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Aeroacoustic analysis of a bottle whistling

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Experimental Methods for Engineers

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1. Abstract

A Helmholtz resonator uses a flapping motion of air to generate a sound at a specific frequency. Using a specific setup with cameras and tone recorders, it is possible to make this motion visible, and therefore confirm the theoretical assumptions made for its mathematical model.

2. Introduction

This experiment examines the aeroacoustic phenomena of a bottle that creates a whistling noise. When an airstream is blown into a bottle, a resulting acoustic tone can be heard. Therefore, the whistling of a bottle can be described as a Helmholtz resonator. Basically, a Helmholtz can be any rigid body with a volume of air and a neck connecting the volume with its surrounding. Such a resonator can be simplified to an oscillatory system of one mass and one spring. It therefore resonates at specific eigenfrequencies (can be single or multiple depending on bottle geometry). Today, techniques exist to visualize this phenomenon. Firstly, it is possible hear this phenomenon. Secondly it is also observable through a specific test setup, as has been used in this experiment. This field of research finds its important place within the engine and turbine construction. There, acoustic resonance can drastically change the behaviour of gasses in a reaction chamber and might alter the outcome to an unwanted result. Aeroacoustics research helps to stabilize these chambers, and therefore increase the engines efficiency immensely.

2. Experimental setup

For this experiment, a jet of air blows into a regular bottle roughly the size of a 50cl coke bottle. A blue laser beam is used, together with a chopper, to visualize a vertical plane within the bottle neck at certain frequencies. A specific camera is also pointed towards the neck to be able to record the opening of the bottle neck. To visualize the air even better, a water vaporizer was used to vaporize the air

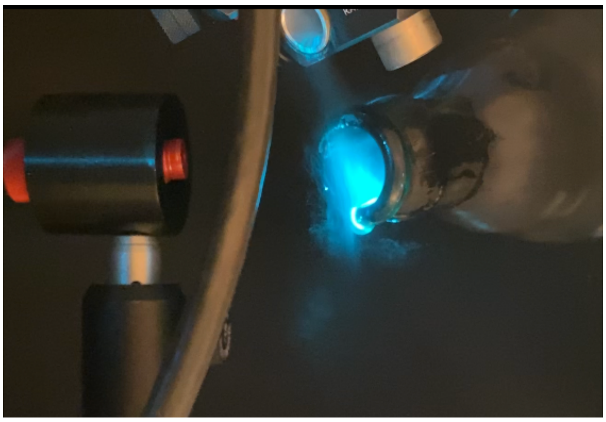

Figure 1: Experimental setup

within the bottleneck and therefore observe the movements of air. To obtain the laser intensity at the bottle opening a photo-diode was installed. Furthermore, a piezo-electric sensor (microphone) was installed to determine the resonance frequency of the bottle.

3. Experimental execution

It is important to mention that this experiment features 2 methods to evaluate the frequency. One is the use of the microphone, which is rather strait forward. The other is the use of the optical test setup. To obtain correct results optically, the chopper had to be operated at a frequency not equal to the frequency of the resonator. This guaranteed datapoints on every place on the resonance curve. If this were not the case, the measurements would have always taken place at the exact same spot on the sine curve, and its data value therefore constant. The camera took samples at a frequency of 30 Hz. In order to protect the eyes, it is important to cover the test setup so that no laser beams can point into eyes during the measurements when the laser is active. To obtain our data the measurement time was set to one minute. During this minute, the camera shot 700 pictures.

4. Results

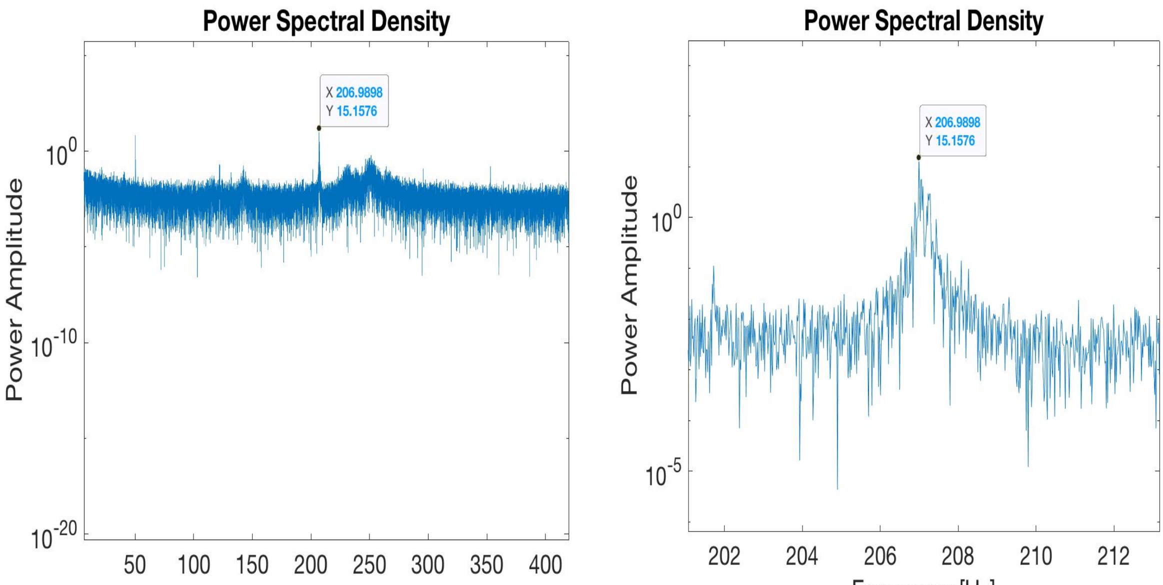

Figure 2: Power Spectral Density

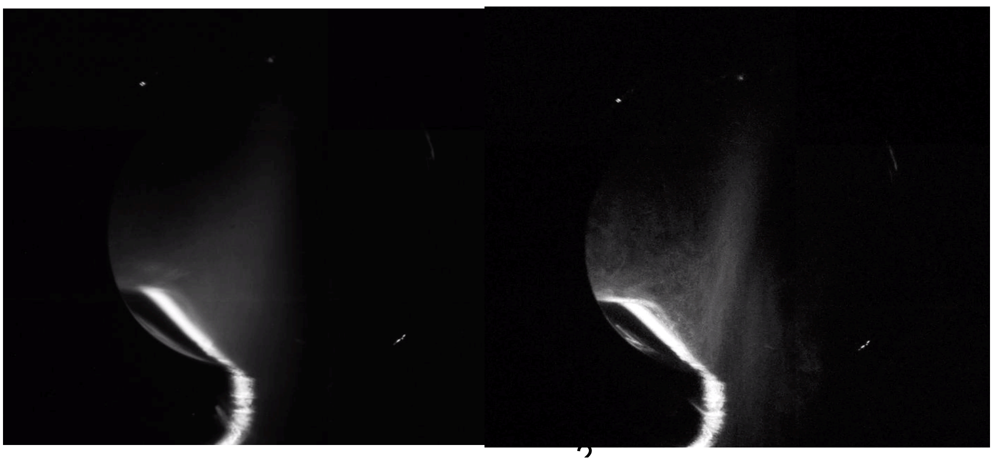

Figure 3: Comparison with and without sidefins phaseaveraging

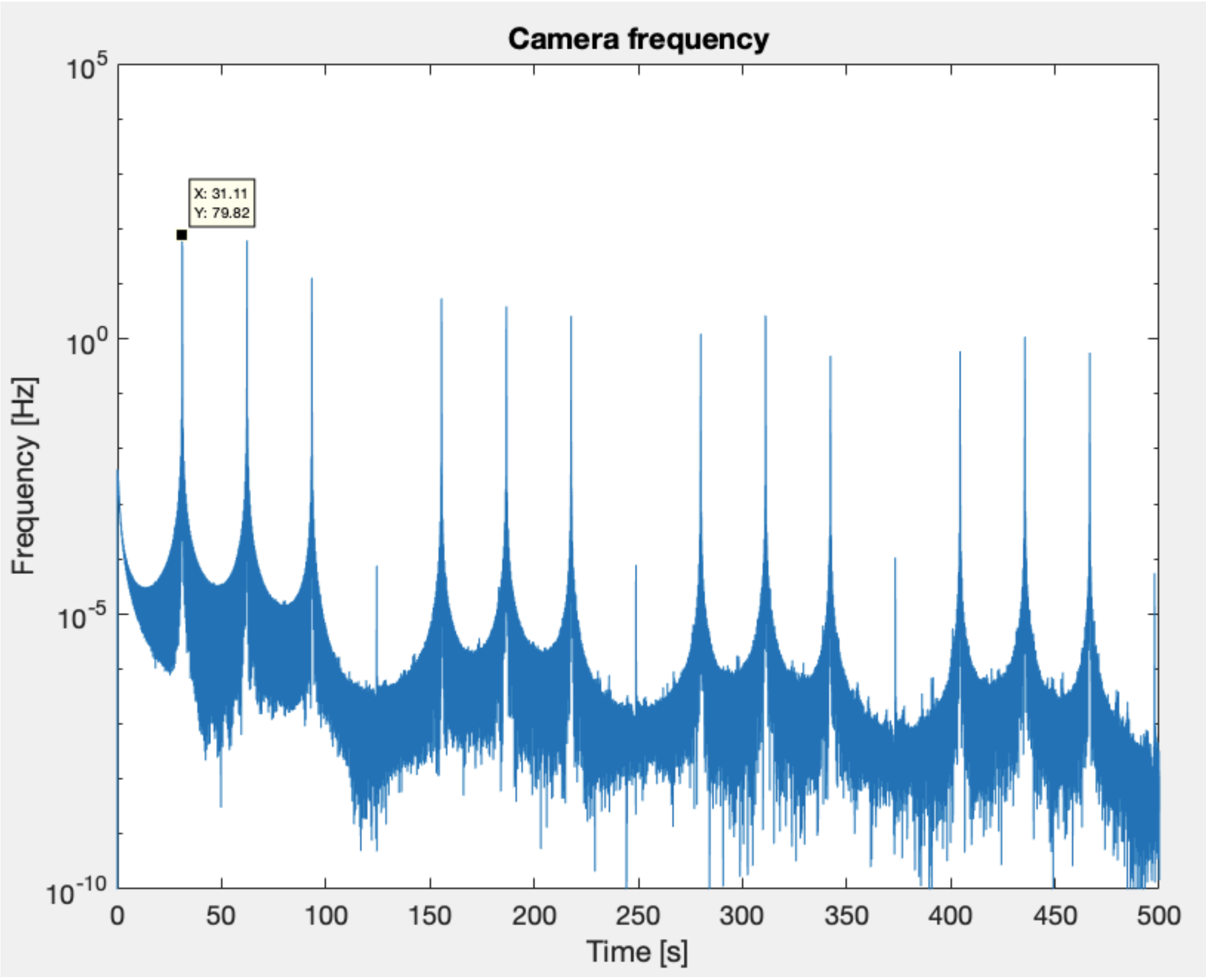

Figure 4: Camera Frequency

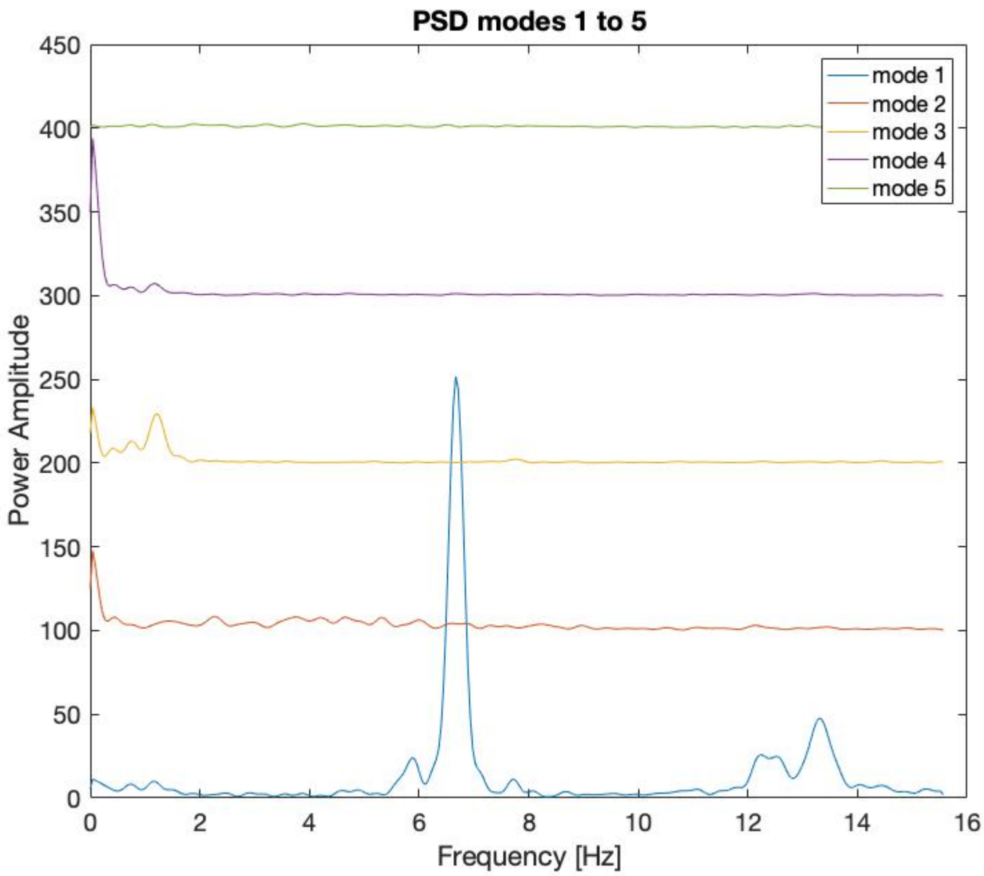

Figure 5: PSD modes

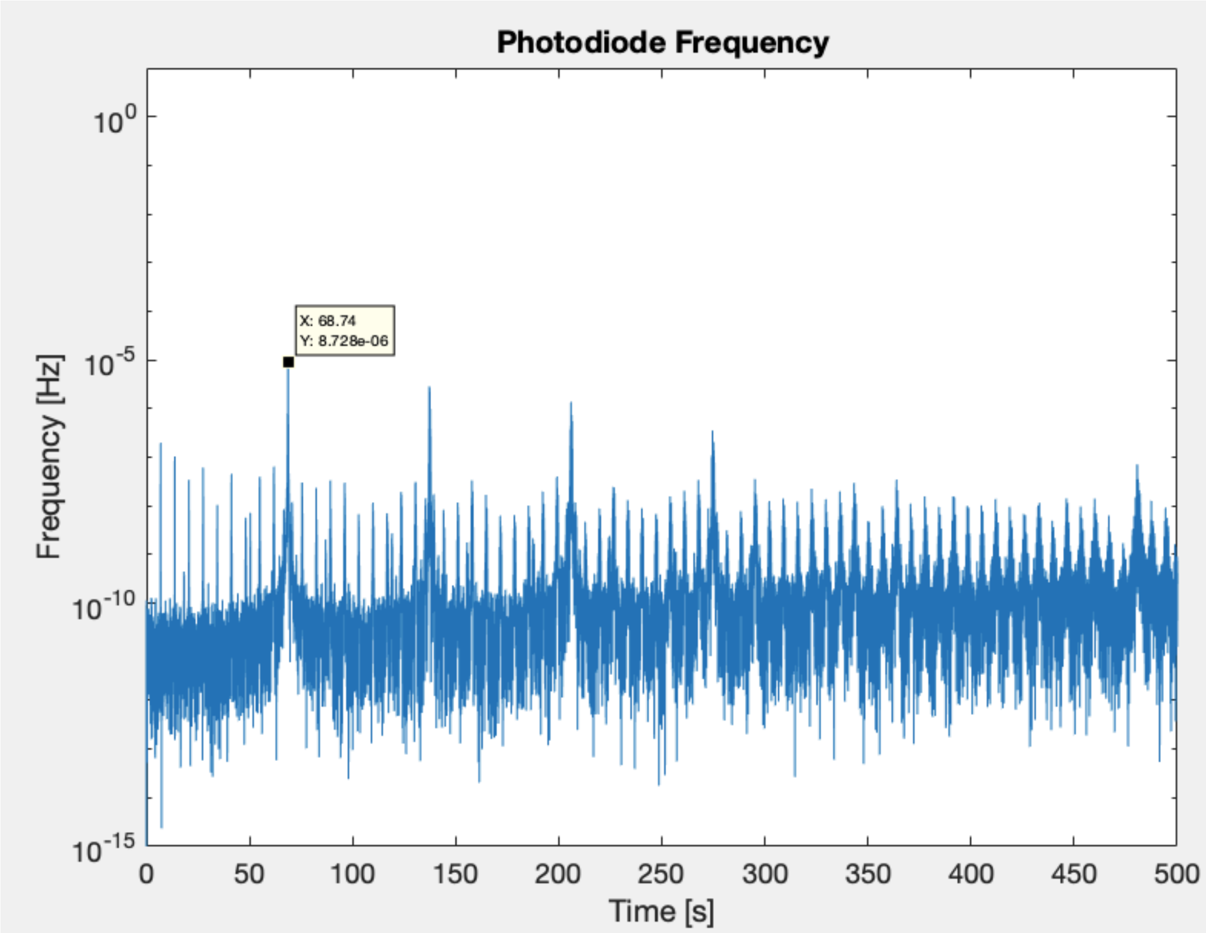

Figure 6: Photodiode Frequency

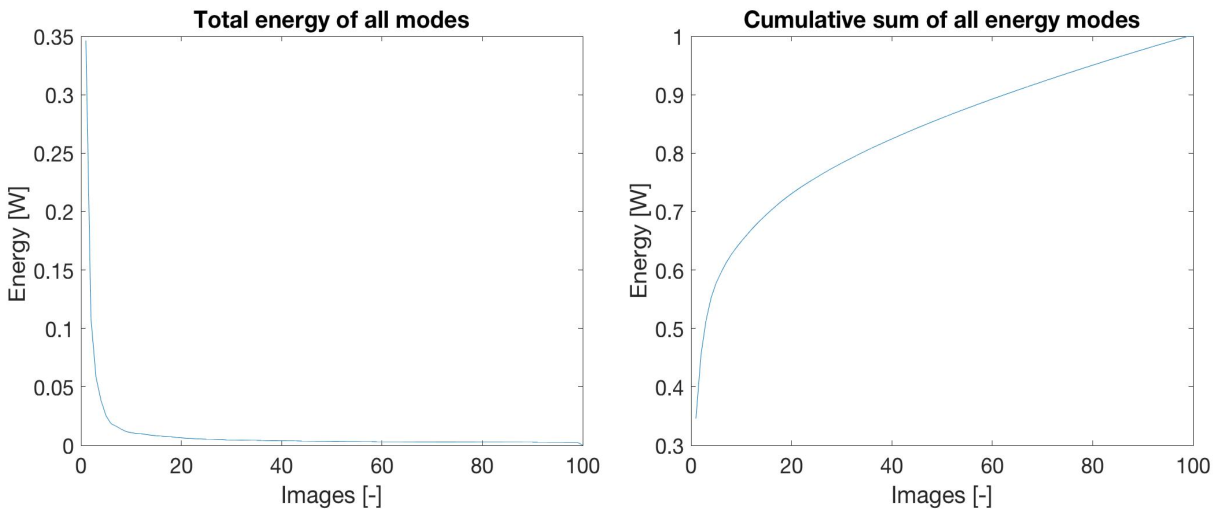

Figure 7: Total energy of all modes and cumulative sum of all energy modes

4.1 Frequency analysis

With our code we were able to plot the frequency of the different sensors. This was done with the matlab-function pwelch. Figure 2 shows the power spectral density of the piezo measurements. A peak can clearly be observed in the region of 200 Hz. If zoomed into this are, as figure 2 (right) does, it can clearly be seen that the piezo sensor registered a resonance frequency of 206.9898 Hz. Further, the piezo sampling frequency turned out to be 30.12 Hz.

The sampling frequency we could calculate with the formula 1. The frequency of the piezo and of the photodiode we had to read out the peak frequency (figures 2 and 6).

$$f_s = \frac{1}{\Delta t} \qquad (1)$$

By using formula 1 we obtained a sampling frequency of 31.21 Hz. Out of figure 6 we got the frequency of the photodiode of 68.74 Hz. Out of figure 2 we can see that the frequency of the piezo sensor is 207 Hz. To verify the camera sampling frequency, we plotted the data of the camera clock as well. Out of figure 4 we can see that the frequency is with an error of 0.01 the same as calculated in formula 1. To get the frequency of the power spectral density (PSD) of the piezo we had to analyse the different modes. We plotted the PSD of the time coefficient of mode 1 to mode 5 (figure 5), because, as shown in figure 3 we can see, that we include already around 60 percent of the total energy (intensity of all modes) if we look at the first 5 modes. We can obtain, that only mode 3 and 4 are having a peak at a frequency below 5Hz. By analysing the computed videos of these modes, we can see that only mode 3 shows the typical flapping motion we also observed during the experiment. Now we got our frequency of the photodiode which is 1.2 Hz. In mode 1 we cannot see any motion of the vapor. However, we can see in figure 5, that there is a frequency peak at around 7 Hz. In mode 1 we can see, that condensate liquid water which flows out of the bottle is very bright. This large intensity is the reason why mode 1 is the most energetic mode with the highest peak. However, this mode is not really interesting for us, because it is image noise. To filter out this frequency noise we created a new video (Mode_3+4.avi), which only shows mode 3 and 4.

Relation between these 3 frequencies we can show with formula 2. Where f_1 a signal of a sensor, which we want to sample. After sampling this curve you get the alias frequency of f_1. In our experiment f_1 is the frequency of the piezo sensor and the sampling frequency is the frequency of the photodiode. As we determined all these frequencies we can plug them in and prove if m is close by an integer number.

$$f_{alias} = f_1 + mF_s \ (with\ m \in Z) \qquad (2)$$

$$\Rightarrow m = \frac{f_{alias} - f_{piezo}}{F_{pd}} = \frac{1.2\ Hz - 207\ Hz}{68.74\ Hz} = 2.994$$

This value for m is very close to the integer 3 which means that we have measured quite precise and computed our frequencies exact.

In case we would remove the chopper wheel, we would not be able to detect the jet oscillation (flapping). Looking at formula 2 f_{alias} is going to be equal to f_{piezo}. The flappig motion would be shown at a frequancy of 207 Hz. But his frequancy can not be registered with our eyes, because we can register motions up to 50 Hz. We wouldn't see anything. If the laser beam is chopped at the frequency recorded by the piezo, we would see a constant signal, because we cut the sinusoid every time at the same point. We can explain this phenomenon aswell with formula 2: $f_{alias} = f_1 +$

$mf_1 = f_1(1+m)$. Here we sample always at the same phase angle. As a consequence of this we would obtain a freezed image.

4.2 Phase averaging

By analysing video ”allmodes.avi” we can see that each picture of the video still contains noisy pixels. By phase averaging we constructed a new video, which is only 5 seconds long, but it shows the phenomena in much more smeared way. The reason why the new video is only 5 seconds long is, that we computed one single clean period. This period is the result of averaging all points which have the same phase angle. This was implemented with the mean function in matlab. The difficulty of this method was, that we had to use points, which all have the same phase angle. What we calculated in formula 3 is that we have to use every 25th picture.

$$\frac{F_s}{f_m} = \frac{31.12\ Hz}{1.2\ Hz} = 25.1 \approx 25 \qquad (3)$$

Video ”pa.avi” is the result of the averaging process. The background is now clean and completely black and free of white pixels.

5. Discussion

To obtain clear results, the test setup had to be tuned to precise settings in order to see a flapping motion. The chopper hat to break the laser beam at a frequency that is different to the frequency of the resonator. The observed behaviour confirms, that the stroboscopic effect does exist, and that the mathematical relations are correct. Due to the very high resonance frequency of the bottle and the lower sampling frequency, it is clear that the frequencies we observe in the video is an alias-frequency, because the actual frequency would be too high to distinguish with eyes only. When the light beam chopped the laser beam at the exact same frequency as the resonance, it was not possible to observe any flapping motion. In the video, it was possible to visualize the flapping motion of the air within the bottle neck. The alternation of the bright and dark within the bottle neck opening can clearly be observed. The mode videos show very clear the different existing frequencies. We were able to separate these modes and analyse each mode separately.

6. Conclusion

The experiment turned out to be successful. The theoretical knowledge could be implemented in a smart test setup. With multiple methods it was possible to determine the resonance frequency of the bottle. Especially the optical method showed clear results. On the video a clear flapping motion of the air inside the bottleneck could be observed, and therefore the stroboscopic effect confirmed. The importance of this field of research lies within engine and turbine construction. In general we can say that this method requires a complicating setup and elaborate data evaluation. However we obtained very exact values for the frequancies how we showed in the calculations in 2. Another positive aspect is that the setup consists out of simple and rather cheep devices.