Application of High-Speed Line Scan Camera for String Vibration Measurements

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A novel high accuracy experimental equipment for acoustical measurements of vibrating objects has been designed and built. This set-up consists of a high frame rate line scan camera and a custom-built optical lens system. The optical tube is designed to capture maximum amount of light, as well as to provide sufficient magnification. The experimental set-up gives possibility to perform accurate non-invasive measurements of vibration of various parts of musical instruments, such as the strings, bridges, necks, etc. The set-up has been calibrated and successfully used to capture the piano and bass guitar string motion. In addition, the captured video data are presented and explained. A robust method of the vibration data extraction from the recorded video file is presented.

1 Introduction

The methods of a contact free measuring of a vibrating string's motion can be divided into three categories: the electromagnetic, the electric field sensing, and the optical. The electromagnetic methods exploit the Faraday's law. The principle of the string displacement detection is the following: the electromagnetic coil is placed near the string, and the motion of the string induces a voltage in the circuit that is proportional to the string's velocity. By integrating the velocity signal, the displacement of the string can be obtained. This method was used and described in [1]. Electromagnetic devices, like the nonlinear pickup of the electric guitar are the most common way to sense the string vibration [2].

The electric field sensing makes use of the phenomenon, where the capacitance between two electrodes changes, when the distance between them is varied. In the simplest approach, a conducting string is grounded, and DC voltage is applied to an electrode plate nearby. The string's movement modulates the voltage between the string and the plate, and information about the string's placement is obtained *cf.* [3].

Principal drawbacks of the electromagnetic and electric field sensing are the facts that these methods work only for conducting (metal) strings and they may slightly influence the string's motion by damping it. In addition, these devices require extensive calibration, before one can start obtaining meaningful data. The limits and benefits of these methods are discussed in [1, 3].

The optical methods exploit various light or laser emitting and detecting sensors to capture the string's motion. For example, the high speed cameras with appropriate video analysis can be successfully used to measure string vibration [4]. Also, different devices that convert laser light into a uniform parallel beam and detect (with CCD, CMOS sensors) the blocked light (shadows) can ensure the result [5]. This technology may be rather expensive if high quality data with high spatial or temporal resolution is desired. The devices that are based on various photovoltaic detectors have also been relatively successful [6, 7, 8]. The shortfalls of these custom built devices are that they require extensive calibration.

This paper describes and analyses a novel optical string detection technique, which is easy to set up as well as to use, and which produces high-quality high-resolution measurement data. The method is relatively inexpensive, does not require extensive calibration prior to measuring, and it can detect the motion of strings made of any material. The string vibration is measured by making use of the commercially available high-speed digital line scan camera.

2 Measurement equipment

The line scan camera differ from usual digital video camera only with respect to the image sensor geometry. Simply put, in a usual video camera the sensor pixels are placed in rows and columns that form a grid. The line camera sensor consist only of a single (or couple) pixel array. This makes them less expensive compared to usual high-speed cameras. We propose to use commercially produced high-speed line scan cameras that have global shutter technology. This means that all pixels capture light simultaneously, and therefore no image distorting lags influence the result.

In this research we use two monochrome Teledyne Dalsa Piranha2 (1k 67 kHz) line scan cameras. These cameras have 1024 x 1 pixel CCD sensors and a frame rate up to 67 000 frames per second (fps). Pixel depth output is selectable between 8 or 10 bits. The physical dimensions of the camera are 50 x 85 x 50 mm, making them quite small compared to the usual high-speed video cameras. These compact cameras can be placed in narrow cavities, which may be beneficial when measuring real musical instruments. In addition, cameras require a Xcelera-CL PX4 Dual frame-grabber circuit board that can be connected to a usual PC's motherboard via PCI Express® x4 slot. The frame-grabber connects the PC with the cameras and is used to control them and to receive the recorded data.

The cameras can be mounted with suitable commercially available macro lenses. We use custom built optical tube, constructed from spare parts purchased form the Thorlabs® product catalogue. The tube with an adjustable length is fitted with a plano-convex lens that has a suitable focal length. The correct object distance, focal length (tube length), and magnification values are obtained by using the theory of thin lenses.

Further, we will explain the methodology behind the measuring of vibration of selected point on the string, both with respect to the vertical and horizontal vibration planes. Two possible set-up configurations and methods of measuring are presented in the next subsections.

2.1 Two camera set-up

By placing two cameras under the right angle (90°), one can record the vibration of a desired point on the string in both vibration polarizations simultaneously. Figure 1 shows the schematic drawing for the two camera set-up. Camera 1 is recording the position of the string with respect to the horizontal *xy*-plane, and camera 2 records the motion with respect to the vertical *xz*-plane. Here it is assumed that the string in its rest position defines the *x*-axis.

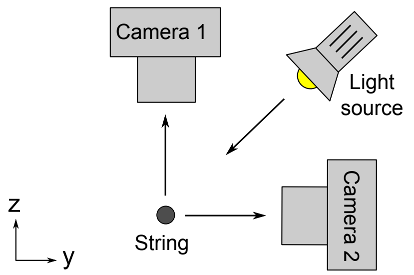

Figure 1: Two camera set-up. Arrows indicate the direction of light propagation.

2.2 Single camera and a mirror set-up

If situation calls for it, a single camera may be used in combination with a mirror. The mirror should be placed behind the string under a 45° angle with respect to the optical axis of the optical tube as shown in Fig. 2. Half of the recorded image will contain displacement data for the vertical, and other half for the horizontal direction.

This set-up has some drawbacks compared to the previous set-up configuration. It is hard to focus the image in its entirety, because the mirror image of the string appears further compared to the string itself. Some compromise in the image quality has to be made, due to the narrow depth of focus of the thin lens that is used here. In addition, the effective spatial resolution (pixels per space unit) of obtained images is two times lower.

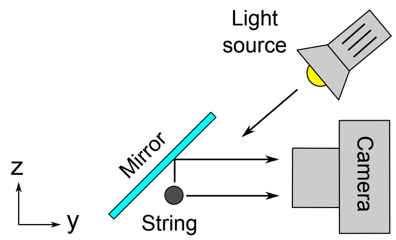

Figure 2: Single camera and a mirror set-up. Arrows indicate the direction of light propagation.

In both experimental set-up configurations, one should provide a plentiful amount of light. Especially, if one is recording the vibration using high fps values. For high fps value the exposure time becomes extremely short, thus requiring a powerful light source in order for the object to be registered by the light sensitive sensor of the line camera (*vide* Figs. 1, 2).

2.3 Calibration and optical aberration

Figure 3 shows examples of recoded video data. Since the image sensor of the line camera consists of a single pixel array the recorded video can be represented as a 2D image, where the vertical axis signifies the pixel number, and the horizontal axis corresponds to the recorded frame number. The images in Fig. 3 are taken under different lighting conditions, and of strings made of different materials. The detailed information of the used strings and the excitation manners are provided in Sec. 4.

The calibration of the frame pixel number to the space scale, and the frame number to the time scale is achieved as follows. The known frame rate of the recorded video (image) is used to map the time scale with the frame numbers. To establish the calibration between pixel numbers and the space units, an object with known dimensions is used. We use a paper with thin parallel lines drawn on it.

It was empirically determined that the image aberration of proposed optical tube was insignificant. This conclusion holds for the following range of the set-up parameters: the string deflection amplitudes < 0.5 cm; the object distance 3 – 8 cm; the lenses with focal lengths 25 – 50 mm; the desired image magnification up to three times.

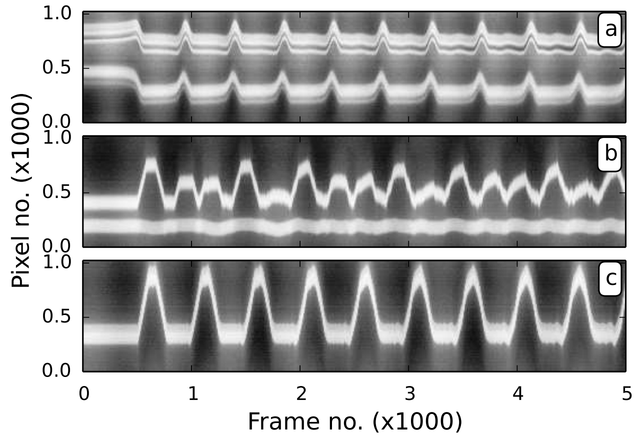

Figure 3: Image files as recorded by the line scan camera under different lighting conditions. a) The bass guitar string motion as recorded by the camera and a mirror set-up. Top half of the image shows the displacement u_z and bottom half the u_y. b) The nylon string recorded by the camera and a mirror set-up. c) The piano string's vertical displacement u_z as recorded by a single camera.

3 Vibration data extraction

Depending on the quality of the obtained images (videos), two methods of image analysis for the extraction of string displacement data can be applied. For images that have poor quality (i.e., out of focus, the variation in pixel depth is small, specular reflection, etc.) the image frame correlation method is recommended. When the image quality is high (i.e., good contrast and no reflection), edge detection algorithms can be used [9, 10].

3.1 Frame correlation

The frame correlation method is based on the discrete 1D correlation integral transform. Figure 4 shows the method application for the case that is qualitatively similar to the case shown in Fig. 3 a. The image depth variations are small (< 20 levels), and the specular reflection creates a rather complicated digital imprint of the string's shape p. In order to extract the placement information of the digital impression of the string p of the recorded frame, a kernel k is constructed. The kernel is selected to be similar to the image p feature we are interested in tracking. By correlating p with k, a correlation frame profile c is obtained. As one can see a resulting profile c has a maximum (shown by bullet). This maximum corresponds to the position of the selected image feature, and can be understood as a string deflection position u (shown by the vertical line). The procedure is repeated for all the remaining recorded frames, thus reconstituting the string deflection time series.

Figure 5 a shows how accurately the frame correlation method is tracing the image of the string (the selected image feature). Figure 5 b shows the corresponding calibrated string displacement waveform $u(t)$.

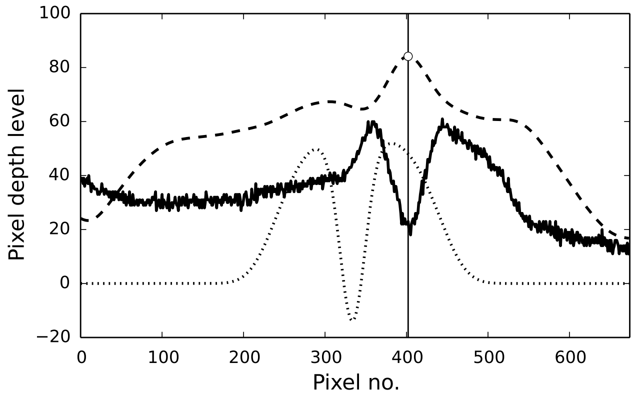

Figure 4: The correlation of a single frame. Solid line p shows the recorded image profile. The correlation kernel k is shown by dotted line. The correlated frame profile c is shown by dashed line. Vertical line show the position of the image region that is most similar to selected kernel profile. Higher depth levels correspond to image regions with higher illumination.

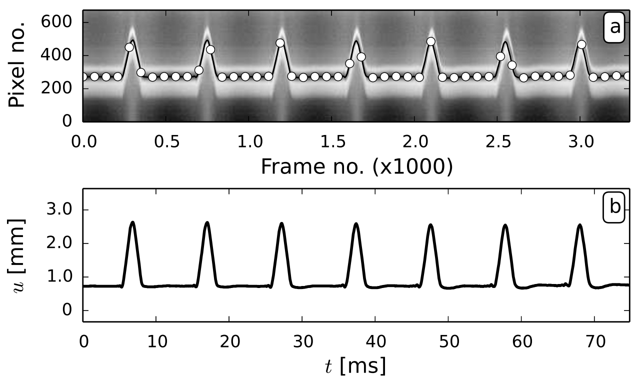

Figure 5: Vibration of a bass guitar G string, with a triangular initial condition. a) The recorded image. Displacement of the maximum of the correlated frame c relative to the image is shown by solid line marked by bullets. b) The corresponding extracted and calibrated displacement $u(t)$.

3.2 Edge detection

As pointed out above, if the image quality is good enough (*vide* Figs. 3 b, 3 c), then the existing and well developed edge detection packages can be used. By selecting one of the two edges of the recorded string image, and by tracking it through all frames, the string displacement data are extracted.

3.3 String displacement

After the string displacement data in the vertical direction $u_z(l, t)$, and in the horizontal direction $u_y(l, t)$ is extracted by using ether the frame correlation or the edge detection methods, it can be used for the reconstruction of the string's motion with respect to a *yz*-plane (*vide* Figs. 6, 8, and 9). Below, three different examples of measured string vibrations are presented.

4 Measurement examples

4.1 Plucked guitar string

Figure 6 shows the vibration of the G string of the bass guitar (Horner Model B500/Mr 4-strings). Vibration data correspond to the video image shown in Fig. 3 a. The string's speaking length $L = 86.5$ cm, and fundamental frequency $f = 98$ Hz. The guitar string is plucked at $x = 9.0$ cm (measured from the bridge) using the index finger (*digitus secundus*). The resulting string vibration is recorded at the point $l = 13.5$ cm.

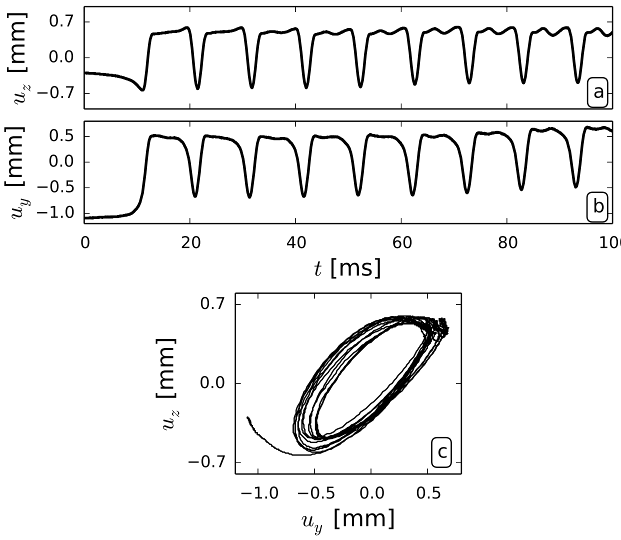

Figure 6: Vibration of the plucked bass guitar string. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String vibration in a *yz*-plane. The time history is assumed to starts a few milliseconds before the finger looses a contact with the string.

Figure 6 c shows two polarizations as a polar plot, in which each point is defined by the horizontal and vertical signal values of Figs. 6 a and 6 b. A typical elliptical trajectory of motion is seen, which is comparable to the results obtained by Pakarinen and Karjalainen in [3].

4.2 Vibration of a nylon string against a rigid obstacle

Figure 8 shows the vibration of a monochord with an elastic nylon string. The vibration corresponds to the video image shown in Fig. 3 b. The elastic nylon string with the speaking length $L = 91$ cm is taken from a brand new set of acoustic guitar strings (string E). The monochord is tuned to a frequency of 210 Hz approximately.

Figure 7 shows the positions of the metal obstacle relative to the string, the initial shape of the string, and the recording point located at $l = 27$ cm. The obstacle is placed parallel to the string at rest at the distance $x = 50$ cm. The surface of the metal object is flat and extends for 2 cm. An initial condition that has a triangular shape with a peak located at the distance x = 71 cm is induced by using a thin cotton thread. A sufficiently fast cut (snap) of the thread is achieved by burning it with a flame (the average duration of the snap for the cotton thread used and for the tension introduced in it, was approximately 1 ms).

The measurement shows that the obstacle has a strong influence on the vibration evolution. Nonlinear limitation of the string displacement amplitude by the obstacle produces a step-like waveform of the string vibration during first couple of fundamental periods. The experimental results presented here are comparable with measured and numerically simulated results presented by Rank and Kubin in [11].

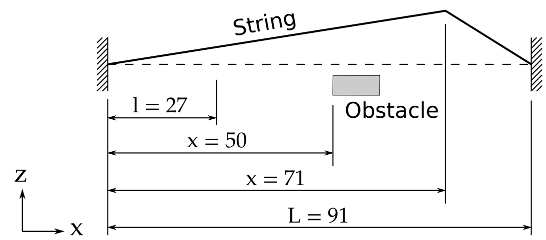

Figure 7: Initial triangular shape of the string in a monochord. Position of the rigid obstacle relative to the string at x = 50 cm. The string vibration recording point shown by distance l.

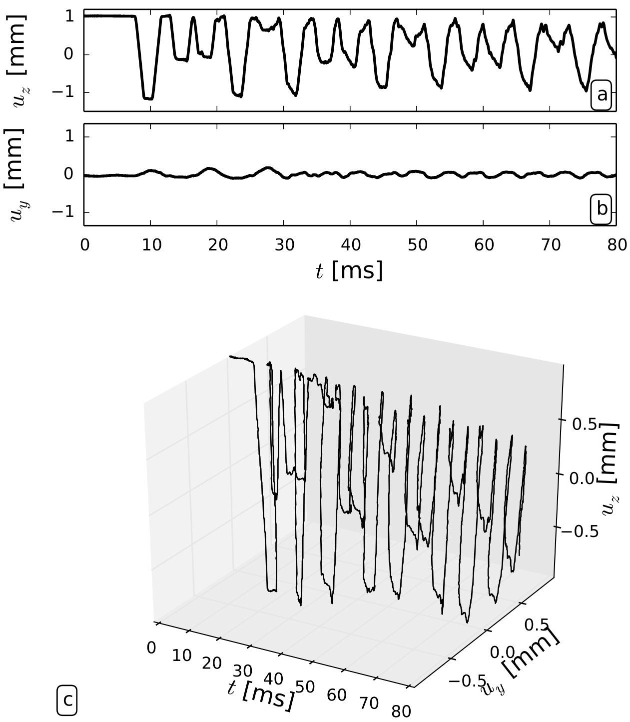

Figure 8: Vibration of a nylon string against a flat metal obstacle. a) The string displacement in the vertical direction. b) The string displacement in the horizontal direction. c) String vibration in the yzt-space.

4.3 Stiff piano string

Figure 9 shows the vibration of a stiff steel string in a monochord. The vibration corresponds to the video image shown in Fig. 3 c. A monochord is constructed using a steel string of length L = 1 m that is used in piano manufacturing. The linear mass density of the string μ = 7.8 g/m and the string's diameter d = 1.125 mm. The monochord is tuned to the frequency of 135 Hz approximately.

An initial condition that has a triangular shape with a peak located at the point x = 79.5 cm is induced by using the cotton tread technique explained in the previous subsection.

The measuring shows that the resulting vibration of the string is strongly dispersive. The dispersion is caused by the fact that the high frequency oscillations travel along the string faster compared to the low frequency wave components.

The obtained result are comparable to previously reported measurements by Podlesak and Lee in [12].

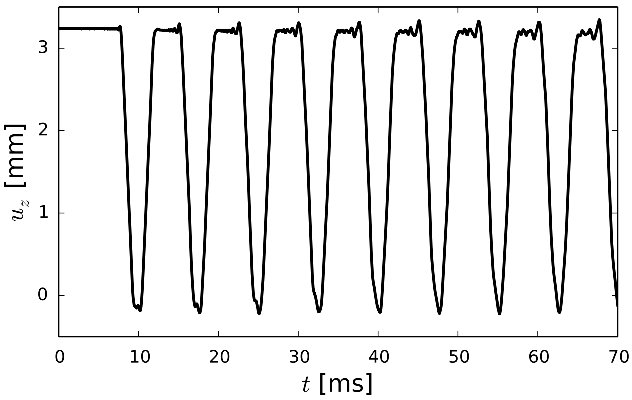

Figure 9: Vibration of a stiff steel string in the vertical direction showing the dispersion effect.

5 Discussion

The presented optical experimental set-up of string vibration measurement worked well for our purposes. However, if situation demands it, the method can be easily improved. Cameras with a better spatial resolution i.e. larger number of pixels in the sensor array, or greater frame rate are commercially available.

If recordings of the string's displacement at several points along the string are needed, the multiple sets of cameras may be used. The hardware solutions that support the using of more than two cameras simultaneously are available.

The proposed method or similar methods can be and have been used for other purposes [13]. In the context of the musical acoustics, the other vibrating parts of the string instruments like bridges, frets, necks, etc. have been successfully measured by the authors. The camera has also been used to capture rotatory motion of a small cylindrical object, by tracking the position of the line drawn on the side of the cylinder relative to the edge of the object.

6 Conclusions

The novel contactless optical method of string vibration measurement was demonstrated, and the recorded video with the extracted displacement data were presented.

The proposed method uses a commercially available digital line scan cameras and a custom built optical tube. Two possible experimental measurement set-up configurations were presented. It was shown that the method does not have the usual drawbacks that are associated with the other widely used contactless string measurement techniques, such as those based on the electromagnetic or electric field sensing, and methods based on the various photovoltaic detectors or the high-speed digital camera usage.

A brief overview on the ways to improve proposed measurement set-up was presented. To obtain the measurement results with a higher quality one can purchase line scan cameras that have higher number of pixels in the image sensor or recording frequency (fps values).

In conclusion, the high-speed line scan cameras have been successfully used for high quality contactless optical string vibration measurements. The recorded vibration data had a high spatial and temporal resolution.

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