Application of vision measurements for modal analysis of wires for the purpose of overhead transmission lines monitoring

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Abstract. Overhead transmission power lines are still one of the crucial elements of electro-energetic system. There are obvious advantages of using overhead transmission in the distribution of electricity. The amount of energy transported through a power line is determined by the distance between the wire and the ground or other objects placed beneath it (e.g. trees). This distance is not fixed and depends on the overhang of the wire. This, in turn, is determined by many factors such as ambient temperature, humidity, precipitation, the value of current flowing through the wire. In order to optimize the wires electrical load, the monitoring of that overhang is required. One way to measure it is the non-contact measurement by vision system. It has the advantage, that using high-speed cameras respectively it also allows for vibration measurement and analysis of dynamic performance. That is very important while the wires are susceptible to the influence of wind, and the resulting vibrations interfere with the correct measurement of the overhang. The paper presents the results of vision measurements of the system vibrations and modal analysis carried out on their basis. The study was conducted on a specially made laboratory stand.

1. Introduction

No one needs convincing about the dominant role of electricity in the life of modern man. Electricity is produced in power plants and distributed by overhead power lines of high and highest voltage. However transmission of electricity over long distances is burdened with power losses which are proportional to the square of the electric current flowing through the conductor. Therefore, the voltage of transmitted electricity is increased and its electrical current is decreased. But one cannot arbitrarily increase the voltage in the wire, and thus increase the amount of transported energy, because it is limited by the risk of surges. To obtain the optimum transmission in overhead power lines one should constantly monitor the distance between the cable and the objects located beneath it. This distance is variable and depends on the wire overhang (assuming that the infrastructure under the transmission line does not change). Therefore, in modern transmission lines of high and highest voltages sensors measuring wire overhang are increasingly used (e.g. inclinometers mounted on the line). Unfortunately, the work of inclinometer is distorted when the cable starts to vibrate and then the readings are unreliable. Therefore, apart from measurements of the wire overhang, monitoring system should also be equip with the ability to measure vibration.

Vibrations can be measured by many methods, which in most of the cases are the contact one, such as accelerometers, strain gauges or FBG sensors. Application of these types of sensors requires them to
be connected to the cable. It rises many complications related to the electricity flowing through the wire and its temperature and it makes such a system very expensive and inconvenient. No operator would be willing to turn off the voltage on their lines for mounting the sensors. It is better then, to develop non-contact measurement technique. There are many such methods presented in the literature [1, 2]. They can be based on geodesic or laser tools, but they rises another complications. That is why vision systems seem to be the best solution.

There are some examples of application of vision systems for overhead transmission lines monitoring. The main fields of application can be grouped as follows: an extraction of transmission line cables for later analysis, an estimation of ice cover thickness and damage detection, measurement of displacements of selected wire points. Although only third group is important from the paper topic point of view, for complete picture, examples of all application groups will be presented below. Paper [3] presents an example of the first group. Authors developed an algorithm for image segmentation to extract cables from the background. The automatic curve detection was done using a UAV. In order to process low contrast images, the Otsu method was applied [4]. In the article [5], segmentation was performed using genetic algorithms and particle swarm optimization. The impact of changing lighting conditions was removed by the use of homomorphic filters [6]. The automatic detection of transmission wires and classification of different types of poles was presented in the paper [7]. The classification of towers was based on edges extraction. The article [8] represents the second group of applications. A vision system was applied to measure the thickness of ice on the cable based on a comparison between the edge images of ice-covered cables and ones without an ice. Two methods of edge detection were implemented: wavelet transform and image morphology. The authors of [9] also presented a system for ice cover monitoring. The image processing consists of many steps, with the main ones being background subtraction, edge extraction and classification of ice cover types. The paper [10] shows an application of 3D vision methods to measure ice cover thickness. Manitoba Hydro presented “the Ice Vision System” [11] dedicated to the early detection of icing, measurement of ice accumulation and classification of the type of icing. Damage detection [12] methods for transmission line cables are also being developed. The paper [13], on the other hand, presents a vision system for lightning-induced cable damage detection. The system detects arc-shaped damage as well as cuts and cracks of cable bundles. The authors of the article [14] present an example of an application belonging to the third group – related thematically to the presented paper. The measurement of a wire’s vibration was carried out in order to estimate the parameters of the structure and to detect the occurrence of damage. The algorithm consists of edges extraction, vertical displacements of measurement points reconstruction and the Fourier transform of the obtained displacement amplitude signal computation. The paper [15] describes a tool which aids vision-based modal analysis of transmission line cables. The image sequence was captured by a camera influenced by external vibrations. Therefore, the frames were blurred due to relative camera and object motion. The authors proposed multi-pattern matching based on DIC, which reconstructs vibration signals. The phenomenon of forcing wire vibrations due to the shedding of an ice cover is described in the paper [16]. A vision-based system is applied to measure the amplitude, frequency and damping factor of a vibrating wire. A ball marker was used as a measurement point. The articles [17,18] show an application of computer vision for geometry estimation and localization of measurement points in the preliminary steps of modal experiments, for the measurement of vibration signals, vision-based modal analysis and damage detection and localization based on vision data. An extension of the proposed method to a full 3D system is proposed in [19]. The paper [20] presents a non-contact method for the measurement of tensile forces in the suspension cables of bridges. A DIC algorithm is applied for displacement computation. The compensation of the random motion of a camera due to wind or vibration is also proposed. The correction is provided by the observation of a fixed object on the scene, e.g. a distant building. Tension in the cables was estimated based on dynamical response and natural frequencies. A damage detection method based on mode shapes was also introduced.

In the next paragraphs the algorithm used for points displacements calculation from recorded video data, experimental setup and performed modal analysis are presented.
2. Measurement algorithm
The vision system consists of two high-speed digital cameras, halogen lamps for lighting and a set of crash test markers mounted on the analyzed wire. The field of view can be adjusted using different lenses, depending on the desired accuracy. Applied method uses a tracking algorithm and three-dimensional reconstruction of the markers’ trajectories. Trajectory reconstruction is based on the positions of corresponding markers on two image planes of the camera system [21]. The system measures the amplitude of vibrations in a reference frame from one of the cameras. This requires the calibration of external and internal parameters [21].

The measurement procedure can described as follows:
1) calibration of the system,
2) measurement setup preparation,
3) image sequence acquisition,
4) tracking and reconstruction of three-dimensional trajectories.

After arrangement of the camera and lighting system, calibration has to be performed. The internal calibration of the system was done using a flat checkerboard pattern. The parameters obtained in the calibration step were used to remove distortions introduced by the optics. The external calibration, necessary for three-dimensional reconstruction algorithms, was performed based on a set of markers and one known dimension on the observed scene. A set of crash test markers was mounted at points of interest on the wire. After acquisition of an image sequence, the image trajectories of markers were tracked across a sequence using Tema's algorithm for quadrant symmetry. The three-dimensional trajectories of markers are reconstructed using a stereo-vision technique. The vibration signal is then scaled to metric units using data obtained in the external calibration step.

3. Performed measurements
In the following paragraph, detailed descriptions of the laboratory measurements are given. The first subsection presents a laboratory stand used for testing an experiment performed to evaluate the sag of a transmission line cable. The second subsection provides information on the experiment in which the dynamic response of a wire was measured.

3.1. Laboratory stand
A laboratory stand for testing contactless measuring methods of the wire type objects was designed and constructed. The modular design of the structure makes it easy to assemble and disassemble with a variable configuration of poles supporting the wire. The cable can be hung 0.8 m above the floor. The tension in the cable can be adjusted continuously. The modularity of the setup makes it possible to analyze the load acting on a given section, as well as the propagation of a disturbance across sections, with one of the sections subjected to a time-dependent force. The variable tension of the cable provides the capability of testing the static states and dynamic characteristics of the system. Figure 1 presents general view of designed stand in the exemplary four-pole configuration.

![Figure 1. The general view of laboratory stand](image-url)
Figure 2 shows the way of wire suspension and adjustable tension mechanism.

3.2. Vision-based measurement of the cable’s vibrations

In the performed test, the vibrations of markers attached to the wire were investigated. The measurement was carried out by a stereo-vision system equipped with two high-speed digital cameras. The examined object was excited by burst random noise signal (50 % ratio) using an electrodynamic shaker. The test setup consisted of the following elements:

1) a stereo-vision system with two high-speed Phantom v9.1 cameras of a maximum resolution of 1632x1200, with a fixed focal length Carl Zeiss lens of f = 25 mm. The system was placed on a stereo-vision head and mounted on a tripod at a distance of 1.3 m from the wire. The baseline of the system was 661.0059 mm. The relative position and orientation of the cameras was obtained in an external calibration as it was said before. The parameters of the cameras were set as follows: resolution – 1632x800, frame rate – 200, exposure time – 0.004 s, acquisition time – 23.7 s, Camera 9645 – Master mode, Camera 9644 – Slave mode.

2) an electrodynamic shaker exciting the analyzed wire with a burst white noise signal.

3) a laboratory stand was set in two-pole configuration (distance between poles – 2.25 m). The wire was covered with 51 evenly spaced crash test markers.

Entire test bench with basic parameters is shown in Figure 3.
During the measurements, two sessions were carried out, one referential case (Reference1) and one involving an extra mass for further tests of the damage detection algorithms (Mass1). In each session, five measurement series were performed. The positions of markers on the lab setup are shown in Figure 4. To increase the spatial resolution of the vision system, motion analysis was conducted on three segments of the analyzed overhead line stand. They correspond to the three smaller fields of view of the stereo-vision system, as demonstrated in Figure 4. Each measurement area (field of view) included 21, 26 and 19 crash-test markers, respectively. For example, at a distance of 1.3 m from the analyzed object, the field of view of the stereo-system amounted 880 mm.

![Figure 4. Schematic layout of the markers on the test bench.](image)

The high-speed camera system’s data was recorded and stored. Next, the data was loaded in TEMA Automotive software [21] in order to extract the positions of each of the markers and track their trajectories across frames of the sequence. The tracking method chosen for the data was Quadrant Symmetry. The "Quadrant Symmetry" tracker with a radius of 4 pixels was used. Figure 5 presents example of configuration of one measurement point in the software.

![Figure 5. Configuration example of the measurement point.](image)
Configuration of markers was controlled during the tracking of points. Errors in positions of the points were detected by observing the position of all points in graphs in a function of time (See Figure 6). Sudden changes in individual points in comparison to others was treated as a prerequisite for an error of the tracking algorithm. All such errors were removed by adjusting the configuration of the point and re-examine the problematic frames of the film.

![Figure 6. Time history fragment for the z axis](image)

Data concerning the three-dimensional trajectories for each of the movie sequences were exported to .xls files and then to the MATLAB programming environment, where the frequency response of the system was estimated. An example of the obtained frequency spectrum is presented in Figure 7.

![Figure 7. Displacement spectrum for point FBG4](image)

4. Modal analysis
The following paragraph presents the procedure and results of experimental modal analysis performed with use of characteristics measured by the vision system.

Using response frequency spectra obtained from vision measurements, the frequency response functions (FRFs) were calculated with respect to the force signal measured simultaneously with vision recording. Next experimental modal analysis was performed. For the estimation of modal parameters VIOMA toolbox was used. It is a Matlab toolbox created at Department of Robotics and Mechatronics AGH [22]. For analyses Least Square Frequency Domain (LSFD) algorithm was selected [23 -]. Calculations were carried for frequency band 0 - 50 Hz. As a result of these analyses five first natural frequencies of the wire were estimated. The results are shown in Table 1.
Table 1. Modal parameters of tested wire

| No. | Natural freq. [Hz] | Modal damp. [%] |
|-----|--------------------|-----------------|
| 1   | 8.03               | 8.23            |
| 2   | 16.37              | 8.58            |
| 3   | 21.95              | 8.59            |
| 4   | 28.73              | 3.58            |
| 5   | 35.12              | 3.49            |

Since the analysis was conducted based on data collected in the three exposures, in order to properly visualize mode shapes (MS), it was necessary to merge together these three pieces. For proper scaling of consecutive fragments, overlapped points were used - those that were found in two neighboring scenes. Scaling was performed in two stages. First the phase of consecutive points was unified. Then the amplitude of the common points was leveled and the resulting scaling factor was used for the remaining points of the exposure. Figure 8 shows the first MS for which at one of the merging points the scaling was done (right side), and at the other was not (left side).

![Figure 8. Mode shape at first natural frequency](image)

5. Conclusions
The article presents the results of a modal analysis performed using vision measurements. Discussed analyses are part of bigger research to develop a system for dynamic energy transfer management of the transmission grid and the monitoring system of that grid. The method used to track the motion of markers (measuring points) on the video sequence was shown and the way to visualize MS obtained in several exhibitions was described.

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