

# **Vibrational Modes of an Uilleann Pipe Reed**

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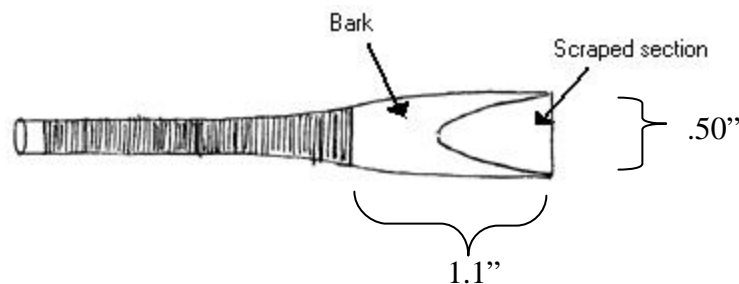
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## ABSTRACT

The vibration of an uilleann pipe reed is studied within. Using a Laser Doppler Velocimeter we have begun to map the modes of vibration for a reed sounding at four different frequencies. We have mapped these shapes up to five harmonics. Our study has shown the inadequacy of existing models to describe the motion of a double reed. We have also begun to describe the phenomena of a “cutoff point” that may separate vibration between the front and back of the reed.

## INTRODUCTION

The uilleann pipes are the national bagpipe of Ireland. The pipes, as they are referred to, are made up of three main parts. There is the bellows, the bag, and the chanter. Bellows pump air into the bag where it is compressed by the player’s arm and then passed into the chanter. This setup allows the player to play continuous sound, and does not require the use of breath. The sound that is produced comes from the chanter, a conical tube with eight tone holes. At the apex of the chanter is a double reed with similar dimensions to a bassoon reed (Fig. 1).

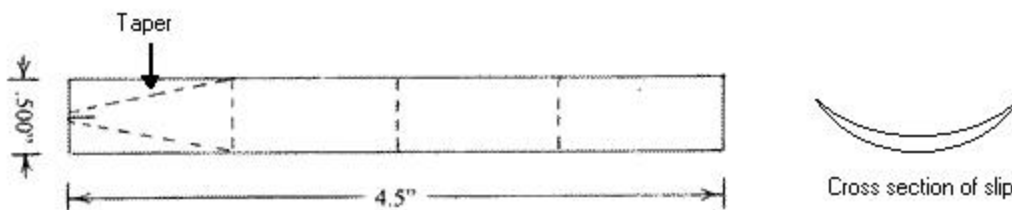


**Fig. 1** – The uilleann pipe reed [1]

Since the pipes are powered by ambient air, the reed can be exposed to an extreme variety of environmental conditions depending on where the musician is playing. As the relative humidity of the environment changes so does the response of the reed. For this reason uilleann pipe reeds are extremely difficult to make and maintain.

The pieces of an uilleann pipe reed are as follows. The vibrating material is made from cane (*Arundo Donax*), a hard grass tube with an external diameter of about one

inch. A half-inch wide section of the tube is cut along the grain and the inside is gouged to a diameter of about 2.5 inches (Fig. 2). This “slip” of cane is then tapered, cut in half, and tied to a brass piece called a staple. The staple is an eighth-inch diameter brass tube that has been formed around a mandrel so that one end takes on an eye shape (Fig. 3). Once the cane has been tied to the staple the bark at the head of the reed is scraped away until the cane vibrates in the appropriate manner.



**Fig. 2 – The slip [1]**



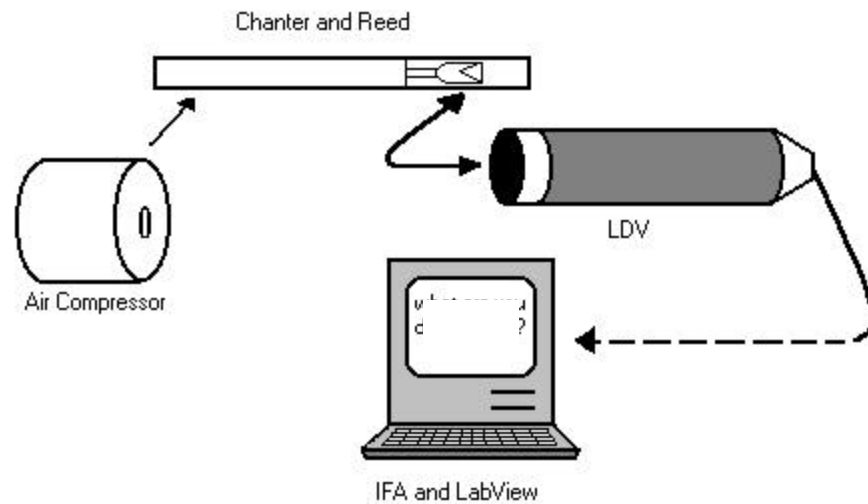
**Fig. 3 – The Staple**

The experiment that is described below bears relevance mostly to the scraping and staple formation elements of reed making. Using a Laser Doppler Velocimeter (LDV) we have been able to roughly map the first five modes of vibration for a reed sounding at four different frequencies. This information can hopefully provide insight into the behavior of double reeds and be used by reed makers to create more stable reeds.

## **EXPERIMENTAL SETUP and METHOD**

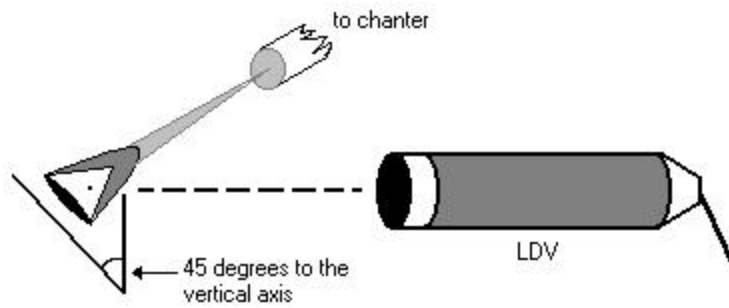
The chanter reed is normally obscured from sight by the chanter stock, a brass tube that houses the reed. For this experiment a clear plastic stock was made so that the reed could be seen. The chanter, with its clear stock, was mounted on a jig, adjustable in three dimensions. All adjustments were done by hand based on a grid drawn onto the

reed. Once mounted, the chanter was supplied air by an air compressor, and tone holes were covered with tape to produce the desired frequencies. Frequencies were measured throughout the experiment, and varied no more than 10 cents from the desired frequency.



**Fig. 4** – Experimental Setup

Data was taken using a Laser Doppler Velocimeter (LDV). The LDV was secured to a laser table in such a way that its two beams would cross and produce a horizontal diffraction pattern on the reed. This measurement volume is an elliptical shape with a diameter of 200 microns and a length of 2 mm [2]. Thus as the reed vibrated, its velocity could be measured. The reed was positioned as close to forty-five degrees to the vertical as possible to ensure a maximum motion through the measurement volume (Fig. 5). The LDV took data at varying rates and sent back velocity measurements to be analyzed by a LabView program. Data rates varied from 7500 Hz up to 24,000 Hz depending on how well the LDV was focused onto the reed, and perhaps the reed's amplitude at that point. All focusing was done by hand by adjusting the chanter jig. Velocity is a relevant measurement in this situation since it is the first derivative of position. Position, in this case, is equivalent to amplitude, the characteristic we are interested in.

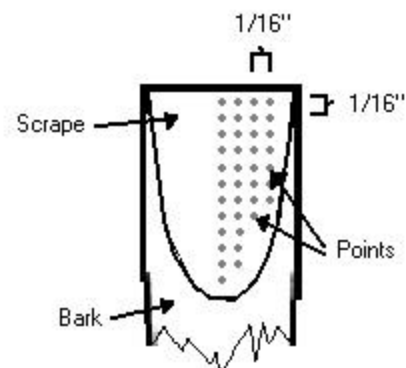


**Fig. 5** – Laser focused on the reed

This study looked at four different frequencies (Fig. 6). The corresponding frequencies span almost the entire range of the chanter. Uilleann pipe chanters are capable of two octaves starting at D<sub>4</sub>. The ‘Bottom D’ and ‘Hard D’ are the same frequency, but sound with different timbres. The title, ‘Back D’ has been given to D<sub>5</sub> by pipers. Each frequency was examined at 38 different points on one-half of the reed (Fig. 7). 20 velocity measurements were taken at each point with sampling rates not below 7500 Hz. This floor for sampling rates was established to ensure that 5 harmonics could be measured for each sounded note. FFT’s were taken of each velocity set, and the resultant data was averaged to give a power spectrum for each point. The amplitudes for each harmonic were then separated from the power spectrum and plotted on a contour graph.

| Note Name   | Frequency (Hz) |
|-------------|----------------|
| D4 (bottom) | 293            |
| D4 (hard)   | 293            |
| D5 (back)   | 587            |
| A5          | 880            |

**Fig. 6** – Frequencies



**Fig. 7** – Points examined

## ERROR

Every effort was taken to eliminate error, but given the difficulty of working with an LDV, error could be a significant factor. First, focusing the LDV onto the reed proved to be extremely difficult. In order to get acceptable sampling rates, the chanter jig had to be adjusted extensively, and with no apparent pattern. As a result, the angle at which the laser viewed the reed was not perfectly constant. The reed angle was ideally 45 degrees, but could vary 5 degrees in either rotational direction. As this angle changes, so perhaps does the perceived amplitude of the reed. This error can be approximated:

$$e = \pm \left( \frac{\cos 40 - \cos 50}{\cos 45} \right) * 100\% = 17.4\%$$

This is a significant percentage, but given the tools available this error could not be avoided.

Secondly, the reed was examined at 38 different points, each a sixteenth of an inch apart. Given the difficulty focusing the laser, there may be some disparity between the locations of points from note to note. This disparity could be as high as 1/64".

An interesting problem that arose is that there seems to be a direct correlation between sampling rate and amplitude. Although we set a lower limit on sampling rates, we did not set an upper limit. Thus sampling rates could vary by as much as a factor of three. In all the data sets the higher sampling rates show higher amplitudes relative to their immediate neighbors, and lower noise floors. This could perhaps be because points with greater amplitudes will move through more of the measurement volume and thus send back more data. We could not establish whether this was the case or not.

Experiments done by Jesse Jones working with titanium dioxide particles in water seem to show that the magnitude of velocity is independent of sampling rate [2].

Another source of error comes from the fact that the experiment had to deal with reeds made from cane, an organic material. The nature of reeds is that they change with time and varying environmental conditions. Our experiment required sounding the reeds sometimes in excess of four hours. This amount of vibration weakens reeds, and they tend to "close up". Thus a reed's vibration will have smaller amplitude after four hours

than it did at the start of the trial. It was not within the scope of this study to quantify the effect the reed closing up.

A final problem that we experienced is time. We were unable to repeat measurements of notes in their entirety because of time constraints. This fact, in conjunction with the fact that we only took data across one-half of the reed, leads to a great uncertainty in the data.

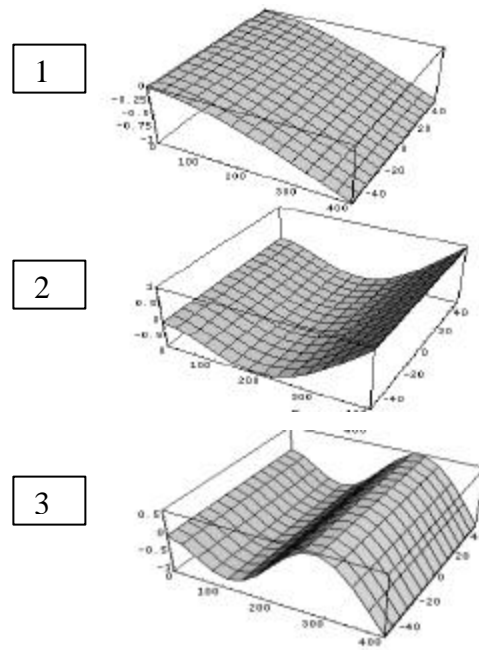
## THEORY

Some study has been done on the modal behavior of clarinet reeds, but there has been little to no study of double reeds. Some conjecture can be made as to the modal behavior of double reeds based on the known behavior of other structures. Cantilever beams, rectangular membranes, rectangular plates, and spruce plates are all structures whose modal behaviors have been studied extensively.

The cane used to make uilleann pipe reeds has a very distinct grain that results in a disparity between the reed's cross-grain stiffness and the stiffness parallel to the grain. If we ignore this disparity and assume the reed's motion is one-dimensional, the reed can be seen as a cantilever beam. Cantilever beams are beams clamped at one end and free at the other. The reed's structure is similar to this as the end of the grain is affixed to the staple while the tip of the reed is free to vibrate. The frequency of a cantilever with constant cross sectional area is described by the following formula where 'K' equals the beam's height times a constant, 'L' is the length of the beam, 'E' is Young's Modulus, and  $\rho$  equals the beam's density:

$$F_n = \frac{\pi K}{8L^2} \sqrt{\frac{E}{\rho}} [1.194^2, 2.988^2, 5^2, \dots, (2n-1)^2]$$

This formula tells us that the modal frequencies for these beams do not increase harmonically, but rather  $[f_0, 6.267f_0, 17.55f_0, \dots, (2n-1)^2 f_0]$  [3].



**Fig. 8** – Cantilever shapes [4]

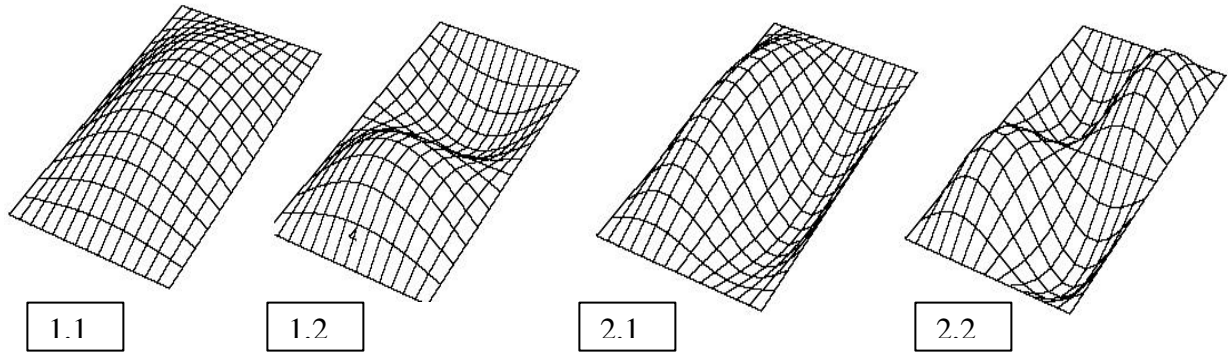
A significant feature of these shapes is that maximum amplitude takes place at the free edge of the structure. We may expect modal shapes of this sort along the center of the reed where the reed's motion is the freest. As we approach the sides however the horizontal stiffness will become more of a factor, maximizing at the reed's edge where the cane is fixed. For this reason we can only hope to see cantilever type motion in the center of the reed if anywhere.

Two other well-studied models are the rectangular membrane and plate. These models have the same shape, a rectangular vibrating member fixed on all sides, but the plate model takes stiffness into account. Since our reed is very stiff, the rectangular plate may be of interest. The modal shapes of this structure are presented in Figure 9, and the theoretical frequencies of this behavior is described by the equation

$$f_{mn} = .453c_L h \left[ \left( \frac{m+1}{L_x} \right)^2 + \left( \frac{n+1}{L_y} \right)^2 \right], \quad c_L = \sqrt{\frac{E}{\rho}}$$

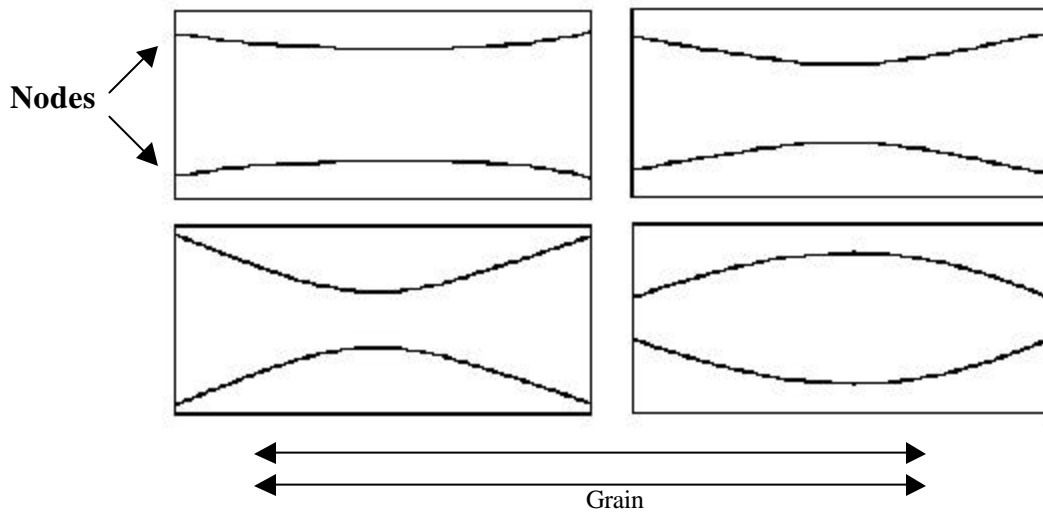
where 'm' and 'n' are integers starting at zero [3]. Here again the modal frequencies are not harmonic. Since our reed is open along one edge this approach is only partially valid.





**Fig. 9** – Rectangular Plate [5]

The final vibrating structure that we should examine is the spruce top. Spruce is a wood with a very well defined grain, and this model takes that into account.



**Fig. 10** – Spruce [3]

The expected frequencies of a spruce board can be calculated via the equation

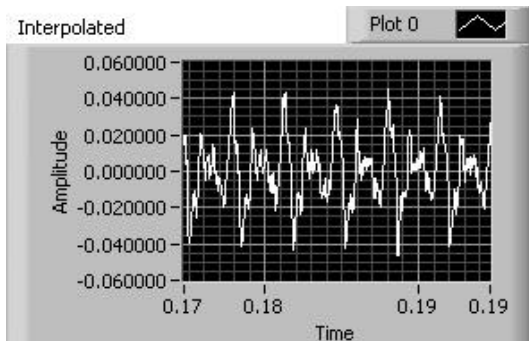
$$f_{mn} = .453h \left[ c_x \left( \frac{m+1}{L_x} \right)^2 + c_y \left( \frac{n+1}{L_y} \right)^2 \right],$$

where  $c_x$  and  $c_y$  are constants taking Young's Modulus, Poisson's Ratio, and density into account for any given piece of wood. Again, 'm' and 'n' are integers starting at zero [3]

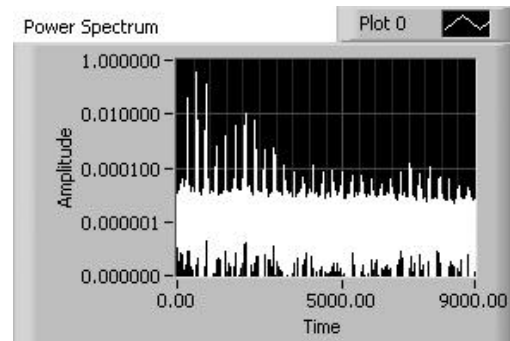
These shapes are for a spruce plate that is free to vibrate on all sides. We can see that the maximum amplitudes occur parallel to the grain, a characteristic we can probably expect from the reed even though it is fixed on three sides.

## RESULTS and DISCUSSION

This is a sample of velocity measurements, and the resultant power spectrum

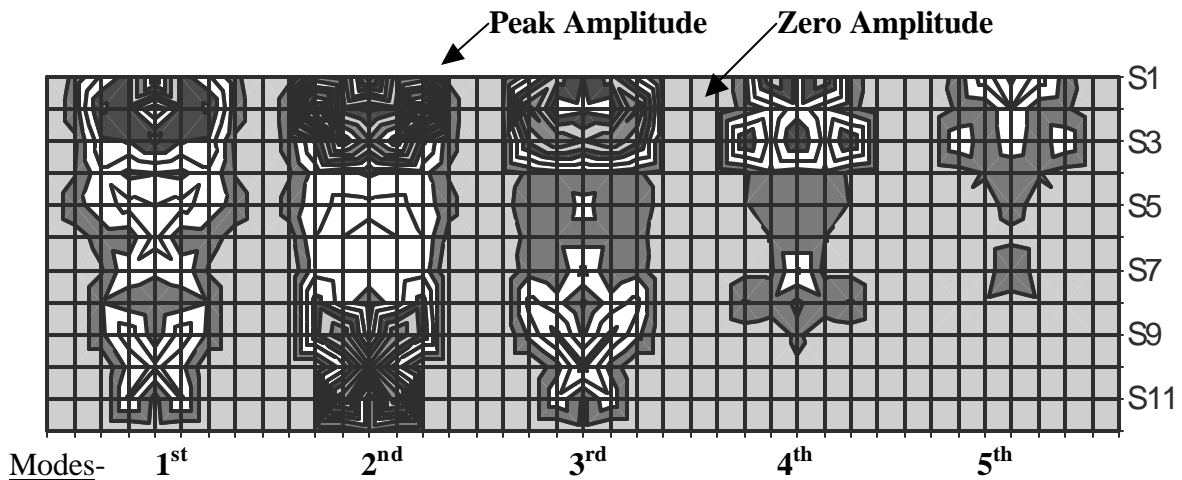


**Velocity over Time**

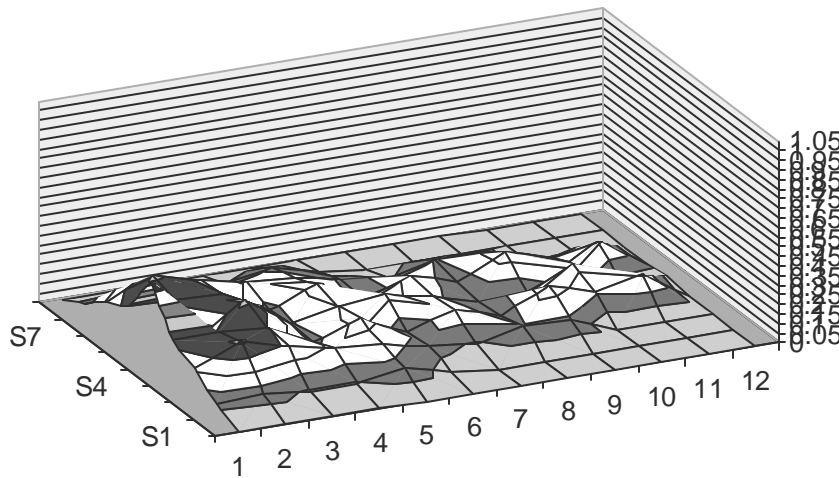


**Resultant Power Spectrum**

Here are the results we obtained for the bottom D, D<sub>4</sub> (293 Hz). To see this data for all the notes see appendix A.



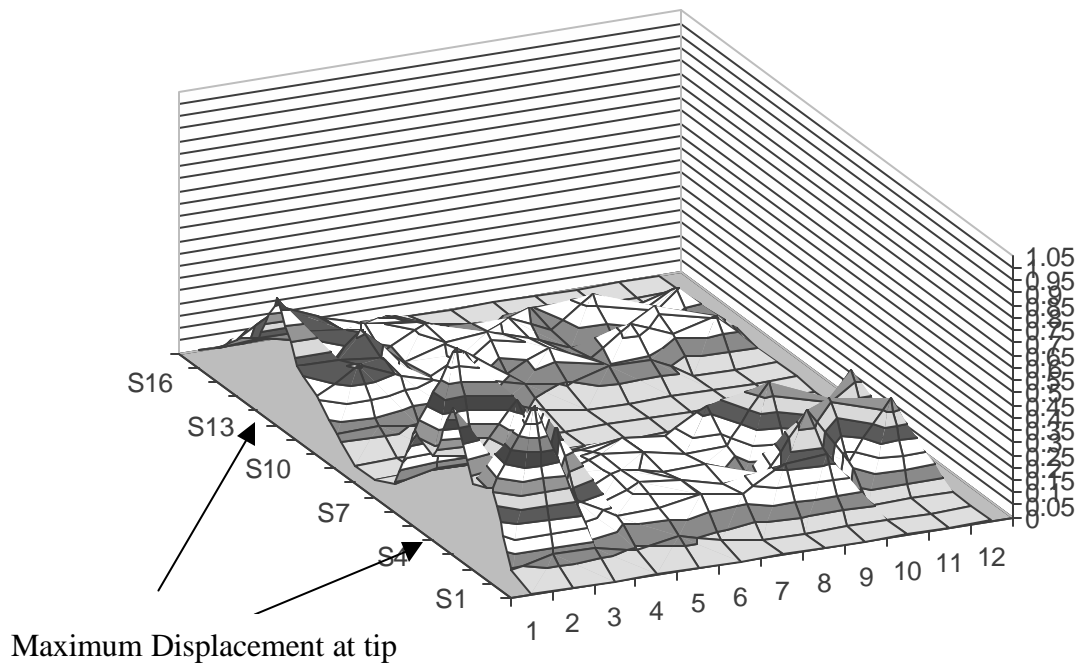
### BOTTOM D - FIRST



### Similarities to previously mentioned models

With the cantilever beam model we expected the maximum displacement to be at the tip. This holds true for the reeds (fig 11).

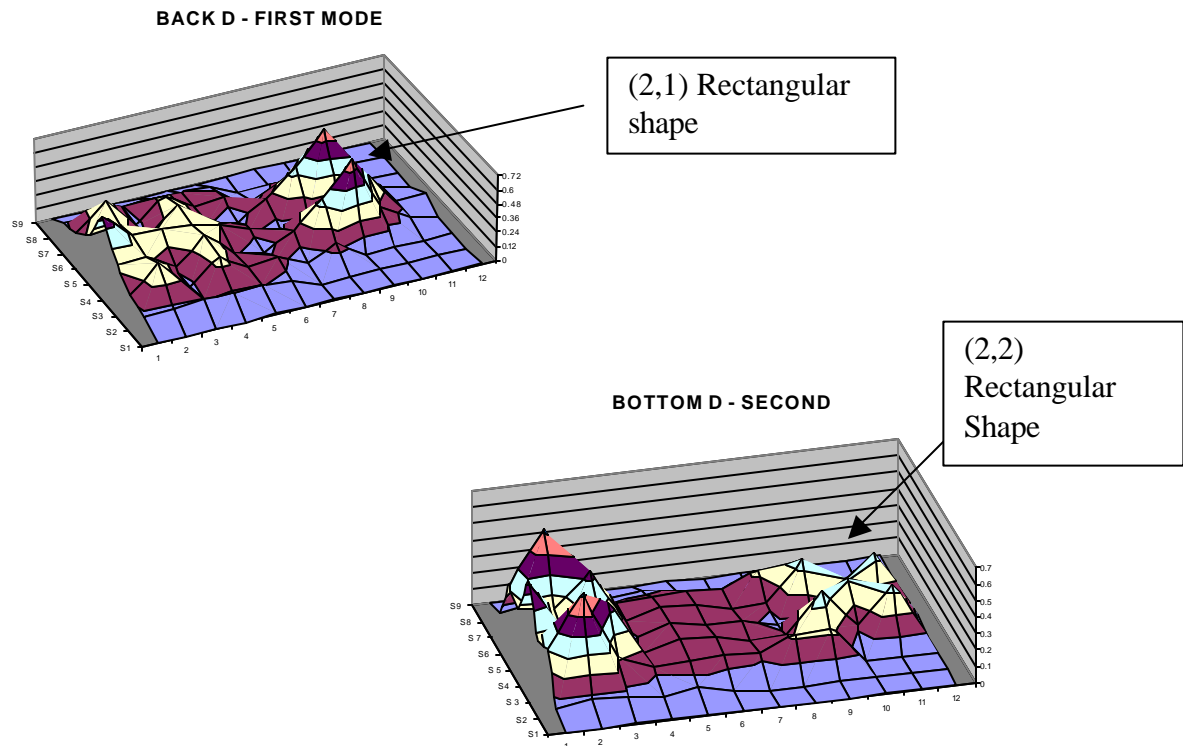
### BOTTOM D - FIRST,SECOND



**Fig. 11** – Bottom D

There are many other elements to the reeds' vibration that cannot be described by the cantilever theory. This is due to the cross-grain stiffness of the reed.

Interestingly there are quite a few points that closely resemble the rectangular membrane and plate models (Fig. 12). These shapes tend to occur towards the back of the reed. This makes sense since this region is much thicker than the front of the reed. Also since this region is so far back from the tip, the open edge may play less of a role in this region's vibration.



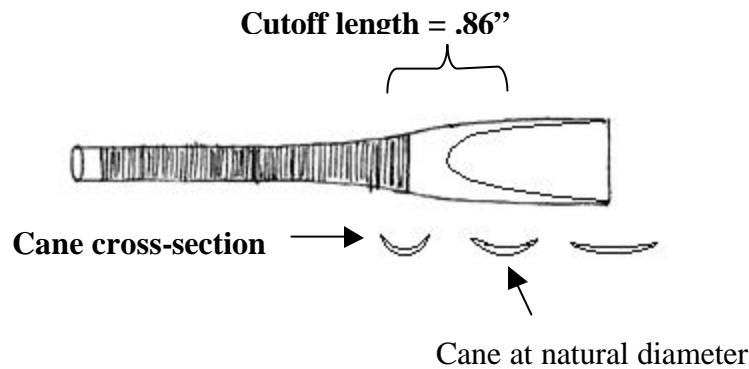
**Fig. 12**

Looking at the data we can see that the previously mentioned models do a poor job of predicting the motion of the reed. A similarity that does come to the forefront is that our reed is presumably not harmonic in its vibrating nature like all of the previously mentioned models. We can see however that the reed vibrates at harmonic frequencies. Indeed since the instrument in question has a conical bore with a pressure node at one end, and an anti-node at the other theory dictates the reed must vibrate at harmonic frequencies. If we trust the models and assume that the free vibration of the reed is not

harmonic then we can say that the air column below the reed dominates the vibrational structure of the reed and forces it to vibrate at harmonic frequencies.

### **The Cutoff Length**

An interesting point that is revealed by the data is a consistent node in the reed. In all cases there is little motion near the seventh row of points on the reed. This node is significant because it corresponds to the area of minimum structural pressure in the reed. In every reed's construction there exists a point at which the inside of the reed changes from compression to expansion, and vice-versa for the outside (Fig. 13 – cane cross section). We have dubbed this point the cutoff length. The location of this point is determined by the angle at which the staple is flattened, and the diameter to which the cane is gouged initially. For the reed used in this experiment the point is .86 inches beyond the staple (Fig. 13). At this point the cane is at its natural diameter, and will most likely react as if no structural pressures were exerted on it.



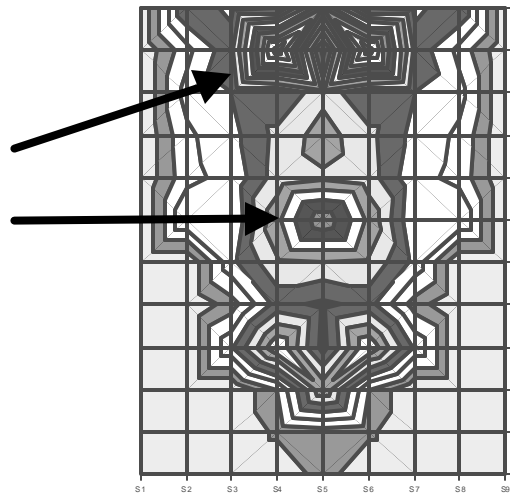
**Fig. 13 – The Cutoff Length**

We can see from the data that there is a significant change in the modal shapes on either side of this point for almost all of the vibrations. This point may act as a “hinge” that separates the front and back on the reed. It is possible the back acts very similarly to a rectangular membrane fixed on all sides with a longitudinal grain.

## Reed Maker's Knowledge

Every reed maker has certain “rules” that he/she shapes his/her reed by. For example when a reed's back D is flat the solution is to cut the reed. Our data should support these “facts”. The high A is supposedly made to vibrate better by shaving the sides of the reed. The data show that this A's amplitude is maximized at the center of the reed. Scraping the sides would reduce the edge's stiffness, and allow the middle vibrate more freely. (fig. 14). The back D is shown to have more significant vibration towards the edge of the reed, thus the theory that leaving these regions strong is validated. The fact that our data supports much of the common knowledge of reed makers is encouraging.

A<sub>5</sub> (880 Hz) is sometimes difficult to play. The reed maker's solution is to scrape the edges of the reed. We see here that the note's maximum amplitude is in the center of the reed. Weakening the edges would free up this motion.



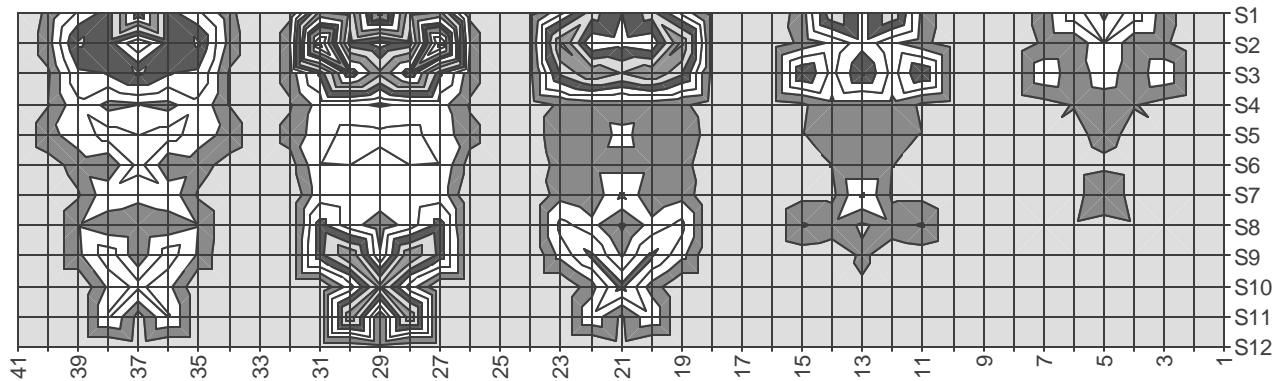
**Fig. 14** – Reed Maker's know-how

## CONCLUSION

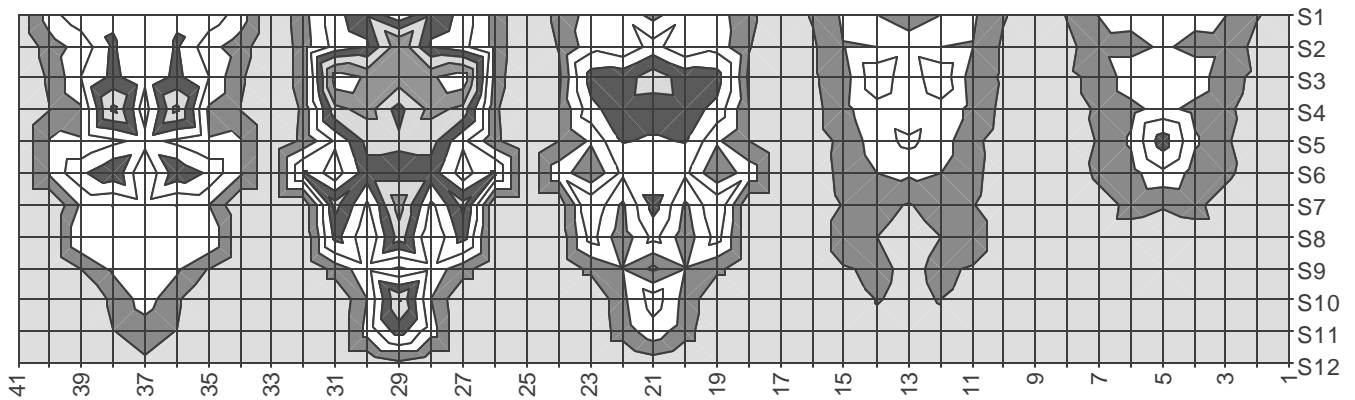
The data presented here is a first step towards understanding the workings of the double reed. We have shown that the existing models cannot adequately describe the motion of this vibrating system. More importantly perhaps, we may have begun to elucidate the nature of a “cutoff point”. This feature should be of interest to all reed makers since all double reeds will have such a point. Of course our data only begins to describe the vibrational significance here. Finally, this study, in conjunction with the reed maker's common knowledge, partially validates the use of an LDV system to study the vibrational characteristics of a moving reed. Hopefully our rough sketches are only the beginning of this study.

## APPENDIX A

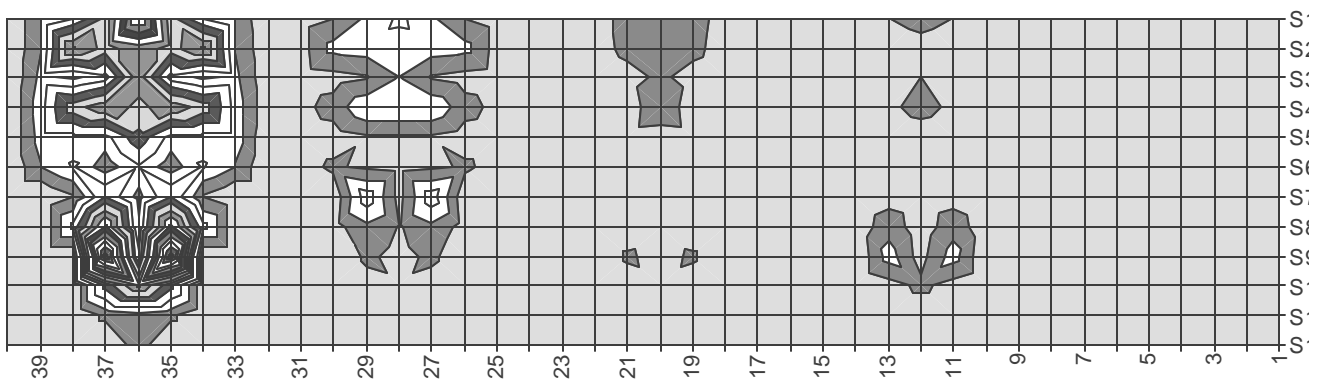
**BOTTOM D - 1,2,3,4,5**



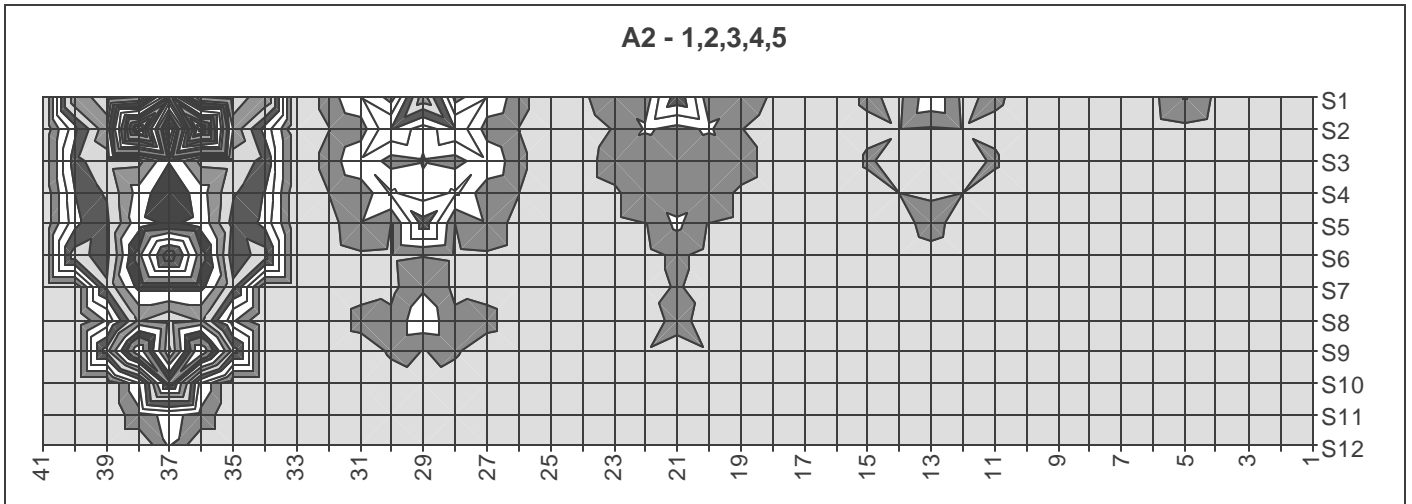
**HARD D - 1,2,3,4,5**



**BACK D (1st trial) - modes 1,2,3,4,5**



## APPENDIX A (cont.)





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