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# Application of IBIS Microwave Interferometer for Measuring Normal-Mode Vibrational Frequencies of Industrial Chimneys**

## 1. General Characteristics of Interferometric Microwave Radar

The microwave radar interferometer, constituting a part of the IBIS surveying system, is a modern device, designed for static and dynamic monitoring of building structures. The IBIS-S version of this system allows to observe dislocations during static loads as well as dynamic surveying of building structures. The basic unit of the system is the ground-based microwave interferometer (Fig. 1).

**Fig. 1.** Microwave interferometric radar during surveying procedure

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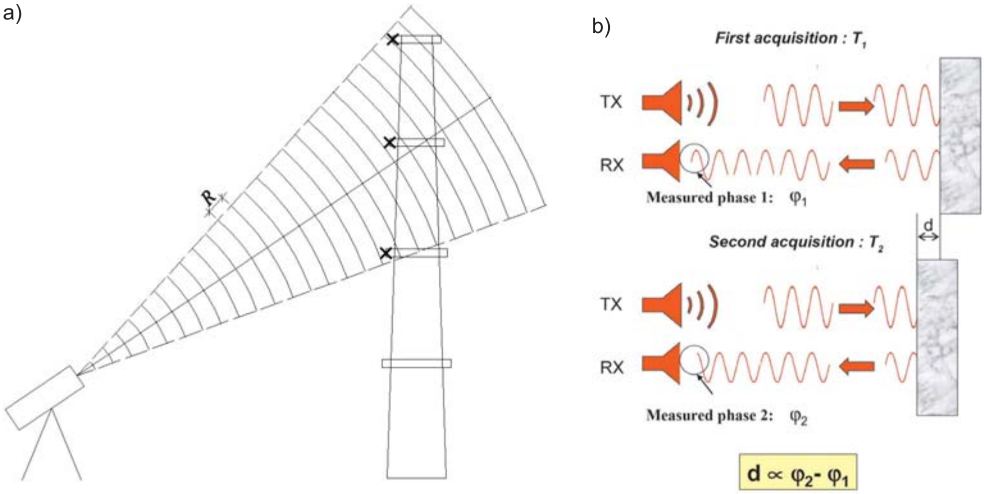


**Fig. 2.** Principle of microwave interferometer operation:
a) surveying diagram; b) idea of microwave interferometry

The surveying set also includes an adequately programmed portable computer which controls the operation of the device, records observations and allows their viewing during the surveying procedure. The battery pack guarantees the operation of the device without external power supply.

The device operates in the microwave band of (17.1–17.3 GHz). The reflected part of the wave returns to the receiving antenna, allowing to determine the dislocations of the points of the object. This could be achieved thanks to the microwave interferometry technique, based on measuring the difference between phases of successive beams of the waves reflected from the object (Fig. 2). The radar records radial motions, i.e. components of the actual movements in the direction of electromagnetic wave propagation. There is no requirement of a direct contact between the device and the tested object. Moreover, it is not necessary to install additional elements on the object, as the reflection of a sent wave from the surface of the object is used.

The device allows a simultaneous identification of multiple virtual sensors on the surface of the tested object. Their number depends upon the intensity of the reflected signal. This makes it possible to receive a global picture of changes in the geometry of the structure. The use of additional technology SFCW stepped-frequency continuous wave, involving a stepwise modulation of continuous wave frequency, ensures reaching a high resolution *R* [2]. If in the range of the *R* width a construction element strongly reflecting a sent wave is found, it will be easy to subsequently follow the changes of its position.

The maximum, possible to obtain survey parameters [4] are:
- distance between the device and the object – 1000 m,
- radial distance resolution $R$ = 0.50 m,
- surveying accuracy of static dislocations in the radial direction – 0.01 mm,
- surveying accuracy of dynamic dislocations in the radial direction – 0.1 mm,
- recording frequency – 200 Hz.

These values are dependent upon the surveying conditions.

The high frequency of recording allows the constant monitoring of the object. This is important in the dynamic surveying of building structures. An essential problem that may occur during the testing of the object vibrations is the correct interpretation of the echo intensity diagram and the selection of relevant points representing the object. The authors' previous experience [3] indicates that even small inhomogeneities of the object surface, such as concrete inequalities, reflect radar beam so strongly that a signal, which is strong enough, returns to the radar. In order to increase the intensity of the echo and the certainty of the identification of the points, metal elements reflecting waves (microwave reflectors) may be used. The use of such reflectors is justified especially in the case of objects with a complex structure, composed of multiple elements that can scatter radar beam. The certainty of identification might be further increased by measuring the distance from the radar to the characteristic points of the object by using geodetic reflectorless total station.

## 2. Measuring Normal-Mode Vibrational Frequencies of Industrial Reinforced Concrete Chimneys

The normal-mode vibrational frequencies and the corresponding forms as well as vibration damping constitute dynamic characteristics of building structures. In the case of reinforced concrete industrial chimneys these are the basic data, which allow an accurate assessment of technical condition of these objects [6, 8]. Currently used techniques for dynamic surveying of tall chimneys are associated with troublesome installation of surveying sensors directly on the object, usually at great heights [5]. The use of interferometric radar for this type of research may be particularly useful as it allows the surveys to be conducted from the ground level.

Within the scope of this work, the first in Poland dynamic surveying of reinforced concrete chimneys (of 260 m each) was carried out, using the *IBIS* interferometric radar (Fig. 3). The surveying scheme with indicating the distance between the radar and the measurement points on the K2 chimney structure have been contained in figure 3. Main technical data of the tested chimneys have been summarized in table 1.


**Fig. 3.** Microwave interferometric radar during dynamic testing of K2 reinforced concrete chimney of $H$ = 260 m

**Table 1.** Technical characteristics of tested chimneys

| Chimney | Height $H$ [m] | Outer diameter [m] | | Structural wall thickness [m] | |
|---|---|---|---|---|---|
| | | ±0.0 | +260 | ±0.0 | +260 |
| K1 | 260 | 27.60 | 7.70 | 0.70 | 0.20 |
| K2 | 260 | 16.00 | 8.30 | 0.70 | 0.20 |

A difficult problem in the dynamic tests of reinforced concrete chimneys is to excite vibrations [1, 5, 6]. In this case, chimney vibrations forced by wind gusts were recorded.

After determining the geometry of the analysed object, data processing software calculates the changes in distances into values of dislocations. Owing to so processed observations it is possible to analyse the behaviour of the test object during the surveying procedure.

Figure 4 presents the 280-second recording of vibrations of the three observed points of the K2 chimney, located around the highest galleries at levels of +173.8, +216.3 and +255.8 m. The highest amplitude of the dislocations of approximately 60 mm was observed at the point located within the top of the chimney.

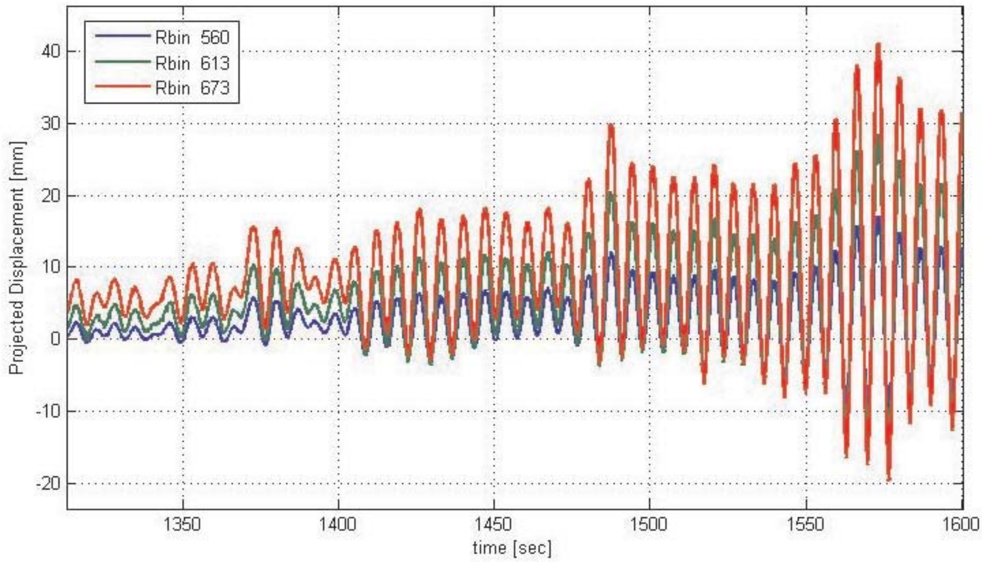


**Fig. 4.** Dislocations of test points on the K2 chimney structure recorded during 280 s

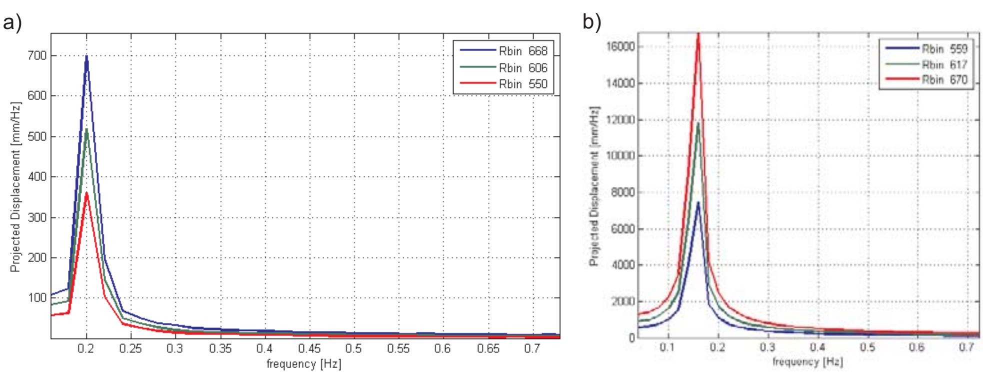


**Fig. 5.** Spectral analysis of recorded waveforms of vibration:
a) K1 chimney; b) K2 chimney

On the grounds of spectral analysis of the recorded vibrations waveform, the first (primary) normal-mode vibrational frequencies of the chimneys were determined (Fig. 5). For the K1 chimney the frequency has a value of 0.20 Hz and for the K2 chimney – the value of 0.16 Hz.

Due to very weak excitation of vibrations, it was possible to record only the first (primary) normal-mode vibrational frequency $f_1$. The use of strong excitations of chimney vibration would also allow to determine higher-frequency normal mode of vibrations and parameters of their damping [5, 6].

Continuous recording of the object working conditions allows the correct interpretation of the recorded changes in its location, i.e. due to the intense sunlight.

The results of the measured and calculated primary frequency values of the normal mode of vibrations $f_1$ of the chimneys K1 and K2 have been summarized in Table 2. The calculations were conducted for the design condition of the chimneys, with no regard to their technical wear. In both cases, the measured frequency values were lower than the calculated values, by 7.0% and 7.5% respectively. This indicates a lower stiffness of reinforced concrete load-bearing structures of those chimneys in relation to their design assumptions. This may be due to the lower than the designed strength of concrete or corrosion defects of concrete in the chimney structures.

The normal-mode vibrational frequency of the K1 chimney is higher than the frequency of the K2 chimney of the same height. This is the result of more rigid load-bearing reinforced concrete chimney structure of the K1 in comparison with rigidity of the K2 chimney structure.

**Table 2.** Summary of measured and calculated values of primary normal-mode vibrational frequency of K1 and K2 chimneys

| Chimney | Measured frequency $f_1$ [Hz] | Calculated frequency $f_1$ [Hz] |
|---|---|---|
| K1 | 0.20 | 0.215 |
| K2 | 0.16 | 0.173 |

It is essential to pay attention to the need for surveying determination of the primary normal-mode vibrational frequency of reinforced concrete chimneys in accordance with the requirements of PN-88/B-03004 [8]. The so-called "0" survey, executed directly after the construction of the chimney, is of particular importance; the results of subsequent periodic dynamic surveying must be compared to it. Any reduction in this frequency would indicate a deterioration of the technical condition of reinforced concrete load-bearing structure of the chimney.

## 3. Summary

The IBIS-S system using microwave interferometric radar is a modern technique which may be applied for precise measurements of dislocations, strains as well as vibrations of building structures. The feasibility of conducting surveys from the distance up to 1000 m from the ground level, without having to install sensors on the object, makes this device a particularly useful one for carrying out dynamic surveying of tower structures, such as tall industrial chimneys. The results of the dynamic tests, which are carried out every few years, are a valuable diagnostic material of reinforced concrete chimneys, as they enable to assess the progress of their technical wear.

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