Visualization of Vibrations in Structural Diagnoses of Technical Objects

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Abstract

One of the key methods for diagnosing the structural degradation of technical objects relies on observations of mechanical vibrations that accompany equipment operation and damage. Hardware and software advancements and the development mathematical methods for modelling and inference have increased the popularity of vibroacoustic diagnostics in mechanical systems. Displacement in the time domain of physical points in a vibrating object is the primary diagnostic symptom that undergoes further processing in the measurement system. At present, vibrations are usually registered with the use of accelerometers or optical sensors. Advanced tools for image recording, processing and analysis are deployed in quasi-realistic observations of motion that cannot be perceived by the human senses. This article discusses a method for visualizing vibrations based on deliberate deformation of the registered image through motion magnification. The presented approach is illustrated with selected examples.

Keywords: motion magnification, vibration, image processing, diagnostics

1. Introduction

Mechanical vibration is a phenomenon that accompanies the operation of machines. In most cases, vibration is regarded as residual process that accompanies the normal operation of machines. Vibration compromises a machine's durability and process parameters, and it exerts a negative influence on the operating environment [1].

In both cases, a thorough knowledge of the parameters describing vibrations and their source is required to guarantee optimal machine operation. Vibrations are monitored to control process parameters, determine the extent of structural wear, and identify assembly defects.

In the traditional approach, a mechanical assembly is inspected during a visual evaluation. This approach has significant limitations because humans are unable to perceive motion that exceeds a certain velocity threshold or the magnitude of the resulting displacement. The subjective character of the human perception and the inability to estimate the observed phenomena in numerical quantities also play an important role in many cases.

Processes that cannot be perceived by the human sense of sight can be observed with the use of indirect methods and physical phenomena that depict motion parameters on a scale that can be interpreted by the observer. This is the basic operating principle of acceleration, speed and location sensors such as accelerometers, optical sensors and eddy current sensors [2].

The primal parameter that describes the state of a vibrating object is the location of a selected point that is related to that object in space and time. In analyses of vibrations resulting from the deformation of physical structures, the mutual location of selected points in the analyzed object is evaluated. Vibration is analyzed by observing changes in the location of points and by determining motion parameters such as trajectory, velocity and acceleration. In practice, one or more parameters are used, subject to the analyzed case.

The manner in which data are acquired based on signals that render motion parameters is dependent on the applied tool. Accelerometers, devices that measure proper acceleration, are most widely used in vibroacoustic analyses. Laser sensors are increasingly often used, and, subject to their design, they measure the location (triangulation sensors) or velocity (Doppler sensors) of a moving object. Subject to the applied sensor and the measured motion parameters, the signal generated by a sensor can be interpreted directly or converted by differentiation or integration. Advanced sensors and the development mathematical methods create new opportunities for observing vibration in research and in industrial applications. However, real-world applications have numerous limitations [2].

Conventional signal transducers generally measure a signal associated with single point in an object. In many applications, the resulting data are sufficient to describe or evaluate the state of a given object or phenomenon. However, the number of measured points has to be increased during observations of complex objects, sets of elements with many degrees of freedom, and structural deformations. These requirements significantly increase the complexity and cost of measuring systems, and not all requirements can be met in practice. The applied solutions often rely on simulation methods and theoretical models.

However, in many situations, a problem cannot be rapidly identified based on a researcher’s or diagnostician’s experience or routine proceedings. The selection and location of a measuring point can pose a challenge in complex objects.

Selected types of sensors are not suitable for vibroacoustic analyses because a sensor’s mass can affect the dynamic parameters of a vibrating object, which detracts from the accuracy of measurements in a real-world setting. Sensors that come into direct contact with the analyzed object can also be difficult to deploy due to limited assembly space or high operating temperature. Such difficulties can be overcome by using contactless sensors, such as laser sensors, provided that their assembly point does not exert a disrupting influence on the conducted measurements [2].

The advancements in image analysis and processing have extended the scope of measuring methods in vibroacoustic analyses of technical objects. The methods discussed in this article present a novel approach to observing vibration processes, and they facilitate rapid evaluation of the phenomena that occur in complex objects. The above approach involves the visualization of the displacement of measuring points that cannot be perceived by the human senses. In the literature, such methods are referred to motion microscopy techniques [3]. The displacement of the points measured on a technical object is recorded with a video camera, and the resulting data are transformed. The result is a set of deformed images, and subtle motions in a video sequence are amplified to visualize deformations that would otherwise be invisible for the analyst. In the literature, this method is known as motion magnification.

2. Review of motion magnification methods

Image processing methods for depicting and describing motion are widely used in many areas, such as traffic monitoring. In vibroacoustic analyses, the direct application of motion magnification techniques can be challenging due to relatively small values of the changes captured in video material and due to human sensory limitations. This chapter reviews the applicability of image processing techniques for observation of mechanical vibration processes.

In methods for the visualization of vibration data, the location of points related to the analyzed object is monitored in regular time intervals in a selected area of a 2D plane (matrix of the registering device). The instantaneous location of these points in a system of coordinates in a 2D plane is described by geometric coordinates x, y. The images in a video sequence are described by variables t_0, t_1, … t_n in successive moments of time.

In visualizations of vibration data, images are processed in the spatial domain x, y, in the temporal dimension t, and in the spatio-temporal domain, as shown in figure 1a. The formal description of changes in plane x, y, illustrating the displacement / deformation of the represented points is based on the principles of fluid mechanics.

In the Lagrangian approach, geometrical changes are observed by monitoring a point on the studied object. The point’s geometric coordinates in the evaluated system (individual frames in a video sequence) are determined based on its location in successive time intervals. In other words, the trajectory of the point’s motion is monitored.

The Eulerian approach describes changes in the parameters of a point in a specific location in a given pair of coordinates. In image analyses, these parameters are mostly represented by the brightness B or intensity I of a pixel. Lagrangian and Eulerian approaches to monitoring dynamic changes in an object are presented in figure 1b, 1c.

Lagrangian and Eulerian approaches can be used interchangeably to elicit information about motion dynamics. The concept of optical flow has been inspired by methods used to model gas and fluid flow. Optical flow is determined based on the sequence of successive images. Pattern preparing methods have been proposed by Lucas-Kanade, Horn-Schunk and Black-Jepson. Their effectiveness and applicability was compared by [4].

The general principle for computing optical flow in the Lucas-Kanade approach is presented in Figure 2. In this method, the information from several nearby pixels is compared in successive frames of the video sequence based on the assumption that the analyzed parameter is characterized by small and approximately constant differences. The motion magnification technique for visualizing small differences in a video sequence in the Lagrangian approach was presented by [5]. The instantaneous velocities of the measured points determined with the use of the Lucas-Kanade method were used to group the trajectories of objects with correlated motions. A set K of trajectories was created. Optical flows were interpolated over all pixels, and pixels were assigned to clusters of trajectory layers. The representation of images in layers was demonstrated by [6]. Motion was magnified by multiplying the displacement of each pixel in the corresponding layers and rendering the pixels in each layer from back to front. The applied algorithm is highly complex and requires sophisticated calculations; therefore, it is difficult to use in real-time. The image holes that are revealed after point displacement (motion magnification) are filled with the texture synthesis method [7].

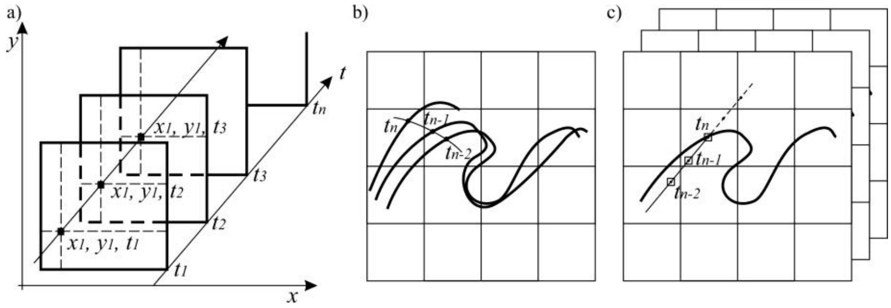

Figure 1. Spatiotemporal representation: pixel in space and time domain (a), Lagrangian (b) and Eulerian (c) approaches to temporal image presentation

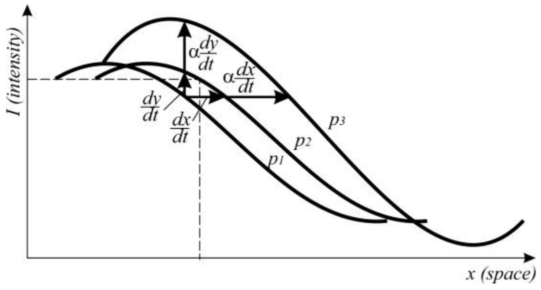

Figure 2. Intensity changes in linear Eulerian motion magnification

In the Lagrangian approach, an image's content and its characteristic points and fragments in the frame are analyzed.

In contrast, the Eulerian approach [8] focuses on changes in the close neighbourhood of pixels in coordinates x, y, and the trajectory of image components is not explicitly determined. Changes in pixel intensity result from the displacement of the image relative to the frame in successive time intervals, as shown in figure 4. Pixel intensity can also be defined as brightness.

Similarly to the Lucas-Kanade approach, it is assumed that changes in intensity are linear. Lines p_1 and p_2 represent the intensity profile at time t_1 and t_2, respectively. The relation can be represented by equation (1):

$$\frac{dI}{dt} = \frac{dI}{dx}\frac{dx}{dt} \tag{1}$$

Motion is magnified by introducing coefficient α (equation (2)).

$$\alpha \frac{dI}{dt} = \frac{dI}{dx} \alpha \frac{dx}{dt} \tag{2}$$

Line p_3 corresponds to the intensity profile resulting from motion magnification. However, this translation also augments noise in the image. The overbumping of line p_3 in figure 4 can produce artefacts in the final image. The stages of data processing in the discussed method are presented in the diagram in figure 3.

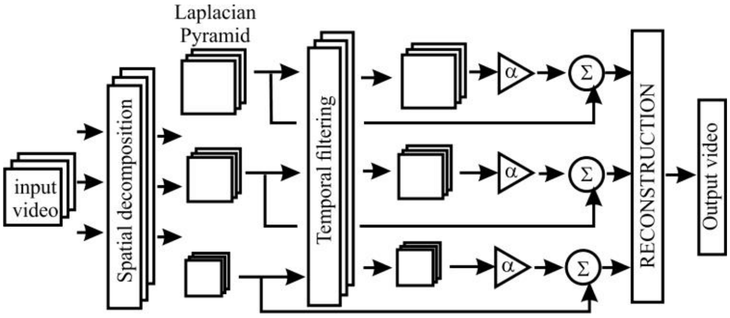

Figure 3. Scheme of linear Eulerian motion magnification

In the Laplacian pyramid approach [9], every frame of the input video sequence is spatially decomposed by temporal filtering of every image layer; the signal is reinforced and added to the original signal to obtain a reconstructed output video. According to some authors, the Laplacian of Gaussian (LoG) operation should be performed to eliminate noise. Due to the linear character of the described processes, this method is referred to as the linear Eulerian motion magnification technique.

The applicability of the Eulerian approach to motion magnification can be improved by abandoning the linearity assumption and rendering intensity with the use of local sine waves. The effectiveness of this method has been validated in contactless monitoring of life functions as well as in technical applications, such as the modal identification of simple structures [10]. In this case, motion is magnified by shifting the local phase. For this purpose, the input video was decomposed with a complex steerable pyramid rather than the Laplacian pyramid [11]. This approach supported amplitude and phase decomposition of local wavelets. Phases were filtered in every location, orientation and scale. The temporary – band passed phases were amplified, and the video was reconstructed. This method is known as phase-based video motion processing [12]. The complex steerable pyramid technique requires numerous calculations, and its applicability for spatial decomposition in real time is limited.

A new compact image pyramid representation for real-time phase-based motion magnification was proposed by [13]. In this approach, the complex steerable pyramid was replaced by the Riesz pyramid what speeds up the processing of video data four-fold.

The Eulerian methods presented in [14, 15] are effective in observations of small motions, but their applicability is limited when both small and large motions appear in a single image. Large motions create significant artefacts. Artefacts and large motions significantly decrease the visibility of small displacements. In the layer-based video magnification approach proposed by [16], the selected region is temporally aligned before subtle variations are magnified. This technique, referred as dynamic video motion magnification (DVMAG), has two main components: warping to discount large motion based on KLT tracking or optical flow, and layer-based Eulerian magnification. The input image is decomposed through an alpha-matte. Images are decomposed into three layers: opacity matte, foreground, and background. Images in opacity and foreground layers are magnified and overlaid onto the background layer. The image holes revealed by the magnified motion are filled in by texture synthesis. In the last stage, the magnified sequence is de-warped back to the original space-time coordinates. In a study by [17], user interactions were reduced through a modified alpha-matte. The distinguishing responses from the background and the foreground based on depth map were presented in a [18].

The motion magnification method continues to be developed. Attempts have been made by [19] to simplify the time-consuming process of filter tuning with the use of convolutional neural networks in the Eulerian approach.

3. Practical application of the motion magnification technique in diagnoses of technical objects

The progress in motion magnification techniques has led to the development of commercial applications for diagnosing industrial objects based on observations of vibration processes. The applicability of the analyzed tools for diagnostic purposes in a real-world industrial setting was evaluated based on an analysis of the problems reported by automation maintenance services:

- Case 1: Supply pump in a heat plant,
- Case 2: Dry feed extruder,
- Case 3: Machine hall ventilation fan.

In each case, the environment of the operating machine was recorded with a video camera. The obtained video footage was enhanced during post-processing in the Motion Amplification program. The condition of each machine was diagnosed based on the enhanced video sequence.

Supply pump in a heat plant. Considerable vibrations on pump casing as well as seal failure were noted during pump operation. An analysis based on the motion magnification method revealed axial motion of the pump's mechanical seal clamps and bearing housing on the side of the delivery casing. Video presenting the movement of pump seals is shown in

http://www.uwm.edu.pl/wnt/mechatronika/images/vibsys/CHV_blisko_filtered_stabilization.mp4.

Dry feed extruder. Vibrations were observed on the extruder casing and the accompanying installations (pipelines, platforms, mezzanine). An observation of the registered vibrations revealed visible motion of the elements mounting the extruder to the ground/foundations. The vibrations were caused by excess clearance of assembly bolts. In the

> *http://www.uwm.edu.pl/wnt/mechatronika/images/vibsys/12_02_2019_02%20extruder%202%20x5115-12_03_filtered.mp4*

and

> *http://www.uwm.edu.pl/wnt/mechatronika/images/vibsys/NO.1%2012_02_2019_02%20extruder%202%20x5115-12_08.mp4*

there is shown video presenting the displacements of elements of object. The frequency of vibrations in the accompanying systems corresponded to the operating frequency of the extruder shaft.

Machine hall ventilation fan. A visible increase in vibration of the fan's drive system was observed during operation. Video data were processed with the motion amplification technique to reveal displacement of the fan's motor and shaft on the side of the gearbox.

In the

> *http://www.uwm.edu.pl/wnt/mechatronika/images/vibsys/se%20went%20rekuperacja_filtered.mp4*

there is shown video presenting the displacements of elements of object.

The motor casing was axially displaced relative to the shaft and the bearing housing, indicating that the clutch had been incorrectly assembled.

4. Conclusions

The diagnostic processes in the described cases confirmed the source of vibroacoustic signals, thus validating the applicability of the motion magnification techniques in an industrial setting. The described method supports observations of numerous machine elements whose motion cannot be captured with the involvement of conventional tools. One of the most important advantages of the discussed technique is that it does not interfere with technological processes. None of the diagnosed objects had to be shut down to enable the analysts to enter the safety zone or install sensors. In all cases, the test stand was prepared and the measurements were conducted in a matter of minutes. These findings indicate that the motion magnification method can be applied in preliminary inspections, including in cases where more sensitive equipment is required for further measurements.

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