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# High-speed line camera measurements of a vibrating string

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A novel high accuracy experimental equipment for acoustical measurements of vibrating parts of musical instruments has been designed and built. This set-up consists of a high frame-rate line-scan camera, a custom-built optical lens system, and a mirror arrangement. The optical tubes are designed to capture maximum amount of light and to offer sufficient magnification. The second dimension of vibration is obtained using a mirror at a 45º angle with respect to the camera plane. The experimental set-up makes it possible to perform accurate non-invasive measurements of the vibration of various parts of musical instruments, such as the strings, bridges, necks, etc. This set-up has been calibrated and successfully used to capture piano and bass guitar string motion. An experimental monochord has been constructed using a piano string in order to analyze the three main string excitation techniques: plucking, striking, and bowing. The captured signals from the oscillation of the monochord are presented and two methods of vibration extraction from two dimensional measurements are described and compared.

## 1 Introduction

Over the last three decades, there have been several approaches for developing contactless methods of measuring string vibrations of musical instruments. These procedures can be classified into electromagnetic, electric field sensing, and optical methods.

In the electromagnetic methods, string detection is done using an electromagnetic coil or a pair of small magnets placed near the string [1]. The vibration of the string induces a voltage proportional to the string's velocity and, by numerical integration of the velocity signal, the displacement of the string can be obtained. Similarly, the electric field sensing methods are based on the capacitance variations caused by changes in distance between two electrodes. In [2], a conducting string is grounded and DC voltage is applied to an electrode plate. When the string vibrates, the voltage between the string and the plate is modified and information about the string's displacement can be obtained. The main weaknesses of the electromagnetic and electric field sensing methods are the need of using metal strings (magnetic or electric conductivity are required), the possibility of slightly influence the vibration by damping it [1, 2], and the required extensive calibration. Furthermore, these techniques present disadvantageous nonlinear properties, as it happens in the pickup of the electric guitar [3].

In the optical methods, various light or laser emitting and detecting sensors can be used to capture the string's motion by performing non-invasive measurements, which means that the behavior of the system is not modified due to the measurement. For example, different devices that use laser light and sensors to detect the blocked light (shadows) can ensure the result [4]. Also, an optoelectronic motion sensor system have been relatively successful in detecting the string vibration [5] and a photovoltaic detector was used to measure the vertical and the horizontal vibration of a piano string in [6]. Closer to the approach to be presented in this article, high-speed area scan cameras were used in [7] and, by processing the recording with an appropriate video analysis, the vibration was effectively measured. The disadvantage of these optical systems is expressed in the fact that they are rather expensive or need extensive calibration.

The present paper describes a new optical technique, which has none of the aforementioned inconveniences on measuring the vibration of strings, and shows the quality of the subsequent results. The string vibration at one point of the string is recorded by a high-speed line-scan camera and image processing is applied to extract the vibration information. Measurements in two dimensions can be performed if a second camera or a mirror set-up is used. The required equipment is relatively inexpensive and the procedure does not involve extensive calibration. The system can detect the motion of strings made of any material but, although it has also been used to measure other vibrating parts of musical instruments, this paper demonstrates how the method works on measuring the vibration of a piano string when different excitation techniques are put into practice.

# 2 Equipment

## 2.1 Apparatus

A line-scan camera is an optical device which is able to record images in a single linear array of sensor pixels. When high frame-rate measurements are needed, a line-scan camera is cheaper, smaller, and lighter than an area-scan high-speed camera. Line-scan cameras are provided in a quite compact format, which allows to place them in narrow cavities when measuring the vibration of some parts of musical instruments. In this work, the used line-scan camera is a monochrome Teledyne DALSA Piranha2 (1k 67 kHz). In this camera, a row of 1024 x 1 pixel CCD sensors operates with global shutter technology, i.e. all pixels capture light simultaneously, delivering an output pixel depth selectable at 8 or 10 bit. The maximum frame-rate available is 67000 frames per second (fps); in this work, it is fixed at 44100 fps. In order to control the camera and receive the recorded data, the camera needs an Xcelera-CL PX4 Dual frame-grabber circuit board that can be connected to a usual PC. This circuit board enables the connection of two cameras, if needed.

The camera set-up is complemented with a commercially-available set of macro lenses and optical tubes. In this research, an optical tube with a plano-convex lens was mounted from spare parts purchased from the Thorlabs product catalogue. In order to obtain focused images, the tube length and the string distance are properly adjusted according to the focal length and the desired magnification using the theory of thin lenses. In high frame-rate measurements, the exposure time is extremely short, thus requiring a powerful light in order to enable the detection of the string by the light sensors. For this application, a halogen lamp is used as the light source.

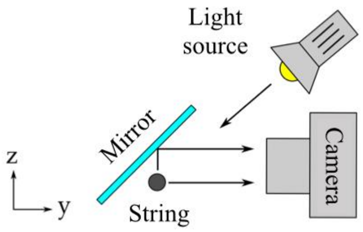


Figure 1: Scheme of the configuration with a single camera and mirror

Two main camera set-up configurations are possible when measurements in two dimensions are carried out. The first one consists of using two cameras placed perpendicular to each other pointing to the same point of the string. And the second configuration uses one camera and a mirror arrangement. The configuration using two cameras has the advantage of providing full range of amplitude for the string oscillation to be recorded, as each camera records only one component of the string motion, and it eases the processing of individual captured images. Its downsides are the expense of the extra camera and the necessity to perform synchronized recording and processing.

In this article, the presented results were obtained using the camera plus mirror configuration, as it is shown in Figure 1. In this case, a single camera is used and it is complemented with a mirrored surface at an angle of 45º with respect to the camera plane which provides the desired second dimension. The benefits of this formation are the savings in expenses, the fact that there is no need for synchronization, and the performance of single focusing and calibration. However, there are some disadvantages. The images of both vertical and horizontal polarization fit in the 1024-pixel row, one next to the other, which implies that the available range of amplitude for each vibration component is smaller than using the two cameras configuration; the reduction may be up to two times. As the mirrored image is placed slightly further away from the camera sensors, the mirror image is distorted compared to the real image. Image aberration is a type of optical distortion caused by the curvature of the magnification lens. For the string amplitudes, the object distance, the focal length, and the image magnification used, it was empirically determined that the image aberration of the optical tube was insignificant.

## 2.2 Calibration

The recorded frames from the vibration measurement can be represented together to obtain the oscillation of one point of the string as a function of time. This representation consists of plotting the amplitude of the string oscillation at the vertical axis and the time at the horizontal axis. The aforementioned equipment provides an image formed by the recorded frames one next to the other. This image can be understood as an amplitude vs. time plot, where the units are pixel number and recorded frame number, respectively. To proceed in coherence, these two scales need to be calibrated.

To calibrate the time scale, there is only need to use the selected frame-rate (44100 fps) to convert recorded-frame number (frames) into time (seconds). In the amplitude scale, the conversion between pixel number (pixels) and string displacement (mm) can be achieved by several means. The general procedure is to record and measure a known dimension. The known dimension can be provided by an object with accurate sizes, by imposing a certain string displacement, by measuring the string thickness, among others. For the measurements in section 4, a conversion factor of 260 pixels/mm was used.

# 3 Vibration extraction

There are different techniques that can be applied to extract the vibration information from the line camera images. In this article, two approaches based on peak and edge detection are described. The extraction of string displacement by means of edge detection algorithms needs focused images without overlapping of string components. Especially when there is a lack of image quality, the peak detection method can provide better results. In more complex cases, for example if there are reflections on the surface of the string, other correlation-based methods with a particularly selected kernel can be used to find, for each vibration component and at each frame, the middle point of the string.

## 3.1 Peak detection and convolution

At each frame, the camera provides a 1024-pixel greyscale array where the darkest parts show the position of the string for both vertical and horizontal components. A fragment of this image is plotted at the background of Figure 2. The vertical component is recorded directly (low part of the image) and the horizontal is seen as a mirrored image (top of the image). As both vibrations are not recorded equally focused, one of them appears darker in the images and this fact eases the vibration extraction method. For extracting the 2-dimensional vibration signal as shown in Figure 2, each grey-scale frame is first convolved with a Hanning window (200-samples wide) in order to smooth it and get rid of quantization. Then, the process consists of picking separately the position of the two peaks at each frame, which approximately indicates the middle point of the string transversal section. The procedure is repeated for all the recorded frames, thus reconstituting the string displacement as a function of time. The vibration signal of the two components is then filtered with a lowpass filter in order to discard high frequency noise.

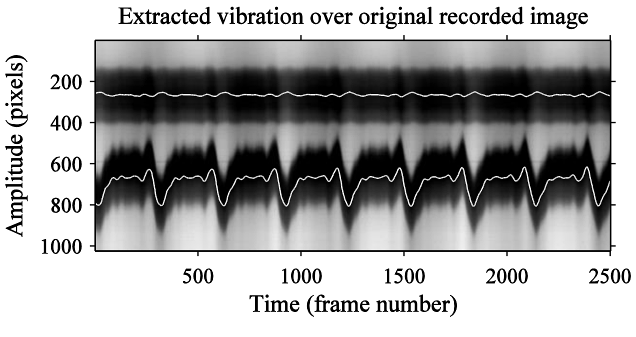


Figure 2: Waveforms of the extracted signal using convolution and peak detection for both polarizations in vertically plucked excitation plotted over the greyscale recorded image

## 3.2 Edge detection

Edge detection is a derivative based method used to extract the vibration signal from a line-camera captured image. It involves finding the upper and lower edges of the oscillation, then finding the middle point between the two edges, thus estimating the position of the string at each polarization. The resulting signals are plotted in Figure 3. In order to achieve this, the image is first cut into two pieces with one polarization each and then converted to a binary image. In this paper, binary image refers to an image composed only with ones and zeroes corresponding to white and black, as shown in the background of (a) and (b) in Figure 3. While converting the recorded grayscale image to a binary image, the threshold value should be selected carefully, and this value may be different for the vertical and the horizontal polarizations. If the threshold is too small, the peak of the greyscale is missed. If the threshold is too large, some portions of the image are blacked out altogether. So a compromise must be found.

After thresholding, several operations are performed on the image. These operations are cleaning the image from outlying isolated pixels, and then closing the image using a disk shaped structuring element. The size of the disk is adjusted individually for each polarization. A clean image is obtained after these operations. The image is then inverted so that the lightest points (the ones) correspond to the string and the darkest points (the zeroes) correspond to the background. The procedure continues by finding the step-up point from zero to one and the step-down point from one to zero. Once these positions are found, the step-up point (the lower edge) is subtracted from the step-down point (the upper edge) and then this subtracted value is added to the lower edge to approximate the position of the string as the middle point.

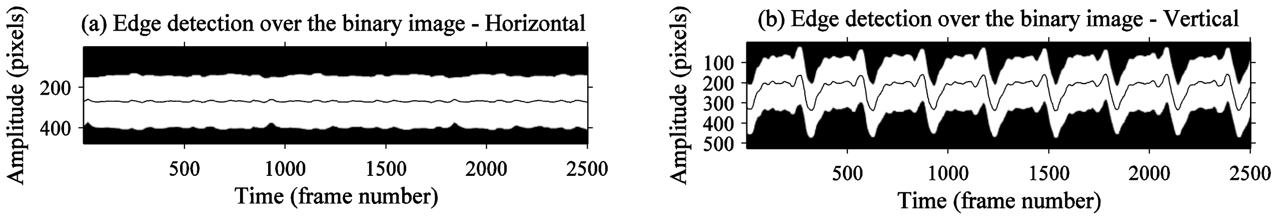


Figure 3: Waveforms of the extracted vibration signal using edge detection for (a) horizontal and (b) vertical polarizations in vertically plucked excitation plotted over the binary image

# 4 Results

In this section, some results from measurements using the described line-camera system are provided. Three different techniques of exciting a string are tested, corresponding to the three main excitations of classical string instruments: plucking, striking, and bowing. In sections 4.2 to 4.4, the vibration extraction is done using the peak detection plus convolution technique. In section 4.5, comparison between the two described vibration extraction methods is provided.

## 4.1 Experiment set-up

A monochord with an original grand piano string has been built and used. The steel string is 1.1 mm wide and 1 m long and it is tuned to have its fundamental frequency at 145 Hz, approximately. In order not to affect the detection of the first ten vibrational modes, the line camera is placed at 1/11 of the entire string length and the excitation is located at 5/6, as it is shown in Figure 4. For the desired magnification, a lens with a focal distance of 50 mm is used and the tube length and string distance are selected to assure focused image acquirement. The calibration of the space scale is done with the imposition of a measured string displacement, as it has been explained previously, and the conversion factor is 260 pixels/mm. The captured images are set to provide 1024 pixels wide and 100000 frames long. The frame rate is adjusted to 44100 Hz. This configuration provides nearly 2.3 s of recording time to actuate on the string.

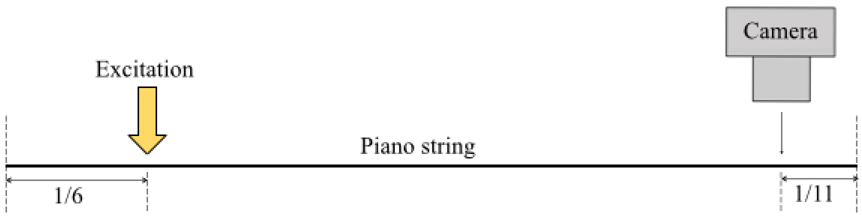


Figure 4: Scheme of the experiment set-up over a 1-meter piano string

## 4.2 Plucking the string

The plucking excitation is realized using the technique proposed in [8], which allows repeated measurements maintaining the same plucking strength among them. This technique is based on using the breaking of a thin copper wire to execute a controlled pluck. The string is pulled with a loop of wire which snaps abruptly at a certain level of stress, providing the same direction and amplitude as initial conditions for all the repetitions. The initial disturbance has a triangular shape with its peak located at the excitation point.

Figure 5 shows the waveforms for horizontal and vertical polarizations when the plucking was vertical. In order to demonstrate the evolution of the waveform at each polarization, plots (a) and (b) show the first periods after the excitation and plots (c) and (d) show the waveforms 0.8 s later. It can be seen how the waveform shape evolves because of the effect of dispersion caused by the faster movement and decaying of some high frequencies, as it was studied in [9].

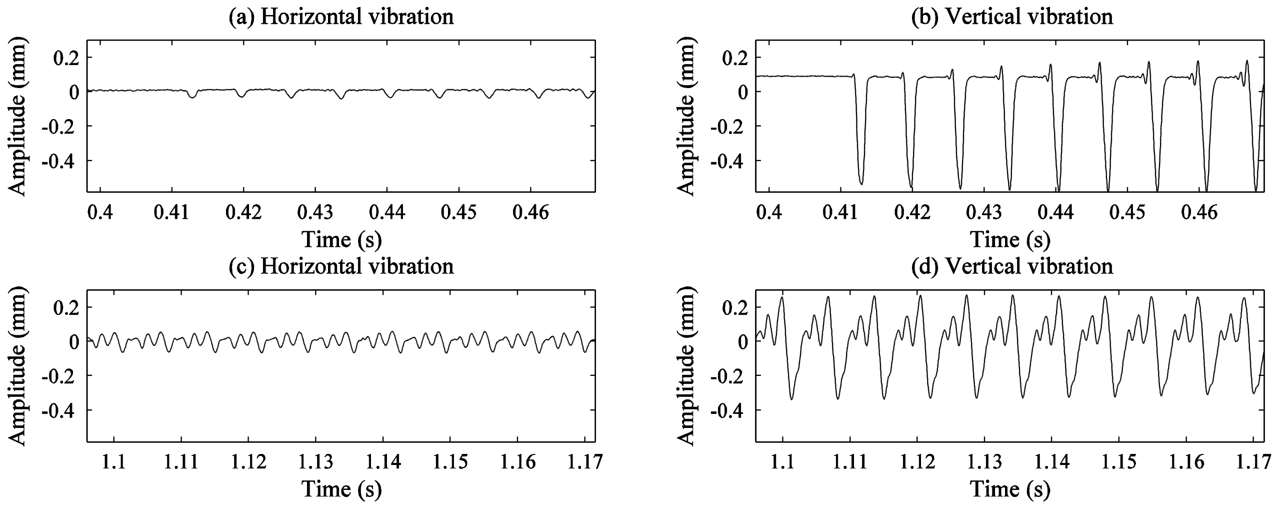


Figure 5: Waveforms of string polarizations in vertically plucked excitation. (a) and (b) are recorded at the beginning of the oscillation and (c) and (d) 0.8 s later.

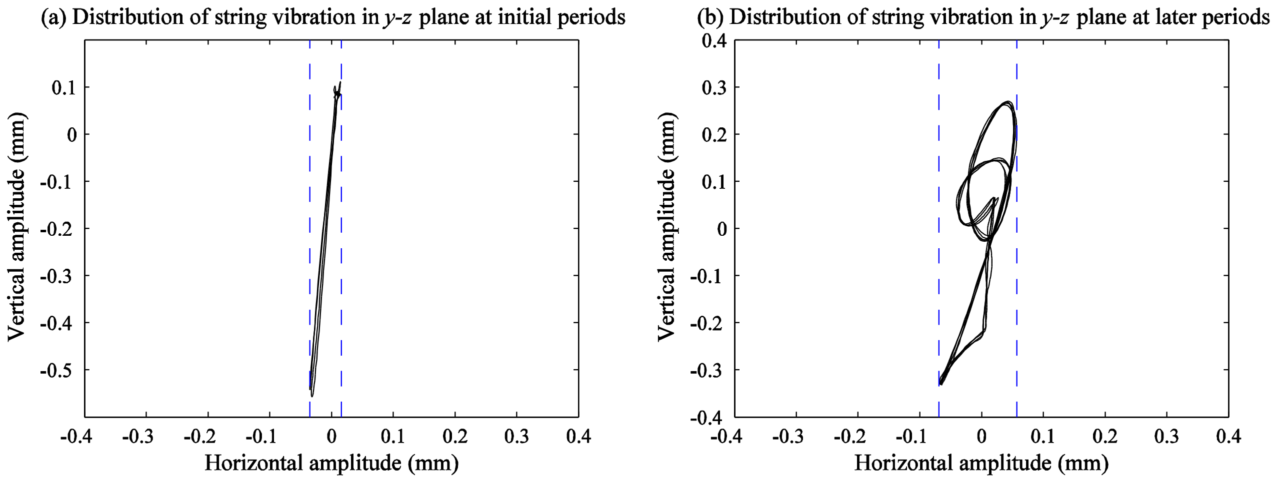


Figure 6: Distribution of string polarizations in *y-z* plane for vertically plucked excitation at (a) the beginning of the oscillation and (b) after 0.8 seconds. Complement lines indicate the edges of the horizontal amplitude.

In Figure 6, patterns of the string motion in the *y-z* plane are presented to show relative amplitude and phase changes, this is the amplitude relation between the vertical and horizontal components. It can be seen that the polarization is mainly vertical, as the string was excited in this direction. Comparing the first periods after the excitation (Figure 6a) with later periods (Figure 6b), it is shown that the horizontal component gains amplitude over time.

Figure 7 contains the spectrum of both components, representing the magnitude with the peak normalized to 0 dB. It can be seen that the 6th frequency harmonic is fairly distinguished, because of the location of the excitation point. The obtained signal-to-noise ratio (SNR) is 19.02 dB for the horizontal polarization and 45.60 dB for the vertical. It should be noticed that the difference in SNR between polarizations is not mainly due to the use of a mirror, but to the fact that the direction of excitation results in higher SNR than the secondary polarization dimension.

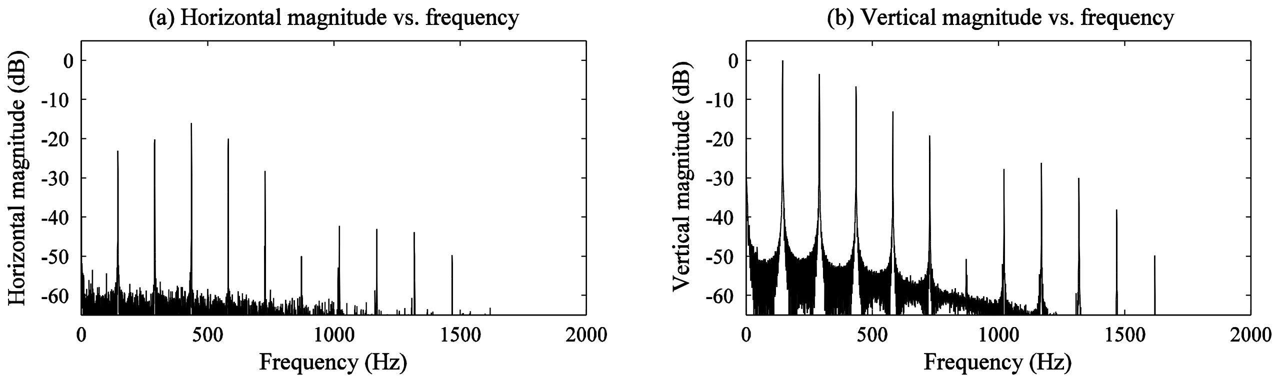


Figure 7: Spectrum of string vibration in vertically plucked excitation for (a) vertical and (b) horizontal polarizations

## 4.3 Striking the string

The striking excitation was done using a piano hammer and the string was hit vertically. This method does not allow accurate repeatability, but it can be useful to measure waveforms similar to the real piano ones. As said, the described equipment can also be set to measure the strings inside the piano.

In Figure 8, the waveforms at the very first periods after the string excitation are presented for both polarizations. As it happened in the case of the plucking excitation, the beginning of the waveform evolution due to dispersion can be seen again. The obtained *y-z* distribution of the vibration polarization shows a tendency to a circular behavior.

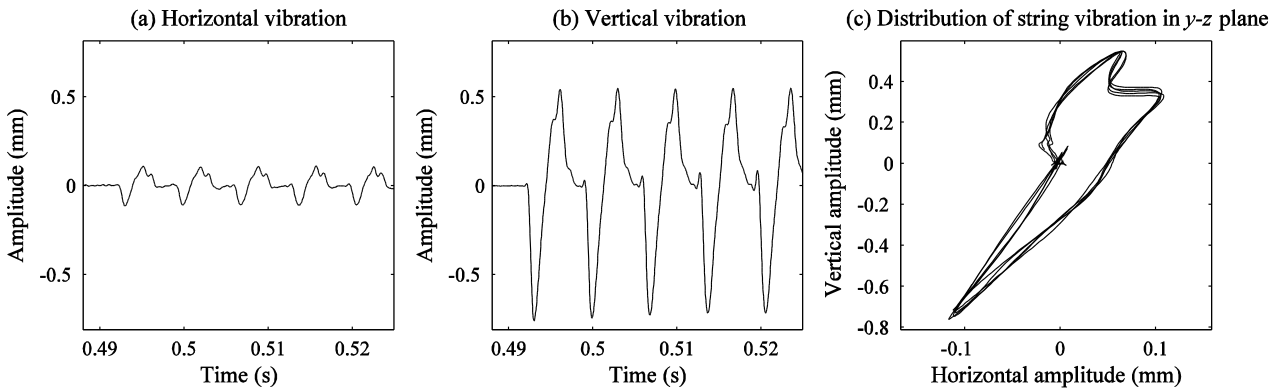


Figure 8: Waveforms of the first periods after vertically struck excitation for (a) horizontal and (b) vertical polarizations and (c) distribution of the vibration in the *y-z* plane

## 4.4 Bowing the string

The bowing excitation was done using a cello bow and an experienced cellist played the monochord. The excitation is mainly horizontal and the string behavior follows the pattern of the Helmholtz-motion, as it was also measured in, e.g., [7, 10]. In Figure 9, the Helmholtz-motion patterns can be seen in the waveform of the string horizontal vibration in the steady state.

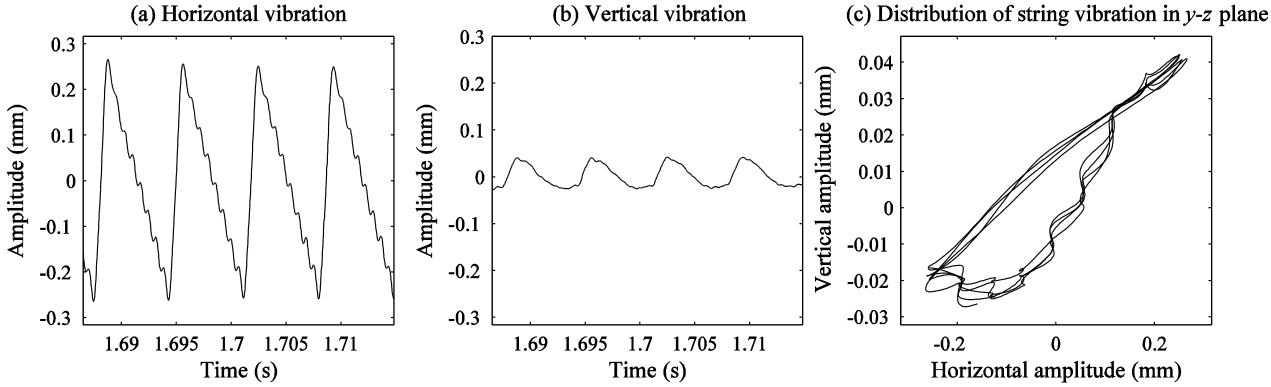


Figure 9: Waveforms of steady periods in horizontally bowed excitation for (a) horizontal and (b) vertical polarizations and (c) distribution of the string vibration in the *y-z* plane

## 4.5 Comparison between vibration extraction methods

In order to compare the peak detection technique with the edge detection one, Figure 10 shows the waveforms of the two string polarizations for both methods. As it has been also shown in Figures 2 and 3, at the vertical component, both techniques produce similar results, with an average difference of 1.9 %. However, for the horizontal, the difference between methods can be up to 17 %. This is because of the fact that the signal-to-noise ratio is larger in the dimension of excitation for both methods (45.60 dB in peak detection and 28.53 dB in edge detection) than the SNR in the secondary dimension (19.03 dB and 10.20 dB, respectively) so it results in a better approximation of the position of the string.

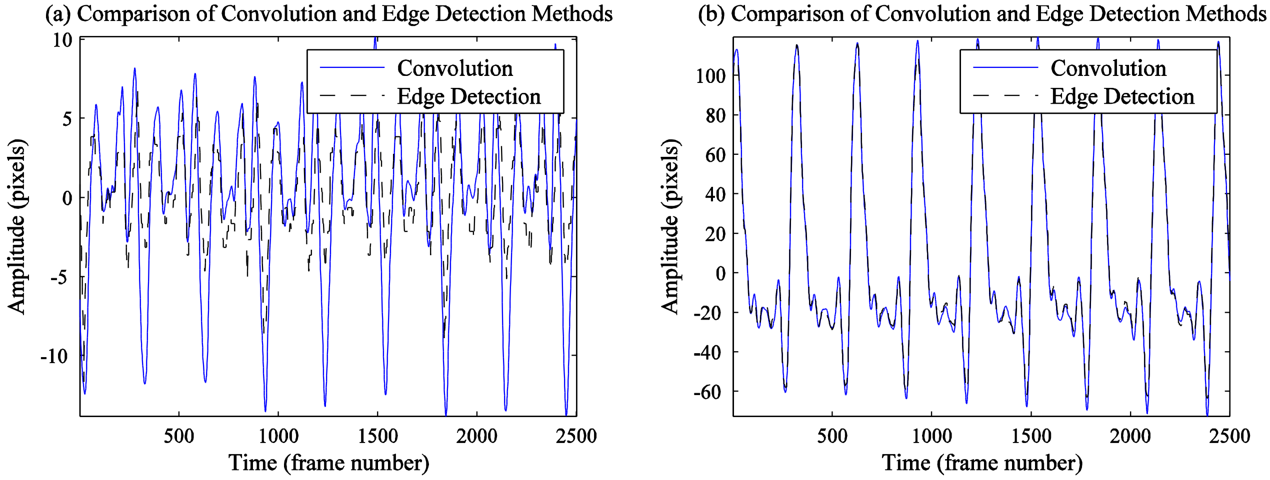


Figure 10: Comparison between vibration extraction methods for vertically plucked excitation

# 5 Conclusions

An experimental system for measuring string vibration based on a high-speed line-scan camera was built and successfully used. With respect to other contactless methods providing similar results, the main advantages that the described technique offers are the savings in costs, the fact that nonlinearities are avoided, the ability to detect any material, the high available frame-rate, the compact format, and the ease in calibration. A mirror was used to measure the vibration of the string in a second dimension perpendicular to the optical axis of the line camera. Other parts of the experimental set-up, such as the lens and the optical tubes, were designed to result in signals with the desired magnification and focusing.

The captured images of string motion were processed using two different techniques: peak detection plus convolution and edge detection. It was observed that both methods yield similar results when the vibration is strong, i.e. the signal-to-noise ratio is high, but they differ when the signal-to-noise ratio is low. This is due to the different approach on handling the ambient noise in the two methods.

As an example to show the system's ability on detecting string vibration, the waveforms for the three most common string excitation techniques have been presented, for both vertical and horizontal polarizations, when the images were processed with the peak detection plus convolution technique. In the case of plucked and struck excitations, the evolution of the waveform shape due to dispersion is presented. And for the bowed string, the Helmholtz-motion characteristic is identified. As expected, in the spectrums of both horizontal and vertical components of vibration, the $6^{th}$ harmonic is suppressed due to the position of the excitation.

In conclusion, the presented technique to measure string vibrations offers a novel procedure which outcomes in high quality results. With appropriate modifications, this methodology has also been successfully used in other parts of music instruments so as to study the vibration of one precise point of the instrument.

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