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Application of high-speed line scan camera for acoustic measurements of vibrating objects

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Summary
A novel high accuracy experimental equipment for the detection and measurements of vibrating objects has been designed and built. The set-up consists of a high frame rate line scan camera and a custom-built optical lens system. The optical tube is designed to provide a sufficient magnification, in order to record the motion of small parts of musical instruments such as thin strings. Also, the magnification helps to register small vibration amplitudes. The experimental set-up gives possibility to perform accurate high quality contactless measurements of vibration of various parts of musical instruments, such as the strings, necks, soundboards, bridges, etc. The high temporal resolution of the cameras allows to capture the effects associated with various aspects of dispersion in the strings. The set-up has been calibrated and successfully used to measure piano and bass guitar string vibrations. In addition, a robust method for the vibration data extraction from the recorded video is presented.

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1. Introduction

In the field of musical acoustics, the vibration measurements of various parts of stringed instruments are important to determine and describe the underlying physics. Of great interest is the vibrational motion of strings, necks, frets, bridges and soundboards.

The contactless string vibration measurement methods 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, similar to the nonlinear pickup of the electric guitar are the most common way to detect the string vibrations [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].

The principal drawbacks of the electromagnetic and electric field sensing are the facts that these methods work only for conducting (metal) strings, and they 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 of vibration measurement that can detect vibration of necks, frets, bridges or soundboards in addition to string vibration, exploit various light or laser emitting and detecting sensors. For example, the high speed digital cameras with appropriate video data processing procedures can be successfully used to measure string vibration [4]. Also, the 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], *cf.* [6]. This technology may be rather expensive when a high quality data with a high spatial or temporal resolution is desired. Different laser vibrom-

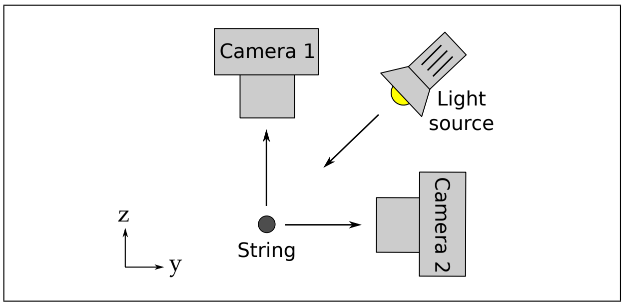

Figure 1. Two camera set-up. Arrows indicate the direction of light propagation.

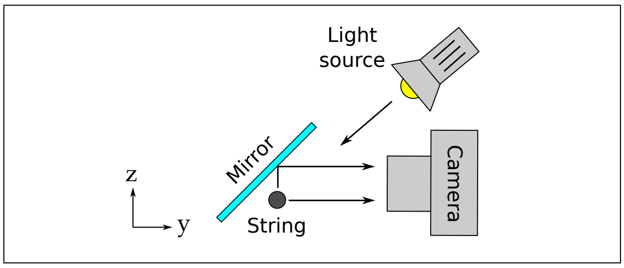

Figure 2. Single camera and a mirror set-up. Arrows indicate the direction of light propagation.

eters can successfully detect the surface vibration of soundboards with a high accuracy. The devices that are based on various photovoltaic detectors have also been relatively successful [7, 8, 9]. The main lack in using these custom built devices is that they require extensive calibration.

In this paper we describe and analyse a novel optical vibration detection technique, which is easy to set up as well as to use, and which produces high-quality high-resolution measurement data. This experimental measurement method was also considered in [10, 11, 12]. The method presented is relatively inexpensive, does not require preliminary extensive calibration, and it can detect the motion of objects made of any material. The vibration motion is measured by making use of the commercially available high-speed digital line scan camera.

2. Measurement equipment

A line scan camera differs from a usual digital video camera by the image sensor geometry. Usually the video camera sensor's pixels are placed in rows and columns that form a grid. The line camera sensor consists only of a single (or couple) pixel array(s). This makes them less expensive, compared to usual high-speed cameras. We propose to use commercially produced high-speed line scan cameras that have the 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 tele-macro or macro lenses. We use a custom built optical tube, assembled from spare parts purchased from 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.

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. The camera 1 is recording the position of the string with respect to the horizontal xy-plane, and the camera 2 records the motion with respect to the vertical xz-plane. Here it is assumed that the direction of the string at rest defines the x-axis.

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 the other half for the horizontal direction.

This set-up has some deficiencies compared to the previous set-up configuration. It is difficult to focus the image entirely, because the mirror image of the string appears further compared to the string itself. Some compromise in the image quality has to be made by using the thin lenses with a short focus length. In addition, the effective spatial resolution (pixels per space unit) of the obtained images is two times lower.

In both experimental set-up configurations, one should provide a plentiful amount of light. Especially, in case if one records the vibration using high fps values, and the exposure time becomes extremely short.

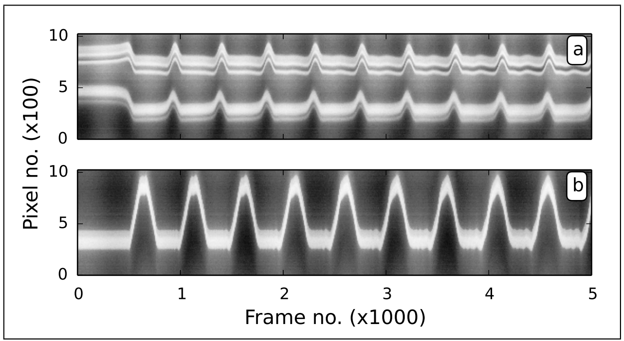

Figure 3. Image files as recorded by the line scan camera under different lighting conditions. a) The bass guitar string motion as recorded by using the camera and a mirror set-up. Top half of the image shows the displacement u_z and bottom half the u_y. b) The piano string's vertical displacement u_z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

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 for two different strings. The detailed information of the used strings, and the excitation manner is 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 relation between the 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 < 5 mm; the object distance 30 – 80 mm; the lenses with focal lengths 25 – 50 mm; the desired image magnification up to three times.

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. In case of a high image quality (i.e., good contrast and no reflection) the edge detection algorithms can be used [13, 14].

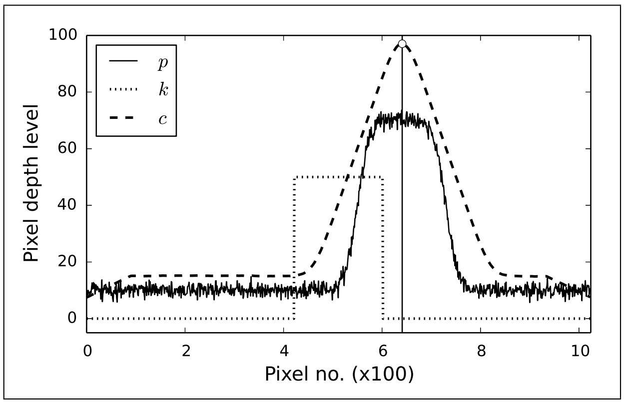

Figure 4. The correlation of a single frame. Solid line p shows the recorded image profile. The correlation kernel k is shown by dotted line. The correlated frame profile c is shown by dashed line. Vertical line show the position of the image region that is most similar to selected kernel profile. Higher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

3.1. Frame correlation method

The frame correlation method is based on the discrete 1D correlation integral transform. Figure 4 shows an example of the application of the method. The light reflected from the string creates a digital imprint of a measured object'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 in shape 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 sharp maximum (shown by bullet). This maximum corresponds to the position of the selected image feature, and can be understood as the string's deflection position u (shown by the vertical line). The procedure is repeated for all the remaining recorded frames, thus reconstituting the string's 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 $u(t)$.

3.2. Edge detection method

As pointed out above, if the image quality is good enough (*vide* Fig. 3 b), 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.

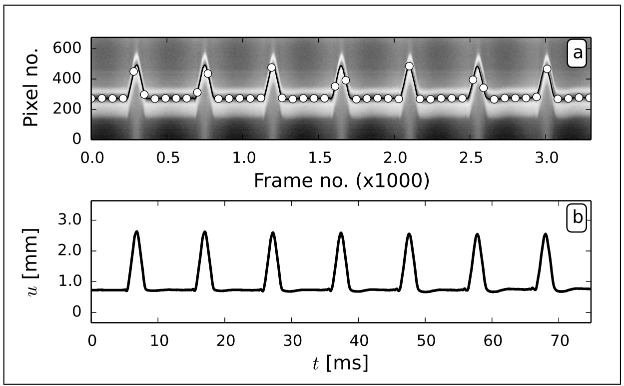

Figure 5. Vibration of a bass guitar G string, with a triangular initial condition. a) The recorded image. Displacement of the maximum of the correlated frame c relative to the image is shown by solid line marked by bullets. b) The corresponding extracted and calibrated displacement $u(t)$.

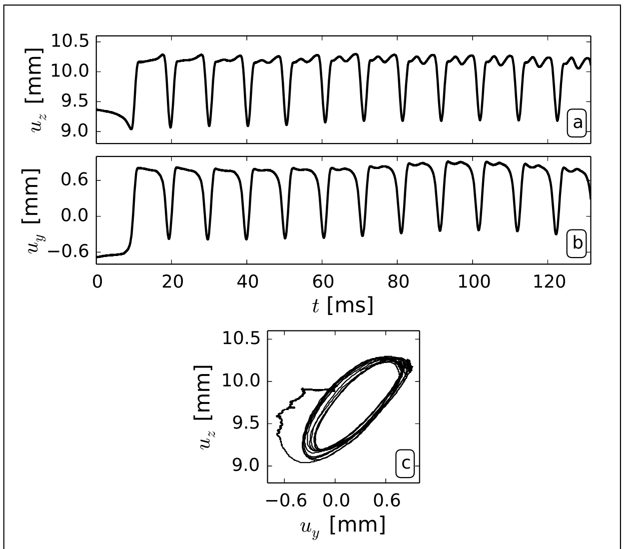

Figure 6. Vibration of the bass guitar string plucked with an index finger. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String motion with respect to yz-plane.

4. Measurement examples

In this section a electric guitar string and a stiff piano string vibrations captured by the single camera and a mirror set-up are presented and described.

4.1. Guitar string vibration

The vibration of the G string of a solid bodied electric bass guitar Hohner Model B500/Mr is considered. The measured string has a speaking length $L = 865$ mm and diameter $d = 1.651$ mm. It is tuned to produce tone G_2 (fundamental frequency $f = 98.0$ Hz).

Figure 6 shows the vibration of the string when plucked with an index finger at the point $x = 90$ mm, measuring from the guitar bridge. The resulting displacement in the vertical direction $u_z(l, t)$, and in the

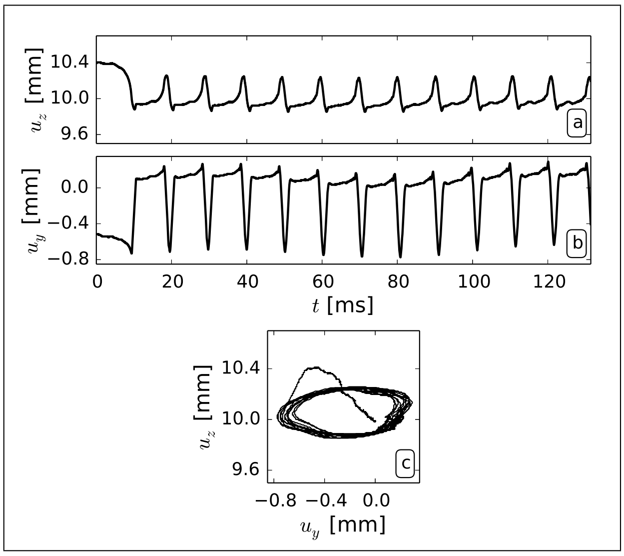

Figure 7. Vibration of the bass guitar string plucked with a plectrum. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String motion with respect to yz-plane.

horizontal direction $u_y(l, t)$ measured at $l = 135$ mm are shown in Figs. 6 a and 6 b respectively. The string's motion with respect to yz-plane is shown in Fig. 6 c, where a typical elliptical trajectory of motion is seen. This result is comparable to the results obtained by Pakarinen and Karjalainen in [3].

Figure 7 shows the vibration of the bass guitar string when it is plucked with a plastic plectrum at the point $x = 90$ mm. In a similar manner, as shown in previous figure, the measured vibrations in the vertical direction $u_z(l, t)$, and horizontal direction $u_y(l, t)$ are shown in Figs. 7 a, and 7 b respectively. Figure 7 c shows the string motion with respect to yz-plane.

The comparison of both cases reveals that the string plucked with a finger has a much smoother waveform, and stronger dispersive behaviour both in the vertical and the horizontal vibration directions. Also, the elliptical trajectory of motion in yz-plane of the finger plucked string appears more oval compared to the motion of the string, which is plucked with a plectrum. Sharper waveform profiles in the case of the plectrum excitation are responsible for the increasing of the upper partial content of the string motion spectrum. This in turn, is responsible for the guitar timbre that also has an enriched high-frequency partial content.

Figures 8 and 9 show the string vibration resulting from an initial condition that has a triangular shape with a peak located at $x = 90$ mm. The string excitation is performed in the following manner. A thin cotton thread is looped around the string at $x = 90$ mm and the string is displaced to a suitable amplitude in the vertical direction. A sufficiently fast snap of the thread is achieved by burning it with a flame. Figure 8 shows the resulting vibration right after the

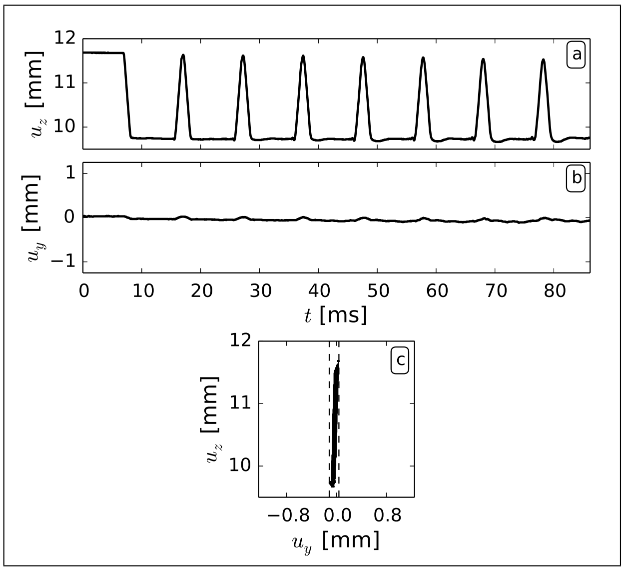

Figure 8. String vibration right after the string was excited in the vertical direction. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String motion with respect to yz-plane. Dashed lines indicate the amplitude extent in the horizontal direction.

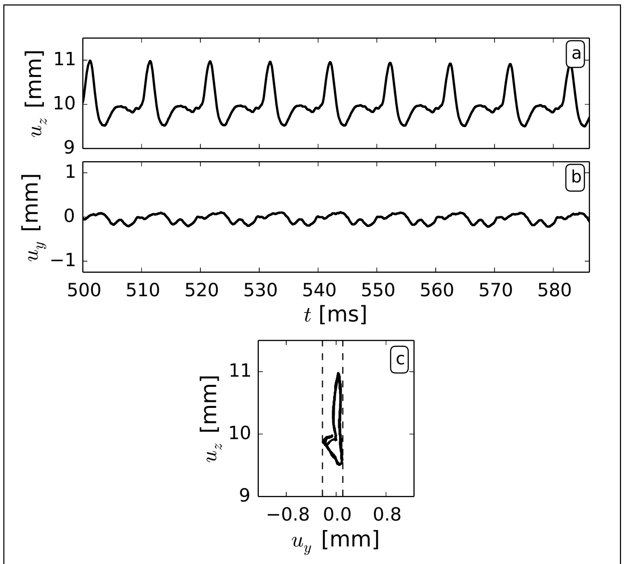

Figure 9. String vibration 0.5 s after excitation in the vertical direction. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String motion with respect to yz-plane. Dashed lines indicate the amplitude extent in the horizontal direction.

string is released and Fig. 9 shows the waveform of the same vibration 0.5 s later. Based on numerous experiments, it was estimated that the proposed method of the string excitation provides the string vibrations mainly in one vibration plane (xz-plane) for approximately 15 periods.

The comparison of Figs. 8 and 9 shows that with the passage of time, the string's trajectory of motion in yz-plane changes and becomes more complicated.

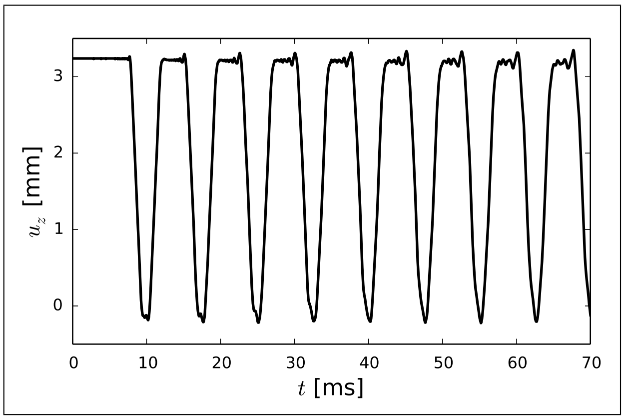

Figure 10. Vibration of a stiff steel string in the vertical direction showing the dispersion effect.

In addition, the amplitude of the vibration with respect to the y-axis becomes approximately two times larger. This phenomenom indicates that part of the transversal vibration energy distributed initially in a vertical plane is transferred to the horizontal plane. Most likely this is due to the different termination conditions for the vertical and horizontal string motion at the guitar bridge and the guitar nut.

4.2. Stiff piano string vibration

Figure 10 shows the vibration of a stiff steel piano string in a monochord. The vibration corresponds to the video image shown in Fig. 3 b. 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 $\mu = 7.8$ 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 $x = 795$ mm is induced by using the cotton thread 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 results are comparable to previously reported measurements by Podlesak and Lee in [15].

5. Discussion

In this paper the vibration examples of two different strings are presented. In the context of musical acoustics, other vibrating parts of the stringed instruments like bridges, frets, and necks have been successfully measured by the authors. For example the vibration of the guitar neck can be measured by video recording the edge of the neck with the line scan camera, and applying the video data processing methods described above on the recorded video. The camera has also been used to capture fast rotatory motion of a small cylindrical object (diameter 1 mm), by tracking the position of a marking line drawn on the lateral side of the cylinder.

For the presented examples, the optical experimental set-up of vibration measurement worked well. However, if situation demands it, the method can be improved. Line scan cameras with a better spatial resolution, i.e. larger number of pixels in the image sensor, or higher frame rate are commercially available. If recordings of object's displacement at several locations are needed, the multiple sets of cameras may be used. The hardware solution that supports the use of more than two cameras simultaneously is available.

6. CONCLUSIONS

The novel contactless optical method of vibration measurement was demonstrated by measuring vibrations of the electric bass guitar, and a stiff piano string. The recorded videos with the extracted displacement data were presented.

The proposed method uses a commercially available digital line scan camera, 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 deficiencies that are associated with the other widely used contactless vibration or string displacement measurement techniques, such as methods based on the electromagnetic or electric field sensing, and methods that are based on the various photovoltaic detectors or the high-speed digital camera usage.

A brief overview on the ways to improve the 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 higher recording frequency (fps values).

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

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