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Stereo-Vision Based Oscillation Measurement for Disaster Prevention

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Abstract - The approach proposed in this paper has been developed to support the stereo-vision based monitoring of building structures or natural formations focusing on the oscillation measurement. First of all the setup of the measurement system together with the related problems such as the camera synchronization, calibration are shown. The results obtained by the performed experiments point out that the proposed measurement approach considering the achieved frequency and accuracy is suitable to effectively monitor civil engineering and natural structures in a non-contact manner.

Keywords - *Oscillation, Image processing, Synchronization, Measurement, Stereo Image*

1. Introduction

The disaster prediction is of key importance in everyday life. Due to quickly evolving technology it became possible to apply various techniques to obtain accurate data in form of time series being suitable to support the prediction of disasters related for instance to the collapse of building structures or natural formations. Through the observation of natural objects and buildings valuable data can be obtained, helpful to support the early prediction of natural disasters or collapse of buildings, bridges and other structures. Here first of all the measurement of various oscillations can be emphasized, where from the obtained characteristics the state of these structures can be determined. Oscillations may occur in structures from various sources, e.g. earthquake, wind, etc. which may cause damage in their structure or sometimes their crack, as well. If the oscillation characteristics of structures being in good conditions are known, their continuous monitoring may advance the early detection of their abnormal structural behavior and such a way prevent possible accidents. However the efficiency of such kind of prediction may strongly depend on the number and significance of observed points. For structural monitoring purposes many methods have been developed. In recent years, first of all the global positioning system (GPS) based measurement devices together with accelerometers are applied for such purposes [1][6]. Although the acceleration measurement devices generate accurate data they are capable to measure only the oscillation of those points they are attached to. Regarding global navigation satellite systems based solutions there are still few limitations due to individual and atmospheric errors affecting their performance [2][4]. The GPS-based solutions are able to detect low frequency oscillations of about 10-20 Hz [8] [9]. To overcome these limitations inclination sensors, accelerometers or terrestrial laser scanners are highly welcome [2][4][7]. In [3] an optical oscillation measuring system based on the detection and processing of stochastic scattered light speckle patterns from rough surfaces was developed. Another way to perform the monitoring is to visually track some automatically selected feature points. Such an approach may ensure to track many points in a noncontact manner by using multiple camera systems.

From the family of non-contact based solutions first of all the laser irradiation based approaches may be emphasized which can offer high accuracy and frequency; however they have limitations in the number of simultaneously measurable points. The vision-based displacement measurement can overcome this limitation [10][11]. Compared to the laser based solution these systems are able to monitor more points, but the detectable frequency of the oscillation is significantly lower (depends on the frame rate of the cameras) than that of the laser based approaches. Depending on the frequency of the oscillation, the frame rate of the applied cameras and their suitable synchronization is significant. In case of camera based monitoring the distance between the cameras and the observed target (critical building) is usually relatively long, therefore due to limited camera resolution and other factors the accuracy issues are of key importance. Numerous experiments have been proposed by the authors in the field of high precision stereo camera based measurement. Many factors and the related characteristics have been studied which more or less influence the accuracy of the camera-based measurement, like the quantization error related to the discreteness of the image sensor, influence of the temperature on the CCD sensor noise, baseline length, etc. In our preceding research these errors have been efficiently reduced [12]. This paper focuses on the oscillation measurement by using conventional cameras without any external trigger input, thus their precise synchronization stands for a key issue.

The paper is organized as follows: In Section II the proposed approach is described together with the calibration related issues. Section III provides various experiments with the corresponding results and analysis. Finally conclusions are reported.

2. The Proposed Approach

When measuring the oscillation of natural formations, buildings, bridges, etc. the accuracy of the measurement and the measurable frequency are of key importance. In order to check the suitability of the stereo-vision based approach for oscillation measurement various experiments have been performed by the authors (see upcoming sections). In each case markers have been attached to the oscillating target and the characteristics of the oscillation have been measured.

Let S stand for the number of tracked markers, Δt the sampling interval and N the number of captured frames. The main steps of the measurement are the following:

1) Extracting markers from the captured frames of both cameras

- Binarization
- Applying Region of Interest (ROI) filter

2) Estimating the time delay between the two image sequences by acquiring a marker rotating with constant angular velocity and determining the elapsed time between the two closest frames according to the angular change of the marker.

2) Determining the synchronized marker locations by linear interpolation

- from time series $\mathbf{m}_{1i}(t_j)=(u_{1i}(t_j),v_{1i}(t_j))$, $\mathbf{m}_{2i}(t_j)=(u_{2i}(t_j),v_{2i}(t_j))$ collected by the stereo camera system, where $i = 1..S$, u_{1i}, v_{1i} and u_{2i}, v_{2i} stand for the image coordinates of the ith marker in the 1st and 2nd camera image respectively. $t_j = j\Delta t$, $j=0..N-1$.
- Estimating the 3D coordinates $\mathbf{M}_i(t_j)=(X_i(t_j), Y_i(t_j), Z_i(t_j))$ of markers by triangulation.
- Reconstructing the trajectory of markers from the collected discrete data by applying discrete Fourier transformation.

2.1 Camera Calibration

The calibration of cameras stands for a crucial task in high precision 3D measurement. Besides applying the most suitable calibration method, the properties of the applied calibration pattern are of key importance. For example it is recommended to use such type of calibration markers, which central point can be detected robustly to different noise sources, such as CCD temperature, illumination, etc. Such markers have been proposed by the authors in [12]. In the present experiment as calibration pattern a white plate was used consisting numerous circular markers of the mentioned type. During the calibration process this pattern has been shifted to known positions along the direction perpendicular to the plane of the pattern while the 3D coordinates of markers and the image coordinates of their projections have been recorded. For camera calibration the Direct Linear Transformation (DLT) method has been used. Since in our case the tracked markers fall inside the volume formed by the slide calibration pattern, thus the DLT method can guarantee suitable accuracy. By the DLT method the elements of the projection matrix can be obtained as the least square solution to the following system of equations:

$$\mathbf{Ab} = \mathbf{0}, \qquad (1)$$

where

$$\mathbf{A} = \begin{bmatrix} X_1 & 0 & X_2 & 0 & \dots & X_n & 0 \\ Y_1 & 0 & Y_2 & 0 & \dots & Y_n & 0 \\ Z_1 & 0 & Z_2 & 0 & \dots & Z_n & 0 \\ 1 & 0 & 1 & 0 & \dots & 1 & 0 \\ 0 & X_1 & 0 & X_2 & \dots & 0 & X_n \\ 0 & Y_1 & 0 & Y_2 & \dots & 0 & Y_n \\ 0 & Z_1 & 0 & Z_2 & \dots & 0 & Z_n \\ 0 & 1 & 0 & 1 & \dots & 0 & 1 \\ -x_1X_1 & -y_1X_1 & -x_2X_2 & -y_2X_2 & \dots & -x_nX_n & -y_nX_n \\ -x_1Y_1 & -y_1Y_1 & -x_2Y_2 & -y_2Y_2 & \dots & -x_nY_n & -y_nY_n \\ -x_1Z_1 & -y_1Z_1 & -x_2Z_2 & -y_2Z_2 & \dots & -x_nZ_n & -y_nZ_n \\ -x_1 & -y_1 & -x_2 & -y_2 & \dots & -x_n & -y_n \end{bmatrix}^T$$

In matrix **A** the X_i, Y_i, Z_i values stand for the 3D coordinates of the *i*th calibration marker, while x_i, y_i are the coordinates of its projection in the image plane of the camera.

$$\mathbf{b} = [b_{11}\, b_{12}\, b_{13}\, b_{14}\, b_{21}\, b_{22}\, b_{23}\, b_{24}\, b_{31}\, b_{32}\, b_{33}\, b_{34}]^T,$$

where the elements b_{ij} stand for the elements of the projection matrix.

2.2 Used Apparatus

One of the aims of this research was to ensure the measurement of high frequency oscillations by using conventional cameras without any external trigger input. Most of today's cameras are utilizing rolling shutter for image acquisition, due to which image distortions can be observed when trying to acquire high speed objects. Based on the above considerations the precise synchronization of cameras and elimination of the rolling shutter effect was crucial. During the experiments the following apparatus has been used:

- Video camera: SONY HDR-CX720V
- Robot arm: Denso VP-6242G
- Resolution of cameras: 1920×1080 pixels
- Frame rate: 60 FPS
- Calibration pattern consisting circular markers.

3. Experimental Results

During the experiment it was important to take into consideration the effect caused by the rolling shutter (see Fig. 1) of the used video cameras. In this case certain parts of the image are acquired in different time moments, i.e. when acquiring a fast moving object, distortion can be observed in the image (in Fig. 1 the edges of the rectangular plate become rounded due to its acquisition by rolling shutter type camera). To avoid this phenomenon the shutter speed was set-up to 1/6000 seconds. To verify the accuracy, as target one circular marker attached to a robot arm was used. At certain positions of the arm the center of the marker was extracted (see Fig. 2). Afterwards its spatial coordinates have been determined by the already calibrated stereo-camera system. The results have been compared with the exact location of the marker (known based on the motion of the robot arm).

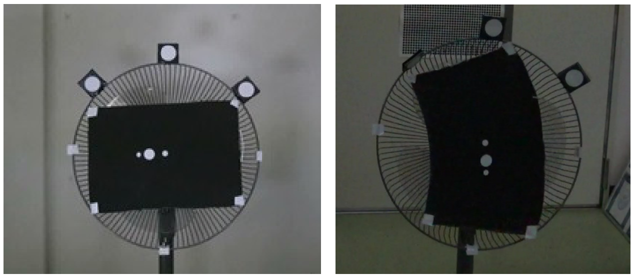

Fig. 1. The rolling shutter effect: steady plate (left), rotating plate (right)

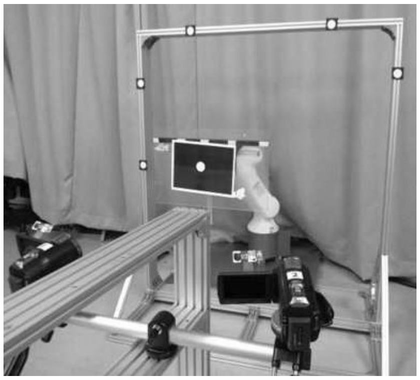

Fig. 2. Accuracy verification

As second target for accuracy verification a frame equipped with several markers has been used. Similarly to the previous case the location of each marker has been estimated and compared with its exact location. This operation was performed at several known positions of the frame.

3.1 Monitoring an Oscillating Plate

In the first experiment the subject of measurement was an oscillating rectangular plate equipped with equidistant circular markers as depicted by Fig. 3. The one end of the plate was fixed while the other was oscillating. The designated markers in Fig. 3 stand for reference markers. The aim was to reconstruct the trajectory of markers from sampled image data.

Because of the higher sampling rate, it was crucial to precisely synchronize the cameras. Concerning this issue - as already mentioned - the image coordinates of markers corresponding to time t, $t_0 \leq t \leq t_{N-1}$ have been estimated by linear interpolation from the collected image time series. The correspondence problem has been solved by applying the epipolar constraint. At the same time the displacement of reference markers has also been considered.

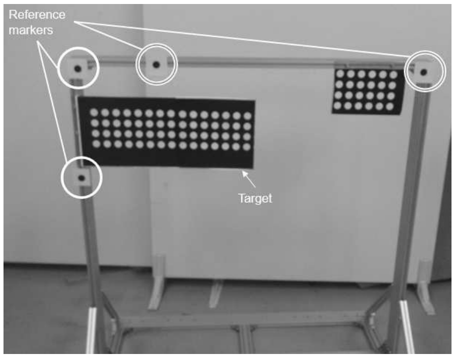

Fig. 3. Setup of the measurement

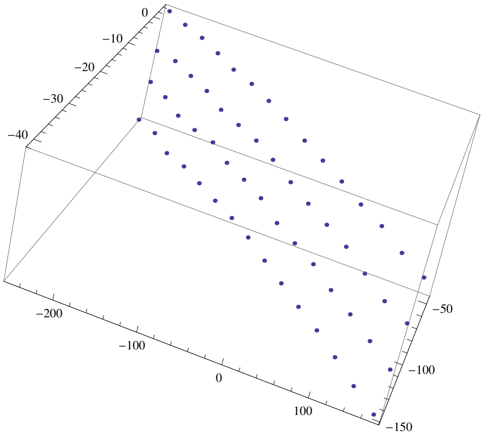

Fig. 4. Reconstructed position of markers

In the below figures the results of the experiment can be followed. Fig. 4 illustrates the reconstructed positions of markers.

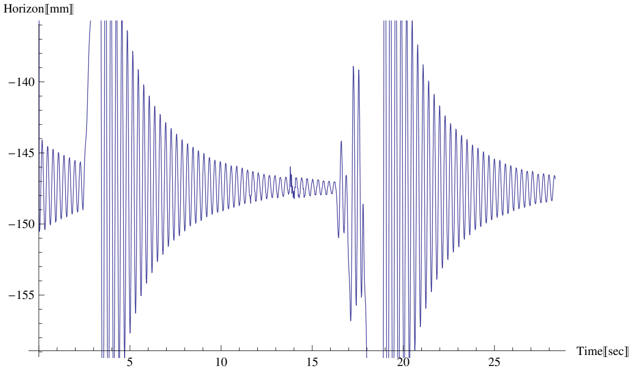

Fig. 5. $X(t)$ coordinate of the rightmost top marker

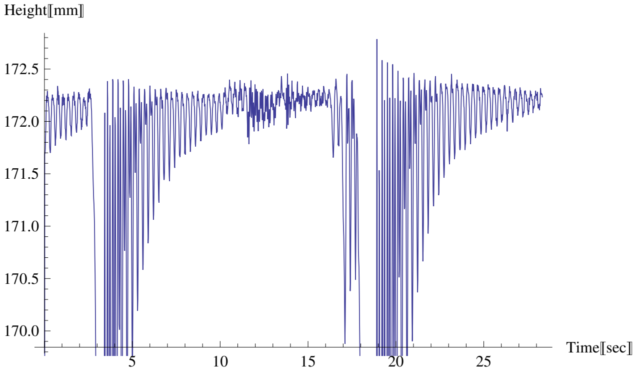

Fig. 6. Y(t) coordinate of the rightmost top marker

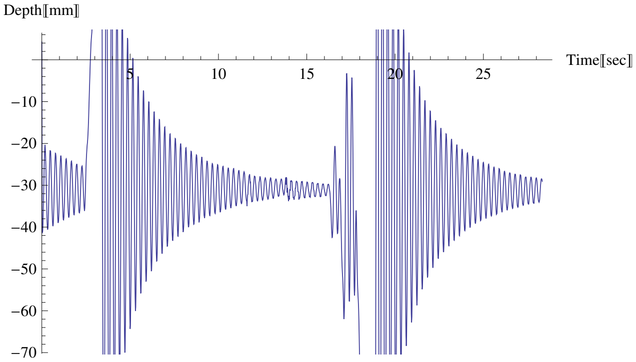

Fig. 7. Z(t) coordinate of the rightmost top marker

In Figs. 5-7 the trajectory of the rightmost top marker can be followed, while in Fig. 8 the results falling into the interval from 20 to 25 seconds is enlarged. The measured frequency of the oscillation in this interval was about 3.5 Hz.

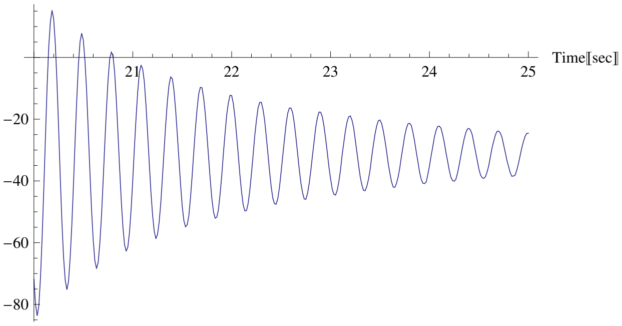

Fig. 8. Enlarged segment of signal depicted in Fig. 7

3.2 Monitoring Rotating Markers

During this experiment as subjects of measurement circular markers have been attached to a rotating element.

The frequency of the rotation was: 10 Hz. The aim was to monitor the markers and reconstruct their trajectory. The pairing of camera frames was performed similarly as in the first experiment. In Fig. 9 the setup of the experiment can be followed. The upper three markers are fixed reference markers while the marker attached near to the center of rotation stands for the subject of measurement. The reconstructed trajectory of this marker is depicted in Fig. 10. In Figs. 11, 12 and 13 the estimated coordinates of the marker can be followed.

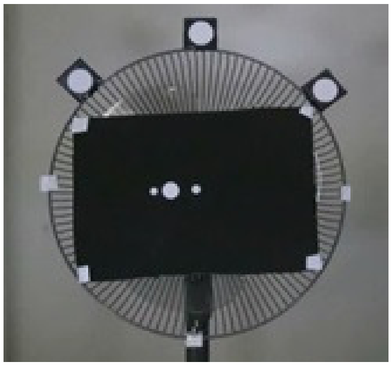

Fig. 9. Simulation Results

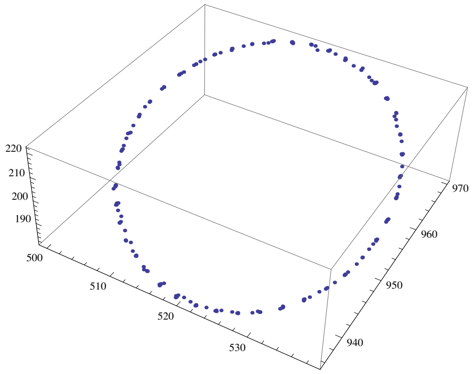

Fig. 10. Simulation Results

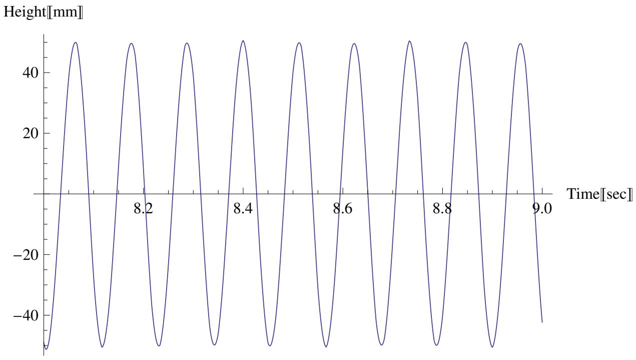

Fig. 11. Simulation Results

Based on the measured data the estimated frequency was 10Hz (see Fig. 15). The estimated distance of the marker from the center point of the rotation can be seen in Fig. 14.

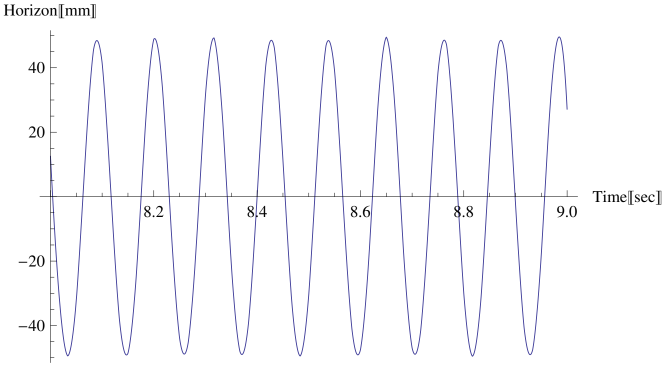

Fig. 12. Simulation Results

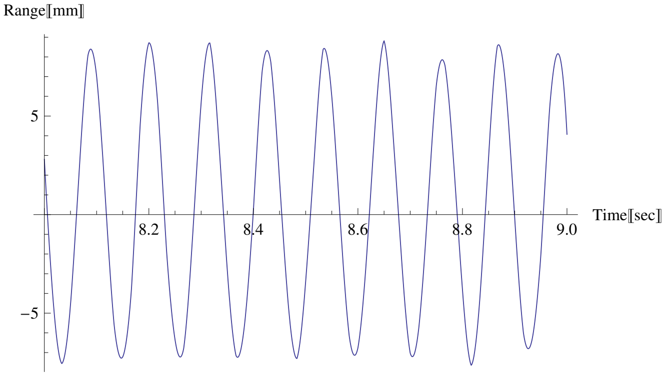

Fig. 13. Simulation Results

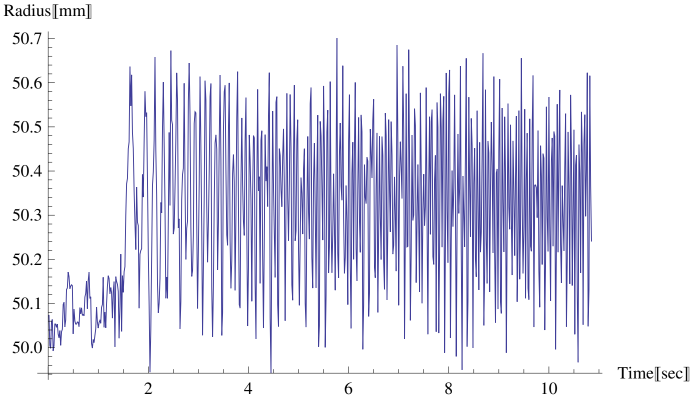

Fig. 14. Measured radius of rotation

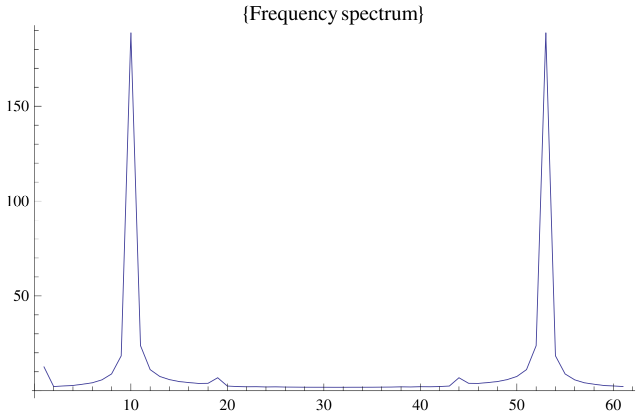

Fig. 15. Frequency spectrum of the "time-height" signal in Fig. 11.

3.3 Testing the Impact of the Frequency on the Measurement Error

An important task during the measurement was to estimate the impact of different frequencies on the measurement error. For this purpose the experimental setup illustrated by Fig. 16 has been utilized. The plate consisting one column of markers was attached to a rigid vibrating arm. As in the above cases reference markers have been used to enhance the matching and improve the accuracy. During the measurement the frequency of the vibration was monotonically increasing till a peak frequency which was 30 Hz while the positions of markers were monitored. The amplitude of the vibration was constant, only the frequency was increased according to the time-frequency characteristics depicted by Fig. 17. The measurement error can be followed in Fig. 18. It can easily be recognized from Fig. 19 that there is a quadratic growth in the error of the estimated amplitude as the frequency increases.

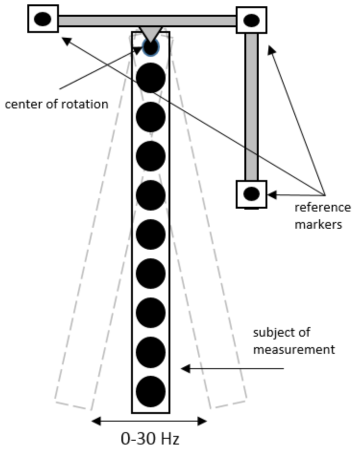

Fig. 16. Illustration of the experimental setup

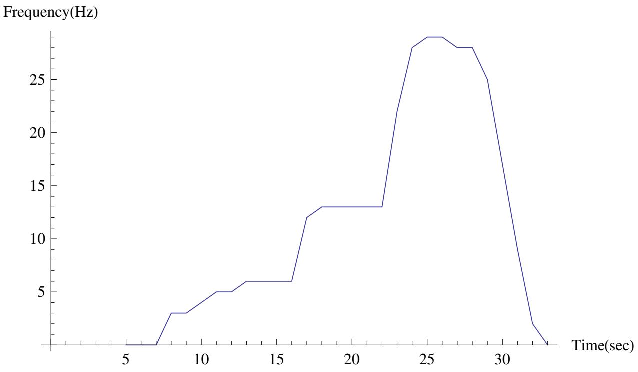

Fig. 17. The change of frequency over time

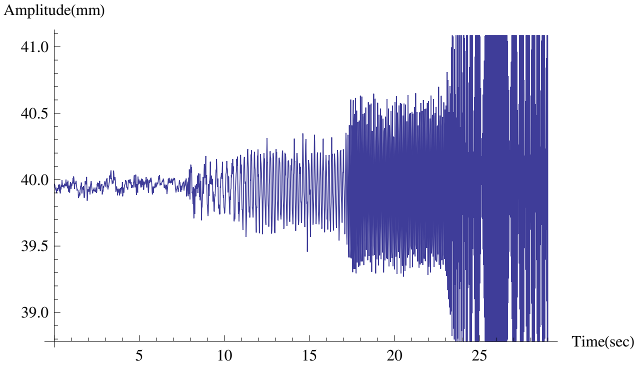

Fig. 18. Amplitude measurement results corresponding to the frequency characteristics depicted in Fig 17.

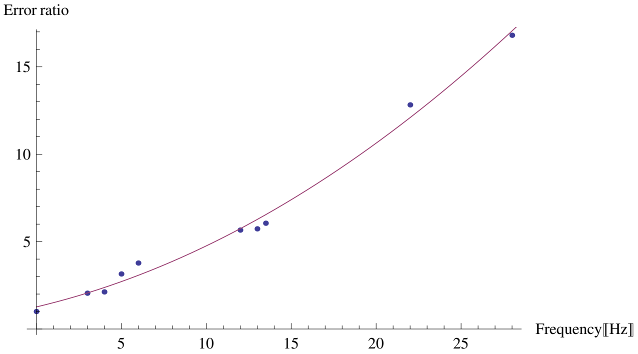

Fig. 19. As the frequency increases one can observe quadratic growth in the error of the estimated amplitude

4. Conclusions

In this paper a stereo-camera based approach was proposed for the measurement of oscillating and rotating targets. To verify the suitability of the proposed approach for measuring fast moving targets two experiments have been performed. In the first one the trajectories of circular markers attached to a vibrating plate have been measured. The frequency of vibration was about 10Hz. In the second experiment the location of a rotating target has been measured. In both cases the results show that the achieved measurement accuracy and frequency is suitable for structural monitoring of targets in non-contact manner.

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