WINE GLASS RESONANCES: SOUND AND WAVES

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ABSTRACT

Wine glasses produce very interesting sound and surface dynamics phenomena. Understanding the largely undescribed nature and correlation of these two phenomena is the basic motivation of this experiment. Wine glasses emit pure tones when their rims are rubbed with a moistened finger. This motion also produces oscillating waves that propagate along the glass wall. The sound and waves of three wine glasses were recorded using a piezoelectric microphone and a high-speed camera respectively; this was performed at a series of different water filling-heights for each glass. The fundamental frequency of the singing wine glass decreases as the filling-height increases. Frequency analysis shows that the fundamental frequency of the glasses is split and this is accounted by the glasses’ asymmetries. The largest split is equal to approximately 3.9±1.4 Hz. The frequencies of the capillary waves formed near the rims of the glasses vary linearly with the given glass’s fundamental frequency, reaching the order of 10^2 Hz.

INTRODUCTION

Pure sounds are emitted when the rims of the glasses are rubbed with a moistened finger. The ‘signing wine glass’ is a more familiar term and also refers to this vibrating system. The sounds produced by playing with a series of singing wine glasses can form beautiful melodies. This arrangement is called the glass harp. The glass harp is tuned by varying the amount of water in each wine glass. The melodies played by the glass harp have a captivating effect on its listeners. According to historical records, a glass harp performance inspired Benjamin Franklin to create the glass harmonica.

Wine glasses resonances were formally described for the first time by A.P. French. Soon after, R. E. Apfel brought attention to the capillary waves that form on the liquid surface near the singing glass rim. Both French and Apfel relied on J.W.S. Rayleigh’s work as a reference on acoustic engineering. Rayleigh analytically expressed the lateral movement of vibrating bars. French applied this concept to the vibrating walls of the signing glass. Apfel made a valuable connection between a cathedral’s effect on acoustic wave travel described by Rayleigh and the glass’s effect on the waves formed on the liquid surface.

The focus of this investigation is on the relationship between the sound waves and water waves that result from wine glass resonance. An attempt is made to obtain valuable experimental information that French and Apfel may not have had as easy access to due to technical limitations of their time. However, it appears that to this day, very little research exists on the behavior of the water surface of wine glasses, while there are no other available measurements that can directly relate the patterns of the water waves to the sounds emitted by wine glasses.

THEORY OF SOUND

The singing wine glass is excited by the process of rubbing the rim of the glass with a moistened finger. From the sound of the excited wine glass, one can detect the fundamental frequency, which varies depending on the characteristic geometry and the material of the wine glass. The rubbing causes the rim of the glass to oscillate in between elliptical deformations (Figure 1(a)). The deformation of the wine glass rim has four nodal points, whose distance with respect to each other stays constant. However, the positions of the nodal points move along the circumference of the glass in accordance with the motion of the finger used to induce the vibration.
2.671 Go Forth and Measure

Figure 1  (a) Singing wine glass rim undergoes elliptical deformations (top view of wine glass). There are four antinodal points indicated; their displacement $\Delta$ and frequency $f$ of deformation can be derived. (b) Propagating bending wave along the rim of a singing wine glass (top view of small segment of the wine glass wall). (c) Side view of cylindrical wine glass, described by its wall thickness $t$, constant radius $R$, filling height $h$, and the total container height $H$.

This movement of the finger will cause bending waves to propagate along the glass wall (Figure 1(b)) as well as sound to be emitted. If the wine glass is modeled as a cylindrical vessel, which rests upon a rigid beam (Figure 1 (c)), the parameters that need to be taken into consideration are the wine glass’s wall thickness $t$, constant radius $R$, filling height $h$, total container height $H$, Young’s modulus $E$, and material density $\rho_s$.

The speed of the bending wave $V_b$ is given by

$$V_b = \left( \frac{\pi V_L ft}{3} \right)^{1/2}$$

where $V_L$ is the longitudinal wave velocity in the wine glass wall and $f$ is the frequency of the oscillating rim. This equation is taken into consideration when calculating the total kinetic and potential energy of the system. This analysis leads to an expression for the lowest mode of vibration heard. This mode is called the fundamental frequency:

$$f_o = 2\pi \left( \frac{3E}{5\rho_s} \right)^{1/2} \frac{t}{R^2} \left( 1 + \frac{4}{3} \frac{R}{H} \right)^{1/2}$$

As the cylinder is filled with water to a height $h$, there is a change in the sound produced and a new fundamental frequency $f_h$ is given by

$$\left( \frac{f_o}{f_h} \right)^2 = 1 + \frac{\alpha}{5} \frac{R}{\rho_s t} \frac{h^4}{H^4}$$

where $\rho_l$ is the density of the water inside the glass, and constant $\alpha$ is approximately equal to 1.4 according to French’s calculations. Moreover, $\alpha$ depends upon his estimate of the coupling efficiency between the rim wall and the water inside. The fundamental frequency of the empty wine glass $f_o$ is distinct for each particular wine glass. Equation (3) is of special importance because it essentially indicates that $f_h$ decreases as $h$ increases.

The resonant frequency $f_h$ of the liquid-glass system can be thought of as a characteristic of the mechanical propagation of pressure and displacement of air molecules, whereas the frequency of the generated surface water waves $f_{\text{wave}}$ reflects water molecule displacements.
METHODS

The acoustics of three different wine glasses, referred to as Glass 1, Glass 2, Glass 3 (Figure 2), were examined.

![Wine glasses](image)

**Figure 2** Wine glasses: (a) Glass 1, (b) Glass 2, and (c) Glass 3.

The glasses’ known physical characteristics are summarized in Table 1.

**Table 1.** Known physical characteristics of the wine glasses used for our study

<table>
<thead>
<tr>
<th>Singing wine glass name</th>
<th>Glass 1</th>
<th>Glass 2</th>
<th>Glass 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Glass</td>
<td>Crystal</td>
<td>Glass</td>
</tr>
<tr>
<td>Container height $H$ (cm)</td>
<td>13.1±0.1</td>
<td>11.0±0.1</td>
<td>10±0.1</td>
</tr>
<tr>
<td>Top Rim Radius (cm)</td>
<td>3.2±0.1</td>
<td>2.9±0.1</td>
<td>3.3±0.1</td>
</tr>
<tr>
<td>Wall thickness $t$ (cm)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Volume (ml)</td>
<td>550±10</td>
<td>320±10</td>
<td>290±10</td>
</tr>
</tbody>
</table>

The sound emitted when rubbing the rim of each glass was sampled with a piezoelectric microphone. The relationship between the amplitude of the sound emitted and its frequency were derived after performing a fast Fourier transform on the collected sample. For each singing wine glass, the fundamental frequency was easily identified in the frequency spectrum as the frequency corresponding to the highest amplitude. The complete frequency spectrum of Glass 1 is shown in Figure 3 along with an inlet of the peak that corresponds to the fundamental frequency. In this magnified plot it is evident that the peak is split. This is not uncommon and previous investigators account for the splitting effect as a result of the asymmetries of the vessel container.\(^4\)

![Frequency spectrum](image)

**Figure 3:** Frequency spectrum of empty singing wine Glass1: the highest amplitude peak indicates the fundamental frequency. The inlet shows a magnification of the highest amplitude peak, which is split.

A high speed Phantom video camera was used to capture precise video recordings of the liquid surface of Glass 1. Glass 1 had the largest radius and thus also the greatest liquid surface area. The camera was oriented on the side of the wine glass and focused on the meniscus. As shown in Figure 4, this arrangement gave a good view of the profile of the capillary waves that formed adjacent to the glass wall when the glass was excited.

![Capillary waves](image)

**Figure 4:** Capillary waves form on the meniscus of the glass, adjacent to the glass wall when the glass is excited.

The wave frequency $f_{\text{wave}}$ was obtained using video analysis software to track the movement of the peaks. The period of the waves was obtained from the time stamps of the video recordings.
SOUND FREQUENCY RESULTS

The sound frequency recordings are used to indicate whether the relationship presented in equation (3) is a valid approximation for wine glasses that are not perfect cylindrical containers. For this purpose, Figure 5 shows the variation between \((h/H)^4\) and \((f_0/f_h)^4\).

![Figure 5](image)

**Figure 5** The \((h/H)^4\) ratios are plotted versus the \((f_0/f_h)^4\) ratios. The applied linear fits have an \(R^2\) of 0.986, 0.990 and 0.964 respectively for Glass 1, Glass 2, and Glass 3.

The plots in Figure 5 suggest that the relationship between the two ratios is linear and that equation (3) can be used to model the sound of the three wine glasses. Table 2 gives the \(\rho_s\) values of each glass, which are derived from the slopes of Figure 5.

<table>
<thead>
<tr>
<th>Singing wine glass name</th>
<th>Glass 1</th>
<th>Glass 2</th>
<th>Glass 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_s) (kg/m(^3))</td>
<td>3751±117</td>
<td>1431±43</td>
<td>2526±79</td>
</tr>
</tbody>
</table>

![Table 2 Derived glass densities \(\rho_s\)](image)

Typical values of glass density vary from 2400 to 6000 kg/m\(^3\). The values of \(\rho_s\) for Glass 1 and Glass 3 fall within this range. Glass 2, which was made from a higher quality crystal glass, has a notably lower density that is not within the known range. This indicates that equation (3) might be less applicable to certain kinds of wine glasses, or alternatively, that the model is reliable only to a certain extent for curved wine glasses.

![Figure 6](image)

**Figure 6** The \(h/H\) ratios are plotted versus \(f_h\). The applied second order polynomial fits have an \(R^2\) of 0.999, 0.996 and 0.998 respectively for Glass 1, Glass 2, and Glass 3.

The plots presented in Figure 6 offer a more intuitive understanding of how \(f_h\) varies with \(h\). The three glasses present similar parabolic trends. This data is in agreement with the anticipated decrease of \(f_h\) in response to the increasing \(h\).

The amount of liquid present in the singing glass can be reflected through the shift of the recorded \(f_h\). Each of the glasses had a distinct size, so they each have a different upper filling height limit. Each peak of Figure 7 represents a specific filling volume of each wine glass.
Each glass presented a distinct $f_h$ range. In particular, Glass 3, which was the smallest of the three wine glasses, displayed the greatest range as shown in Figure 7. Glass 3 is of interest in this case because, unlike Glass 1 and Glass 2, it also failed to reach frequencies below 350 Hz. The exact composition of each glass is not known, however, it is likely that Glass 3 had the highest $E/\rho_s$ ratio. According to equation (2), a high $E/\rho_s$ ratio would explain why Glass 3 starts out with a much higher fundamental frequency of 817.5 Hz, whereas Glass 1 and Glass 2 start out at 586.5 Hz and 541.7 Hz respectively. Although the three glasses are not perfect cylinders, the $R/H$ ratios of the glasses do not present great enough differences among them to account for this finding concerning Glass 3.

It is evident from Figure 7 that each plotted fundamental frequency spectrum has a split peak. The frequency difference between the $f_h$ peak and the secondary lower amplitude peak is denoted as $\Delta f$. There is no clear correlation between the value of $\Delta f$ and the filling height. Figure 8 presents the mean $\Delta f$ for each of the three glasses.

Figure 7 Frequency shift of $f_h$ as the height $h$ of the fluid inside is increased near the filling height $H$ obtained from (a) Glass 1, (b) Glass 2, and (c) Glass 3.
According to Figure 8, Glass 2 appears to have the highest $\Delta f$. However, there is no statistically significant difference among the $\Delta f$ values corresponding to each glass. Since the split peaks are known to be related to the glass design irregularities, the higher quality Glass 2 was anticipated to have a lower $\Delta f$ compared to that of the lower quality Glass 1 and Glass 3.

**FREQUENCY MEASUREMENTS OF CAPILLARY WAVES**

The energy transfer of the resonating singing glass to the water is reflected in the liquid surface dynamics. The video recording analysis performed on Glass 1 made it possible to attain frequency $f_{\text{wave}}$ values for different filling heights. An attempt is made in Figure 9 to related $f_{\text{wave}}$ with the emitted sounds’ $f_h$. The lowest filling height of Glass 1 at which capillary waves were observed was 3.8 cm.

The capillary wave motion seems to be directly linked to $f_h$. Essentially, Figure 9 suggests that $f_{\text{wave}}$ varies linearly with $f_h$. It is also worth noting that the magnitudes of $f_{\text{wave}}$ and $f_h$ are quite similar. The excitation energy provided by playing the singing wine glass is transferred to both air and water molecules whose displacements bring about both sound and water waves. This double transfer is likely the main cause of the linear relationship shown in Figure 9, as well as of the small magnitude deviation between the two frequencies.

The acoustic resonance creates surface waves along the glass rim that are almost undetectable to the naked eye. During the first few seconds of trying to excite the glass, there were no waves present. This indicates that the glass rim motion had to reach certain acceleration before capillary waves could form on the surface.

**CONCLUSIONS**

Each wine glass produces a characteristic fundamental frequency depending on its filling height. This frequency is the acoustic resonant frequency of the glass. Moreover, each glass has a set range of fundamental frequencies it can achieve. For example, Glass 1’s $f_h$ ranged from 281.5 to 541.7 Hz, Glass 2’s from 270.0 to 586.5 Hz, and Glass 3’s from 409.9 to 817.5 Hz. FFT analyses allow careful examination of the fundamental frequency peaks, which consistently appear to be split in the case of the singing wine glasses. However, the derived $\Delta f$ values of this study’s glasses did not present significant differences, given the values’ degree of uncertainty.

The frequency of the capillary waves, $f_{\text{wave}}$, increases with increases in $f_h$, and thus $f_{\text{wave}}$ also decreases with increasing $h$. More specifically, a linear relationship appears to exist between $f_{\text{wave}}$ and $f_h$. The signing wine glass is one of the few musical instruments in which both a sound and a water wave frequency may arise.

Future work involves attaining recordings from a greater variety of wine glasses. A sound library can be created to effectively assist tuning glass harp instruments. In essence, each glass will be filled to the exact height that corresponds to the desired fundamental frequency. In addition to gathering more data to expand the scope of this study, there is another interesting aspect of the
singing wine glasses: water droplets emit from the surface at a relatively high filling heights. These droplets can be more easily examined if silicone oil is used instead of water to perform the video recordings.

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