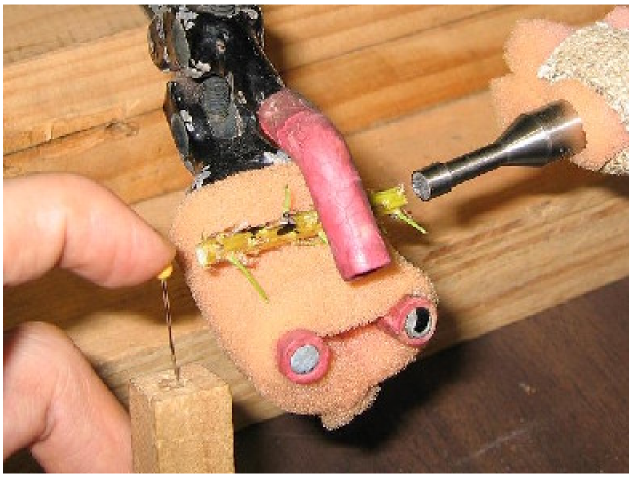


**Figure 15.** 50mm section of seedling (needles removed) being hit with pin head to excite resonances.

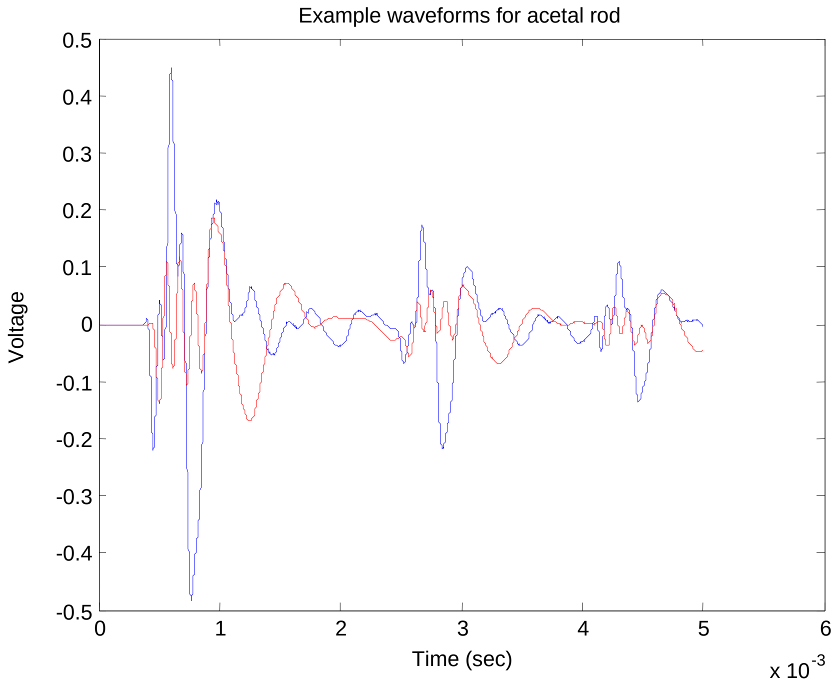



**Figure 16.** Example of raw accelerometer waveforms for a seedling stem. Pulse trainsat 2.5 milliseconds and 4 milliseconds are probably due to extra pin head hits – not reflections.

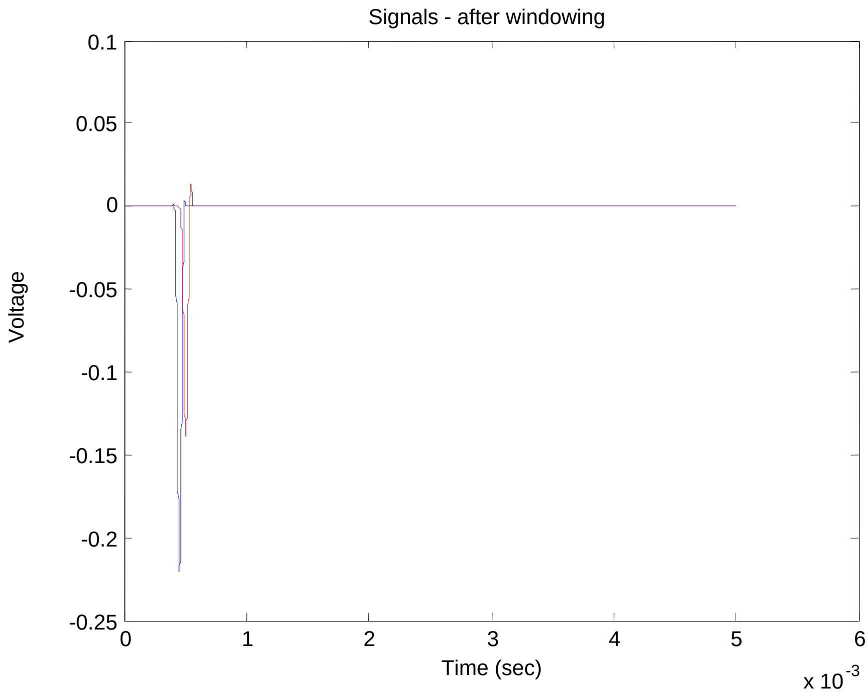



**Figure 17.** Example of accelerometer waveforms for a seedling stem after windowing to select the first pulse.

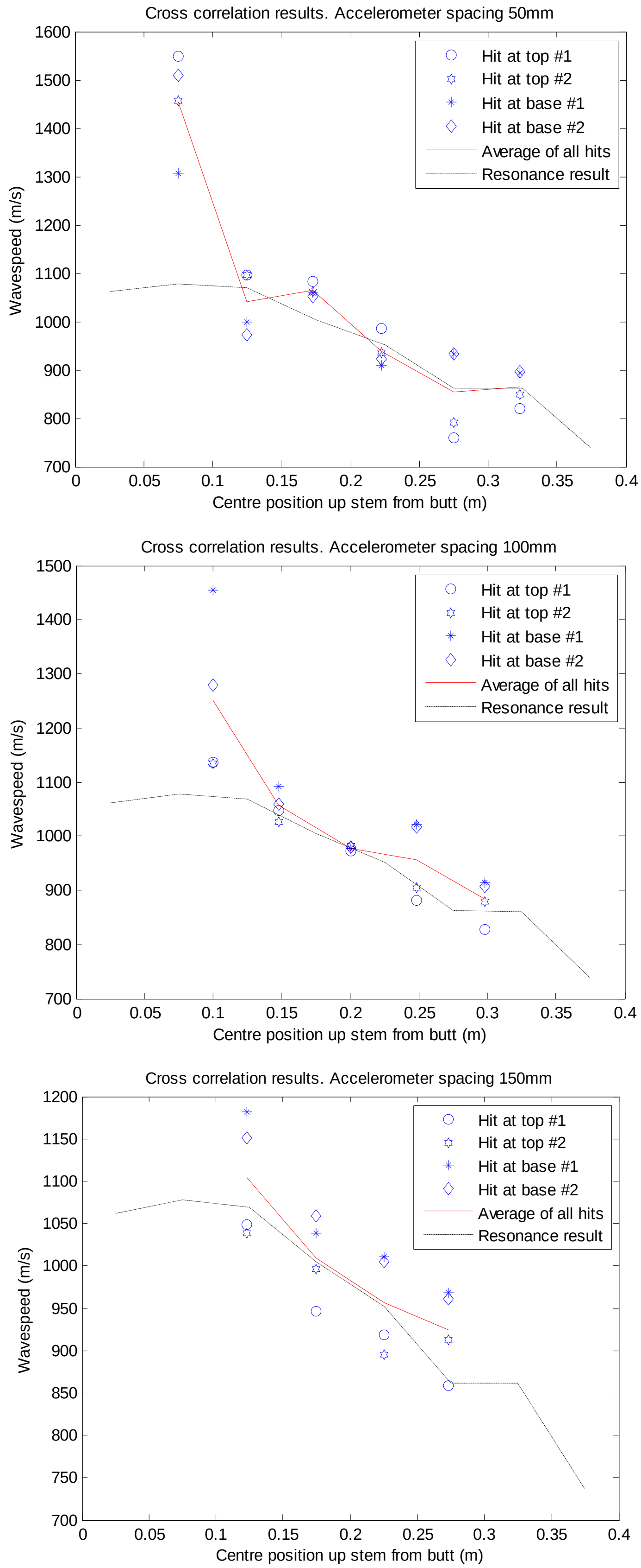



**Figure 18.** Sound speed of 1-year-old *Pinus radiata* seedling at 50-mm intervals up the stem and for different accelerometer spacings. Measured using the cross-correlation time-of-flight method for different accelerometer spacings. Compared to resonance results of 50-mm sections with needles on the stem sections.

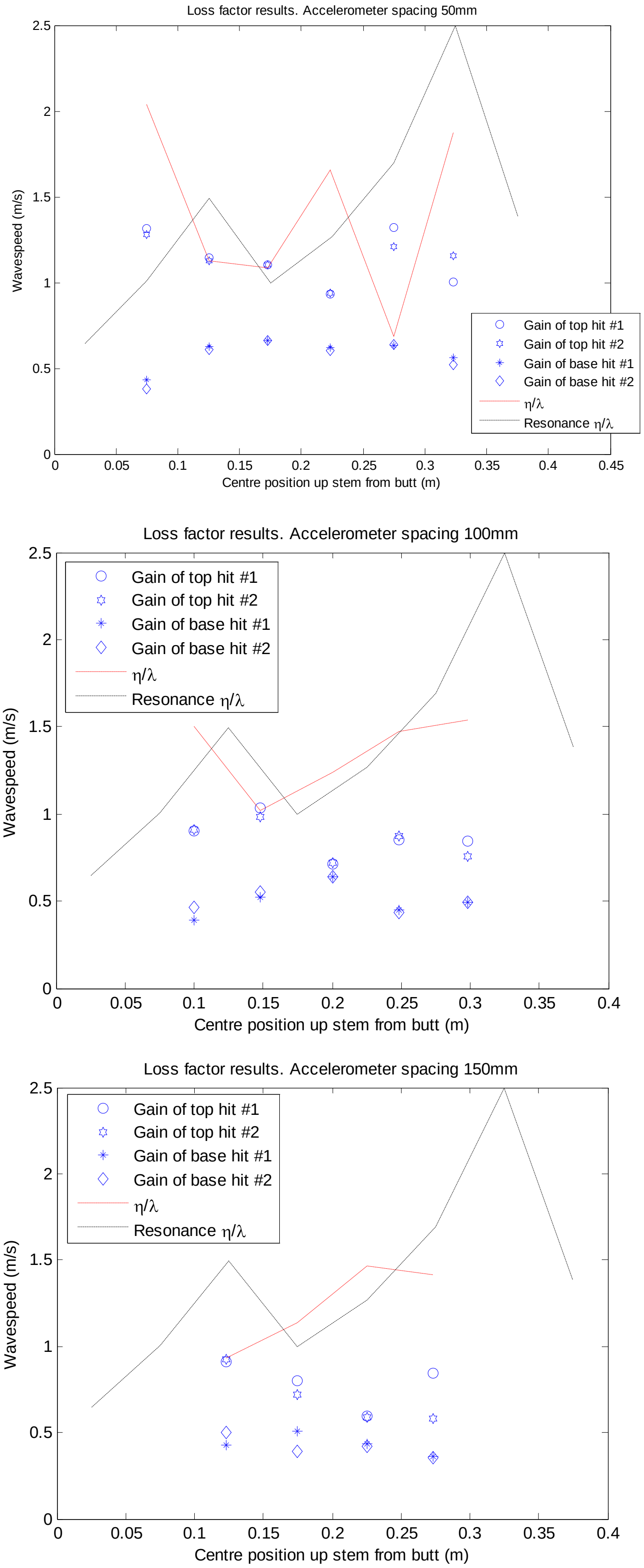
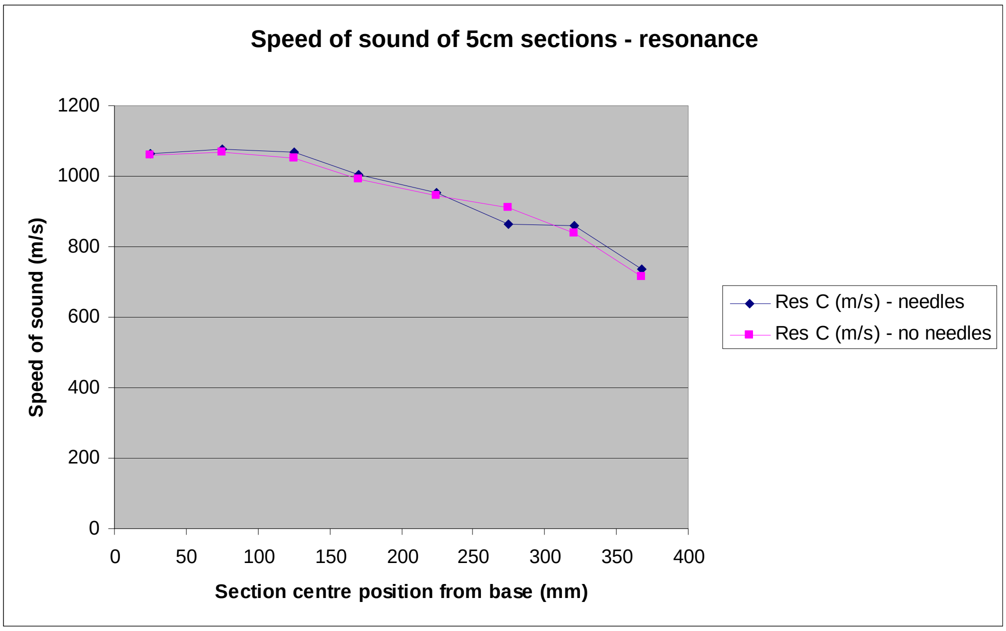



**Figure 19.** Loss factor measurement (normalised by the wavelength) for acetal rod. Comparison with loss factor determined using longitudinal resonance of 50-mm sections with needles and branching.



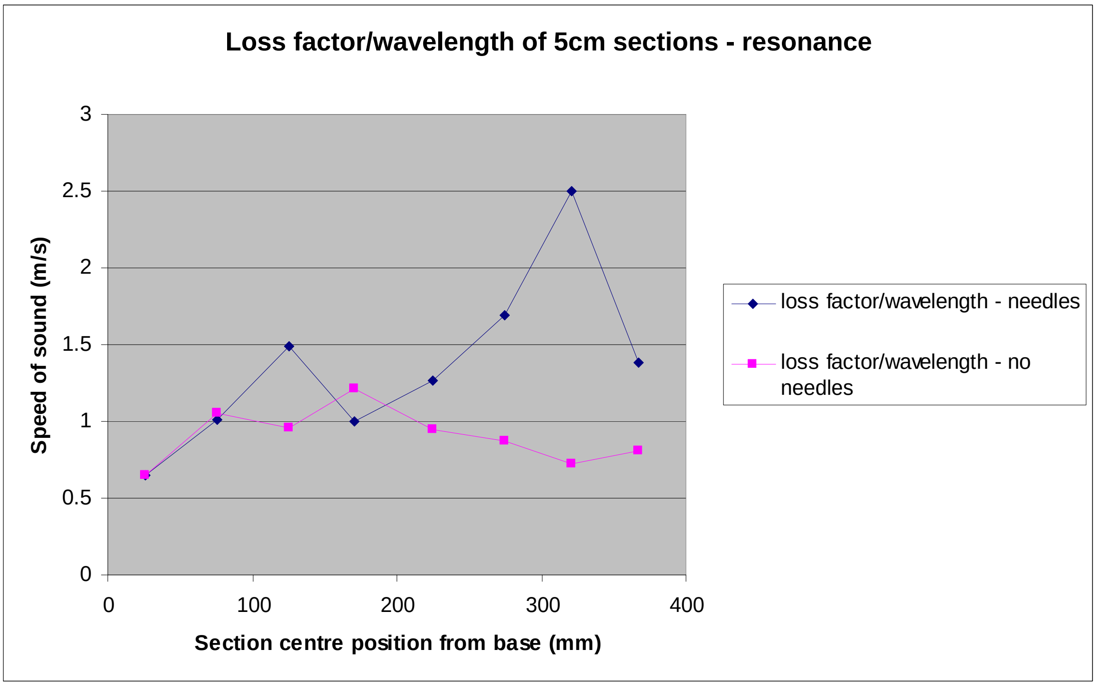




**Figure 20.** Sound speed and loss factor plots comparing results of resonance measurements on 50-mm sections for sections with needles and branching, and after the needles and branches were removed.

## Measurements on Clonal Seedlings

Lots of three different genotypes were selected. Lots A and B were 1-year-olds, grown from small genetic samples. Lot C was two-year-olds, grown from cuttings. Each lot consisted of three individuals.

For each specimen accelerometers were mounted using beeswax and clips approximately 100 mm and 200 mm from the base (100 mm separation), and cross-correlation time-of-flight measurements were made to find the sound speed over that particular 100-mm section. The accelerometers were dismounted and remounted three times and the measurements repeated to provide an estimate of the repeatability of the measurement.

The relevant 100-mm section was cut from each seedling, and longitudinal resonance measurements were made to determine sound speed and loss factor for the section. The needles and branches were then removed and the resonance measurements repeated. Finally the material outside the cambium layer was removed and the resonance measurements were repeated (see Figure 23).

The results of the repeatability measurements on the seedlings are shown in Table 1. We can see that the relative standard deviation of the repeatability is, on average, better than 2.

Table 2 shows the results of the resonance measurements performed on the seedling sections.

Figure 24 and Figure 25 plot the resonance sound speed results for the seedling sections with and without needles against the cross-correlation time-of-flight measurements. Linear regressions were done on the data, forced through the origins[1], and showed little difference between the results with and without needles. The slope of the linear regression was close to unity, and the mean-square error was about 2%.

[1] The linear correlation is forced through the origin because we expect no constant offset in the results, and because we do not have an even spread of measurement values, possibly resulting in unrealistically good correlations if the fitted line were not forced through the origin.


**Figure 21.** Photos of clones of seedling genotypes A and B – one year old.


**Figure 22.** Photos of clones of seedling genotype C – two year old.


**Figure 23.** Photos of a seedling section used in resonance acoustic measurement: (a) with needles and branches; (b) needles and branches removed; (c) cambium and bark removed by peeling.

**Table 1.** Results of cross-correlation time-of-flight measurements on sections 100 mm to 200 mm from base of seedling clones. Measurement was repeated four times for each seedling to obtain repeatability standard deviations.

**Cross-correlation time-of-flight measurements**

**Complete (with needles)**

| Seedling | Section Length (mm) | Section Mass (g) | Average Sound Speed (m/s) | Relative Standard Deviation. Across Clonal Lots. | Overall Relative Standard Deviation |
|---|---|---|---|---|---|
| 'Seedling A-1' | 106 | 11.924 | 968 | 0.0215 | 0.0174 |
| 'Seedling A-2' | 97 | 7.435 | 1030 | | |
| 'Seedling A-3' | 101 | 8.587 | 1024 | | |
| 'Seedling B-1' | 103 | 5.548 | 880 | 0.0151 | |
| 'Seedling B-2' | 100 | 7.316 | 895 | | |
| 'Seedling B-3' | 100 | 7.404 | 826 | | |
| 'Seedling C-1' | 98 | 3.579 | 1432 | 0.0165 | |
| 'Seedling C-2' | 98 | 2.921 | 1441 | | |
| 'Seedling C-3' | 99 | 2.085 | 1443 | | |

**Table 2.** Results of longitudinal resonance measurements on 100mm sections cut from seedling clones.

**Resonance measurements**

**Complete (with needles)**

| Seedling | Section Length (mm) | Section Mass (g) | Res freq (Hz) | Loss factor | Sound Speed (m/s) |
|---|---|---|---|---|---|
| 'Seedling A-1' | 106 | 11.924 | 4420 | 0.115135 | 937 |
| 'Seedling A-2' | 97 | 7.435 | 5520 | 0.141605 | 1071 |
| 'Seedling A-3' | 101 | 8.587 | 5220 | 0.138402 | 1054 |
| 'Seedling B-1' | 103 | 5.548 | 4160 | 0.141383 | 857 |
| 'Seedling B-2' | 100 | 7.316 | 4580 | 0.280599 | 916 |
| 'Seedling B-3' | 100 | 7.404 | 3950 | 0.187632 | 790 |
| 'Seedling C-1' | 98 | 3.579 | 7140 | 0.054223 | 1399 |
| 'Seedling C-2' | 98 | 2.921 | 7080 | 0.050635 | 1388 |
| 'Seedling C-3' | 99 | 2.085 | 7190 | 0.03823 | 1424 |

**Needles Removed**

| Seedling | Section Length (mm) | Section Mass (g) | Res freq (Hz) | Loss factor | Sound Speed (m/s) |
|---|---|---|---|---|---|
| 'Seedling A-1' | 106 | 4.548 | 4510 | 0.043092 | 956 |
| 'Seedling A-2' | 97 | 3.103 | 5350 | 0.034818 | 1038 |
| 'Seedling A-3' | 101 | 4.395 | 5209 | 0.03824 | 1052 |
| 'Seedling B-1' | 103 | 2.363 | 4219 | 0.064353 | 869 |
| 'Seedling B-2' | 100 | 2.693 | 4510 | 0.04663 | 902 |
| 'Seedling B-3' | 100 | 2.315 | 4111 | 0.040363 | 822 |
| 'Seedling C-1' | 98 | 3.094 | 7210 | 0.046487 | 1413 |
| 'Seedling C-2' | 98 | 2.84 | 7080 | 0.047437 | 1388 |
| 'Seedling C-3' | 99 | 2.075 | 7191 | 0.037441 | 1424 |

**Bark and Cambium Removed**

| Seedling | Section Length (mm) | Section Mass (g) | Res freq (Hz) | Loss factor | Sound Speed (m/s) |
|---|---|---|---|---|---|
| 'Seedling A-1' | 106 | 2.668 | 5800 | 0.037686 | 1230 |
| 'Seedling A-2' | 97 | 1.846 | 6730 | 0.049603 | 1306 |
| 'Seedling A-3' | 101 | 2.122 | 7090 | 0.048924 | 1432 |
| 'Seedling B-1' | 103 | 1.15 | 5500 | 0.051501 | 1133 |
| 'Seedling B-2' | 100 | 1.483 | 5800 | 0.107986 | 1160 |
| 'Seedling B-3' | 100 | 1.124 | 5590 | 0.041966 | 1118 |
| 'Seedling C-1' | 98 | 1.812 | 9280 | 0.050835 | 1819 |
| 'Seedling C-2' | 98 | 1.449 | 9650 | 0.026909 | 1891 |
| 'Seedling C-3' | 99 | 1.149 | 9630 | 0.04892 | 1907 |

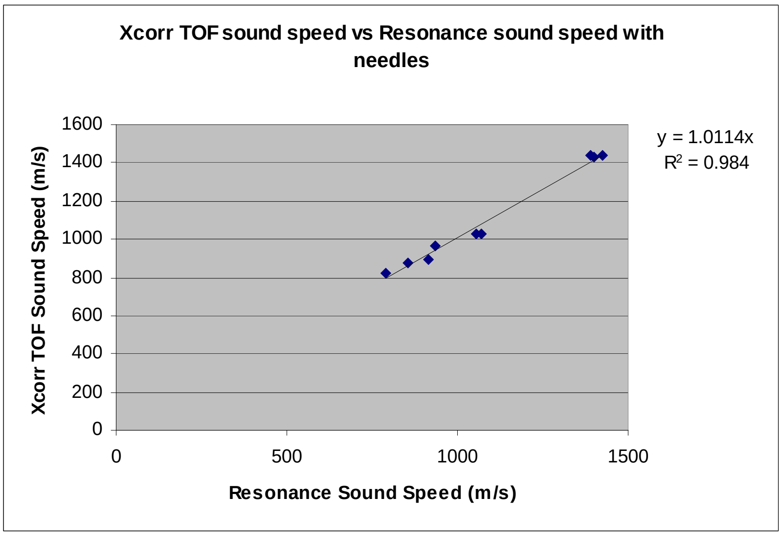



**Figure 24.** Sound speed from cross-correlation measurement against sound speed from resonance measurements on 100-mm section with needles and branches.

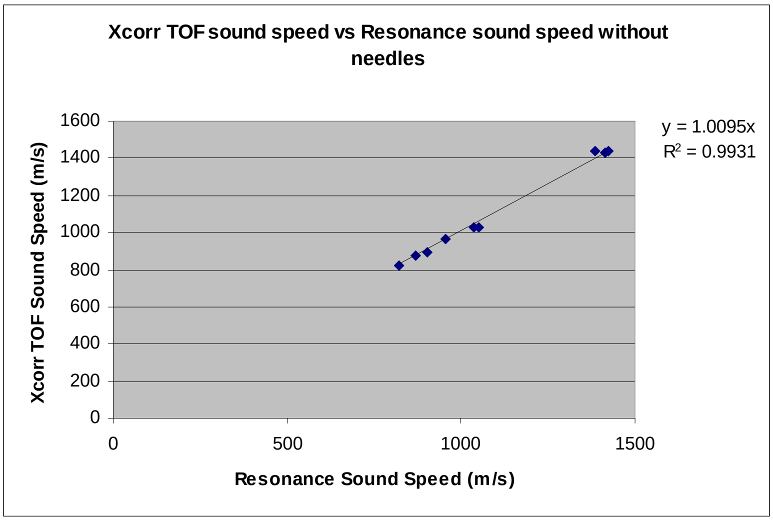



**Figure 25.** Sound speed from cross-correlation measurement against sound speed from resonance measurements on 100-mm section with needles and branches removed.

## Predicting xylem Sound Speeds

Figure 26 plots the resonance sound speed results for the seedling sections with the bark and cambium removed (leaving the wet xylem) against the cross-correlation time-of-flight measurements. A linear regression was done on the data, forced through the origin. Removing the cambium and bark removes a lot of material which has mass but little stiffness. Therefore we expect the speed of sound of the xylem alone to be faster. The linear regression shows a good linear correlation with a mean-square error of about 2.5% and a slop of 0.7647. It would appear, therefore, that the influence of the cambium and bark do not add a large level of uncertainty to the results, so it may be possible to predict the speed of sound in the xylem alone from speed of sound results which include the cambium and bark (as must be measured non-destructively).

Another way to determine the xylem sound speed is by factoring out the influence of the cambium and the bark. This presupposes that we are able to determine the mass of the cambium and bark and the mass of the xylem. These were measured for the nine seedling clones. If we know the ratio of these masses and we assume that the stiffness of the cambium and bark is insignificant compared to the xylem, then we can determine the speed of sound of the xylem from

$$c_{xylem} = c_{all}\sqrt{(m_{all} / m_{xylem})} \text{ ,}$$

where $c_{xylem}$ is the sound speed of the xylem, $c_{all}$ is the sound speed of the overall stem, $m_{all}$ is the mass of the whole stem (excluding needles), and $m_{xylem}$ is the mass of the xylem.

Table 3 shows the measured cambium-bark and xylem masses. Figure 27 shows the predicted sound speeds against the measure sound speeds. This shows that knowing the mass of the xylem relative to the whole stem (without branches and needles) can enable effective prediction of the sound speed of the xylem.

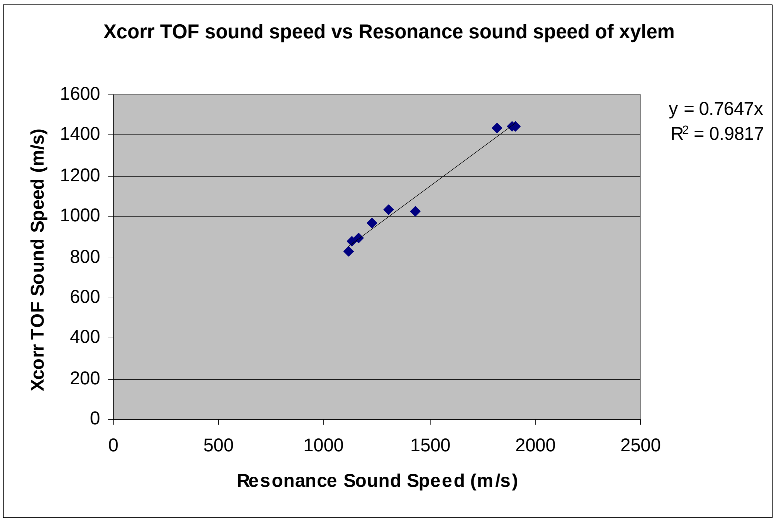



**Figure 26.** Sound speed from cross-correlation measurement against sound speed from resonance measurements on 100-mm section with bark and cambium removed.

**Table 3.** Predicted xylem sound speed from mass of xylem and mass of cambium and bark. Predictions are based on resonance measurements of the sound speed of sections with cambium and bark.

| Seedling | Cambium & bark mass (g) | Xylem Mass (g) | Ratio of Cambium mass to Xylem mass | Predicted Xylem Sound Speed (m/s) |
|---|---|---|---|---|
| 'Seedling A-1' | 1.88 | 2.668 | 0.7046 | 1248 |
| 'Seedling A-2' | 1.257 | 1.846 | 0.6809 | 1346 |
| 'Seedling A-3' | 2.273 | 2.122 | 1.0712 | 1514 |
| 'Seedling B-1' | 1.213 | 1.15 | 1.0548 | 1246 |
| 'Seedling B-2' | 1.21 | 1.483 | 0.8159 | 1215 |
| 'Seedling B-3' | 1.191 | 1.124 | 1.0596 | 1180 |
| 'Seedling C-1' | 1.282 | 1.812 | 0.7075 | 1847 |
| 'Seedling C-2' | 1.391 | 1.449 | 0.9600 | 1943 |
| 'Seedling C-3' | 0.926 | 1.149 | 0.8059 | 1913 |

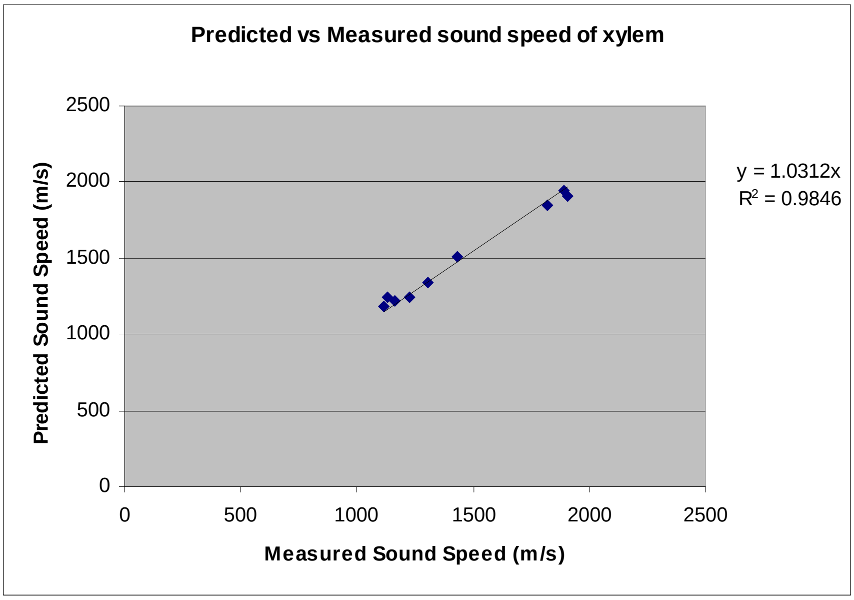



**Figure 27.** Predicted versus measured sound speed of xylem. Prediction calculated from the sound speed of stem with cambium and bark and xylem/cambium-bark mass ratios.

# CONCLUSION

A time-of-flight method (dubbed cross-correlation time-of-flight) which can measure the speed of sound in a seedling non-destructively and non-intrusively has been developed.

The method was tested on nine 1- and 2-year-old seedlings. Comparing the results of the method to a destructive resonance test showed that the results are unbiased with a mean square error difference of 2%. Repeatability tests show an uncertainty standard deviation of less than 2%.

The method measures the sound speed of the seedling stem as a whole, and does not selectively measure the fastest path (which is possibly the stiffest part). In the case of seedlings, the non-xylem components of the stem can be a very significant part of the stem (in terms of cross-sectional area and mass), so if one wishes to consider only the xylem, then the mass of the non-xylem components needs to be factored out.

## Future Work

Currently the system uses a two-stage signal acquisition and processing step. A program could be written which combines the signal acquisition and processing into one so that immediate feedback of the result is obtained.

Flicking the pin head can be a tricky process, requiring skill to ensure the strike is sharp and that the stem is not disturbed before the pin head hits it. Perhaps a device can be made which does the job more easily.

# ACKNOWLEDGEMENTS

Bernadette Nanayakkara for supplying the seedlings, and suggesting changes to the report.
Jonathan Harrington for patiently listening to me when he is so busy.
Lynn Bulman for checking the document format.
文贤，谢谢你的爱。

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