AUTHORS PREPRINT

Visual Vibration Analysis for High Amplitude Movements using Pixel Matching

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ABSTRACT

This paper presents an innovative, contactless system for analyzing low-frequency, high-amplitude vibrations in machinery using video-based motion tracking. Traditional vibration meters, which require physical attachment and are limited in capturing high-amplitude or low-frequency vibrations, are often inadequate to detect deviations in machinery motion. To address these limitations, we propose a system that utilizes video feeds to track specific regions of interest (ROIs) in moving objects, allowing for accurate vibration measurement without interrupting machine operations. By employing a kernel-matching algorithm, the system provides real-time motion tracking and precise analysis of vibration patterns. Our approach enables early fault detection and predictive maintenance, reducing unplanned downtimes and minimizing long-term damage. The effectiveness of the system is demonstrated through experiments on various setups, including pendulums and spring-based mechanisms. These results confirm the potential of this method to outperform conventional vibration meters, making it an ideal solution for industries that require advanced motion analysis and monitoring of machinery health.

KEYWORDS
Visual Vibration Analysis; Pixel Matching; High Amplitude Movements

1. Introduction

Misalignment and loose screws in machines frequently result in unintended vibrations within machine components, which contribute to considerable wear and tear. This problem becomes particularly severe when large moving parts, such as fan blades, deviate from their intended path. Such deviations risk substantial damage to the machinery in the long term. Addressing these vibrations is crucial because they can signif-

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icantly accelerate machine degradation thus resulting in costly repairs and unplanned downtime.

To mitigate this issue, there is a need for a system that can measure these vibrations accurately, allowing for timely maintenance before serious damage occurs. Currently, vibration meters are employed to detect vibrations, but they are limited to small amplitude vibrations and must be physically attached to the machine's surface. These devices are unsuitable for measuring deviations in the movement paths of machines, particularly when dealing with low-frequency and high-amplitude vibrations.

In this paper, we introduce a novel system that measures low-frequency visible vibrations of objects using video feeds. This system is capable of tracking the precise motion of an object, thereby facilitating predictive maintenance. Unlike traditional vibration meters, our method does not require physical contact and can accurately measure large amplitude movements. The core of our system utilizes kernel matching to track specific areas of interest within video frames, allowing for comprehensive analysis of the vibrations.

In our system, the user simply needs to input a video of the machine and specify the areas of interest, after which the system processes the frames to return a detailed analysis of the vibrations. The application of kernel matching ensures precise tracking of these areas, providing a high level of accuracy in identifying and quantifying the movements. This lets the system track the precise route of the moving parts in addition to detecting vibrations at low frequencies and large amplitudes. As a result, maintenance teams can not only diagnose potential issues early but also plan maintenance schedules more effectively, thus avoiding unscheduled downtime. Moreover, the non intrusive nature of this system ensures that it can be implemented without interrupting the normal operation of machinery, making it a practical solution for real-time monitoring. Alert systems can be made that alert the operators once the vibrations exceed a certain threshold. The results of this study provide new opportunities for predictive maintenance across a range of industries, especially in situations where conventional vibration meters are insufficient, including precision instruments or huge industrial machines where accurate motion tracking is essential.

2. Literature survey

One of the first studies on visual vibration analysis is by John T. Renwick and Paul E. Babson [1] in which they discuss how predictive maintenance using vibration analysis served as an effective tool for diagnosing machinery problems and scheduling maintenance tasks. They emphasized that quality information and a structured methodology were crucial for the success of such programs, which ultimately led to reduced downtime and improved maintenance effectiveness.

Muneo Hori, et al. [2] proposed a strong motion measurement method using security video cameras. They examined the utilization of video images to capture strong motion effects and developed analysis methods that extracted strong motion data, demonstrating the feasibility of this approach through various tests.

Eri Zeze and Kan Akatsu [3] investigated the relationship between the vibration of an interior permanent magnet synchronous motor and the inverter PWM carrier signal. They analyzed the effects of PWM carrier frequencies on electromagnetic force vibrations and proposed a hysteresis control method to reduce these vibrations effectively.

Hsiung-Cheng Lin, et al. [4] developed an enhanced fast Fourier transform algorithm for on-line bearing vibration detection and analysis. They established a mathematical model that related the major vibration frequencies to the dispersed energy, which improved the accuracy and efficiency of vibration signal analysis. Their proposed model achieved reliable outcomes in practical applications, demonstrating its effectiveness in predictive maintenance.

Vishnu Kv, et al. [5] reviewed the significance of vibration analysis in monitoring machine health and preventing failures. They discussed the causes of vibration, measurement techniques, and the importance of regular monitoring to enhance machine longevity and efficiency, ultimately saving time and resources.

Mohamad Hazwan, et al.[5] presented a systematic review of vibration analysis techniques for machine monitoring and diagnosis. They highlighted the importance of data acquisition, signal processing, and artificial intelligence in identifying machine faults, discussing various methods, their advantages, and limitations. They emphasized the future integration of deep learning approaches to enhance fault detection and diagnosis in industrial settings.

Pooja Khatri, et al. [6] explained the use of cameras for recording and analyzing low-frequency vibrations of visible objects. They demonstrated that cameras can serve as low-cost, high-resolution vibration sensors through spatial and temporal analysis, providing a new method for vibration analysis. They also have reviewed various applications of visual vibration analysis [7], emphasizing the use of video cameras for extracting and analyzing vibrations from visible objects. They have highlighted the advantages of this method over traditional sensors, particularly in structural health monitoring and non-destructive testing. Their work has demonstrated the potential of motion magnification techniques in recovering sound and estimating material properties from recorded video.

Qi Li [8] and colleagues have explored a hybrid computer-vision-based approach to extract operational deflection shapes (ODS) of an arch dam model using phase-based video processing. They have validated their method through a cantilever beam test and demonstrated its effectiveness in identifying the dynamic characteristics of the arch dam, comparing results with traditional operational modal analysis (OMA) techniques. Their findings have indicated that the video processing technique can accurately capture the natural frequencies and ODSs of complex structures like arch dams.

Xux Ek, et al. [9] have investigated the application of vibration analysis techniques for predictive maintenance in a six-die nut manufacturing machine. They demonstrated that methods such as Fast Fourier Transform, Empirical Mode Decomposition, and Multiscale Entropy can effectively identify fault indicators, enabling timely maintenance to optimize machine efficiency and product quality.

Kritchanan Charoensuk and Thunyaseth Sethaput [10] investigated the effects of multi-notch locations on the vibration characteristics of steel plates through experimental and finite element modelling. They found that natural frequencies vary significantly with different notch configurations, providing insights into predicting damage and fracture in structural applications.

Daniel Jancarczyk et al. [11] explored the enhancement of vibration analysis in hydraulic presses through advanced measurement systems. They demonstrated that the placement of sensors and sampling frequency significantly influenced measurement results, ultimately highlighting the importance of vibration monitoring for optimizing production parameters and maintenance planning.

Radharaman Tripathi, et al. [12] presented a methodology for vibration analysis of shipboard piping systems to mitigate excessive vibrations caused by mechanical and base excitations. They emphasized the importance of modal characteristics and proposed using finite element analysis based on MIL-STD-167-1A to optimize testing requirements and ensure environmental sustainability.

3. Methodology

3.1. *Vibration analysis*

Vibration analysis is a crucial technique for identifying and addressing issues caused by unintended vibrations in machinery. These vibrations often arise from factors like misalignment, loose fasteners, imbalance, or improper installation. To detect and analyze these vibrations, sensors such as accelerometers and proximity probes are used to monitor oscillatory movements in machine components. By employing techniques like the Fast Fourier Transform (FFT), vibration signals can be decomposed into their constituent frequencies, providing insights into potential faults. Industry standards, like ISO 10816 [13], offer benchmarks for acceptable vibration levels, enabling engineers to assess the condition of machinery. effectively. In early FSW fixtures, improper clamping, insufficient rigidity, or inadequate damping mechanisms often contributed to unintended vibrations during the welding process. By analyzing vibration data collected engineers can identify specific issues such as joint looseness, tool misalignment, or structural resonance.

Regular vibration analysis greatly enhances preventive maintenance, enabling early detection of issues, minimizing unplanned downtime, and reducing costly repairs. Techniques like dynamic balancing can mitigate imbalance-induced vibrations, while proper lubrication helps prevent friction-related issues. Additionally, bearing defects, such as pitting or wear, can be identified through characteristic frequencies in vibration data. When integrated into condition monitoring systems, vibration analysis facilitates automated fault detection and predictive maintenance, ensuring safer, more reliable, and longer-lasting machinery.

3.2. *Visual Vibration Analysis*

Visual vibration analysis is the usage of computer vision techniques to analyze vibrations. This technique uses a camera as a sensor. The advantages of this is that the system can be made cost effective and flexible. The system can work without having to attach vibration-meters on to objects. Also large amplitude motions can be measured.

In this study, we propose a novel methodology for vibration analysis using video-based tracking of Areas of Interest in vibrating objects. This system calculates the vibrations based on the pixel tracking of areas of interest (AOI). AOIs are small areas usually near the object's edges that help track the object's motion. They can help find out the vibration of the object along various axes. For example in a weighted scaled pendulum with four corners, there can be four areas of interest. The relative motion of the four corners can give an idea about the movement in the vertical direction, horizontal direction, yaw, pitch and roll.

In order to track the movements of the camera if any, a stable AOI point can be chosen as a reference point. The vibrations of the other points can be recalculated with reference to this point.

Once the AOIs are tracked, the position information can be used to calculate the motion frequencies using various signal processing techniques like FFT. The complete

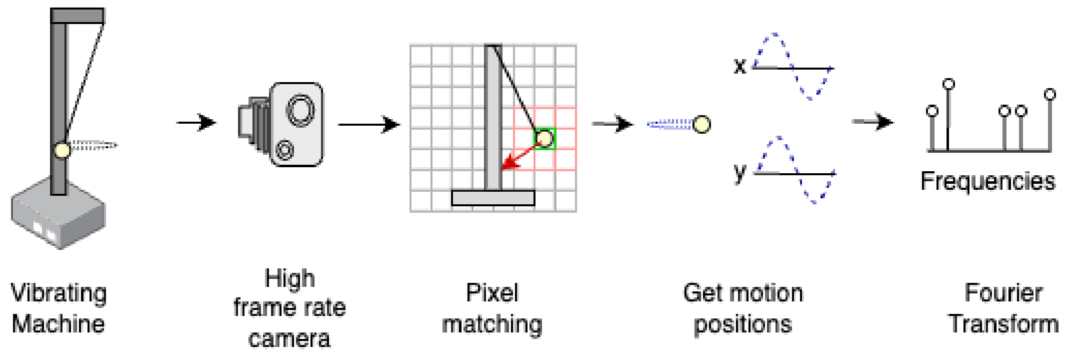


Figure 1.: This figure illustrates our vibration analysis system using video-based tracking of Areas of Interest (AOIs). A camera captures the motion of a vibrating object, and specific points (AOIs) on the object are tracked. These tracked positions are then processed to extract vibration frequencies using signal processing techniques like FFT. The analysis results are visualized as data points or waveforms, highlighting the object's motion across various axes. The system also compensates for camera movements by using a stable reference point for accurate measurements.

methodology is given in Figure 2. The position data of the AOIs is then processed to extract motion frequencies using signal processing techniques such as Fast Fourier Transform (FFT). Filtering methods are further applied to refine the signal analysis. The proposed approach offers a non-intrusive and efficient solution for capturing and analyzing vibrations in various applications, with the potential for significant advancements in the field of structural health monitoring and other vibration-sensitive domains.

3.3. *System architecture*

Our system consists of 4 processing modules. Figure 1 explains the structure of our system in brief.

The first module is a camera module. It converts the physical motion of the target machine into a digital signal consisting of video frames. The camera may be a normal camera or a high frame rate camera depending on the frequency of motion. the quality of the camera does not really matter. In fact cameras with lesser resolution can track the vibrations faster than those with higher resolution.

These frames are processed by the motion tracking module which uses template matching to track the motion of the areas of interest across time. These positions are tracked and displayed in the form of graphs by the third module. These graphs give an idea about the amplitude and the path of motion of motion. For example, it can show how a pendulum motion is dampening across time, or how the motion is deviating across its intended path of motion. The next module performs Fourier analysis on the tracked positions. This can help in identifying if certain frequencies exceed the desired frequency range.

3.4. *Tracking areas of interest*

Analysis of movements of areas of interest is done through template matching. Template pixels of small areas of interest are tracked in the video frames to find out the

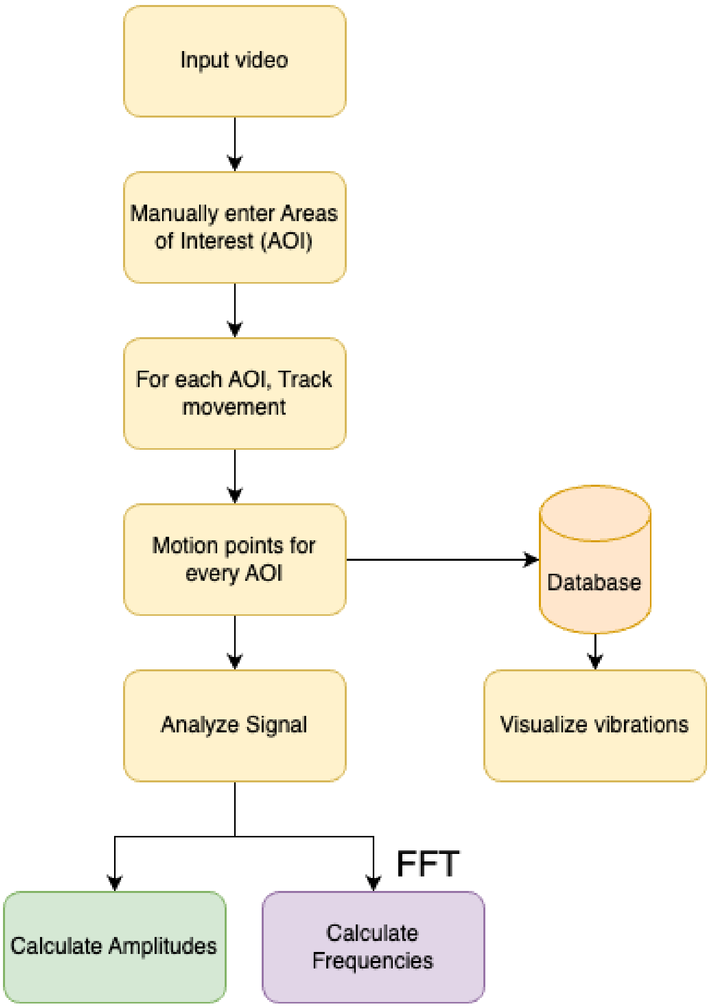


Figure 2.: Flowchart for visual vibration analysis. The flowchart shows the various steps in our visual vibration analysis methodology. The first step is selecting areas of interest from input video feeds. Then out pixel matching algorithm tracks the movement of every area of interest and feeds them to the database for further analysis. The signal can be analyzed through amplitude and frequency calculations. Further analysis can be performed through frequency decomposing through algorithms like FFT

vibration of the object. In order to speed up the algorithm, The points are only calculated up to distance d. The exact algorithm used is given in Algorithm 1.

Algorithm 1 Template matching algorithm for tracking movements of an area of interest

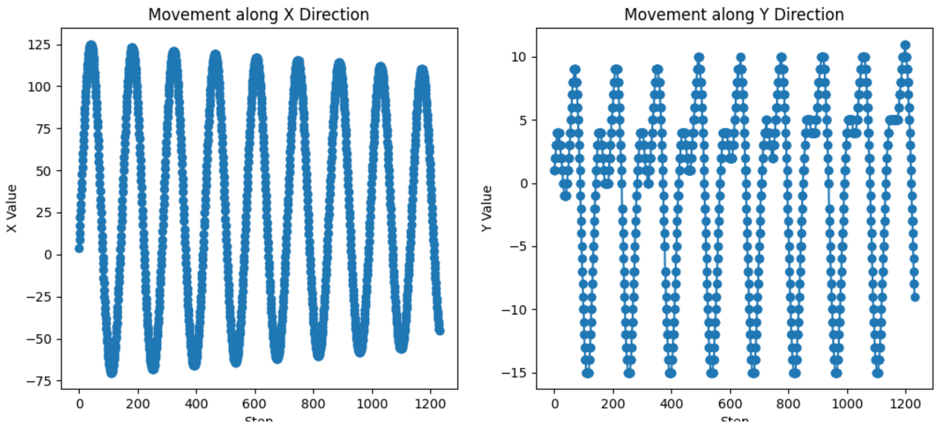
input:
  x_0 : Initial X pixel coordinate of center of area of interest
  y_0 : Initial Y pixel coordinate of center of area of interest
  k : Width of the area of interest
  d : Searching distance (defines the bounds of the search area)
  F_t : Frame of video at time t
  X , Y : Boundaries of the frame
output:
  L: List of positions traversed by the area of interest
procedure TrackMovement
  $x_t, y_t \leftarrow x_0, y_0$
  $L \leftarrow$ empty list
  for each frame F_t at time t **do**
    $Temp \leftarrow 0$
    $Max \leftarrow -\infty$
    $x_{\text{left}} \leftarrow \max(x_t - \frac{d}{2}, 0)$
    $x_{\text{right}} \leftarrow \min(x_t + \frac{d}{2}, X)$
    $y_{\text{bot}} \leftarrow \max(y_t - \frac{d}{2}, 0)$
    $y_{\text{top}} \leftarrow \min(y_t + \frac{d}{2}, Y)$
    for x in range (x_{left}, x_{right}) **do**
      for y in range (y_{bot}, y_{top}) **do**
        $Temp \leftarrow \sum \left|(F_t(x-\frac{k}{2} : x+\frac{k}{2}, y-\frac{k}{2} : y+\frac{k}{2}) - F_{t-1}(x_t-\frac{k}{2} : x_t+\frac{k}{2}, y_t+\frac{k}{2} : y_t + \frac{k}{2}))\right|$ // Sum of the absolute difference between the templates.
        if $Temp > Max$ **then**
          $Max \leftarrow Temp$
          $x_t \leftarrow x$
          $y_t \leftarrow y$
        end if
      end for
    end for
    L.append$((x_t, y_t))$
  end for
  return L
end procedure

4. Results

The results demonstrate the system's capability to track and analyze the movement paths accurately, providing a detailed assessment of the vibrations.

In the initial experiment, we utilized a simple pendulum setup to test the system's ability to track a single area of interest. The pendulum's motion was recorded, and the kernel matching algorithm was applied to track the pendulum's movement. The resulting data is plotted in Figure 3b, showing the movement along the X and Y directions, respectively. This experiment confirmed that our system could accurately measure the pendulum's oscillations, which are represented as sinusoidal waves in the graphs.

(a) Tracking area of interest in a simple pendulum.



(b) In this experiment a pendulum's movements were tracked. These movements are high amplitude and low frequecncy (when compared to the frame rate and processing power). The mass blob of the pendulum is tracked through time. Movement of the pendulum along the X and Y directions tracked by the kernel matching algorithm. The X direction shows clear sinusoidal oscillations, while the Y direction captures the vertical displacements. The damping of the oscillations is also visible

Figure 3.: Experimental results showcasing the system's capability to track and analyze vibrations.

In a subsequent experiment, we enhanced the system to track multiple areas of interest within a single video feed. This was tested using a setup with a weight suspended by a spring, as shown in Figure 4. The system was able to simultaneously monitor the movement of different parts of the setup, providing a comprehensive analysis of the vibrations. This capability is particularly beneficial for complex machinery where multiple components need to be monitored simultaneously to ensure optimal performance.

The results of these experiments illustrate the robustness and precision of our system in measuring low-frequency, high-amplitude vibrations. The ability to track multiple

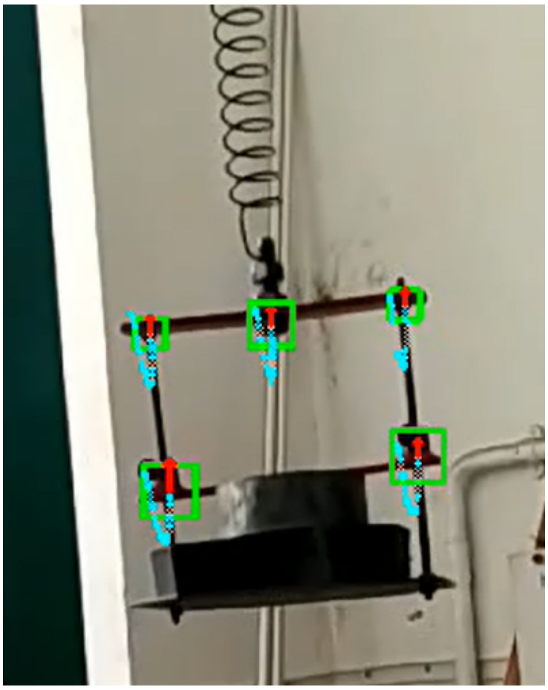


Figure 4.: Tracking multiple areas of interest (in green) in a weight suspended by a spring. The system accurately identifies and monitors the movement of various parts of the setup, allowing for a detailed vibration analysis. As these corners move up and down, their motion is captured and analyzed by the camera. The blue trail represents the past motion points of the objects while the red arrows represent the direction of motion.

regions of interest non-intrusively highlights the potential of our method for real-time monitoring and predictive maintenance in various industrial applications. This system can be particularly useful in environments where traditional vibration meters are inadequate, offering a practical solution for maintaining machinery health and preventing unexpected downtimes.

5. Conclusion

This study presented a novel, non-intrusive system for measuring low-frequency, high-amplitude vibrations using video feeds and kernel matching. The system was tested on a pendulum and a weight suspended by a spring, successfully tracking single and multiple regions of interest, respectively. The results demonstrated the system's capability to accurately measure vibrations and provide detailed motion analysis. Unlike traditional vibration meters, our method does not require physical contact, making it suitable for real-time monitoring and predictive maintenance. This system offers significant potential to improve machinery health management, especially in industrial settings where conventional methods are insufficient. Future work will focus on enhancing accuracy and expanding the system's application range.

This system is poised to revolutionize maintenance strategies in various industries by enabling highly accurate, predictive maintenance without physical contact. It excels at measuring low-frequency, high-amplitude vibrations, a capability that traditional vibration meters often struggle with. This makes it ideal for monitoring large industrial machinery, precision instruments, and other critical equipment. Detecting potential issues early can help prevent catastrophic failures, unplanned downtime, and costly repairs. Its non-intrusive nature ensures easy integration into existing operations, leading to more efficient, reliable, and cost-effective maintenance practices. This innovation not only enhances operational safety but also extends the lifespan of machinery, boosting productivity and sustainability in modern industrial settings.

6. Future Scope

- **USes complex algorithms like YOLO and Optical flow:** Use of advanced computer vision systems like YOLO and SIFT feature matching that will help prevent any error drift for long term working of the solution.
- **Developing a Sports Tracking System for Coaching:** Future enhancements could include applications in the field of sports to the motion of bats in sports such as tennis, cricket, table tennis, baseball and even for weightlifting. Such a system will help analyze trajectories and movements to help athletes improve their techniques and performance.
- **Integration with Augmented Reality for Maintenance Guidance:** Another potential development is the integration of augmented reality (AR) technology allowing maintenance personnel to receive real-time visual overlays of vibration data on the machinery to quickly identify issues.

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