

# Vibrational Behavior of a Wine Glass

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## ABSTRACT

This study determines the most prominent frequencies of a white wine glass, which are responsible for the sound of clinking two wine glasses. To find these frequencies, the natural frequencies and mode shapes are determined in several ways. In one way, the glass is hit with a force hammer, while a laser measures the velocity to get a frequency response function (FRF). In another way, the laser is substituted by a microphone which records the emitted sound so that an acoustic FRF is determined. In a third way, the glass is modelled in an FEM environment and the frequency response is simulated. The mode shapes are generated with the experiment data and with the FEM-model and subsequently compared. Due to unknown exact geometry and unknown material properties of the wine glass, it is impossible to match the model completely with the experiment. However, the mode shapes compare very well. By evaluating the magnitude and phase of each frequency in the experiment, it is possible to determine the most prominent frequencies, which are responsible for the emitted sound when clinking two wine glasses.

## 1. Introduction

In 2011, an experiment concerning the frequencies of beer bottles responsible for the clinking sound when tapping them together was performed at Pennsylvania State University [1]. To find the frequencies, the emitted sound caused by hitting the beer bottle with a force hammer was recorded with a microphone and compared to the frequency response functions (FRFs) recorded with an accelerometer at several points. The beer bottle was suspended with rubber bands at all times, so that it was assumed to have no constraints. The bottle was hit on several points on a line from the top to the bottom and on several circumferential lines. With the results of the experiment, it was possible to determine the natural frequencies and mode shapes of the beer bottle. The natural frequencies with the biggest magnitudes in the acoustics FRF were determined to be most responsible for the emitted sound when clinking two beer bottles together.

This experiment was the inspiration for a similar experiment, which instead regards the frequencies that are responsible for the clinking sound of two wine glasses. To get this information, the vibration and acoustic FRFs will be determined through experiments and compared to an FEM-Model, which will be developed. The FEM-Model will be validated and the most prominent frequencies will be found, so that it finally will be known, which frequencies are responsible for the clinking sound of two wine glasses.

In literature and publications, it is apparent that many people have focused on vibrations of wine glasses. A similar field of research is the phenomenon often called “the singing wine glass” [2]. It occurs when a wet finger is run along the edge of a wine glass. Then the wine glass begins to emit sound. This phenomenon has been widely investigated and understood. There are also investigations examining what influence the amount of liquid in the wine glass has.

Another topic, on which people have focused in the past, is the attempt to destroy a wine glass just by using the human voice or speakers [3]. To destroy a wine glass in this way the dominant natural frequency needs to be excited by the voice or the speakers. This experiment contributes to our project as the frequency which is used to break the

glass is also one dominant frequency that occurs when clinking two wine glasses. Due to that correlation, the final step of our project will be to attempt to break the glass using speakers.

## 2. Modeling:

To determine the frequencies which are responsible for the emitted sound made by clinking two wine glasses, a FEM model will be developed out of a CAD model. For the future CAD model of the wine glass, its dimensions are measured with a caliper. The outer diameter is measured every centimeter along the glass, from the top to the bottom. The thickness of the bowl can only be determined at the rim. The proper observation of the wine glass shows changes in thickness on the actual glass along the bowl, though. With the measured data, a CAD model is created in CATIA. To consider the differences in thickness along the bowl, the model is manually adjusted to compensate. As these adjustments are not based on physical measurements, the model does not represent the geometry of the actual wine glass very accurately.

The CAD model is then transformed to an FEM model in CATIA, where other sources of inaccuracy occur because of the wine glasses mechanical properties. No material analysis of the wine glass is done, so that the properties of the glass are picked based on research of material properties for glass. The property data of glass varies regarding different types of glass and different information sources. Due to varying data, the material properties in the model are altered to match the results of the model with the measured results from the experiment with the force hammer. The results from the FEM calculation show animations of the mode shapes from the wine glass.

With the experiment data, a model that simplifies the wine glass will be developed in MATLAB. This model will consist of the 3D coordinates of the points which will be measured and will also be able to show the magnitude and phase of every of every point. The model is shown in Figure 2.

## 3. Experiment

### 3.1. Experiment Set-up

For the first experiment, the wine glass is hit with a force hammer approximately at that point where it gets in contact with another glass during clinking. In addition, the sound is recorded with a microphone, placed right next to the wine glass. During this experiment, the wine glass is just suspended with rubber bands in a base frame to simulate free-free boundary conditions, as shown in Figure 1. The program SigLab is used to generate the FRFs..



Figure 1: Suspended wine glass

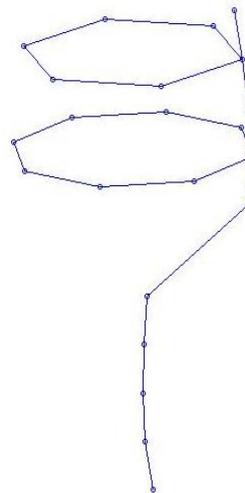


Figure 2: MATLAB - model

For the second experiment, the glass is marked on several locations, also called spots. These spots are distributed in equal distances next to each other. The glass is marked on two different circumferences on the bowl. The smaller, upper circumference is marked with six spots and the bigger, lower circumference with eight spots. Additionally, the glass is marked on a vertical line consisting of five spots on the bowl and five spots on the stem of the glass. A MATLAB model with all spots in a three dimensional environment is shown in Figure 2. The glass is suspended in the same way as before. It is also manually hit with a force hammer, but now on each different spot. Thus, an impulse is applied to the glass. The resulting vibration of the glass is recorded with a laser which is located above the wine glass. The laser measures the velocity of the certain point it is directed at. In this experiment, the point for the laser is placed on the vertical line between two spots. For a better reflection, a reflecting sticker is placed on the point, because otherwise the glass wouldn't reflect enough radiation. Each spot's force and velocity is evaluated by Siglab to get the resulting FRF, similar to how it was done in the first experiment.

In both experiments, each spot is hit seven times to average the data, so that the influence of noises gets low and the resulting data is clear. The range of frequencies measured is from 0 Hz to 10000 Hz.

### 3.2. Evaluation of the Experiment

In the following, the vibration experiment will be evaluated. With all the FRFs, the natural frequencies and mode shapes can be determined. For example, the FRFs of the five spots in the vertical line on the bowl are shown in Figure 3. In total there are 11 peaks, which all correlate to a mode shape. The very first peak at ca. 0 Hz is neglected, because this is the rigid body mode. From now on only the other 10 peaks will be examined, so that the first peak is at ca. 288 Hz. The FRFs of the stem spots have only one peak at 288 Hz (first peak), while those of all other spots have 10 peaks, as shown in the example. The frequency of every peak can be found in the Appendix.

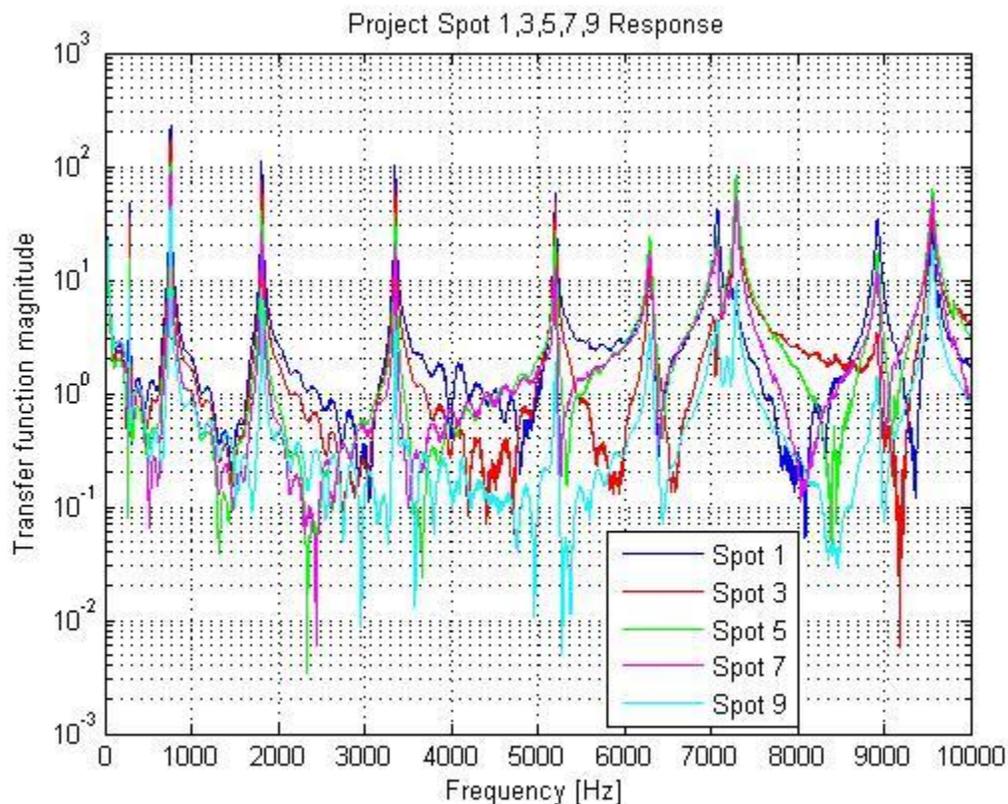


Figure 3: FRFs of the five spots in the vertical line on the bowl.

All FRFs have basically three kinds of information: The magnitude and phase, and the corresponding frequency. The magnitude and phase of every peak for each spot are gathered and put into two matrices with MATLAB. With this data, a response function is created for every spot and every peak. A sine-wave is assigned to all spots and videos are created with MATLAB to show the deflection of the wineglass for every mode in an animation. One frame of this video is shown for every peak in the Appendix. In these pictures the blue dots and lines represent the original position of every spot, while the red dots and lines represent the deflection. The deflections shown in the appendix are very unrealistic, because the glass would burst before it would get a shape as shown, but it is easier to detect the mode shapes like this.

#### 4. Validation

##### 4.1. Acoustics – Mechanics

The relative comparison between the resulting FRF of the first experiment (recorded sound) and of a certain spot in the second experiment (recorded vibration) is shown in Figure 4. In this plot, the magnitude of the acoustic FRF is multiplied by a factor of 30 because it is much smaller than the result from the vibrational FRF, so that it is easier to compare both. In this figure, a FRF of a circumferential spot is chosen to compare the vibrational with the acoustic FRF. This choice is made because all peaks are clearly visible in the vibrations plot, so that it is easier to compare. In general, any spot's FRF can be chosen to compare it with the acoustic FRF. The figure shows clearly the same natural frequencies for both FRF, as the peaks appear at nearly the same frequencies.

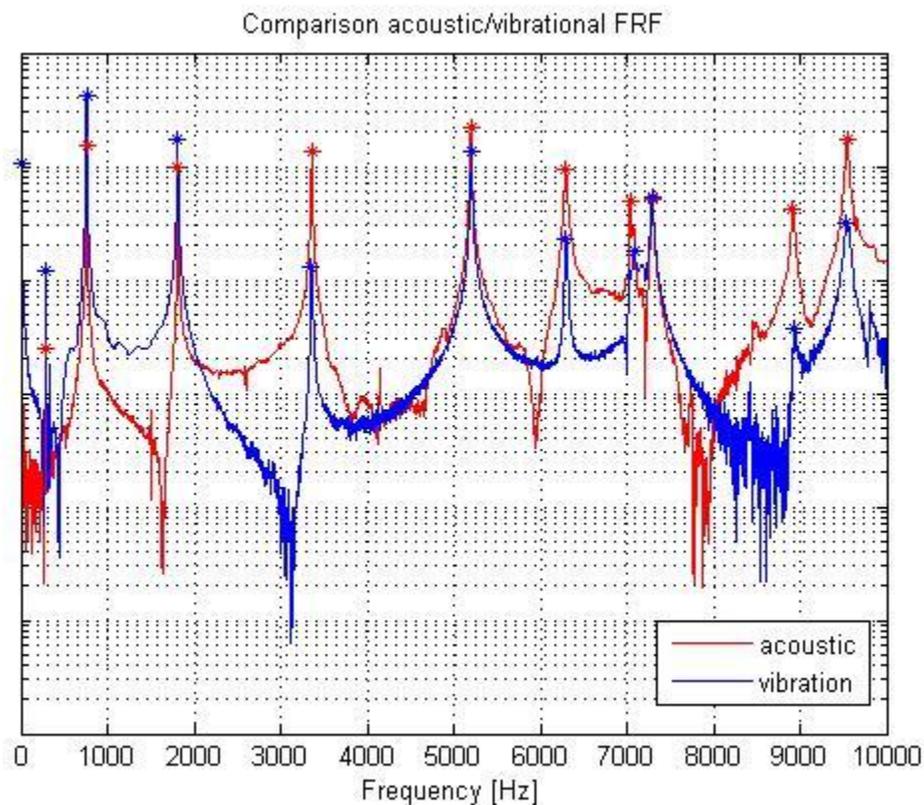


Figure 4: Relative comparison between FRFs of acoustic and a circumference-spot of vibration experiment

It is interesting that the order from highest to lowest peak is different for the vibrational and acoustic FRF. This means that, for example, the peak with the maximal magnitude for one vibrational FRF, regardless of which spot, is always around 758Hz, whereas the maximal peak for the acoustic FRF is at 5197Hz. The vibrational FRF has a peak around 5203Hz but this is not the maximal peak. The second biggest peak for the acoustic FRF occurs around 9544Hz, whereas the vibrational FRF has a peak around 9556Hz, which is not its second biggest peak. These differences in the order of magnitude could appear because of the fact that the acoustic magnitudes are all very small in general. Overall, the accuracy of a measurement decreases when the values to measure are getting smaller.

#### **4.2. Vibration – FEM-Model**

In the Appendix, there are two pages with tables, which both have three lines. The upper line shows the mode shapes simulated with the FEM model. The lower line shows the deflection of all spots taken together in the three dimensional MATLAB model, with the experimental data. The middle line of the column compares the frequencies of the FEM model and the experimental data, where these mode shapes occur. Also, the error between these two frequencies is given.

In general, if a breathing mode shows  $n$  corners, there are  $2 \cdot n$  spots needed in the experiment to determine the mode reliably. It is noticeable that the mode shapes for the first six peaks compare very well. Both figures of each mode shape are rotated in a way that makes it clearly visible that both mode shapes fit to each other. To be able to determine the mode shape for the fifth peak, it is necessary to turn the MATLAB plot and lay the spots of circumference on top of each other. From the mode of the seventh peak onwards, it is not easy anymore to match the MATLAB plots with the simulations from the FEM model. The simulation with the FEM model shows more modes than could be detected with the experiment, which makes it more difficult to match the correct modes. It is especially difficult to match the modes for the seventh and eighth peak, determined by the experiment with the FEM model. As it is shown in the Appendix, they do not accompany with the FEM model, because in the model the mode for the eighth peak occurs before the mode for the seventh peak. However, the MATLAB plots of the measured dots fit best as it is shown. The errors in frequency between experiment and model match in general, but show especially in the first two mode's bigger deviations.

Reasons for the occurred errors are the unknown exact geometry, unknown exact material properties and uncertainty of the influence of the rubber bands used for suspension in the experiment. The geometry of the glass is measured on the outer contour of the glass as no other measurement method is available, and to measure the inner contour on the same spots as the outer contour is not possible due to the difficult geometry of the glass. By observation, it can be seen that the thickness of the glass increases along the bowl. This increase is modeled manually based on observation. The thickness of the glass also shows an increase along the foot of the glass which is modeled based on observation as well. Soda lime glass is assumed to be the material of which the wine glass is made of. Various simulations show that the most influential properties are the Young's modulus and density of the glass. Different sources claim that the Young's modulus for soda lime glass is  $70 - 72 \text{ GPa}$  and the density is  $2400 - 2530 \text{ kg/m}^3$  [4] [5] [6] [7]. The results shown in the experiment are reached with a Young's modulus of  $65 \text{ GPa}$  and a density of  $2620 \text{ kg/m}^3$ . The tested wine glass is a very cheap, low-quality wine glass, which is heavy compared to other glasses. Due to these facts, the chosen values seem to be reasonable.

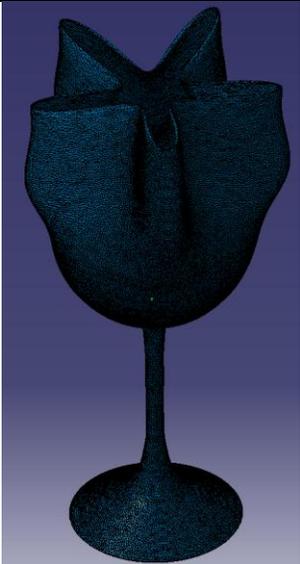
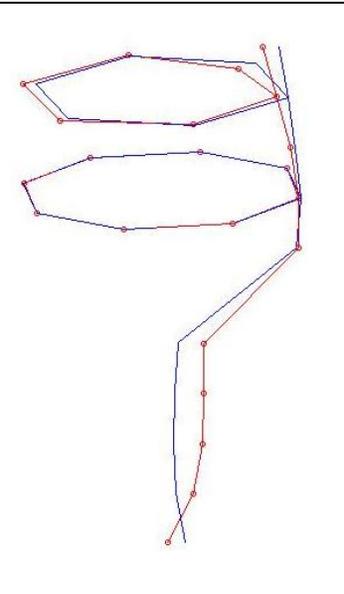
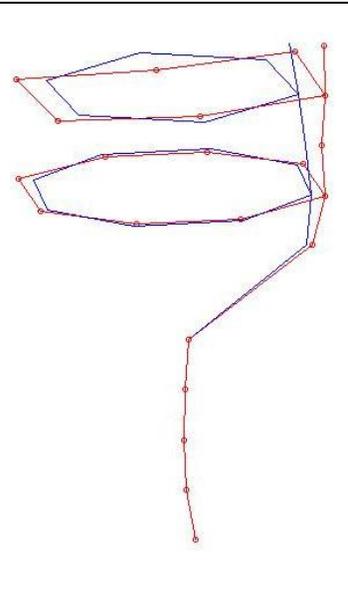
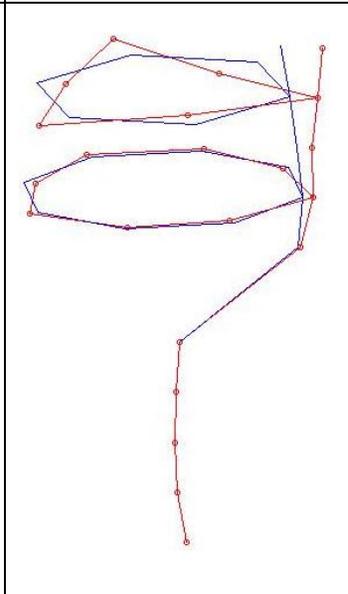
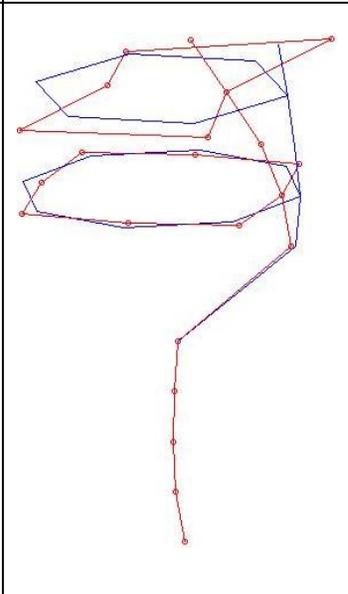
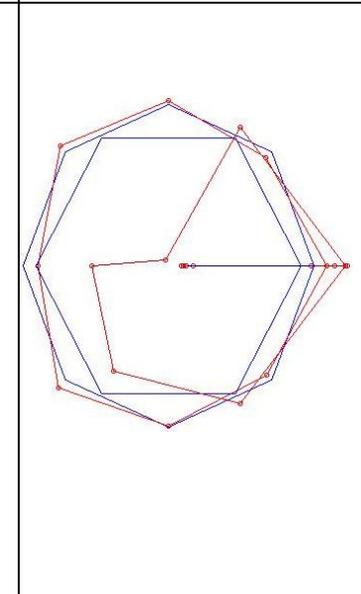
#### **4.3. Destruction of the wine glass**

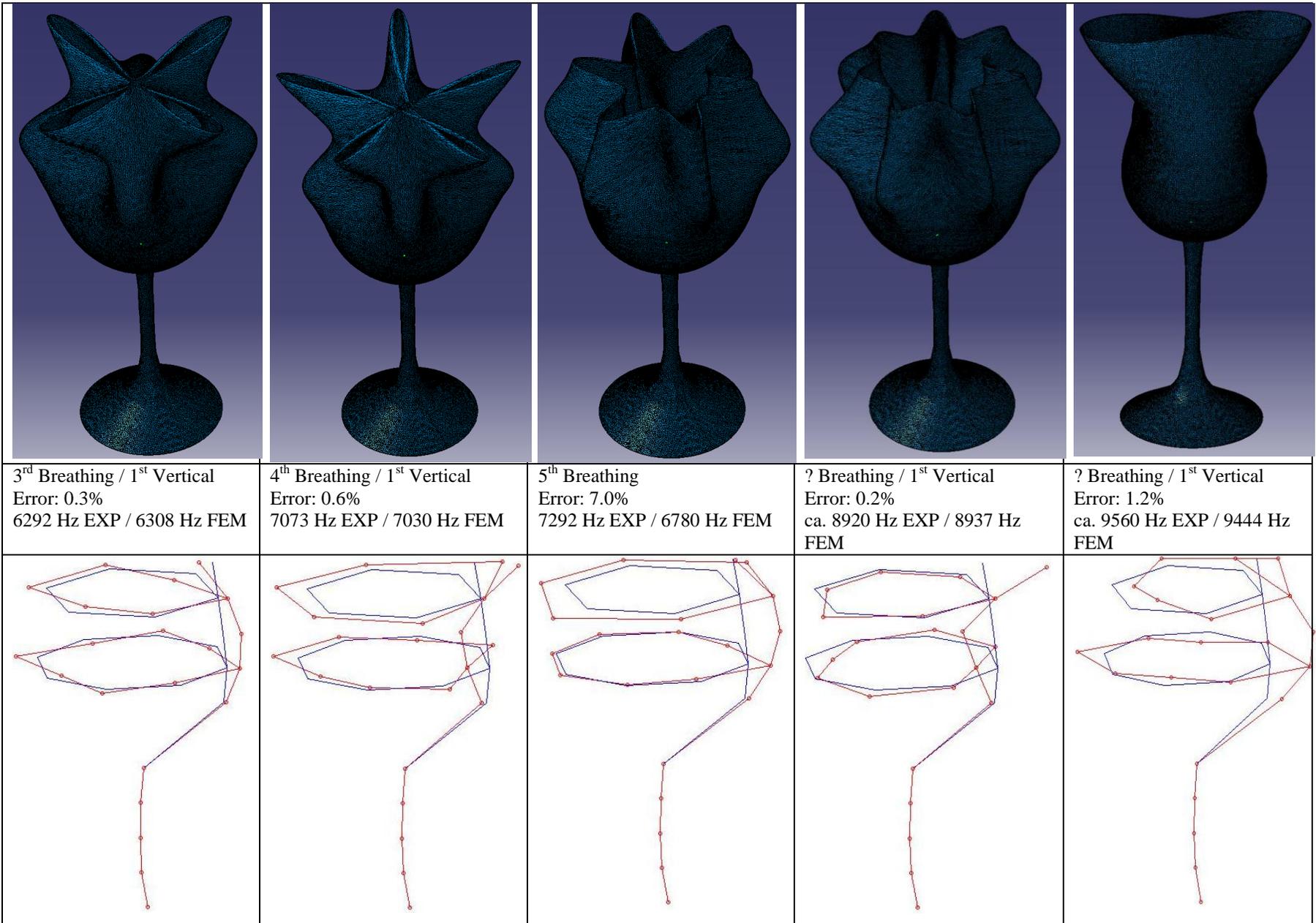
The final step is to excite the wine glass with speakers at its first breathing mode (758 Hz) and to break it. This will prove that there is a natural frequency at the first breathing mode's frequency. In literature, there is a lot of information about breaking wineglasses with speakers. One video shows the breaking of a red wine glass which is similar to the white wine glass examined in this study [8]. In this video, it is clearly visible that the glass is excited in its first breathing mode before it breaks. The first breathing mode of this glass is at ca. 630 Hz, ca. 17% lower compared to the glass examined in this study. Unfortunately, there are no speakers available, so that the breaking of the glass cannot be performed before the deadline of this project.

## **5. Summary**

The goal of the project is achieved. The most prominent frequencies responsible for the emitted sound when clinking two wine glasses were determined in three different ways. The mode shapes were determined by the FEM model and the experiment and match well. The simulations with the FEM model were extremely helpful to determine the mode shapes, as they can be animated. The project gave valuable experience in the process of testing and test evaluation. Common difficulties in matching the experiment with the model were experienced, as the exact geometry and exact material properties of the glass were not analyzed and so had to be estimated. The assumption was made that the glass has no constraints. However, the influence of the rubber bands with which the wine glass was mounted in the experiment is not clear. To improve the results of the FEM model, the geometry of the glass needs to be analyzed more accurately and the material properties need to be determined too.

# Appendix

				
<p>1<sup>st</sup> Bending    Error: 13.2 % 288 Hz EXP / 326 Hz FEM</p>	<p>1<sup>st</sup> Breathing    Error: 7.5% 758 Hz EXP / 815 Hz FEM</p>	<p>2<sup>nd</sup> Breathing    Error: 1.4 % 1815 Hz EXP / 1790 Hz FEM</p>	<p>3<sup>rd</sup> Breathing    Error: 3.3 % 3355 Hz EXP / 3245 Hz FEM</p>	<p>4<sup>th</sup> Breathing    Error: 5.2 % 5203 Hz EXP / 4935 Hz FEM</p>
				



## References

- [1] <http://www.acs.psu.edu/drussell/Demos/BeerBottle/beerbottle.html>, retrieved on 12/15/2013
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