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Analysis of Dynamic Strains of Suspension Bridge on the Example of Pedestrian Footbridge**

1. Introduction

Modern survey technologies adapting the concepts of contemporary physics play an increasingly important role in studies of vibrations and displacements. Use and maintenance of engineering structures often involves changing their position and/or shape.

For the control of engineering structures of elongated shape, such as:
- chimneys,
- towers,
- bridges,

recording of transient movements of the objects that result from the operation of various forces is important.

Dynamic strains are usually the result of the weather conditions, seismic activity and the impact of industry and transport. The significance of dynamic studies of structures are even confirmed by Polish building standards.

Vibration measurements of engineering structures is not a typical surveying task and therefore requires a selection of appropriate technology, providing primarily movement measurement of relevant points of the object, sufficient frequency of data recording and its high accuracy.

The essence of the object vibration monitoring system is to obtain a global picture of the strains for the overall study structure. The presented study used the ground-based radar interferometer, which is the only one in Poland and it can be found at the Faculty of Mining Surveying and Environmental Engineering of the AGH University of Science and Technology in Krakow.

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2. The Principle of Ground-Based Radar Interferometer Operation

In 2008 an innovative system IBIS developed by the Italian company IDS appeared on the market. The name of the system comes from the acronym of the English name: Image by Interferometric Survey. The system uses the following techniques: microwave interferometry, stepwise modulation of wave frequency and synthetic aperture radar. Their combination enables measurements of the range and accuracy which have not been carried out in land surveying so far.

The system is produced in two versions:

1) IBIS-S – using the first two techniques,
2) IBIS-L – using all three techniques.

The carried out surveys used the system IBIS-S (Fig. 1), which allows the observations of building structure displacements under the influence of static loads as well as the survey of dynamic changes in their location.

Fig. 1. IBIS-S system during the surveys

The base of the system is the ground-based radar interferometer. Its work is controlled by an appropriately programmed portable computer, which at the same time allows to record the observations and enables their preview during the survey. The radar is installed on a tripod with a movable head, which allows appropriate setting towards the test object. The system is powered by a battery pack. The survey uses special horn reflectors (Fig. 2), which strongly reflect the survey signal, enabling precise analysis of the results.

Fig. 2. Horn reflectors installed on the object

The analysed radar interferometer uses bandwidth with a range of 300 MHz. The wave frequency is around 17 GHz (K_u band), and the frequency of data recording is up to 200 Hz. Using the IBIS-S system, observations with a range up to 1 km can be carried out, and the use of microwave technique allows to achieve surveying accuracy of approximately 0.1 mm. The radar has a maximum resolution of $\Delta R = 0.5$ m. The resolution shall be construed as the minimum distance between two points on the object at which they may be considered as different points. If the distance is less than ΔR, the points are not distinguished. The distance is measured along the direction of wave propagation. Due to the high resolution, as the result of the survey we obtain the record of displacements of numerous points distant from each other by 0.5 meters (in radial direction). The accuracy of the device results from the application of the interferometry technique, which uses the phenomenon of wave interference, i.e. amplification or attenuation of the reflected signal, depending on the phases of the waves. During operation, the radar illuminates the object with a beam of waves, which are scattered on a heterogeneous structure of the object. The movement of a point in the direction of electromagnetic wave propagation results in a phase shift between the signals reflected from the surface of the object (Fig. 3). The displacement of the point is calculated based on the differences in phases of waves received by the receiver at different times.

The IBIS-S radar is particularly useful for surveying objects of tower and bridge types [2]. It allows to detect and analyse slow sustained movements and fast-changing transient movements. An undeniable advantage is no need of a direct access to the object, which eliminates the necessity of installation of elements reflecting the waves, which is both time consuming and dangerous, especially on high structures. The high sampling rate allows to talk about the continuity of displacement surveying and about a specific type of monitoring.

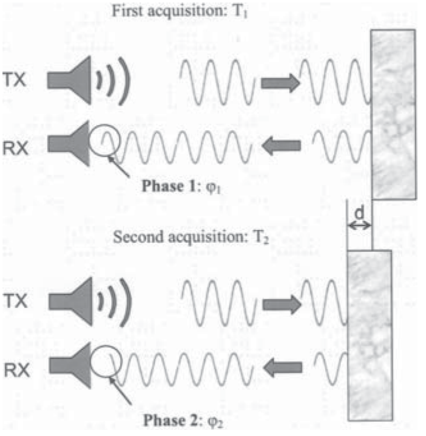

Fig. 3. Phase shift as a result of displacement of the object
Source: [1]

3. Using the IBIS-S Radar for Object Vibration Surveys

In order to examine the application of the IBIS-S radar to measure vibrations and displacements, research surveys were carried out on the river Raba. The object was a single-span, timber and steel pedestrian footbridge of the suspension construction, of a width of approximately 1 metre and spans ranging nearly 70 metres [3, 4]. Five horn reflectors were fixed on the footbridge (Fig. 4) – one at mid-length of the span (point p54) and two (at both edges) in the 1/4 of the length of the span (points p46, p48) and in the 3/4 of the length of the span (points p65, p66). The footbridge was very light and frail. It was made subject to vertical and torsional vibrations, applying movement-inducing force at different points.

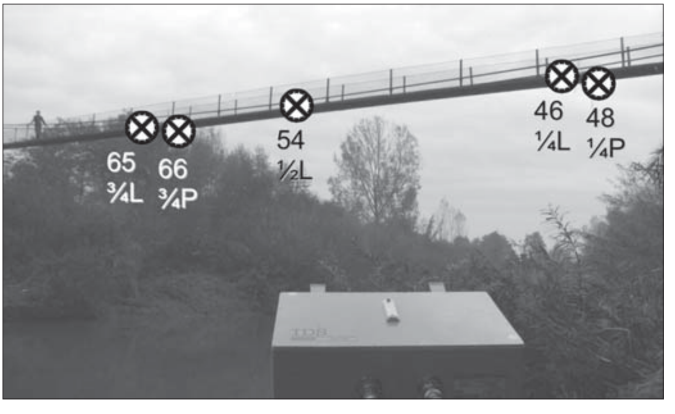

Fig. 4. Arrangement of reflectors on the footbridge

During the tests, the radar recorded the location of the object points with the frequency of 97 Hz.

3.1. Excitation of Vertical Vibrations

Forcing vertical vibrations was performed in several ways. Firstly, vertical vibrations of the footbridge were observed during the crossing of two persons. In addition to the strain caused by loading of the span (Fig. 5), the footbridge demonstrates vibrations of the harmonic type. The maximum observed vertical displacements of points are 100 mm. The points located in the same section, but on the opposite sides of the footbridge, vibrate virtually harmoniously in the phase, which proves that the vertical excitation does not produce torsional vibrations (Fig. 6a). It was found that the vibrations of the points in the 1/4 and the 3/4 of the length of the span are mutually shifted in the phase by 180° (Fig. 6b).

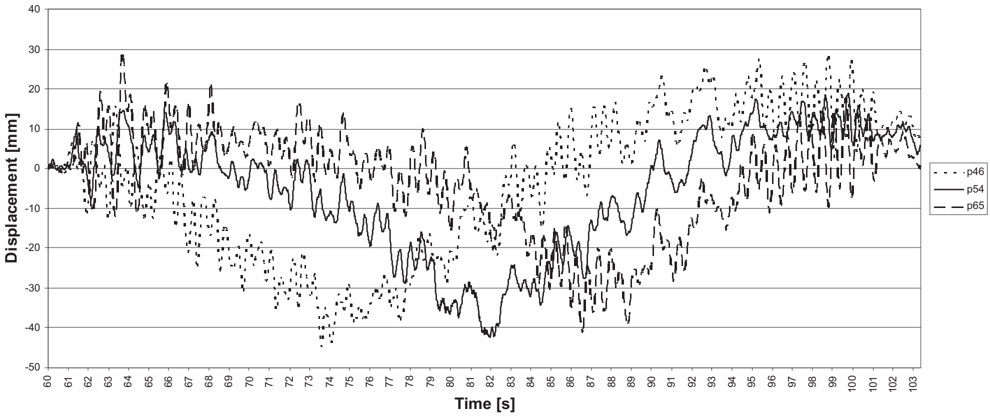

Fig. 5. Footbridge swings induced by two persons crossing

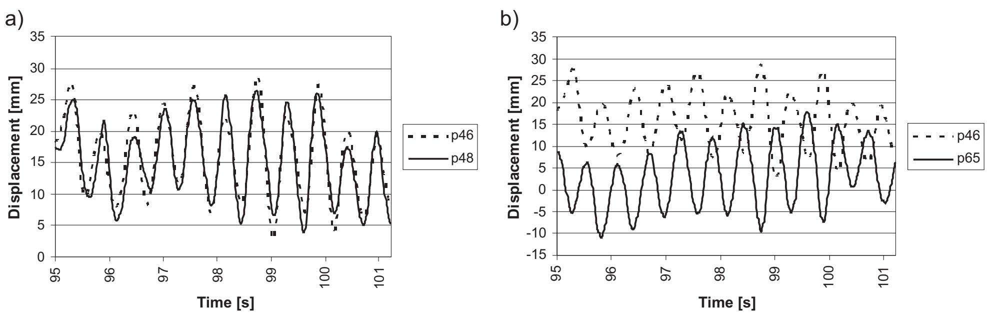

Fig. 6. Comparison of vibration graphs of points: a) p46 and p48; b) p46 and p65

Another experiment was the induction of vertical movements in the 1/4 (or the 3/4) of the length of the span with normal mode frequency. The largest amplitude of vibrations was determined at about 50 mm (Fig. 7).

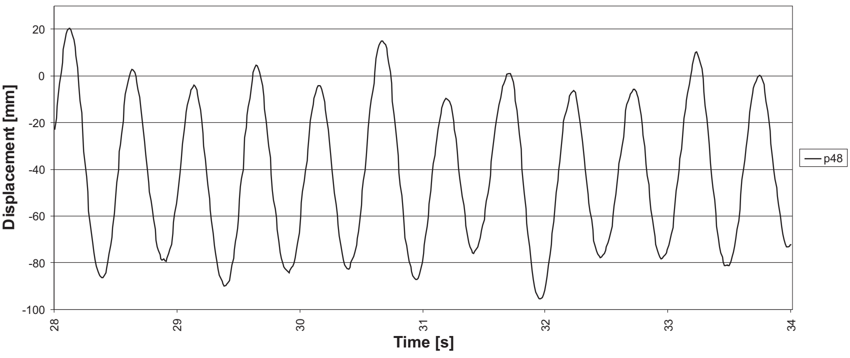

Fig. 7. The largest amplitude observed

The values of vibration amplitudes of all the observed points are similar. There was no excitation of torsional vibrations observed. In contrast to the previous test, in this case the vibration of the points in the 1/4 and the 3/4 of the length are harmonious in the phase, while the mid-point vibrations are contrary to them (Fig. 8).

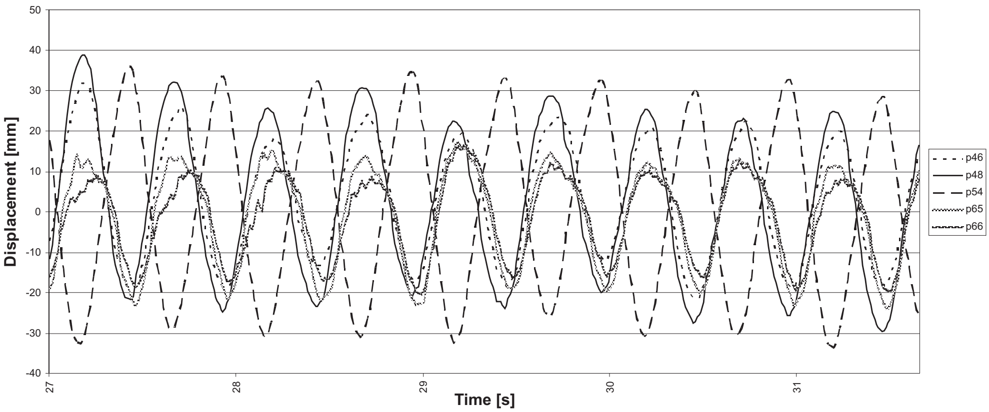

Fig. 8. Contrary vibrations of the footbridge mid-point in relation to the others

Location of the force in the mid-length of the span gives similar results to forcing vibrations in the 1/4 and the 3/4 of the length. The moment of attenuating the footbridge vibrations and their re-excitation (Fig. 9) was presented on the example of application of a vibration-inducing force in 1/2 of the length of the span.

The collected time series were subjected to spectral analysis to determine the frequency of the footbridge vibrations. The results of spectral analysis performed in the IBIS Data Viewer programme were presented in Figure 10.

Figure 10a presents the frequency of vibrations observed during the crossing of two persons. Different frequencies were obtained during the analysis of the vertical vibrations forced in the 1/4 (or the 3/4) of the length of the footbridge span (Fig. 10b).

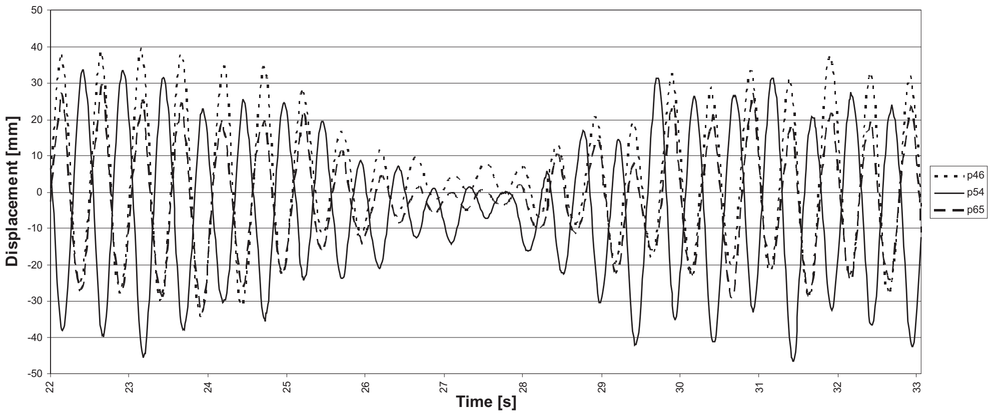

Fig. 9. Recording of the moment of attenuation and excitation of the footbridge vibrations

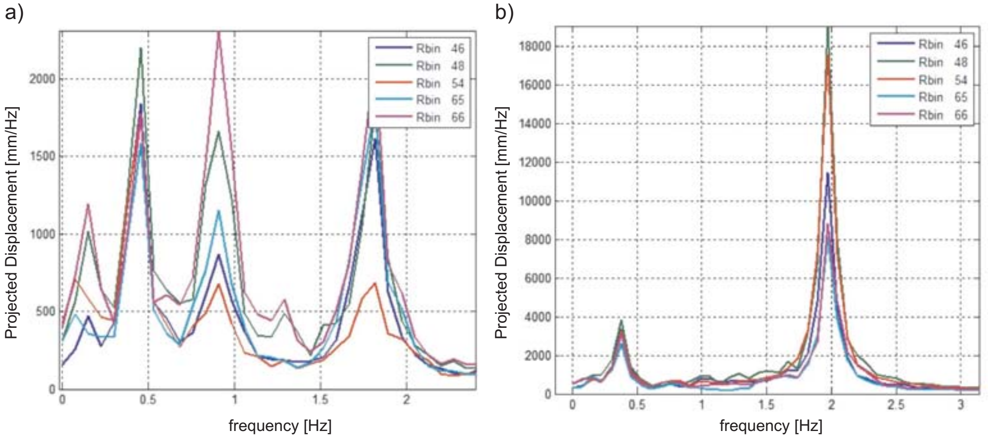

Fig. 10. The results of spectral analysis for various types of vertical forcing

3.2. Excitation of Torsional Vibrations

Excitation of torsional vibrations was carried out in the middle of the footbridge and in the 1/4 (or 3/4) of the length of the footbridge. During the test the phase shift between successive points is noticeable along the bridge length (Fig. 11).

The point in the middle of the footbridge shows a high amplitude of vibrations. It vibrates in accordance with the other points on the same edge. The maximum observed amplitude of vibration are 300 mm. The comparison of vibration excitation in various places indicates that points in the 1/4 and the 3/4 of the length vibrate less. Application of the force in the 1/4 and the 3/4 of the length of the footbridge results in a doubling of the vibration amplitude of the point p54.

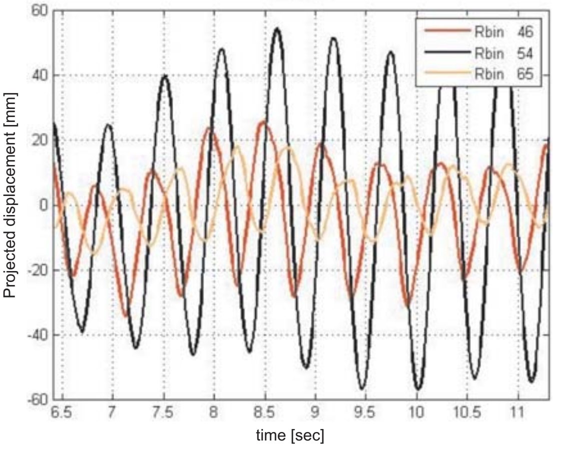

Fig. 11. Footbridge motion during torsional excitation in 1/4 of the bridge length

It is worth noting that the place of application of the force inducing torsional vibrations affects the designation of frequency of the object vibrations. Excitation of vibrations in the mid-length of the span (Fig. 12a) gives a different frequency spectrum than the excitation of vibrations in the 1/4 (or the 3/4) of the length (Fig. 12b), and in consequence – other shapes of normal modes.

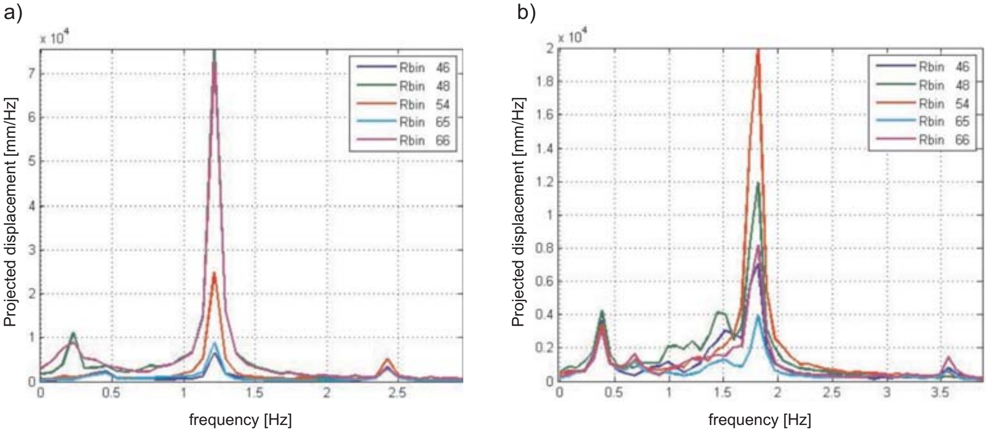

Fig. 12. The results of spectral analysis for various inductions of torsional vibrations

Data analysis using IBIS-S allows to conclude that the bridge is more rigid to vertical than torsional vibrations. It is necessary to apply a much stronger vertical force than torsional force to produce the same displacement of the points.

3.3. Survey without Reflectors

The grounds for selecting the points representing the object and being suitable for the displacement analysis is the radar profile (Fig. 13). In order to compare the usefulness of surveys without prior fixing of horn reflectors, having analysed the reflection spectrum, the point p41 was selected, which was characterized by the strongest intensity of the reflected signal among the points for which the reflectors had not been not applied. For the point p41 the reflected signal, which is expressed with the SNR parameter (the ratio of the useful signal to the noise), has a value of 40.3 dB, while the use of reflectors gives a signal in the range of 59.1–64.5 dB. The point p41 is located at the distance of 2.5 metres before the first reflector (point p46), measured along the span. The movement of this point, which constitutes a part of the footbridge construction, may be compared with the movement of the reflector p46.

Figure 14 presents the diagram of vertical displacements of points p41 and p46 observed during the excitation of vertical vibrations.

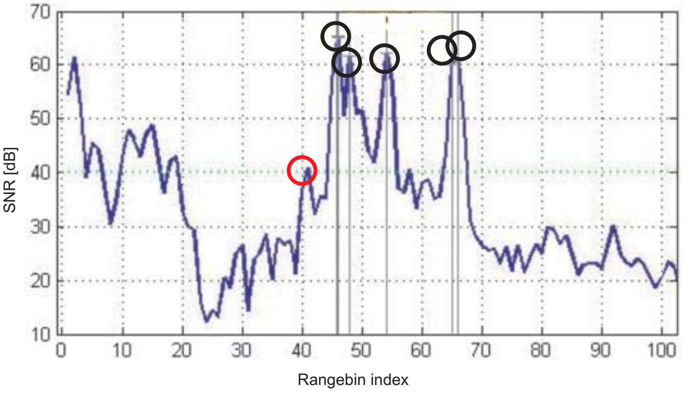

Fig. 13. Radar profile of the surveyed footbridge

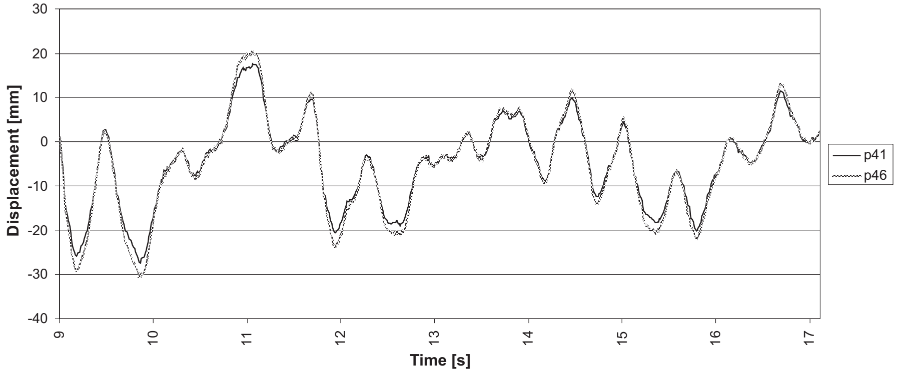

Fig. 14. Diagram of displacements of points p41 and p46

As it follows from the diagram (Fig. 14), the movement of the point p41 coincides with the movement of the reflector p46 within the measurement accuracy. Furthermore, the displacement differences result from the mutual shift of the points. The footbridge is not rigid, which results in differences in displacements of the points away from each other.

The conducted analysis of vibrations gives grounds to conclude that when surveying objects with structural elements (in this case: metal) which strongly distract waves emitted by the radar, the use of the reflectors is not necessary, and the resulting accuracy is sufficient to carry out further dynamic analysis.

4. Conclusions

The IBIS-S system allows continuous recording of numerous points simultaneously and makes possible to measure transient movements with objects which are difficult to access or complex in their structure. Therefore it is useful for the analysis of construction vibrations and helps to assess changes in its rigidity. Submillimetre accuracy and high frequency of displacement surveying ensures the usefulness of the system for dynamic analysis of structures.

The ground-based radar interferometer allows to investigate at the same time the mutual displacements of the points both located close together and far apart. The device does not require a direct access to the object. In many cases, installing horn reflectors turns out to be superfluous. The surveys carried out with the ground-based radar interferometer allow to observe the object reactions to acting forces as well as to their decline, recording the process of excitation and attenuation of vibrations. Precise surveys conducted with this technology constitute the grounds for professionals in the construction industry to assess the safety of the building structures.

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