A New Junction Identification Method Utilizing Acoustic Reflectometry

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Abstract

Acoustic reflectometry (APR) is a non-invasive, time-domain method of identifying the geometry of an acoustical space from its impulse response. The impulse response can provide details about the length, cross-sectional area, and scattering junction of each segment of the cavity. These details can be obtained from the temporal cues, magnitude, and contour of each reflection. Previous works were able to identify these scattering junctions via algorithms that attempt to extract particular contours from the impulse response. In the present study, the prominent reflections of the space are observed, isolated, and then compared to a training database of all possible scattering junctions. This method eliminates the necessity to create a contour identification algorithm, as scattering junctions are defined based on its most similar neighbors in the training database. Results suggest that this computer-learning algorithm can successfully identify reflection contours of a space with varying cross-sectional areas from those that were stored in the training database, which suggests that this method could be a more efficient and versatile alternative to previous identification processes.
Chapter 1

Introduction

Acoustic reconstruction methods utilized before acoustic reflectometry were quite accurate, although quite time consuming [Backus 1976]. This method was dependant on many computationally inefficient methods. First, the volume flow rate and pressure at the entrance of the space, in this case a musical instrument, were measured. These two results were then divided to obtain the input impedance in the frequency domain. Reflectometry has provided a time domain reconstruction method that allows all frequencies to be dealt with at once, resulting in a far less time-consuming effort. Another benefit to reflectometry is its need of only a pressure measurement, which eliminates the necessity to measure the volume flow rate of the space.

Typically, the spaces investigated with acoustic pulse reflectometry are quite small, as they have ranged from lungs to a musical instrument. This is due to ease of computation, as the impulse response become more complex as the size of the space increases. The more complex the impulse response, the more unique each space is to the next, leading to a much more difficult reconstruction process. However, there is potential for acoustic pulse reflectometry to be implemented in larger environments. In order to do so, the process must be scaled a bit differently in order to ignore irrelevant idiosyncrasies and identify the most important characteristics that make the space in question comparable to previously examined spaces. One way to identify the relevant data is through computer-
learning. Suppose an impulse response of a hallway was taken, and then taken again with a person standing ten feet away from the microphone in the center of the hallway. The two impulse responses would be quite different, but there would still be information in the impulse response that was fundamentally the same. This data would need to be identified, isolated, and stored for future comparisons in order to identify rooms with similar features and scattering junctions.

While this work does not investigate larger spaces, it does propose a computer-learning method for the identification of scattering junctions. In doing so, an essentially different space of unique dimensions can be compared to a diverse database and classified based on findings from previous tests. This computer-learning method can be computationally more efficient than previous processes, especially in the case of identifying more complex scattering junctions such as T and L-intersections. Also, there is an incredible amount of flexibility utilizing this computer learning method. Each set of tests can rely on its own set identification principles. If another unique scattering junction were needed to be identified, the user would simply need to create a database for that particular instance. In this study, the important peaks for isolation were quite simple to identify, however larger spaces may require a more unique peak set, though the process will be conceptually equivalent.
Chapter 2

Historical Context

This method was first developed as a seismological technique for observations regarding the earth’s crust. Similarly to the concept of this work, the input impulse response told a great deal of the test object. The different types of rocks that compose the earth’s crust have unique densities. When an impulse reaches a rock of a different density, there is a change of impedance as a particular level of absorption and reflection occurs. When all of these reflections are recorded at the surface, a distinct reflection footprint is created. Ware and Aki [1969] created a method to take this footprint, known as the input impulse response, and calculate the particular reflection coefficient for each impedance change. The Ware and Aki method was able to solve what is known as the inverse problem [Sondhi 1981]. The direct problem would provide an input impulse response based on a given set of dimensions of an object. While this solution did provide somewhat accurate results, it did not take the losses of the input and reflected waves while traveling through the different layers into account.
In the early 1970s, Sondhi and Gopinath [1971] devised a method for determining the shape of the vocal tract from the acoustic impulse response measured at the lips. This method followed that of Ware and Aki in determining that losses in the input and reflected waves are negligible. Later studies did attempt to include the effects of losses [Sondhi 1974 and Sondi and Resnick 1983] though its implementation was quite basic, as a constant number was devised to approximate this feature.

Jackson [1977} and Jackson & Olsen [1980] reported one of the first designs of a reflectometer featuring a source tube with microphone embedded in its wall part of the way down. This device was used to measure the size of the airways and lungs in dogs. Results were modeled as a series of joined cylindrical segments with differing cross-sectional areas. The input impulse response of the airway was obtained by deconvolving the airway reflections with the shape of the input pulse. The Ware-Aki algorithm was used to calculate the segment areas. Similar tests were done by Fredberg [1980] and Marshall [1992] on human patients.

Bernade and Smith [1981] were the first to apply acoustic pulse reflectometry principles to analyze the dimensions of musical instruments. A microphone placed at the mouthpiece of a tuba recorded the reflections of a spark source used as an impulse. However, no deconvolution was used to remove the input pulse shape. Similar work was done by Ayers [1985].

A source tube similar to the one in Jackson’s research was first used Goodwin [1981] and Duffield [1984] to measure musical instruments. The source tube in these reports was much longer as the instruments themselves are of greater length than the airways of a dog. The source tube became a necessity to separate the instrument’s reflections from
that of the source. These tests were the first to attempt to use a speaker as the impulse source. The speaker provided a consistent sound source, providing the opportunity to increase the signal-to-noise ratio by averaging consecutive tests. However, deconvolution attempts were unsuccessful. The spark source was chosen instead as a reliable impulse as deconvolution is unnecessary. Deane [1986] was more successful at deconvolving the impulse. By doing so, consistency was greatly improved, as well as a better signal-to-noise ratio.

Until 1995, reconstruction algorithms continued to use the methods devised by Sondhi and Ware and Aki. A common symptom of these reconstructions was their tendency to increasingly underpredict the actual radius along the series of tubes. Some [Watson 1989] attempted to manually adjust the DC value until the readings matched the actual diameter of the object, though this method is quite cumbersome.

Amir [1995] created a reconstruction algorithm that took the losses into account. A more advanced ‘layer peeling’ method was used by Sharp and Campbell [1997], as well as a way to calculate the correct DC offset by inserting a 50 cm tube between the source tube and the test object. Because there are no reflections that occur during this 50 cm section, this section can be calibrated likewise. A virtual DC tube method [Kemp 2001] was later introduced.

In addition to providing a new reconstruction algorithm, Amir also investigated a possible method of measuring longer tubular objects. Embedding the loudspeaker part of the way down the source tube helps to reduce source reflection contamination, as well as avoid an inaccurate impulse that comes from driving the speaker into distortion.
Sharp [1996] utilized acoustic reflectometry to detect leaks in pipes. This method is particularly important in terms of musical acoustics, as this provides a means to find keys or valves in an instrument. However, the method is only able to find leaks of consistent size (i.e. flute) and bypass unique occurrences, such as a flaring bell.

Smyth [2006] and Carneal [2006] both provided waveguide geometry methods to estimate particular tube configurations using acoustic reflectometry principles. Smyth’s work investigated both straight and conical tubes and then modeled the impulse responses of the test objects via digital waveguides. The waveguides filter elements matched the impulse response measurements with elements that characterized the end reflection, propagation losses, and its junction reflection and transmission. The testing apparatus used by Smyth is very similar to the one used in this thesis, especially the speaker to source tube portion. A funnel gradually decreases the diameter from the size of the speaker to the source tube diameter.

Carneal focused on unique scattering junctions that are typically uncommon in musical instruments. This work used duct theory to find the resulting cross-sectional area ratio change at each point of reflection, which is relative to the duct entrance area. The implementation of duct theory is much more simple than the layer-peeling algorithm of Sharp. However, duct theory provides a lesser-detailed result, as its estimations are less precise and the propagation losses of the impulse are not taken into account.

One noteworthy innovation of Carneal’s study was the inclusion of bifurcation identification. T-intersections could be correctly identified in a variety of configurations. Some of the test objects had the source tube connected to one of the wings, instead of connecting the source tube the primary tube that would then split. It was found that only
one point of bifurcation per test object could be identified properly due to the lack of energy after the first bifurcation reflection and its energy lost propagating along the related wings. The geometric results were accurate within 10% of the actual, though its findings were obtained in a computationally expensive manner as each test object was examined in an isolated manner. Carneal hints that these methods may be utilized for larger environments, namely hallways, however a three-dimensional approach must be considered, as all previous tests have examined their tube configurations in only one dimension.

This experiment utilizes many methodologies that were at the core of these past works and expand upon them.

**Goals**

The objectives for this study are:

1) Identify and define elements of an object’s impulse response that provide information regarding its configuration. These tubes will be of varying sizes, number, and scattering junction types.

2) Prove that computer-learning can be utilized to compare reflection profiles of cavities with different cross-sectional areas.

3) Create a working database of correctly identified scattering junctions. This database will allow individual components of new test objects to be evaluated independently, which will simplify the identification process.
4) Find the amount of neighbors needed for accurate results. This point will be the instance when the accuracy of the algorithm provides consistent and reliable results.

In this study, there are four possible types of scattering junctions in the test object: a T-intersection, L-intersection, cross-sectional increase, and cross-sectional area decrease. Unlike the work of Sharp [1996], there will be no leaks in any of the tubes being tested. The final tube of the scattering junction will be either open or closed. The reconstruction algorithm described in this research will be able to define all of the aforementioned features in addition to the lengths of each individual tube, as well. The diameters of the tubes will range in size from .635 to 1.27 centimeters. Each test configuration can consist of any variety of these tubes. Obviously the junctions will vary in size according to the cross-sectional areas of the tubes.

Chapter 3 will cover acoustic principles that make the data gathered via acoustic reflectometry significant. These principles will help illustrate the unique fingerprint of each impulse response. Also, examples of simple input impulse responses will be shown and dissected.

Chapter 4 details the experimental setup and procedure. One portion of this chapter will provide diagrams and descriptions of the apparatus. Explanations for specific design details will also be given. Many of these details follow the previous test mentioned in the historical context chapter. In addition, the testing procedure and apparatus measurements will be given.

Chapter 5 provides analysis of how the algorithm works. Examples of each type of junction and tube will be shown. The first half of this chapter will show how these
reflections are isolated. It will also show how to obtain the more simple characteristics of the test object: the length, termination type, and diameter in relation to the source tube’s cross-sectional area. Duct theory will be used to find the diameter. The second half of the chapter will define the junction identification method via machine learning and investigate what type of obstacles arise when multiple bifurcations are present in a single test object. This portion will explain the type of information that is pertinent to database creation for acoustic pulse reflectometry. In addition to database creation, the number of similar junctions that are needed to be stored in the database ensuring reliable depictions will be detailed.

Chapter 6 contains analysis of the results. Each portion of the test object definition will be examined to pinpoint the strengths of this method. As previously mentioned, the results will contain junction identification, sectional length, total length, termination type, and cross-sectional area.

Chapter 7 discusses potential improvements using this new method. The results discussed in Chapter 6 will be reexamined to isolate instances in which this algorithm is less successful. The potential obstacles that could arise as the size of the test object increases are also examined.

The overriding goal of this work is to find whether machine learning can be utilized to define a variety of scattering junctions. The accuracy of the length and cross-sectional area should be within 10% of the actual test object. Absolute accuracy of the machine learning technique is not as important as finding consistency; the results should at least provide insight to how this method could be improved in future implementations. This
research is intended to be the first step in a series of works that will ultimately characterize large acoustic environments.
Chapter 3

Basic Theory of Acoustic Reflectometry

Frequencies in which the acoustic wavelength is much larger than the cross-sectional area of a duct are known to be traveling as plane waves. In a cylindrical tube, higher order modes decay rapidly along the duct and their presence becomes negligible after a very short distance. Each higher order mode has a cut off frequency $f_c/w_c$ associated with it. Higher order modes of frequencies below this cut off frequency are non-propagating. The cut off frequency of the first non-planar mode is $f_c=100/r$ or $w_c=1.84c/r$ where $c$ is the speed of sound and $r$ is the radius (in meters) of the tube [Li 2004]. $w_c$ is the cut off frequency in radians, while $f_c$ is in Hertz. The smallest radius of a tube used in testing ($3.175 \times 10^{-3}$ m) first non-planar mode has a cut-off frequency of 31.4 kHz, while the largest tube used in testing ($6.35 \times 10^{-3}$ m) has a first non-planar mode with a cut-off frequency of 15.7 kHz.

Plane waves are assumed to have the same direction of propagation everywhere in space. Also, their wavefronts propagate perpendicularly to the direction of propagation. This is quite different than the propagation of non-planar waves. Non-planar waves propagate three-dimensionally; this type of complex propagation is quite difficult model as it is dependant on a variety of environmental factors. Considering that the average cross-sectional area of the tubes in this test is approximately 4 cm and that the first non-planar
mode will have a cut off frequency above 15.7 kHz, it is sufficient to consider the in
terms of a planar wave model for frequencies smaller than the cut-off frequency. This is
the reason why it is typically impractical to test larger objects with the acoustic pulse
reflectometry method.
For the planar waves traveling in a single direction, it is accurate to depict a the pressure
wave of frequency $w$ at the boundary of a semi-infinite tube of cross sectional area $S_0$
joined at $x=0$ as:

$$P_0^+ = P_0^+ e^{j(wt-kx)}$$

When striking the boundary, a reflected wave of

$$P_0^- = P_0^- e^{j(wt-kx)}$$

returns and a transmitted wave of

$$P_1^+ = P_1^+ e^{j(wt-kx)}$$

continues. $w$ is the angular frequency given by $w=2\pi f$ ($f$ is the frequency in Hertz), $x$ is
the one-dimensional propagation direction, and $k= w / c$ is the wave number. Obviously,
the $P^+$ refers to a wave traveling in the positive direction ($+x$), whereas $P^-$ refers to the negative direction ($-x$). The pressure and velocity must be continuous across the boundary of $x$. This is defined by:

$$P_0 = P_1^+ + P_0^-$$

and

$$U_0^+ + U_0^- = U_1^+$$

where $U_i^\pm$ is the volume velocity associated with a planar wave propagating in cylinder $I$ in both positive and negative directions [Sharp 1996].

Based on these definitions, it is clear that at distance $x=0$ the ratio of the instantaneous pressures of the reflected and transmitted waves is a merely a ratio of amplitudes [Li 2004]. Therefore, the reflection coefficient at $r_{0,1}$, which is the ratio of the pressure amplitude of the reflected and incident waves, can be found by:

$$r_{0,1} = P_0^- / P_0^+ = (S_0 - S_I) / (S_0 + S_I)$$

The reflection coefficient is the pressure amplitude ratio between the reflected wave and that of the incident wave. $r_{0,1}$ is the ratio that results at the scattering junction between sections 0 and 1. This means that the reflection coefficient is entirely dependant on the change of cross sectional area. $r_{0,1}$ is the scattering junction between sections 0 and 1. Because of this finding, the cross-sectional area of the first segment of tube will be defined using duct theory [Carneal et al 2006]. Duct theory provides a method that can estimate the area ratio change relative to the entrance area of the duct due to a reflection coefficient that is entirely dependant on the change of cross-sectional area. This relationship is defined as the area ratio, $a = S_2 / S_I$ for the cross-sectional area of the first
section compared to the second section’s cross-sectional area. This ratio can be used to find the magnitude ratio $M$, which is the ratio between the first reflection divided by the initial pulse [Carneal 2006]. Both $M$ and $a$ are defined by the equation:

$$M = \frac{(1 - a)}{(1 + a)}$$

or

$$a = \frac{(1 - M)}{(1 + M)}$$

Because of these equations, it is apparent that if the cross-sectional area ($a$) increases from segment one to segment two, that the magnitude ratio will be negative. This means that a downward peak will signify an increase in $a$ and an upward peak will correspond to a decrease in $a$. An example of this can be seen in figures 3.2 and 3.3. 3.2 exhibits a change from a larger diameter tube (.9525 cm) to a smaller (.635 cm) at sample 151, whereas 3.3 has a change from small (.9525 cm) to large (1.27 cm) at sample 176.

**Figure 3.2 - Common decrease example**  **Figure 3.3 - Common increase example**

**Test Object with Multiple Scattering Junctions**

While the previous section discussed what occurs in a simple configuration of a single scattering junction, it is best to investigate the series of reflections that are present in the
impulse response of a test object. As in the previous section, wave traveling in a planar manner is assumed. Typically, a series of tubes of varying cross-sectional areas is modeled as a collection of distinct cylindrical segments. These discontinuous segments are each of length \( l \) with a duration of \( T = 2l / c \) [Marshall et al 1991]. Each segments time is twice as long due to the wave traveling from the entrance of that particular segment, then reflected at its end, and then traveling back towards the entrance again.

In order to detail the impulse response of a test object with multiple discontinuities, consider the discrete signal \( p_{0,r}^+[nT] \). This notation is very similar to the identification of the pressure signal descriptors used in the previous section. \( 0,r, \) and \( + \) identifies the signal as traveling in a positive direction on the rightmost side of the first cylindrical segment. A label of \( l \) would depict the signal at the leftmost side of a cylindrical segment. The \( nT \) portion of the notation that the signal is of discrete samples at time \( nT \).

In this example, \( n \) will be of half increments to best illustrate the manner of reflection and zero propagation losses will be taken into account. The impulse signal that is used to determine the test object is

\[
P_{0,r}^+[nT] = \begin{cases} 
1 & \text{when } n = 0 \\
0 & \text{when } n \neq 0 
\end{cases}
\]

and the resulting impulse response is

\[
P_{0,r}[nT] = iir[nT]
\]

An object’s \( iir \) is the resulting reflections retrieved when an impulse is transmitted into its acoustical space.

Figure 3.4 [Sharp 1996] is an example of the impulse response of an object with multiple scattering junctions. As the pulse reaches the front of segment \( i \), the reflection and
Figure 3.4 - Multiple scattering junction example
transmission that occurs is much the same as Figure 3.1. The transmitted portion of the impulse \((P_{1,1}^+ [0 \ T])\) then continues on until it reaches segment 2 at time \(T/2\). Again, the remaining impulse undergoes another partial transmission and reflection. The reflected signal \((P_{1,r}^- [T/2])\) that results from the change of impedance at segment 2 then undergoes its own partial transmission and reflection as it reaches the boundary between segment 1 and 0. This process continues at each additional segment until the impulse reaches the end of the tube configuration. The impulse response becomes significantly more complex as a result of additional segmentation. What is of interest to note is that at time \(T\), the only reflection that returns is of the scattering junction between segments 1 and 2, much like the simple case mentioned in the previous section. There is only a single reflection at this point, as more time is needed before the impulse is reflected back from later junctions. After time \(T\), the resulting signal consists of reflections from junctions of multiple segments. The reflections that are of most interest are the test object’s primary reflections. These are the reflections that only need one reflection to return back to its own entrance. For the majority of all of this study, secondary reflections are not particularly noteworthy, however it is important to note the distinction for later reflections.

**Deconvolution**

Typically, one would find the impulse response of a system by introducing a very short pulse that contains all frequencies of equal energy. However, due to the addition of a source tube, the impulse response of a space is determined by deconvolving the duct’s
reflections with the shape of the input pulse resulting from its travel along the source tube. The shape of the input pulse can be found by finding the impulse response of the source tube itself. In order to find its impulse response, a thick and reflective material must terminate the end of tube that typically connects to the test object. In the case of this experiment, a copper cap with a thickness of approximately five millimeters was used. This process is quite important, as it will ensure that the impulse and the object’s reflections have both traveled the same path in the source tube, as well as ensure that source tube portion $l_2$ is not included in the resulting impulse response of the test object. Consequently, the two signals have both experienced the same losses while traveling back to the microphone via the source tube a distance of $l_2$. In effect, the recorded reflected pulse is used as the input pulse in acoustic reflectometry.

Deconvolution is carried out in the frequency domain, which done by performing an FFT on both the duct reflections and the input pulse. Next, the two resulting signals are then divided:

$$\text{IR (w)} = \frac{R (w)}{I (w) + q}$$

where $w$ is the discrete angular frequency, $R (w)$ is the FFT the duct reflections and $I (w)$ is the input pulse. The signal that is retrieved from this complex division ($\text{IR (w)}$) is then inverse Fourier Transformed in order obtain the impulse response in the time domain. While the above equation is accurate technically, a constraining factor of $q$ is added to the input pulse in order to avoid division by zero, which can occur at higher
frequencies where the background noise can envelop the pulse. Effectively, the factor of $q$ works as a low-pass filter.
Chapter 4

Experiment Setup/Methodology

Figure 4.1 is the schematic diagram of the acoustic reflectometer used in this experiment. A photograph of the apparatus is shown in figure 4.2. A sine sweep is produced by RME’s Fireface 400 D/A A/D and then amplified by a Samson Servo 120 power amplifier. The signal was then emanated from an AuSim’s AuProbe Emitter. The loudspeaker is approximately 3 in. in diameter. This speaker is coupled to the .9525 cm diameter source tube via a 5 in. long funnel. The gradual reduction in diameter limits coupler reflections. If the diameter was cut abruptly at this point, Sharp [1996] found that this resulted in a large discontinuity at the join between the source tube and the object, leading to a large reflection at the start of the object reflections. This ‘ringing’ of the input pulse is due to a great amount of pressure reflecting back at the change of impedance, which returns to the source and reflects back. This process could repeat many times due to the large amount of pressure reflected.

The distance $l_1$ labeled in the schematic diagram is the length of source tubing from the
Figure 4.1: Schematic diagram of reflectometer

microphone embedded along the source tube’s wall. The microphone is not placed inside of the source tube, but placed tightly to the wall in order to not disrupt the impulse and also capture reflections properly. $l_1$ is important for many reasons, though in the experimental setup, it is there to provide adequate time for the microphone to record the object reflections without contamination from source reflections. The amount of time before contamination is $2l_1/c$. Not only do the principle test object reflections need to be recorded before contamination, but secondary reflections as well in order to avoid inaccurate results during deconvolution. Each repetition of the test must wait for the signal to completely die out. For this experiment, a two second delay was observed before emitting another impulse.

In this experiment, the length of $l_1$ was 3.25 m long. It is not uncommon for $l_1$ to range from three to five meters depending on the length of objects being tested. Obviously, the longer the test object, the more time that is necessary to record all primary reflections, which also means a longer $l_1$. Eventually, a conflict results, as longer test objects require equally long length of $l_1$ resulting in less accurate impulse response, as the impulse must
travel a greater distance. It is possible to increase the amplitude of the pulse though there is a limit based on the point of speaker and amplifier distortion. Because the test objects used in this study were reasonably short, it was deemed unnecessary to implement strategies introduced by Sharp [1996].

$l_2$ is necessary to ensure that the reflections returning from the test object are reliable. This length separates the impulse emitted from the source and the primary reflection from the source tube. Because of $l_2$, it is ensured that the input pulse will be completely passed the microphone before the first reflections return. The length of $l_2$ is 3.25 m long. Generally, $l_2$ does not need to be as long as $l_1$ and a length shorter than what is used in this experiment is not uncommon.

The test object is connected to the source tube via a simple tube coupler with a sharp attenuation or increase from source to test object. Like the tubes themselves, the couplers
were made of copper. The sharp change from one cross-sectional area to the other is necessary to identify the corresponding change of cross-sectional area of the tubes themselves. A gradual reduction or increase would make it difficult to identify relevant scattering junctions.

Testing Optimization

The data is sampled at 44.1 kHz and then stored on a computer. A 25-second sine sweep was used as the measured pulse. This impulse was repeated ten times and all of its repetitions were averaged in order to reduce the signal-to-noise ratio. Preliminary tests implemented a sine sweep of three seconds, which repeated 1000 times. Interestingly, the results of the longer sweep repeated far fewer times yielded comparable results despite its significantly fewer repetitions. The 25-second sweep was also chosen for its ability to obtain as many diverse test samples as possible in a manageable time window. The Figures 4.3 and 4.4 show the negligible difference between the two different testing procedures.

While the source tube was fastened tightly to a surface, repeated impulse responses were
obtained in between test object experiments in order to verify consistency for each test. This became increasingly important as the experiment itself took place over a number of weeks.

A metal cap was placed at the end of the final tube of each configuration to maximize reflectivity. Ideally, the entire impulse should be reflected perfectly with a minimal amount of attenuation. The metal caps were chosen due to their thickness, durability, as well as uniformity to the tubes used in testing.
Chapter 5

Analysis

In this chapter, collections of impulse responses of various tube configurations are presented. The first half of the chapter explains the plot retrieved of the test object and the pertinent information that can be retrieved from these impulse responses. The resulting lengths and possible diameters of each segment in a number of test configurations are described as well. The second half of the chapter details the steps taken for database compilation and junction identification. The algorithms that are implemented to find the characteristics defined for both of the sections of this chapter are located in the appendix.

Test Object Reconstruction

Figure 5.1 shows a typical impulse response of one of the tube configurations used in testing. In this particular case, a 1.27 diameter, 33 cm long bronze tube is terminated by an copper cap of similar thickness to the cap that terminated the source tube when determining the shape of the input pulse. Most of the source tube portion of the plot has
been removed in order to get a closer view at the most important aspects of the impulse response. The 0 at the beginning of the x-axis is merely the beginning of this particular window and is not literal by any means. Likewise, the apparent end of the signal at sample 400 is only the end of this zoomed view as the signal itself is one second long (44100 samples).

The two most noteworthy peaks are located samples 64 and 151. The downward peak at the 64\textsuperscript{th} sample represents the termination of the source tube. The resulting peak from the termination of the source tube will always be of negative amplitude no matter the diameter of the test object’s first segment or source tube. This feature may appear to contradict the duct theory method described in Chapter 3. While it is the case that a peak of negative amplitude would represent a tube of increased size, the plot first reflection will not correspond to rules due to the deconvolution process utilized in this study. The time
domain signal before deconvolution does follow the principles set by duct theory. The reconstruction technique utilized to accommodate such instances will be discussed later in this chapter.

The second prominent peak in Figure 5.1 is the point of test object termination. All closed tube terminations have a positive peak, while all negative peaks signify an open tube termination. These peaks do follow the principles set by duct theory, as an open tube leads to a large space that is effectively infinitely large whereas a closed tube leads to an infinitely smaller space. Figure 5.2 is the impulse response of the same tube as Figure 5.1, but with an opened termination.

In both Figures 5.1 and 5.2 there is an additional peak at a time of 240 samples and an even less strong peak at 332 samples. Both of these peaks are reflected pulses that reached the border between the source tube and test object, returned back towards the end of the test object, and then reflected towards the segmental border again. This process
continues until the energy of the pulse dies. This characteristic helps illustrate the concept depicted in Figure 3.4. It is clear that these are in fact secondary reflections due to their periodicity, as their distance apart from each other closely mirrors the length of the test object itself.

In order to select the appropriate reflections of the test object, a peak-picking algorithm must be devised. Because the source tube is approximately 6.57 m long and the distance $l_2$ is nearly half the length of the source tube, there are 863 samples between the front of the test object and possible source contamination. That means that any peaks that occur in the impulse response between sample 856 and 1727 must be directly related to the test object itself. Pertinent reflections are obtained by setting a reliable threshold. In the case of this experiment, the threshold was set to a threshold of .0038. All peaks were compared to the threshold as an absolute value to ensure that negative peaks were also obtained.

In the event of a more complex reflection where multiple peaks occur above the threshold (as is the case in Figure 5.3), the algorithm selects the greatest peak that occurs in the related sequence of peaks. As a result, no test object segments used in this study are shorter than 24 cm (31 samples). This helps avoid reflection contamination, which would greatly complicate the peak picking process.

Finding the corresponding lengths of each segment is a straightforward task. After obtaining the reflections via the peak-picking algorithm, the lengths can be found as follows:

$$ SD (i) = \begin{cases} \frac{P (i+1) - P (i)}{0} & \text{when } i > 0 \\ 0 & \text{when } i = 0 \end{cases} $$
while \( i \) is less than the number of total peaks. \( P \) is the time in samples of each peak and \( SD \) is the distance (in samples) between the corresponding peaks. In the event of an T-intersection, the last two peaks are subtracted from the third to last to correctly identify the proper distance from the intersection. Now that the distance between the peaks is found we can find the length of each tube segment:

\[
D(i) = \left( \frac{SD(i)}{Fs} \right) \times c
\]

Where \( D \) is the distance (in meters), \( Fs \) is the sampling frequency, and \( c \) is the speed of sound. As mentioned previously, the sampling rate used in this study is 44.1 kHz.

**Junction Identification Method**

In this study, scattering junction identification is achieved by means of computer-learning methods. This means that a significant portion of each type of scattering junction is stored in a database and a smaller collection will be used for testing. The computer-

![Figure 5.3 – L-intersection](image)
learning method utilized for this study was K nearest neighbor.

K nearest neighbor (k-NN) is a rather simple algorithm that is a type of instance-based learning, known also as lazy learning. Instance-based learning methods delay generalizations made upon the training set until a query of a new test set is made. What this means is that group classifications are given to the training set when a test comparison is made. Instance-based learning is conceptually different than eager learning methods as they attempt to make generalizations about the training data before queries are made.

The K nearest neighbor method was chosen for this particular study due to its quick training phase, which is characteristic of most lazy learning methods. Each training sample is stored as a vector in a multidimensional space. Each vector is given a user-defined classification based on that should be grouped based on similar features. A successfully defined feature will consist of similarly placed values in the multidimensional space that are separate from a different defined feature. When a query is made, the algorithm looks for the $k$ closest datasets. The dataset that is being tested will be defined as most prevalent classification amongst the $k$ closest vectors.

In the particular case of Figure 5.3, a 1.27 diameter, 33 cm long bronze tube is connected to a 1.27 diameter, 36 cm bronze tube via a L-intersection. If this signal were to be used as a training set, the trainer can choose any of the relevant peaks and store them in the database. Along with the peak, the 20 samples ($4.5 \times 10^{-4}$ seconds) surrounding the peak are also stored. The maximum peak was located at the sixth sample of its particular window with the 5 samples previous to the maximum peak to the left and the 14 samples
that occurred subsequent samples to the right. The window was arranged in this matter to emphasize the unique idiosyncrasies of the signal following its prominent peak, which were found to have greater evidence of the type of junction at that location. The five samples in the window that occurred before the peak were included to capture the resulting slope that lead to the resulting reflection. The values of each sample were divided by the absolute value of the maximum peak for normalization across the entire database. This provided certainty that the nearest neighbors that border the test reflection do so because of a similar contour, rather than merely sharing similar amplitudes.

A theoretical peak window is shown in Figure 5.4. This window is vital for the identification process, as it provides the contextual data needed for distinct classifications in the case of a query. If this impulse response were to be used in the testing phase, each stored reflection is sequentially defined via the k-NN algorithm. An exception to this process occurs when a reflection is classified as a T-intersection. When this occurs, a separate function identifies the next two peaks that are above the threshold as wings. A
different peak picking strategy must be implemented for T-intersections, as the reflections that return from wings will likely cohabitate the same peak window. It is worth noting the difference of contour upon comparing the second peak of Figure 5.1 in comparison to the second peak of Figure 5.3. The differences between the two reflections are a result of their different junction types and the classification algorithm will try to identify such distinct difference. Figure 5.1’s second piece will be defined as a common decrease reflection; meaning that its contour is similar to that of a tube of closed type or the coupling junction where the cross-sectional area of the test object will decrease.

All of the identified scattering junctions and the segmental distances of the cavity are then placed into a reconstruction algorithm that labels where scattering junctions occur in the test object. The only means for identifying a reflection as point of termination of the tube or of a cross-sectional increase/decrease is during the peak picking process. The reflection of the final segment of a tube tends to be of much greater amplitude than reflections that arrive after the source-to-test object junction. If there is reflection stored after the peak and it is labeled as a junction of common type, then the peak is stored is considered the end of the test object. If there is another peak of common type stored after the present peak, then it is a common increase/decrease instead. However, it is important to note that both of these types are one in the same; the distinction is only made to better illustrate the test object itself upon reconstruction.

---

* The clarification for this reasoning is located on page 29.
Duct Theory Implementation

As mentioned in chapter 3, duct theory will be utilized to define the cross-sectional area of the first segment of the test object. Other segments will only be defined as a value that is either greater than or less than the principle cross-sectional area. Due to the fact that all first reflections of any test object in the deconvolved version were of negative amplitude, it is critical to use the original impulse response for this portion. The original impulse response contains an accurate first reflection that confirms what type of change in cross-sectional area occurs. Figure 5.5 illustrates this process. It is quite clear that both impulse responses both undulate in unison at points of reflections.

After the reflection classification portion of the algorithm concludes, the peak amplitude of the deconvolved impulse response is substituted with the peak amplitude of the original impulse response. One conflict with utilizing duct theory where there is a significant distance between the pulse source and first point of reflection is that the
calculated cross-sectional area tends to be somewhat less than the actual. This inaccuracy can be attributed to losses due to propagation. Despite this, the measurements of the first segment tested were predicted within 90% of its actual value. Supporting the belief of inaccuracy due to propagational losses is that all predictions were less than the actual diameter. Tube diameters that were closer to that of the source tube were consistently more accurate during predictions.
Chapter 6

Results

In total, there are forty-six impulse responses of unique test configurations stored. For each type of scattering junction (common increase, common decrease, T-intersection, and L-intersection), eight specific instances of each stored for training purposes, while two are used for testing. Only the relevant reflection window is stored in the training database, while testing signal include the entire impulse response that can have any combination of the four scattering junctions. All objects tested included a .9525 cm diameter segment as the first portion of the test object. This was a conscious decision as no objects stored in the training database included the same type of cross-sectional area change. By making the testing objects distinct from the training data, a correct classification means that junction identification algorithm was able to interpret the relationship between unique reflection and the stored data, rather than locate the exact

<table>
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<th>Test Segments</th>
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<td>Diameter Deviation</td>
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</tbody>
</table>

Table 6.1.1 – Reconstruction results
Table 6.1.2 – Reconstruction results

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<th>Reconstruction Features</th>
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<th>7b</th>
<th>7c</th>
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<th>8b</th>
<th>9a</th>
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<th>10b</th>
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<td>1.5</td>
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<td>3</td>
<td>2.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Diameter Deviation</td>
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<td>0</td>
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<td>-</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.1 provides the results of the first phase of testing in which the length and diameter predictions are examined. Columns 1-10 correspond to the impulse responses of the 10 tube configurations used for testing*. The letter that follows the test number is each consecutive segment of that test object. In the case of a T-intersection, segment b is the shorter of the two wings connected to the first segment. The composition of each test object can be found in the appendix. Length deviation and diameter deviation are expressed in terms of percentage difference from the actual. This value has been rounded to the nearest half percent. The ‘-’ symbol in both tables signifies that the diameter of that particular segment was not taken, as only the diameter of the first segment of each test object was calculated. As mentioned previously, subsequent segments after one are only defined in relation to the first segment.

Clearly, the results are quite accurate, as each measurement is easily within 10% of the actual value. The two greatest length deviations are both T-intersections, but these predictions are only off by approximately 1.5 cm. Of all of the objects tested, the T-intersections are the longest, which is could be one explanation for its inaccuracy. Also, T-intersections tend to have a more complex reflection contour, and its highest peak may

* The value of k was altered while obtaining results for test object 2 in order to retrieve reconstruction results for all instances. Classification results are detailed in Table 6.2.
be affected by the complexity. The diameter predictions for the test objects are nearly equivalent to the actual in all of the test cases, as the greatest deviation occurred on test nine. These consistent results were to be expected considering all of the test objects have the same diameter for the first segment. Diameter measurements of various other tubes used in training yielded less accurate results, though they were still near 10% deviation.

Table 6.2 details the junction identification phase of testing. The leftmost column corresponds to 10 test objects. The letter next to the test number refers to what kind scattering junction occurs at the end of that segment; i means common increase, d means common decrease, l means L-intersection, and t means T-intersection. Test configurations 2 and 7 are both T-intersections and do not have their wings identified via the k nearest neighbor method due to the nature of the identification algorithm. For this reason, there are no other variations of 2 and 7 in the table below. Each column is a based on the number of nearest k’s used. A * means that the reflection was correctly

<table>
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<th>K Nearest Neighbors</th>
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<tr>
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<tr>
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<td>*</td>
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<tr>
<td>3 d</td>
<td>*</td>
</tr>
<tr>
<td>4 i</td>
<td>*</td>
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<td>4 d</td>
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<td>8 d</td>
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<td>*</td>
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<td>9 d</td>
<td>*</td>
</tr>
<tr>
<td>10 d</td>
<td>*</td>
</tr>
<tr>
<td>10 d</td>
<td>*</td>
</tr>
</tbody>
</table>

Table 6.2 – Junction identification results
identified as its actual scattering junction. Void is present in the table when a T-intersection was wrongly identified at the previous scattering junction and the identification process omitted the following reflection. An i or t represents a junction that was incorrectly defined as a common increase or T-intersection, respectively.

Based on Table 6.2, accuracy of identification differs depending on the number of k neighbors included. It appears that three of the four types of scattering junctions (increase, decrease, and L-intersection) have a distinct and consistent contour resulting in many of the training types sharing the same multidimensional space closely with junctions of the same type. These three types are consistently identified correctly over the course of testing. However, it appears that the T-intersections have a less consistent contour, as test object 2 is routinely classified incorrectly until k is 9. At this point, the amount of k’s is nearly 25% percent of the entire training database, which is not an optimal k value in such a small training database. Another explanation for the confusion between common increases and T-intersections is result of the having the most similar contours of the junction types. It is important to note that this is much less of a factor because the common increase scattering junctions are routinely identified correctly whereas T-intersection 2 is not. Despite the case of test object 2, the k nearest neighbor method utilized in this is quite accurate, especially when k is between three and eight.
Chapter 7

Conclusion and Future Work

The results found in this study show that computer-learning methods can be utilized to predict the dimensions of an acoustic space. Scattering junctions can be identified based on their unique reflectivity obtained from an impulse response. Also, the lengths of each segment can be found with regularity.

Based on the results presented in chapter 6, it is evident that there is potential for broader applications of this study in future work. The first step in expanding would be to create a large database with a more diverse collection of tubes with widely varying cross-sectional areas. After a new set of training data has been accumulated, it would interesting to see how greatly the diameters of the testing database can differ from the training database. This would provide insight to how versatile the computer-learning method described in this study could be.

After confirming the methods presented in this study, it would be beneficial to find if this method could predict larger acoustical spaces where sound does not propagates as a plane waves. The intension of this study was to create a foundational method that can learn new features based on an appropriate amount of training no matter the complexity of the wave. As long as there is a consistent feature that can be witnessed across all instances, the algorithm can be taught to effectively identify its occurrence in other instances. In
future works, each classification in the database could be specialized to greater lengths in order to simplify more complex acoustical environments.
Bibliography


IR Descriptions

Training Set*

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<tr>
<th>NAME</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>One</td>
<td>1.27 cm diameter 33 cm</td>
</tr>
<tr>
<td>Two</td>
<td>1.27 cm diameter 33 cm to T with L wing 34 cm and R wing 48 cm</td>
</tr>
<tr>
<td>Three</td>
<td>1.27 cm diameter 33 cm to L with 36 cm leftward</td>
</tr>
<tr>
<td>Four</td>
<td>1.27 cm diameter 33 cm to .9525 cm diameter 34.5 cm</td>
</tr>
<tr>
<td>Five</td>
<td>1.27 cm diameter 33 cm to .635 cm diameter 25 cm</td>
</tr>
<tr>
<td>Eleven</td>
<td>.635 cm diameter 30 cm</td>
</tr>
<tr>
<td>Twelve</td>
<td>.635 cm diameter 30 cm to T with L wing 36 cm and R wing 24 cm</td>
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<td>Fourteen</td>
<td>.635 cm diameter 30 cm to 1.27 cm diameter 33 cm</td>
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<tr>
<td>Fifteen</td>
<td>.635 cm diameter 30 cm to .9525 cm diameter 45 cm</td>
</tr>
<tr>
<td>Sixteen</td>
<td>1.27 cm diameter 33 cm open</td>
</tr>
<tr>
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<td>1.27 cm diameter 33 cm to T with L wing 48 cm and R wing 34 cm</td>
</tr>
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<td>Eighteen</td>
<td>1.27 cm diameter 36 cm to T with L wing 33 cm and R wing 48 cm</td>
</tr>
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<td>1.27 cm diameter 36 cm to T with L wing 48 cm and R wing 33 cm</td>
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<td>Twenty</td>
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<td>Twentythree</td>
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<tr>
<td>Forty</td>
<td>.635 cm diameter 24 cm to 9525 cm diameter 34 cm</td>
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</tbody>
</table>

- The diameter of both wings at a T-intersection are the same as the first tube that is post source. This hold true for L-intersections as well. If there are two different diameters mentioned, it is a simple junction.
- All test objects are terminated with a cap unless otherwise mentioned
# Testing Set

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<td>.9525 cm diameter 45 cm to L with 47 cm leftward</td>
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function peak_ex = locate (source,input,peak_re)

% Acoustic Pulse Reflectometry Training Algorithm
% ---------------------------------------------
% locate (source,input,peak_re)
% % source -> Impulse response of the source tube
% % input -> Impulse response of test object connect to the source tube
% % peak_re -> Optional isolated reflection that can be used for database
% creation
% % By: Adam Kestian
% 2007 New York University

if nargin < 3
    peak_re = 0;
end

sig = deconvolve (source,input); % only storing from 800 1200 samples

xlim ('Time (in samples)')
ylabel ('Amplitude')

peak_storage = [];
database = [];
peak_counter = 1;
sig_len = length(sig);
thresh = .0038;
for i = (2: 1 : sig_len-1)
    if ((sig(i)>sig(i-1) && sig(i)>sig(i+1) &&
         sig(i)>thresh) ||
         sig(i)<sig(i-1) && sig(i)<sig(i+1) &&
         sig(i)<(thresh * -1))
        if (peak_counter == 1)
            peak_storage(1,1) = sig(i);
            peak_storage(1,2) = i;
            database (1, 1:6) = sig (i-5:i);
            database (1, 7:20) = sig (i+1 : i+14);
            peak_counter = peak_counter + 1;
        elseif (peak_counter > 1 && (i > (peak_storage(peak_counter-1,2) + 40)))
            if (sig (i) > peak_storage(peak_counter-1,1))
                peak_storage(peak_counter,1) = sig(i);
                peak_storage(peak_counter,2) = i;
                database (peak_counter, 1:6) = sig (i-5:i);
                database (peak_counter, 7:20) = sig (i+1 : i+14);
                peak_counter = peak_counter + 1;
            end
        elseif (abs(sig(i)) > abs(peak_storage(peak_counter-1,1))) && i <
         peak_storage(peak_counter-1,2) + 40)
            peak_storage(peak_counter-1,1) = sig(i);
            peak_storage(peak_counter-1,2) = i;
            database (peak_counter-1, 1:6) = sig (i-5:i);
            database (peak_counter-1, 7:20) = sig (i+1:i+14);
        end
    end
end

if (peak_re > length (peak_storage(:,1)))
    disp ('Reflection requested is greater than the number of reflections observed.');
    disp ('No reflection stored.');
    peak_ex = 0;
    plot (sig)
elseif (peak_re > 0)
    peak_ex = normalize(database (peak_re,:)); % allows me to extract particular reflections for storage
    plot (peak_ex)
end

function testing (source,input,trained, group)
% Acoustic Pulse Reflectometry Classification Algorithm
% --------------------------------------------------------------------
% testing (source,input,trained,group)
% % source -> Impulse response of the source tube
% % input -> Impulse response of test object connected to the source tube
% % group -> Classification list of all reflections stored in the database
% % creation
% %
% % By: Adam Kestian
% % 2007 New York University

load training
if nargin < 3
    peak_re = 1;
end
sig = deconvo (source,input); %only storing from 800 1200 samples
plot (sig (1:400))
hold on
shift_in=input(1354:1754);
plot (shift_in (1:400), 'r')
hold off
peak_storage = [];
database = [];
results = [];
wing1 = [];
wing2 = [];
peak_counter = 1;
sig_len = length(sig);
thresh= .0038;
T_id=0; %T-intersection identification
for i= (2: l : sig_len-1)
if ((sig(i)>sig(i-1) && sig(i) > sig(i+1) && sig(i) > thresh) || (sig(i)<sig(i-1) && sig(i) < sig(i+1) && sig(i) < (thresh * -1))
        if (peak_counter == 1)
            peak_storage(1,1) = sig(i);
            peak_storage(1,2) = i;
            peak_storage(1,3) = shift_in(i);
            database (1, 1:6) = sig (i-5:i);
            database (1, 7:20) = sig (i+1 : i+14);
            results (peak_counter) = 1;  %first peak is always same
        elseif (peak_counter > 1 && (i > (peak_storage(peak_counter - 1,2) + 40)))
            if (sig (i) > (peak_storage(peak_counter-1,1)))
                peak_storage(peak_counter,1) = sig(i);
                peak_storage(peak_counter,2) = i;
                peak_storage(peak_counter,3) = shift_in(i);
                database (peak_counter, 1:6) = sig (i-5:i);
                database (peak_counter, 7:20) = sig (i+1:i+14);
                peak_counter = peak_counter + 1;
            end
        elseif (abs(sig(i)) > abs(peak_storage(peak_counter-1,1)) && i < peak_storage(peak_counter-1,2) + 40)
            peak_storage(peak_counter-1,1) = sig(i);
            peak_storage(peak_counter-1,2) = i;
            peak_storage(peak_counter-1,3) = shift_in(i);
            database (peak_counter-1, 1:8) = sig (i-7:i);
            database (peak_counter-1, 9:20) = sig (i+1:i+12);
            peak_counter = peak_counter + 1;
        end
    end
end

% Classification
junct_num = length (peak_storage(:,1));    % IF T NEED TO TERMINATION ID
for i= (2:1:junct_num)
    if (T_id < 1)
        results (i-1) = classify (normalize(database(i,:)),trained,group);
        if (results (i-1) == 4)
            [wing1,wing2] = T_wings (sig, peak_storage(i,2), shift_in);
            peak_storage(i+1,:) = wing1 (1,:);
            peak_storage(i+2,:) = wing2 (1,:);
            T_id = 1;
        end
    end
end
results=[results,zeros(1,junct_num)];

% Diameter and termination ID
seg_length = [];
samp_diff = [];
diameter = zeros (junct_num-1,1);    % stores the diameter in meters
T_id = 0;
wing_num = 0;
for i = (1:1:junct_num-1)
    if (i == 1)
        mag_ratio = (1 - peak_storage(1,3)) / (1 + peak_storage (1,3));
        peak_storage(1,3) = mag_ratio * .7128;  % cross sectional area
        diameter(1) = sqrt(peak_storage(1,3) / pi) * 2;
        peak_storage(1,4) = diameter(1);
        samp_diff(1) = peak_storage (2,2) - peak_storage (1,2);
        seg_length(1) = ((samp_diff(i) * 343) / 44100) / 2;
        disp ('First tube diameter: ')
        disp (diameter(1));
        disp ('First tube length: ')
        disp (seg_length(1));
    else
        samp_diff(i) = peak_storage (i+1,2) - peak_storage (i,2);
        seg_length(i) = ((samp_diff(i) * 343) / 44100) / 2;
        if (results(i-1) == 3)
            disp ('L-intersection to tube length: ')
            disp (seg_length(i));
        elseif (results(i-1) == 2)
            if (T_id == 0)
                disp ('Diameter increase to tube length: ')
                disp (seg_length(i));
            end
        elseif (results(i-1) == 1)
            if (T_id == 0)
                disp ('Diameter decrease to tube length: ')
                disp (seg_length(i));
            end
        elseif (results(i-1) == 4)
            disp ('T-intersection');
            T_id = 1;
        end
    end
end
if (T_id == 1)  % obtaining the correct length of the later T wing
    seg_length(junct_num-1) = seg_length(junct_num-1) +
    seg_length(junct_num-2);
end
if (isempty (wing1))
    if (peak_storage (junct_num,1) > 0)
        disp ('Closed termination');
    else
        disp ('Open termination');
    end
else
    if (wing1(1,1) > 0)
        disp ('Closed termination of closest wing of length: ')
        disp (seg_length(junct_num-2));
    else
        disp ('Open termination of closest wing of length: ')
        disp (seg_length(junct_num-2));
    end
    if (wing2(1,1) > 0)
        disp ('Closed termination of furthest wing of length: ')
        disp (seg_length(junct_num-1));
end
if (results(1) == 3)  % cross sectional area
    disp ('L-intersection to tube length: ')
    disp (seg_length(1));
elseif (results(1) == 2)
    if (T_id == 0)
        disp ('Diameter increase to tube length: ')
        disp (seg_length(1));
    end
elseif (results(1) == 1)
    if (T_id == 0)
        disp ('Diameter decrease to tube length: ')
        disp (seg_length(1));
    end
elseif (results(1) == 4)
    disp ('T-intersection');
    T_id = 1;
end
else
    disp ('Open termination of furthest wing of length: ')
    disp (seg_length(junct_num-1));
end
end

function resp=deconvo (input,duct)
fft_input=fft(input);
fft_duct=fft(duct);
    iir=fft_duct./(fft_input+eps);
sig=real(ifft(iir));
resp=sig(800:1200);
plot (resp)
end

function [wing1, wing2]= T_wings(sig,sample_start,shift_in) % sample start for sig(sample_start:sig(len))
    thresh = .0038;
    wing1 = zeros (1,3);
    wing2 = zeros (1,3);
    wing = zeros (2,3);
    wing_count = 1;
for i = (sample_start+10:1:length (sig)-1) % plus ten is to avoid selecting the peak of the T itself
    if (((sig(i) > sig(i+1)) && (sig(i) > sig(i-1))) || ((sig(i) < sig(i-1)) && sig(i) < sig(i+1)))
        if (abs(sig (i)) > thresh  && wing_count < 3)
            wing(wing_count,1) = sig (i);
            wing(wing_count,2) = i;
            wing(wing_count,3) = shift_in (i);
            wing_count = wing_count + 1;
        end
    end
end
    wing1(1,:)=wing(1,:);
    wing2(1,:)=wing(2,:);
end

function norm=normalize(peak)
    n_peak=[];
    for i=(1:1:length(peak))
        n_peak(i)=(peak(i)/(abs(peak(6))));
    end;
norm=n_peak;