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Vision-based Sensor System for Vibration Measurement

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ABSTRACT

An on-line vision based vibration measurement system has been developed. Conventional methods of data acquisition for vibration measurements involve employing physical sensors such as accelerometers or other contact-based sensors on the vibrating target. The measurements resulting from physical sensors provide localized reading. Moreover, installation is sometimes difficult and there is an added disadvantage of degrading the accuracy of measurements by employment of an additional mass. However, the advent of latest image processing techniques allow for minimizing these drawbacks, by providing intuitionist exhibition of the actual vibration. In this study, a camera acquires video of vibrating target continuously at desired frame rate. Since the vibration in the target results in transitional shift of target from one image to next image, it is shown here that the shift between them can be used to extract the amplitude and frequency of vibration. Study carried out on various systems is presented here and results show that with sub-pixel level estimation, vibrations of smaller amplitude can also be detected effectively. Results using different interpolation on images are discussed in the end of the article.

Keywords

Phase Cjorrelation, Sub pixel, Interpolation

INTRODUCTION

The ability of a machine to perform its intended function in light of the inevitable aging and degradation resulting from operational environments, imbalance, misalignment of components, and even loose connections defines overall “health” of the machine.[1] Machines are inevitably prone to vibration causing degradation in performance if vibration amplitudes cross a permissible threshold. The most natural method to reduce the vibratory level is to act at the level of vibration sources. Nevertheless, at times, it is necessary to make use of anti-vibration systems that enable the minimization of the vibratory level as much as possible.[2] In addition, the installation of anti-vibration systems makes it possible to decrease the dynamic stresses in the structure holding the dynamic sets and thus to increase the reliability of the installed components. From an industrial point of view, it is proved that, in order to be viable, these mechanical systems must meet certain requirements such as low cost (development, manufacture, maintenance), minimum mass of the system, and possibility to follow-up the industrial evolution of the product. Although these anti-vibrating systems ensure minimized vibration, it is necessary to monitor the vibration of the net system. Trends in the data acquired through sensors provide health information about the machine and help detect machine faults early which prevent unexpected failure and costly repair. This warning sign can provide three months of lead time before the actual failure date.

VISION SENSOR SYSTEMS

With anadvent of image processing techniques, it has become possible to develop anon-line vision-based vibration monitoring system. Phase correlation technique, instead of the classic cross correlation technique, is proved to be more accurate and faster for motion extraction in vertical and horizontal directions.[3]The integer level motion extraction results are extracted by locating maximum values in cross-correlation matrices between the two-Dimensional Discrete Fourier transform (2D DFT) of the base template and the object images. Although the phase correlation algorithm is theoretically more complicated and time-consuming than the time-domain cross-correlation algorithm, the integer level motion extraction can be achieved in only one calculation.

An efficient sub-pixel level motion extraction algorithmis proposed in our research with consideration for both efficiency and accuracy. Weighted Centroid interpolation has been implemented in this study. Results using weighted centroid interpolation have been attached in Section 4. Two experiments under laboratory conditions are carried out to evaluate the performance of developed sensor system.

The rest of the paper is organized as follows: Section 2 introduces the components and capability parameters of the high-speed vision-based sensor system. Section 3 presents theory of phase correlation technique and two sub-pixel refinement approaches. Section 4 evaluates the performance of a developed sensor system through a motion a simple pendulum test. Discussions and outlooks are also presented in this Section. Section 5 concludes the whole article.

1. VISUAL SENSOR MEASUREMENT SYSTEM

The developed vision-based sensor system mainly consists of a high-speed camera, Mikrotron and a computer (Intel xeon CPU 3.60 GHz, 32GB ram, 64-bit OS) as shown in Figure 1 (a) and(b). A high-performance charge-coupled device (CCD) which can capture 8-bit gray-scale images (300 pixel X 300 pixels) with, at most, 1000 fps is integrated into the camera head as the image receiver. The proposed algorithm has been incorporated in the sensor system using Visual Studio C++ and Open Source Computer Vision (OpenCV) library on the computer. VisualiMarc software is used to capture the video at the desired frame rate and resolution.The programmed algorithm consists of 4 modules, namely, Video_from_USB_cam, Mouse_acquire, Phase_Correlate, and Frequency_Analysis. The Video_from_USB_cam module interfaces the high-speed camera to the computer, Mouse_acquire helps choose the template area by clicking on the video, Phase_Correlate gives the displacements in x-y direction in successive frames using phasecorrelation and sub-pixel interpolation, and Frequency_Analysis performs 1-D DFT of the displacement sequence to find the frequency spectrum. While acquiring the video of any distant vibrating target, artificial contrast templates are recommended to be fixed on the object as shown in Figure 2 which depicts a Scanning Electron Microscope platform with artificial templates fixed on the video capturing side. Naturally contrasting textures or edges would be sufficient in case of high resolution, closely spaced objects.

(a) **(b)**

Fig. 1 Computer with VisualiMarc (software for video capturing) and Visual studio/OpenCV for algorithm implementation(a), Mikrotron high speed camera with extended lens(b)

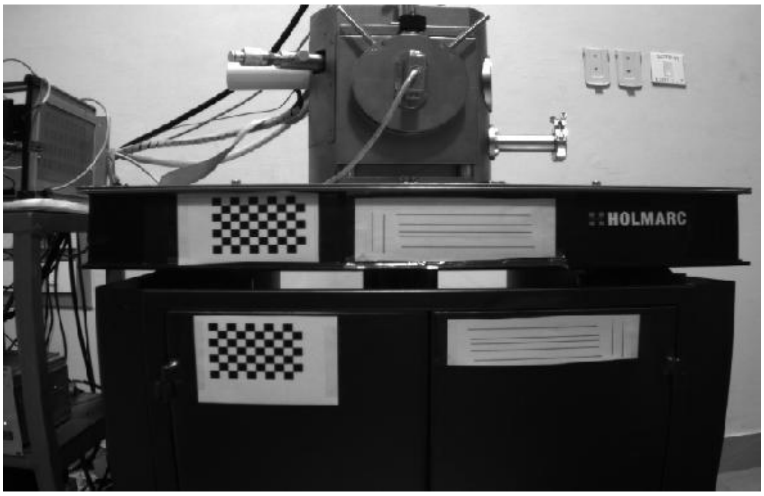
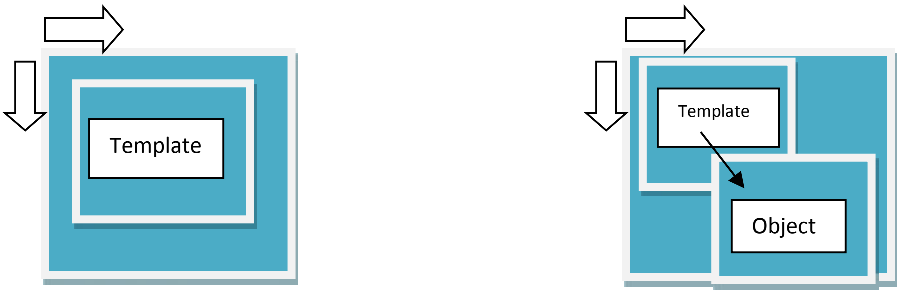


Fig. 2 Scanning electron microscope platform with checkbox artificial template.

2. METHODOLOGY

In this study, a high speed camera (Mikrotron) captures video of the vibrating target at 20fps. A template image, where vibration is most likely to occur, is selected from the first frame of the video sequence as shown in Figures 3 (a) and (b). In the consecutive frames, object images at the same offset from the origin (left-top corner) with respect to the template are cropped. The analysis is carried out between these object images and the template image.[4] In the presence of vibration, pixel locations will change in consecutive frames and these translational shifts can be calculated by phase-correlation between the template image and nth object image. Integer level displacements are limited by the dimension of a pixel. Thus, sub-pixel motion estimation has also been included for better accuracy.



(a) (b)

Fig. 3 Initial template selection in first frame (a), Object images shifts in consecutive frames due to vibration (b).

- Integer Displacement Measurement using Phase Correlation

Phase Correlation between 2 images is obtained by multiplying the DFT of one image by the conjugate of the DFT of second image element wise and finally normalizing it element wise.

2D Discrete Fourier Transform of an M x N image 'f' is:

$$G(u,v) = \sum_{x=0}^{M} \sum_{y=0}^{N} f(x,y) e^{-2\Pi i(\frac{ux}{M}+\frac{vy}{N})} \qquad (1)$$

Now let R be the cross-power spectrum of the DFT of template image (G_a) and DFT of successive object images (G_b). $\circ$ is Hadamard Product (or entry-wise product). Using Eq 1, we have,

$$R(u,v) = \frac{G_a \circ G_b^*}{\left|G_a \circ G_b^*\right|}$$

$$= \frac{G_a \circ G_a^* e^{2\pi i(\frac{ux}{M}+\frac{vy}{N})}}{\left|G_a \circ G_a^* e^{2\pi i(\frac{ux}{M}+\frac{vy}{N})}\right|}, \qquad \text{(Fourier shift property gives } G_b = G_a\, e^{-2\pi i(\frac{u\Delta\Delta}{M}+\frac{v\Delta\Delta}{N})}\text{)}$$

$$= e^{2\pi i(\frac{ux}{M}+\frac{vy}{N})}, \qquad (2)$$

since the magnitude of an imaginary exponential always is one, and the phase of $G_a \circ G_a^*$ always is zero.

Inverse 2D DFT of MxN image 'G' is:

$$g(x,y) = \sum_{u=0}^{M}\sum_{v=0}^{N} G(u,v) e^{2\pi i(\frac{ux}{M}+\frac{vy}{N})} \qquad (3)$$

Subsequently, the cross-power spectrum matrix R from Eq. 3 is converted back into the spatial domain using Eq. 4. The inverse Fourier transform of a complex exponential is a Kronecker delta, i.e. a single peak as shown in Figure 4:

$$r(x,y) = F^{-1}\{R\} = \delta(x+\Delta x, y+\Delta y) \qquad (5)$$

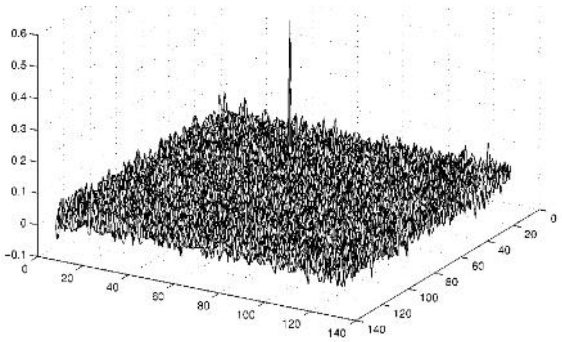


Fig. 4 Spatial domain representation of Phase-Correlation matrix

Matrix 'r' will have a peak whose coordinates correspond to maximum x-y displacements between the two sets of images and smaller peaks at all other coordinates.

Finally, from Eq. 5

$$(\Delta x, \Delta y) = \arg\max\{r\}_{(x,y)} \qquad (6)$$

where Δx and Δy are integer-level displacements in horizontal and vertical directions respectively.

Since the location information of the maximum cross-correlation value has a significant relationship with the coordinate translation, this image registration algorithm provides a simple and intuitive way to find the movement between two images. For a vibration video containing a series of images, the motion information can be easily extracted when the location of maximum cross-correlation value is searched repeatedly between the 2D DFT of the base image and every object image in the following video sequence. According to the

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analysis above, the procedure of phase-correlation (PC) based motion extraction algorithm is summarized as follows:

1. Capture the video and make sure the moving target is always in the photographic range.

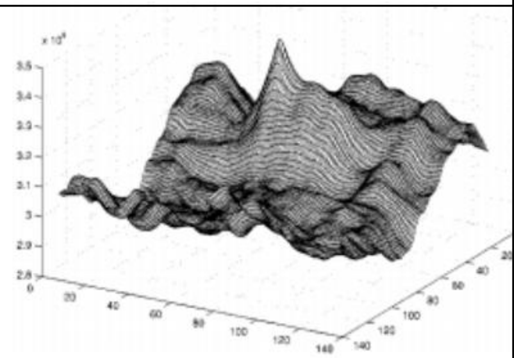
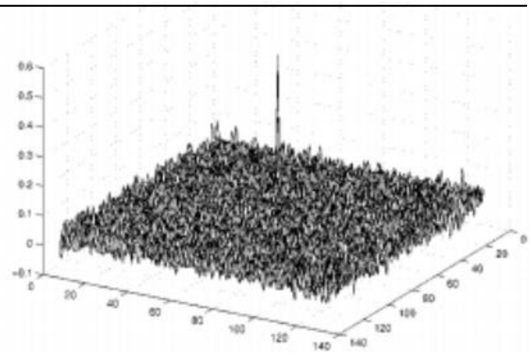
2. If video resolution is satisfactory, artificially introduce a contrasting template on the vibrating target for better identification.

3. Cut the template image in the first frame and cut the object images to be aligned in the following video image sequence at the same offset.

4. Calculate the phase-correlation matrices between the 2D DFT of the template image and every object image. Then, record the coordinates of the maximum value in every phase correlation matrix.

Eventually, the image motion in the horizontal and vertical directions can be calculated using these coordinate information. For the reason that the change of coordinate in obtained cross-correlation matrices represent pixel movement in practice, the PC-based motion extraction algorithm provides an effective approach to realize the displacement measurement.

) Comparison of Cross-Correlation and Phase Correlation

Cross Correlation	Phase Correlation
	
1. $R(x,y) = \sum_{x',y'}(T(x',y').I(x+x',y+y'))$ 2. $p(x,y) \, X F^{Z1}\{P\} \, X¢(x \Gamma \zeta x, y \Gamma \zeta y)$ 2. Matrix 'R' is computed by moving 'T, matrix on 'I' matrix. Here, 'I' would be the original image and 'T' he smaller template.	1. $P(u,v) \, X \frac{G_a \, o G_b^*}{\lvert G_a \, o G_b^* \rvert}$

'R' is Cross Correlation matrix at a every, 'I' is the Original image and 'T' is the Template image which is matched throughout 'I'. 'p' is Phase Correlation matrixin spatial domain, G_a and G_b are DFT of Template and Object images of equal sizes for computing PhaseCorrelation.

Advantage of phase correlation method compared to the cross correlation method is the accuracy by which the peak of the correlation function can be detected.[5] It provides a distinct sharp peak at the point of registration whereas the standard cross correlation yields several broad peaks and a main peak whose maximum is not always exactly centered at the right point. A second important advantage of this method is due to whitening of the signals by normalization, which makes the phase correlation notably robust to those types of noise that are correlated to the image function, e.g., uniform variations of illumination, offsets in average intensity, and fixed gain errors due to calibration. Most importantly, the displacements are found in one calculation unlike the template-matching method used in cross-correlation.

- Sub-pixel Refinement using Weighted Centroid Interpolation

Bilinear Interpolation determines the grey level value from the weighted average of the four closest pixels to the specified input coordinates, and assigns that value to the output coordinates. [6] In this study, neighboring region weighted centroid based estimation is adopted. A weighted centroid of 5x5 region around the peak of Phase-Correlation matrix is calculated to achieve sub-pixel accuracy as given below:

$$(\zeta x, \zeta y)\ X weightedCentroid\{\max\{\arg r\}\}_{(x,y)}, \qquad (8)$$

where $(\zeta x, \zeta y)$ are horizontal and vertical sub-pixel displacements, respectively.

EDGE EFFECT: WINDOWING OF IMAGE

Image of the vibrating target is translated linearly in spatial domain rather than circularly, the calculated phase correlation *r* does not directly indicate shift in the image with respect to template. These edge effects can be minimized by multiplying image by a window function (such as Hamming, Hanningor Tukey windows), or by zero padding of images at the edges. Hanning window is adopted for this study.

AVERAGING OF SPECTRA

Spectral analysis of the shifts in both horizontal and vertical directions can be computed and analyzed to estimate the frequency and direction of vibration. Due to noise in imaging and sub-pixel estimation, the spectra may not reveal true peaks of vibration. To avoid this, the consecutive spectra obtained are averaged to obtain a time averaged spectra. By doing this, only the true peaks are revealed.

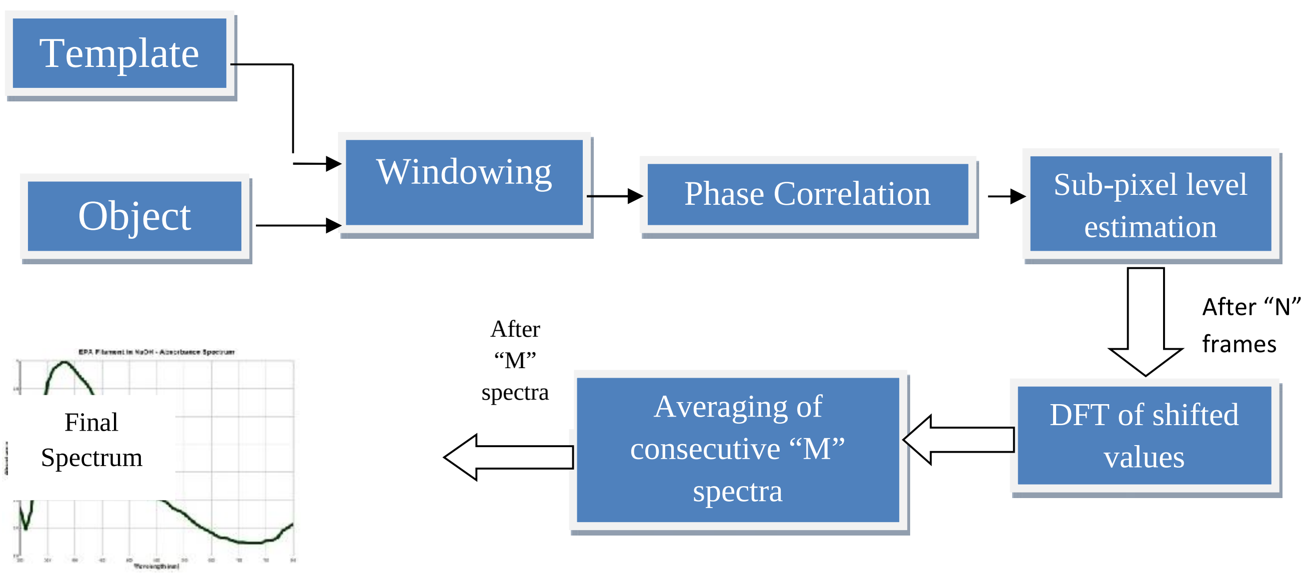


Fig. 5Block digram of phase correlation and sub-pixel estimation method.

3. RESULTS

1. Pendulum experiment

Video of a pendulum, oscillating with its natural frequency, was captured. The algorithm was applied at the checkbox unit on the pendulum as shown in Figure 6. The results were compliant with the previously established values using mathematical formulae.

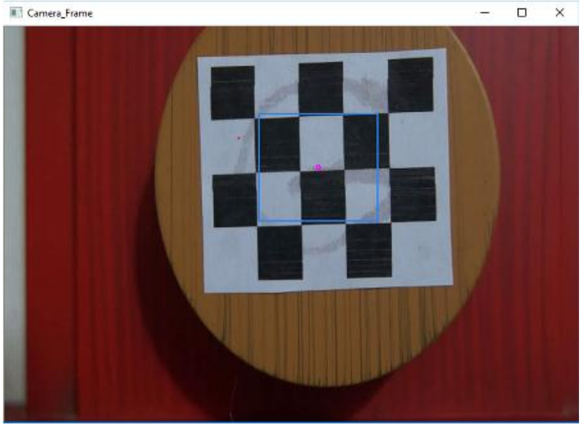


Fig. 6 Pendulum bob with checkbox template pasted

Table 1 shows the results of the experiment compared with the results through mathematical formula.

Table 1: Pendulum results.

OBSERVATION TYPE	Amplitude (pixel)	Frequency (Hertz)
Mathematical value	-	~ 1.25
Using video analytics(phase correlation and weighted centroid interpolation)	0.865612	1.27

Figure 7 depicts the vibration pattern of the pendulum in horizontal direction. The decreasing amplitude with increase in time indicates natural decay in the oscillations. After weighted centroid interpolation, up to 1 by $10^6 th$ of a pixel displacement was sampled.

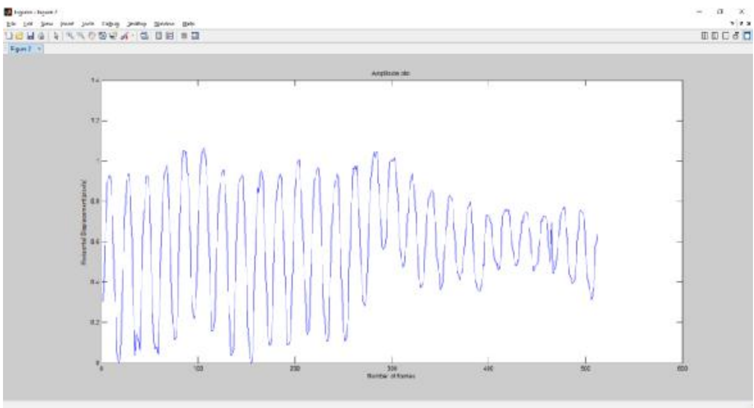


Fig. 7 Graph of pendulum vibration amplitude in horizontal direction vs no. of frames.

After averaging over 10 spectra, the averaged frequency spectrum is shown in Figure 8. Following are the results after using different types of interpolation for the same scene.

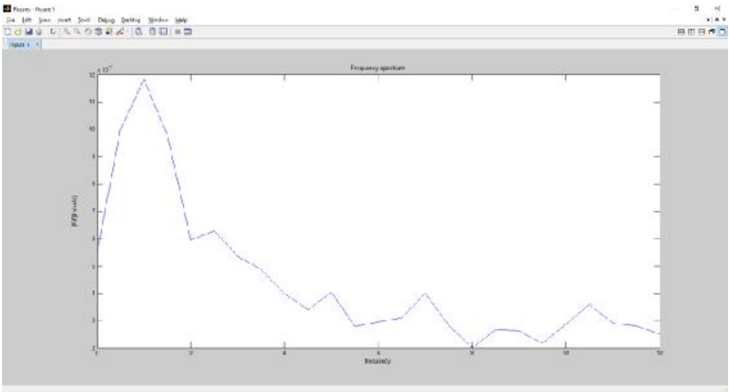


Fig. 8 Frequency spectrum of pendulum vibration.

2. Vibrating Set Up

An artificial vibrating set up consisting of a stepper motor and a vibrating steal scale to the right is considered for this experiment. The vibration frequency was validated against the known rpm of the rotating red wheel on the set up.The marked rectangular portion shown in Fig. 9 encompasses the vibrating target and the algorithm is applied on this region of interest.

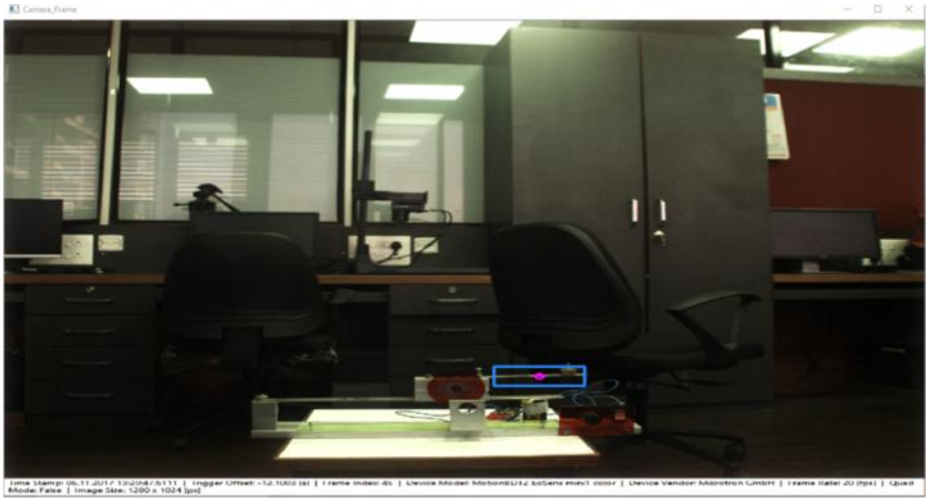


Fig. 9 Vibrating set up with stepper motor behind red wheel vibrating scale inside rectangular marked box.

Table 2 represents the results with pre-known rpm f motor vs results using the proposed algorithm.

Table 2: Vibration setup results.

OBSERVATION TYPE	Amplitude (pixel)	Frequency (Hertz)
Calculated pre-known value	-	~ 8.25
Using video analytics(phase correlation and weighted centroid interpolation)	0.162719	8.2667

The amplitude plotin Figure 10 shows the increasing vertical displacement corresponding to the gradual increase in acceleration of stepper motor(behind red wheel).

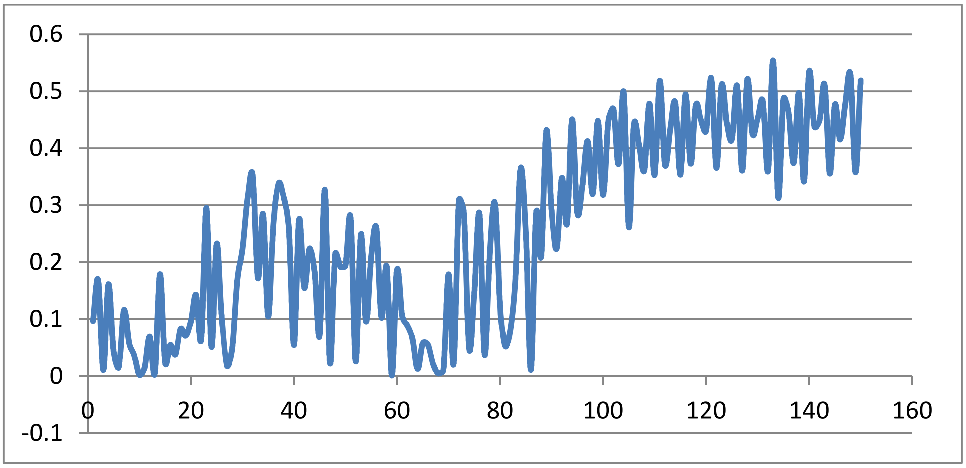


Fig. 10 Scale vibration amplitude in vertical direction vs no of frames

The frequency spectrum of the minutely vibrating scale is shown in Figure 11. The major frequency is around 8.2667 Hertz in compliance with the pre-recorded rpm of the wheel.

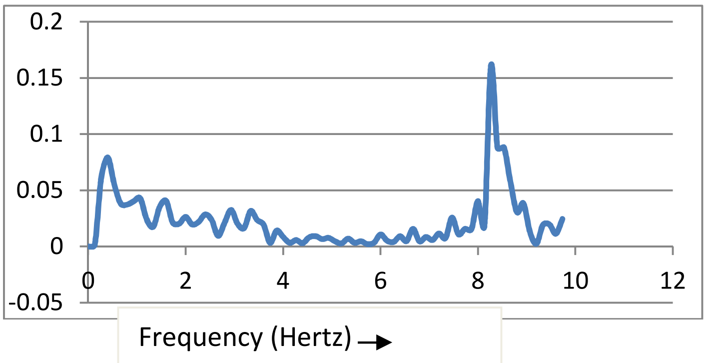


Fig. 11 Frequency spectrum of scale vibration

4. CONCLUSION

This study describes an efficient motion extraction algorithm to measure structure vibration using a high-speed digital camera. The integer level vibration signal can be obtained by calculating the cross-correlation matrix between the 2D DFT of template image and the object image and locating the maximum value in the cross-correlation matrix. Weighted centroid interpolation method is used to refine the integer level motion extraction results on the sub pixel level. From the experiments in laboratory conditions andthe real environment, we can see that the algorithm can extract vibrationsignals with impressive efficiency and satisfactory error performance. This advantage makes the vision-based sensor system realize real-time videoprocessing.

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