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MEASUREMENTS OF VIOLIN BOWS
USING AN AUTOMATIC BOWING MACHINE

CLARE NADIG
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Abstract

The majority of research performed to date related to stringed instruments has been focused on the violin body itself, while very little study has been done on the violin bow. This project seeks to partially fill this gap by investigating the connection between the mechanical properties of bows, such as stiffness, damping coefficient and frequency response, and the vibration they induce in a string. Another goal of the project is to determine the physical properties in a bow that produce the most desirable sound.

This project uses a mechanical bowing machine to provide a consistent bow stroke and an accelerometer and a force sensor to measure the vibrations produced by the bow. Tests completed so far show that the repeatability of the data needs improvement, and that the factors that cause the most significant variation include the distance from the bridge to the bow hair and the tuning of the string, while the bow tension has virtually no effect on the induced vibrations. A preliminary comparison of six different bows and a test performed using an impact hammer to record the frequency response of one bow are also presented, though time constraints have prevented taking enough data to draw conclusions based on these tests. The project will continue to explore other factors that could affect the repeatability of the results, such as the angle of the bow relative to the string, the humidity in the room, and the amount of rosin on the bow hair. Finally, other tests (mentioned above) that have been put on hold due to time constraints or issues with repeatability will be continued.
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1. Introduction

Figure 1: Parts of a violin (left) [10] and bow (right) [11]:
1. Scroll
2. Tuning Peg
3. Fingerboard
4. Neck
5. Strings
6. Bridge
7. F-Hole
8. Fine Tuner
9. Chin rest
10. Tailpiece

11. Stick
12. Tip
13. Grip
14. Hair
15. Screw (to adjust tension)
16. Frog

This thesis is part of a study on violin bows and the ways in which their mechanical properties (mass, stiffness, damping coefficients, frequency response) impact the quality of the sound they produce. To facilitate understanding, a brief description of the structure of the violin and bow and the manner in
which they produce sound is provided. Refer to Figure 1 for a visual clarification of various features of the violin and bow.

The violin consists of a hollow wooden body over which four strings are stretched. The bridge, placed between the strings and the body, provides the primary path through which vibrations pass between the body and the strings. The bow is a stick (usually made from wood, though other materials such as carbon fiber are sometimes used) which maintains tension in a section of horse hair (occasionally synthetic). As the bow is drawn across the string, the hair alternately sticks to the string and slips, exciting its natural frequency. The sticking is aided by the application of rosin, a solid pine resin, to the hair.

Violin bodies and their dynamics have been studied fairly extensively by scientists, engineers and luthiers (violin makers), though the work is very limited compared to more mainstream topics. This work has led to understanding of the basic mechanics of sound production of a bowed stringed instrument and characterization of structural and cavity modes of the body. Though extensive dynamic testing has been applied to stringed instruments for the past 40 years, it has had very little impact on instrument design [6]. Violin design has evolved over hundreds of years almost exclusively through a combination of tradition, experience and trial and error, although early violin makers are known to have used "tap tones" (tapping the plate and listening to the tone it produces) in constructing the top and back plates of violins [5].

Though no such method has yet been found for bows, Bazant, Stepanek, and Malka were able to define two different methods of predicting the sound quality of a violin based on the frequency response of the instrument. 43 violins of varying quality were rated on a scale of 1-5 by violin makers and players. The methods developed were able to use the frequency response of a violin to predict this rating with correlation coefficients of 0.852 and 0.827 [3].

A much smaller body of work has been performed on the properties and dynamics of violin bows. Anders Askenfelt, of KTH Royal Institute of Technology, Sweden published two papers in 1995 which document very thorough measurements of mass and stiffness distribution along the bow stick and of the mechanical properties and resonances of bow hair [1]. Askenfelt also studied the mechanisms by which a string is excited by the bow and the transfer of vibration from bow to string and string to bridge. He found that bow resonances can couple with string resonances to transmit, reflect or absorb energy, although he was unable to find clear evidence of bow resonances having a significant impact on sound output of the instrument [2].

Further studies of the properties of bow hair were made by Helga Pöcherstorfer, who made a comparison of eight different varieties of bow hair. The characteristics studied were the cross-section of the hair, core structure, elasticity, surface structure, and sound produced, measured using a bowing machine. Examination of these characteristics showed the most variation from one hair type to another in cross-section, elasticity, and surface structure, and little variation in core structure and sound [7].

Diana S. Young, of Massachusetts Institute of Technology, developed a wireless sensor system to measure violin bowing parameters. This system consists of accelerometers and inertial sensors to determine the angle of the bow with respect to the string, strain sensors on the stick to measure bow force, and an electromagnetic sensor to track the position and velocity of the bow. The system was intended to record various parameters of violin players' bowing technique with minimal modifications to the bow and little interference with playing. Using data collected from these sensors,
she was able to create an algorithm which was 95% successful in distinguishing among six different common bowing techniques, and 94% successful in distinguishing among 8 different players. She was also able to use the sensor system to control an electronically synthesized violin physical model [9].

Mechanical bowing machines, such as the one used in this study, are machines created for the purpose of exciting a string with a bow in a more controllable and repeatable manner than hand bowing. They have been used many times in the past, for many different purposes, including Helga Pöcherstorfer’s study, mentioned above. In addition, J. S. Bradley and T. W. W. Stewart made a comparison of violin response curves produced by hand bowing, mechanical bowing, and electromagnetic drivers. They found that the responses due to hand bowing and machine bowing were very well correlated, with about 80 percent of the 80 notes tested having Sound Pressure Levels within 3 dB [4].

Scarcity of pernambuco, the wood traditionally used for professional-level bows, has created increased interest in alternative materials, particularly carbon fiber. It is in this area where research has had the most significant impact on bow design, though little information is published and available to the public. Arcus, a company which produces carbon fiber bows, has conducted research into several aspects of bow design. They found that the pattern of fibers in either a wood or a carbon fiber bow plays a significant role in sound quality. They were also able to “tune” the mass and stiffness of the sticks to create an optimal sound [8].

2. Objective

The goal of the project, of which this thesis documents a part, is to study the mechanical properties of violin bows, and the impact these properties have on the sound produced by the bow. A mechanical bowing machine is used to provide repeatable measurements of the vibration induced in a string by various bows under varying conditions. These responses will be compared with measured mechanical parameters of the bows, such as stiffness, damping coefficient and frequency response. Eventually, the data will be compared against subjective evaluations of tone quality by professional musicians in order to determine what properties produce the most desirable sound.

3. Experimental Setup and Procedures

The response of a string to different bows is measured using an automatic bowing machine, shown in Figure 2 and Figure 3. This machine grips the bow in a manner similar to a player's grip, and draws the bow across the string using a belt driven by a motor. It uses a balance system with a moveable weight on a threaded rod to maintain a constant downward force, and a computerized control to maintain the desired constant bow speed.
The string used for the tests is a Helicore violin D-string mounted on a monochord constructed from a square aluminum tube which is filled with sand. The setup is intended to create as similar conditions as possible to an actual violin while minimizing resonant responses of the string’s supports. The monochord is shown in Figure 4. The orange foam shown in the picture prevents the section of the string behind the bridge from resonating.
The vibrations induced by the bow are measured in two ways. First, a very small (0.3 g) accelerometer made by PCB Piezotronics (model number 352A73) is attached to the inside of the bow tip using wax, just above the hair, as shown in Figure 5. A custom-built piezo-ceramic force sensor, shown in Figure 6, is also mounted between the string and the bridge on the monochord. The outputs of these sensors are fed into a Zoom H4n handheld digital audio recorder and converted into a 48 KHz WAV file, which can be analyzed using MATLAB.
The controlled variables for the tests are the bow being used, the distance from the point where the string contacts the bridge to the center of the bow hair, the downward force exerted by the bow on the string, and the speed of the bow. For all tests other than those investigating the effects of these variables, the values of 15 millimeters, 65 grams, and 20 centimeters per second, respectively, are used. Bow tension is regulated using the distance between the stick and the hair as a reference. To tighten the bow consistently, a small wooden cylinder (cut from a pencil) is inserted between the stick and the hair. The bow is then slowly tightened until the cylinder just falls out.

4. Results

4.1. Various Methods for Presenting the Data

Data collected so far has been processed using MATLAB and Microsoft Excel. The most useful tool in analyzing and comparing data has been the Fast Fourier Transform (FFT), which shows the relative amplitudes of the various frequency components of a signal. The FFT is a simple and effective way to characterize the response of the bow and the string. Several methods have been used to present this data in an attempt to find one type of graph which can best represent the character of a bow. The first is the waterfall plot, a three-dimensional graph that shows how the frequency content of the signal changes over time. This type of graph is useful because it shows more detail than a traditional two-dimensional FFT. Features such as starting transients and the sudden drop-off in some frequencies in the bow tip can be seen. Examples of waterfall plots are shown in Figure 7. Simpler two-dimensional graphs have also been used, such as an instantaneous FFT taken 75 percent of the distance from the frog to the tip of the bow (on a down bow) (Figure 8a) and an FFT averaged over the entire bow stroke (Figure 8b). By far the most convenient way of comparing data from two or more different runs has been a plot of only the peaks of the FFT averaged over the entire bow stroke. An example of this type of plot is shown in Figure 9. Averaging over the entire bow stroke results in a significant reduction in noise levels, and plotting only the peaks (with or without connecting lines)
creates a much cleaner graph when multiple data sets are plotted simultaneously. A similar peaks-only FFT was created by averaging over a half-second time period at three-quarters of the distance from frog to tip (shown in Figure 13). The intent was to determine if the starting transients were affecting the repeatability of the results by producing plots that did not include the beginning segment of the bow stroke.

Figure 7: Waterfall plots generated by the force sensor on the bridge (a) and the acceleration sensor on the bow tip (b)

Figure 8: FFT taken at 75 percent of the distance from the frog to the tip (a) versus FFT averaged over entire bow stroke (b)
4.2. Testing the Repeatability of the Results

One of the first tests performed was to check the repeatability of the results. Initially, one bow (made by Rodney B. Mohr) was tested on several different days over approximately two months, as well as multiple times on the same day. The results were compared using a peaks-only average FFT of the data from the force sensor on the bridge, shown in Figure 9. The results from each test were fairly similar; the magnitudes of most peaks were within ten decibels. However, the results of two tests performed back to back were nearly identical. Further testing has been started to determine what factors influence the variation and how to better control these factors.

**Figure 9: Peaks of averaged FFT for Mohr bow recordings taken on different days**

Several factors have been considered as possible causes of the variation, including the humidity of the room, the tension in the bow hair, the angle of the bow relative to the string (both horizontally and vertically), whether or not the bow hair lies perfectly flat on the string, the amount of rosin on the bow and the string, how well the string is tuned, and small variations in weight, speed and distance from bridge to hair. For each test of these factors, all data was taken on the same day without anything on the bowing machine between tests.

The first factor to be tested was bow tension. Bow tension is adjusted using a screw on the frog of the bow. The effects of changing the tension in the bow were investigated by recording data at normal tension (defined in the procedure section on page 6), one half turn and one full turn tighter, and one half turn and one full turn looser than normal. The results are displayed in Figure 10, and clearly show that bow tension has a very minimal effect on the frequency content.

Distance from the bridge to the center of the bow hair was also tested as a possible factor in the variation. This was accomplished by changing the distance in 3 mm increments, up to 6 mm greater than and less than the nominal value of 15 mm. The results of this test, shown in Figure 11, indicate that bridge to hair distance does have an effect on the results.
The final factor tested was the tuning of the string. The string is normally tuned using an electric tuner calibrated to A440, or A (just over a half-octave above the D to which the string is tuned) equal to 440 Hz. To investigate the effects of the string being out of tune, it was tuned with the calibration setting on the tuner changed in 2 Hz increments. These results are presented in Figure 12, and show that mis-tuning could also be a contributing factor to the variability of the results.

One other possible method was explored to improve the repeatability of the results. The waterfall plots generated from the data collected (such as in Figure 7) show significant starting transients. In order to determine whether the variation was limited to these transients, FFTs averaged over only a half-second period approximately three-quarters of the distance from the frog to the tip were calculated. The plot created with this method is shown in Figure 13. From this chart, it is clear that the variation is present in the middle of the bow stroke, and not limited to the starting transients. Therefore, attempts to better control the factors that cause this variation will continue.

![Figure 10: Effects of bow tension variation from one turn tighter to one turn looser than normal. Plot shows peaks of FFT averaged over entire bow stroke.](image)
Figure 11: Effects of changing the distance from the bridge to the center of the bow hair. Plot shows peaks of FFT averaged over entire bow stroke.

Figure 12: Effects of changing the frequency to which the string is tuned. Plot shows peaks of FFT averaged over a half second at the three-quarter bow.
### Mohr Repeatability Testing - taken at 3/4 bow

![Graph showing FFTs for Mohr bowing]  

**Figure 13:** Peaks of FFTs averaged over a half-second period three quarters of the distance from frog to tip.

#### 4.3. Comparison of Machine Bowing to Hand Bowing

In attempt to further validate the use of the mechanical bowing machine, a comparison between the results of hand and machine bowing (both using the monochord) was made using the Mohr bow. Hand bowed data was taken by gripping the bow in the normal manner used for playing and drawing it across the string at the same distance from the bridge (15 mm) used for the bow machine.

Figure 14 and Figure 15 show time histories (one fundamental period) of data taken by hand and machine bowing. The bridge force data from the hand bowed test has the triangular waveform that is typical of a bowed string, but this is much less clear in the machine bowed data. The bow tip acceleration data appears to be much more similar between the hand bowed and machine bowed responses.

Figure 16 and Figure 17 show averaged FFTs for hand and machine bowed responses. These plots are much more similar than the time histories, and like the time histories, the tip acceleration data seems more consistent between the two plots than the bridge force data.

Figure 18 and Figure 19 show waterfall plots of the same data. These plots show considerable differences between hand and machine bowing. These differences could be partly due to the fact that it is impossible to match the bowing machine’s ability to bow with a constant speed, position relative to the bridge, and downward force when bowing by hand.
Figure 14: Time history of bridge force and bow tip acceleration produced by hand bowing

Figure 15: Time history of bridge force and bow tip acceleration produced by machine bowing
Figure 16: FFT averaged over entire bow stroke, of hand-bowed response

Figure 17: FFT averaged over entire bow stroke, of machine-bowed response
These figures show similarities between hand and machine bowing which validate the use of the bowing machine to some extent, though there is still room for improvement in using a machine to mimic a hand bowed response. Of the three types of plots shown, the most similar are the averaged FFTs (Figure 16 and Figure 17), which have been the primary type of figure used to present and compare data. This similarity suggests that averaged FFTs, which are visually one of the best ways to compare data between different bows or test conditions, may also be one of the most accurate in terms of consistency with hand bowing. Although the data from the bridge force sensor has been used primarily so far, the data from the accelerometer on the bow tip seems to generally be more consistent with hand bowing, so perhaps this data should be used more in the future.

This final test was performed after several modifications were made to the bowing machine. Some of the bearings in the machine itself were modified to allow for smoother operation, and a new monochord was constructed (shown in Figure 20), with an upturned plastic trough filled with
concrete in place of the sand-filled aluminum. In addition, data was recorded at 44.1 kHz instead of 48kHz.

Figure 20: Plastic/Concrete Monochord

5. Conclusion and Future Work

The results presented in this thesis show that the bowing machine has the potential to be a consistent and controlled way to imitate hand bowing, although more work needs to be done to make it more consistent, and there is still room for improvement in making it comparable to hand bowing. Of the three variables that were tested in order to determine the sources of variability, the tuning of the string and the distance between the bridge and the bow hair were found to be much more important than the tension in the bow. Several other factors, such as the angle between the bow and the string, the amount of rosin used, humidity, and small variations in downward force and bow speed, should also be evaluated as possible sources of this variability.

Once the variation in results from one day to another is brought to an acceptable level, other bows will be tested, as well as the effects of the controlled variables (bridge to bow hair distance, downward force, and bow speed). Preliminary tests of various bows are shown in Figure 21. One test has also been performed by varying the downward force and the distance from the bridge to the hair. Time constraints and lack of consistency in the bow machine results have prevented thorough analysis of this data, as well as the data from the impact hammer testing described below.

The data compiled on each of the bows will be compared to data on the mechanical properties of each bow, such as stiffness, damping coefficient and frequency response. The objective of this step is to determine how these properties of the bows influence the vibration induced in a string by the bows. One test has been performed so far for this purpose. The bow stick near the frog was tapped with a miniature impact hammer manufactured by PCB Piezotronics (model number 086C80) tipped with hard rubber while the bow was gripped by the bowing machine. The responses of the impact hammer and the accelerometer on the bow tip were recorded and used to calculate a transfer function. Figure 22 shows a comparison between the sound produced by the Mohr bow using the
bowing machine and this transfer function. This data can also be used to compute the natural frequencies and damping coefficients of a bow.

The final step planned at this point is to compare the data collected, both the mechanical properties of the bows and the response of the string excited by them, to subjective assessments of the tone quality produced by the bows completed by professional musicians. These comparisons will be used to determine what properties of a bow produce the optimal sound.

Figure 21: FFTs produced by six different bows using the bowing machine
Figure 22: Comparison of sound produced by Mohr bow and the bow's frequency response
6. References


Appendix A: Bow Data Sheets

Manufacturer: Rodney D. Mohr

Weight: 61.2g

FFT averaged over entire bow stroke

Instantaneous FFT taken at 3/4 bow
Time history taken at 3/4 bow

Waterfall plots taken using accelerometer on bow tip (a) and force sensor on bridge (b)
Manufacturer: Karl Meisel

Weight: 60.9g

FFT averaged over entire bow stroke

STE-042-meisel.wav|02-Apr-2012|4.7-7.5 sec|| Avg FFT

STE-040-hisel_27-Oct-2011_1.4-2.1 sec_10/7 up bow FFT
Instantaneous FFT taken at 3/4 bow

![Instantaneous FFT](image)

Time history taken at 3/4 bow

![Time History](image)

Waterfall plots taken using accelerometer on bow tip (a) and force sensor on bridge (b)
Manufacturer: Morgan Andersen

FFT averaged over entire bow stroke

Instantaneous FFT taken at 3/4 bow
Time history taken at 3/4 bow

Waterfall plots taken using accelerometer on bow tip (a) and force sensor on bridge (b)
Manufacturer: Burke

FFT averaged over entire bow stroke

Instantaneous FFT taken at 3/4 bow
Time history taken at 3/4 bow

Waterfall plots taken using accelerometer on bow tip (a) and force sensor on bridge (b)
Manufacturer: B. Roland

FFT averaged over entire bow stroke

STE-078-roland_28-Oct-2011_3-3.4 sec_10-28-11 down bow FFT

Instantaneous FFT taken at 3/4 bow
Time history taken at 3/4 bow

Waterfall plots taken using accelerometer on bow tip (a) and force sensor on bridge (b)
Manufacturer: Coda Prodigy

**FFT averaged over entire bow stroke**

![FFT averaged over entire bow stroke](image)

**Instantaneous FFT taken at 3/4 bow**

![Instantaneous FFT taken at 3/4 bow](image)
Time history taken at 3/4 bow

Waterfall plots taken using accelerometer on bow tip (a) and force sensor on bridge (b)
### Appendix B: List of Equipment Used

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Manufacturer</th>
<th>Model No.</th>
<th>Serial No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>PCB Piezotronics</td>
<td>352A73</td>
<td>123569</td>
</tr>
<tr>
<td>Handheld digital audio recorder</td>
<td>Zoom Corporation</td>
<td>H4n</td>
<td>00183625</td>
</tr>
<tr>
<td>Power unit</td>
<td>PCB Piezotronics</td>
<td>480D06</td>
<td>6996</td>
</tr>
<tr>
<td>Scale</td>
<td>OHAUS</td>
<td>Scout Pro</td>
<td>7132050004</td>
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<tr>
<td>Impact Hammer</td>
<td>PCB Piezotronics</td>
<td>086C80</td>
<td>1710</td>
</tr>
<tr>
<td>Digital Signal Analyzer</td>
<td>DSP Technology, Inc.</td>
<td>20-22A</td>
<td>1467</td>
</tr>
<tr>
<td>Chromatic Tuner</td>
<td>Korg</td>
<td>CA-20</td>
<td>(none listed)</td>
</tr>
</tbody>
</table>
Appendix C: Step-by-Step Testing Procedure

1. Tighten the bow: Place a small piece cut from a pencil between the stick and the hair, and slowly tighten the bow until the pencil just falls out. Rosin the bow if needed.
2. Place the bow in the grip on the machine with the edge of the plastic clamp lined up with the end of the rubber grip on the bow. Tighten the screws, and secure with the rubber band.
3. Secure the accelerometer to the inside of the bow tip, just above the hair, using wax. Tape the cable to the bow stick to keep it out of the way.
4. Use a clip-on tuner clipped to the tuning peg to tune the string to D above middle C (293 Hz).
5. Check sensor connections: The accelerometer should connect to the microphone input on the recorder through the power unit; the force sensor on the bridge should connect directly to the microphone input. The recorder should be connected to the computer through USB.
6. Start up the "PID not timer" LabView program, and run it. Set the speed to 20 cm/s, or other desired speed.
7. Use the program to move the bow all the way to the right. Place the monochord so that the string contacts the bow hair just under the end of the bow grip. The center of the hair should be 15mm (or desired distance) away from the bridge.
8. Run the bow back and forth a few times, and use the fine tuning peg (A) on the machine to make sure the arm of the bow machine has as little as possible vertical movement.
9. Place the scale to the left of the string, elevate it, and place a small block on top so that the top of the block is level with the string. Zero the scale with the block on top. Move the bow to the left far enough that the hair can rest on the block. Move the monochord aside, and adjust the weight on the back of the bow machine arm until the scale reads 65g (or the desired weight). Lay the block on its side and replace the monochord.
10. Double check that the bow hair is the correct distance from the bridge at the frog, then move the bow all the way to the left. Turn the silver piece (B) on the bow machine's grip to adjust the distance from the bridge to the hair at the tip end so it is the same as at the frog.
11. Return the bow to the right, and use a triangle to check that the bow hair is perpendicular to the string. Move the string as necessary, and re-check the bridge to hair distance.
12. Record a test track using Audacity (click record in Audacity, then move the bow left (down) then right (up) using LabView) to ensure the input is not overloaded. Adjust the gain on the recorder if necessary.
13. Record data as in step 12.
14. Export the data as a WAV file, and use the MATLAB script "bow7" to produce the desired figures.
Appendix D: MATLAB Code Used for Data Analysis

```matlab
%FFT ANALYSIS FOR BOWING MACHINE
%calculates the FFT using Hanning Window
%waterfall output plot
%FFT averaged over time
%2 channel input
%Write avg FFT to data file
%CH1 (Left) = Bow Tip Force or Acceleration
%CH2 (Right) = Bridge Force
%bow7.m 2 March 2012 JSL

dir
clear
clc
close all
format compact
today=date;
filename=input(' wav filename = ','s');
filein=strcat(filename,'.wav');
fileout1=strcat(filename,'1.txt');
fileout2=strcat(filename,'2.txt');
tstart=input(' Starting time = '); % starting time (seconds)
tend=input(' Ending time = '); % ending time (seconds)

% if = tstart, plot the inst FFT for one sample
label=input(' Label = ','s');

%FFT CALCULATIONS

[wave,fs]=wavread(filein); % read 48 or 44.1KHz stereo .wav file
ns=2048; % number of data samples per slice
nslice=round(fs*(tend-tstart)/ns); % number of NS point FFT slices in data sample

nslice=max(1,nslice);
dt=1/fs; % time increment - seconds
df=fs/ns; % frequency interval - Hz
fmax=fs/2; % Nyquist frequency - Hz
scale=ns/4; % fft amplitude scaling factor
nlast=int32((5000/df)+1); % index of last frequency point to plot, at ~5000 Hz

t=(0:1:(ns-1))*dt; % relative time vector, first value is 0 seconds relative to tstart
f=(0:1:(ns-1))*df; % frequency vector, first value is 0 Hz
timeint=(tstart:timeint:tend-timeint);
time=(tstart:timeint:tend-timeint);

% extract NSLICE slices of NS samples each and perform fft on each time slice

for k=1:nslice
    iend=int32(istart+ns-1); % array index of ending point for this slice
    channel1=wave(istart:iend,1); % extract sound data from wave vector,
```

33
channel2=wave(istart:iend,2); % extract sound data from wave vector, 
% second column is channel 2 Right 
\[ t=((k-1)*ns:1:(k-1)*ns+(ns-1))*dt; \] % absolute time 

% calculate fft using hanning window 
fft1=abs(fft(hanning(ns).*channel1/scale)); 
fft2=abs(fft(hanning(ns).*channel2/scale)); 
dbmag1=20*log10(abs(fft1)); % log magnitude of Ch1 
dbmag2=20*log10(abs(fft2)); % log magnitude of Ch2 
linmag1=abs(fft1); % linear magnitude of Ch1 
linmag2=abs(fft2); % linear magnitude of Ch2 
bowfft1(1:nlast,k)=linmag1(1:nlast); % 2-D matrices - amplitude as 
bowfft2(1:nlast,k)=linmag2(1:nlast); % function of frequency and time 
fftavg1=fftavg1+fft1; % ensemble average FFT of bow tip acceleration 
fftavg2=fftavg2+fft2; % ensemble average FFT of bridge force 

%-------------------PLOT TIME HISTORY AND FFT FOR SINGLE AVERAGE -------------------

if nslice==1, 
% if start time is same as end time, plot the time history and FFT for one sample 

h=figure('PaperUnits','normal', 'PaperOrientation','land'); 
hold on; 
plot(t,channel1); 
plot(t,channel2,':r','LineWidth',2); % plot bridge force with red dashed line 

legend('Tip Accel ','Bridge Force');
xlabel('Time (s)');
ylabel('Amplitude');
title(strcat(filein, '|',today, '|',num2str(tstart),'-',num2str(tend),... 
' sec', '|',label,' | Time History '));
axis([0 0.008 -1.0 1.0 ]); 

%plot log FFT of this sample, both channels 

h=figure('PaperUnits','normal', 'PaperOrientation','land'); 
hold on; 
plot(f,dbmag1); 
plot(f,dbmag2,':r','LineWidth',2); % plot bridge force with red dashed line 
axis([0 5000 -60 0]); 
legend('Tip Accel ','Bridge Force');
xlabel('Frequency (Hz)');
ylabel('dBV re 1V');
title(strcat(filein, '|',today, '|',num2str(tstart),'-',num2str(tend),... 
' sec', '|',label,' | inst FFT '));
end

%-------------------PLOT AVERAGE FFT OVER ENTIRE TIME SAMPLE-------------------

if nslice>1, % skip remaining plots if only one sample 
fftavg1=20*log10(fftavg1/nslice); % FFT Average for bow tip acceleration 
fftavg2=20*log10(fftavg2/nslice); % FFT Average for bridge force 

% Write averaged bow tip acceleration FFT to data file named "fileout1.txt" 
y=[freq(1:nlast);fftavg1(1:nlast)]; % create 2D freq - amplitude matrix 
fid=fopen(fileout1,'w');
fprintf(fid, '%10.2f %10.4f
', y);
fclose(fid);
% Write averaged bridge force FFT to data file named "fileout2.txt"
y=[freq(1:nlast); fftavg2(1:nlast)]; % create 2D freq - amplitude matrix
fid=fopen(fileout2, 'w');
fprintf(fid, '%10.2f %10.4f
', y);
fclose(fid);

%plot log FFT average for Channel 2 (Bridge Force)
h=figure('PaperUnits', 'normal', 'PaperOrientation', 'land');
hold on;
plot(f, fftavg2);
plot(f, fftavg2, ':r', ...'LineWidth', 2);
% plot bridge force with red dashed line
axis([0 5000 -60 -10]);
legend('Tip Accel', 'Bridge Force');
xlabel('Frequency (Hz)');
ylabel('Log Magnitude');
title(strcat(filein, '|', today, '|', num2str(tstart), '-', num2str(tend), ...'
  sec', '|', label, ' | Avg FFT '));

% ---------------------------------WATERFALL PLOTS -----------------------------------

% Channel 1 (Left) waterfall plot
h=figure('PaperUnits', 'normal', 'PaperOrientation', 'land');
surf(freq, time, bowfft1, 'FaceColor', 'interp', ...
'EdgeColor', 'none', ...
'FaceLighting', 'phong');
axis([0 5000 tstart tend 0 1]);
axis 'autoz';
colormap(jet);
title(strcat(filein, '|', today, '|', num2str(tstart), '-', num2str(tend), ...'
  sec', '|', label, ' | Tip Accel '));
xlabel('Frequency (Hz)');
ylabel('Time (s)');
zlabel('Amplitude');

% Channel 2 (Right) waterfall plot
h=figure('PaperUnits', 'normal', 'PaperOrientation', 'land');
surf(freq, time, bowfft2, 'FaceColor', 'interp', ...
'EdgeColor', 'none', ...
'FaceLighting', 'phong');
axis([0 5000 tstart tend 0 1]);
axis 'autoz';
caxis auto;
colormap(jet);
title(strcat(filein, '|', today, '|', num2str(tstart), '-', num2str(tend), ...'
  sec', '|', label, ' | Bridge Force '));
xlabel('Frequency (Hz)');
ylabel('Time (s)');
zlabel('Amplitude');
end

%------------------ extra plots -----------------------------------------

%plot the time history last sample Channel 2
h=figure('PaperUnits', 'normal', 'PaperOrientation', 'land');
plot(t, channel2, ...'linestyle', ':');
legend('Tip Acceleration');
xlabel('Time (s)');
ylabel('Amplitude');
title(strcat(filename, '.wav | ', today, ' | ', num2str(tstart), '| ',...
   num2str(tend), ' sec', ' | ', label, ' | CH2 Time History'));
axis([0 .008 -.6 .6]);

%plot linear FFT last sample Channel 1
h=figure('PaperUnits','normal', 'PaperOrientation','land');
plot(f,linmag1);
axis([0 4000 0 .2]);
xlabel('Frequency (Hz)');
ylabel('Linear Magnitude');
title(strcat(filename, '.wav | ', today, ' | ', num2str(tstart), '| ',...
   num2str(tend), ' sec', ' | ', label, ' | CH1 FFT '));

%print;

%plot log FFT last sample Channel 2
h=figure('PaperUnits','normal', 'PaperOrientation','land');
plot(f,dbmag2);
axis([0 5000 -60 -10]);
xlabel('Frequency (Hz)');
ylabel('dBV re 1V');
title(strcat(filename, '.wav | ', today, ' | ', num2str(tstart), '| ',...
   num2str(tend), ' sec', ' | ', label, ' | CH2 FFT '));

%print;
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EDUCATION
Bachelor of Science in Mechanical Engineering  Expected May 2012
Product Realization Minor
The Pennsylvania State University
Schreyer Honors College

RELEVANT COURSES
The Pennsylvania State University
 Microcomputer Interfacing for Mechanical Engineers
 Honors Modeling of Dynamic Systems
 Vibration of Mechanical Systems
 Technology-Based Entrepreneurship
 Effective Speech
 Technical Writing
 SolidWorks Fundamentals
National University of Singapore
 Fundamentals of Product Development

RESEARCH EXPERIENCE
 Honors Thesis Research, Schreyer Honors College  2011-present
  Studying the dynamic properties of violin bows; analyzing and comparing the frequency content of the sound they produce to determine what properties and mode shapes produce the optimal sound
 NREIP Intern, Naval Surface Warfare Center, Philadelphia, PA  2011
  Built and conducted a laboratory fluid flow test for a superconductor system, as part of the Naval Research Enterprise Internship Program (NREIP)

ADDITIONAL EXPERIENCE
 Engineering Intern, BAE Systems, Troy, MI  2010
  Supervised risk management plan for a subset of an advanced hybrid development program; performed several other responsibilities in the areas of Systems Engineering and Program Management
 Hardware and Software Engineer, Undead Robot Society  2009
  Contributed to the building and programming of two tabletop robots for a team that placed fourth out of twelve in Beyond Botball, a worldwide robotics competition

COMPUTER SKILLS
 SolidWorks Certified Associate
 MATLAB
 C++ and Java programming

ACTIVITIES
 PSU R/C Race Club  2010-present
  Treasurer, 2011-present
 PSU Robotics Club  2009-2010
 PSU Marching Blue Band  2008-present
  Squad Leader, 2011-present
 PSU Pride of the Lions Basketball Pep Band  2008-present
 Rohrerstown community band  2006-present