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Application of ground-based radar interferometry technique to bridge load testing

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Abstract

Safety assessment of bridge structures, due to their specific character, is performed, inter alia, through load testing. In accordance with the domestic and foreign practice, as well as pursuant to the regulations and guidelines, testing of bridge structures can be divided into two groups: acceptance load tests of new bridges and diagnostics of the existing structures. Ground-based radar interferometry is the perfect tool allowing to carry out accurate measurements both in the static and dynamic modes during load testing. The following publication will present some results obtained on different types of bridges, giving a broad picture of the application of this innovative technology with view to both measurements as well as data analysis.

Keywords: signal processing, radar interferometry, load testing.

Zastosowanie naziemnej interferometrii radarowej do wykonywania badań obiektów mostowych pod próbnym obciążeniem

Streszczenie

Ocena bezpieczeństwa obiektu mostowego ze względu na charakter tych konstrukcji jest realizowana między innymi poprzez badania pod próbnymi obciążeniami. Zgodnie z praktyką krajową i zagraniczną jak również przepisami oraz wytycznymi, badania konstrukcji mostowych można podzielić na dwa zakresy: badania odbiorcze nowych obiektów oraz prace związane z diagnostyką obiektów istniejących. Naziemna interferometria radarowa stanowi doskonałe narzędzie pozwalające realizować dokładne pomiary zarówno podczas obciążeń statycznych jaki i dynamicznych. Prezentowana publikacja przedstawi uzyskane wyniki na różnych typach obiektów mostowych dając szeroki obraz zastosowania tej nowatorskiej techniki w części pomiarowej oraz podczas analizy uzyskanych danych. Przykłady wykonanych prac które są przedstawione w publikacji zrealizowano na czterech różnych obiektach mostowych. Zaprezentowano wyniki i analizy uzyskane dla mostu o konstrukcji wantowej, mostu podwieszonego składającego się z przęsła stalowego zespolonego z płytą pomostową, mostu żelbetowego oraz mostu o konstrukcji extradosed.

Słowa kluczowe: analiza sygnałów, interferometria radarowa, obciążenia próbne.

1. Introduction

Safety assessment of bridge structures, due to their specific character, is carried out, inter alia, through load testing [1, 2]. In accordance with the domestic and foreign practice, as well as pursuant to the regulations and guidelines, testing of bridge structures can be divided into two groups: acceptance load tests of new bridges and diagnostics of the existing structures [3]. The measurements that must be implemented for main bridge spans are particularly difficult. Conventional surveying methods, allowing to obtain reliable measurement results, such as analog or digital sensors, are not applicable here. A properly designed program of acceptance measurements cannot be restricted due to some technological barriers which are associated with the correct data acquisition, especially given the current state of the art.

Ground-based radar interferometry is the perfect tool allowing to conduct accurate measurements both under static and dynamic loads. It has been widely discussed in numerous publications, including, inter alia, the monograph [4]. In contrast to traditional methods, it allows to obtain measurement results from multiple points at the same time, and the obtained time series of displacements are characterized by very stable sampling. Application of this technology includes both static and dynamic testing, however, based on the author's experience, it can be concluded that these are dynamic tests which fully demonstrate the potential of this technology.

The presented results were obtained on different types of bridge structures, and therefore they offer a broad view of applying this innovative technology both during the surveys and the analysis of the obtained data.

The provided examples of implemented research studies are the subject of activity of the team from the Department of Engineering Surveying and Civil Engineering at AGH in Krakow: Tomasz Owerko, Ph.D. eng., Przemysław Kuras, Ph.D. eng., Łukasz Ortyl, Ph.D. eng., Rafal Kocierz, M.Sc. eng. The author was supervising the works. The presented studies include the use and development of microwave (satellite and terrestrial), electro-optical and electronic systems in surveying displacements, deformation and vibration of engineering and building structures.

Each of the presented bridges represents a different type of structure. In consequence, there is a different response to static loads and dynamic excitation, as well as different character of the radar profile. All presented works were performed based on the ground-based radar interferometry, in collaboration with accredited research laboratories.

2. Load testing of main spans of bridge structures

The first of the discussed examples is the cable-stayed bridge, with a single pylon and a deck of a prestressed, slab-and-girder structure, suspended by steel tie rods formed in a shape of a fan (Fig. 1).

Fig. 1. Suspended cable-stayed bridge in Zembrzyce
Rys. 1. Podwieszony most w Zembrzycach

The structure is located within a road which is the ring road of the village of Zembrzyce (Małopolska province). Its dynamic characteristics have already been discussed in detail in the publication [5], as well as in Chapter 7 of the monograph [4]. In particular, a comparison of the frequency of vibrations obtained during the research experiment carried out at the stage of load testing was analyzed, relative to the corresponding frequencies resulting from the adopted calculation model.

With respect to the surveys performed with radar interferometry, the construction of such bridge structures has its clear consequences. Figure 1 presents a photograph of the pylon and the longest main bridge span. In this photograph, the cross-bars are clearly visible and, as it was expected, they ensure a very good reflection of radar waves and are clearly revealed on the radar profile. During the analysis of time series from vibration measurements of such a structure, it should be remembered that even the use of radar antennas with narrow characteristics may result in capturing the surveying material which also contains the vibration of individual load-bearing elements, which currently are not the subject of the measurement, for example, cable stays.

Resolution of data for the measurement of points during sampling frequency of about 49 Hz in the IBIS system can be as good as 0.5m. Therefore, all the cross-bars will stand out as a separate measuring points (Rbin) due to the fact that the difference in radial distance between each of them and the radar unit exceeds this value.

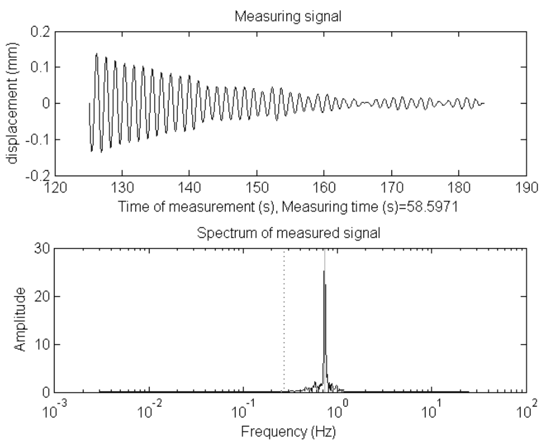

Fig. 2. Example of a filtered measurement signal – excitation by a truck driving at 50 km/h. [4] Fig 7.13 c) and d)
Rys. 2. Przykład przefiltrowanego sygnału pomiarowego, źródło wzbudzenia ciężarówka jadąca 50 km/h. [4] Rys. 7.13 c) and d)

Radar measurement signals representing the free vibrations of such a structure will be characterized by a large noise and relatively little vibration amplitude. This does not preclude, however, a possibility to obtain a long signal (several tens of seconds). In order to be able to conduct analyses of frequency and time, it is required to perform the filtering of such a signal. Example of the filtered signal for the frequency of 0.72 Hz, and the first mode of vibration of this bridge have been presented in Figure 2. At the top, there is a time series, and below there is an amplitude spectrum in a logarithmic frequency scale.

The conducted autocorrelation analysis shows the stability of the frequency response (Fig.3). It should be emphasized that the subject of the analysis was a time series of free vibration of the amplitude of 0.2 mm. Having applied a digital filtering operation, it was possible to determine both the amplitude spectrum as well as the calculation of the logarithmic damping decrement.

The second of the presented examples concerns behavior analysis of the main span, which is part of the suspension bridge M-2 in Bydgoszcz over the River Brda (Figure 4). It is a suspended steel bridge structure, combined with a 200 meter-long concrete deck.

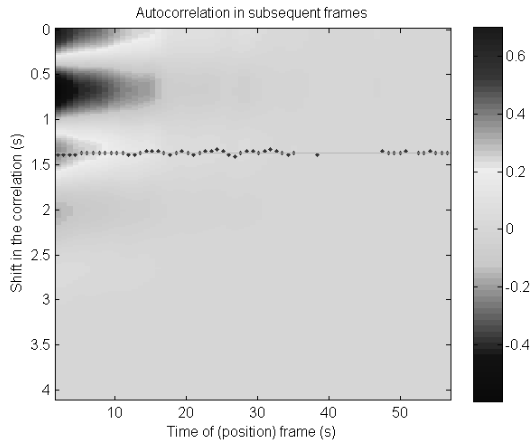

Fig. 3. Autocorrelation in subsequent frames
Rys. 3. Autokorelacja w kolejnych ramkach

Fig. 4. Measurement of the main bridge span in Bydgoszcz
Rys. 4. Pomiar nurtowego przęsła w Bydgoszczy

The type of the obstacle at the largest predicted deflection of the load-bearing structure makes it impossible to use conventional equipment for dynamic measurements. Figure 5 depicts an example of a recorded time series during the dynamic tests.

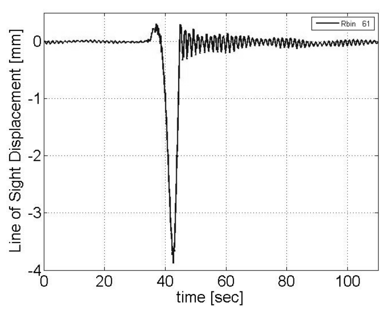

Fig. 5. Example of recorded time series
Rys. 5. Przykład zarejestrowanego szeregu czasowego

It should be noted that the presented data illustrate deflection of the span in the direction of the radar unit. IBIS-S is a one-dimensional device, therefore, in order to obtain the results of the bridge deflection during the dynamic load tests (which are necessary, for example, to calculate the dynamic factor) the measurement should be reduced, based on the ratio of the distance between the radar unit and the analyzed Rbin, to the difference in their heights. Nevertheless, a time series presented in such a way can be subjected to spectral analysis. Due to the fact that frequency-modulated continuous-wave (FMCW) interferometric radars sample very evenly, and the sampling frequency is significantly higher than twice the maximum value of the expected frequency of vibration of the structure to be analyzed, FFT can be successfully used (Fig. 6) without any concerns about the effect of the spectral replication in the studied range.

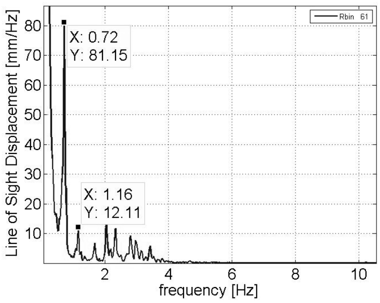

Fig. 6. Exemplary result of the spectral analysis
Rys. 6. Przykładowy rezultat przeprowadzonej analizy spektralnej

From the point of view of radar interferometry and signal analysis, such a bridge has the following characteristics:
a) a very good radar profile;
b) the amplitude of vibration caused by the excitation passage is clear;
c) very clear and long dynamic vibration, a possibility of the occurrence of beats. As for a structure of this size, it is relatively susceptible dynamically.

The recorded data allow to capture the components of basic modes of vibration. The point 61 (Rbin 61) clearly exemplifies that the component of the first form of vibration has a significant value in the diagram of the conducted spectral analysis (0.72 Hz). If it is suspected that a value which is close to it might occur (a potential occurrence of beats), the analysis may be performed on a dataset vector which is longer than the captured one. In this way, the spectral resolution will be increased, but there must be a measurement in which both frequencies which are close to each other have a sufficiently large value (vibration energy is significantly identifiable in these frequencies), so that they are not lost in the measurement noise during this mathematical operation.

Fig. 7. Acceptance tests of one of the longest bridge spans in Poland
Rys. 7. Pomiary odbiorcze jednego z najdłuższych przęseł mostowych w Polsce

Studies of the bridge over the Vistula River in Kwidzyn, which is part of the national road number 90, included the determination of both static and dynamic deflections. The bridge in Kwidzyn is the largest extradosed structure in Europe. So far, three bridges have been constructed in the world in this technology and of a similar span: two in Japan and one in Switzerland. Extradosed technology combines the advantages of a suspended bridge and of a prestressed girder bridge. Some post-tensioning tendons run outside the cross-section of the girder. The length of the spans in this technology ranges from 100 to 200 meters. In the analyzed structure, the length of the spans ranges from 130 to 204 meters (Fig. 7).

Figure 8 depicts an exemplary response of the studied span to the passage of a truck weighing 40 tonnes. When conducting tests of this type of structures, significant deflections of the spans in static and dynamic modes are expected (Fig. 8).

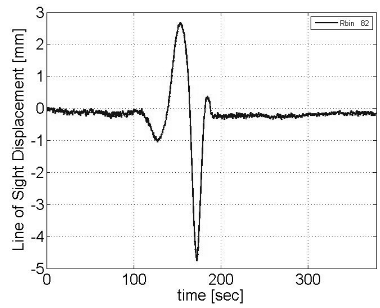

Fig. 8. Response of the extradosed bridge span
Rys. 8. Odpowiedź przęsła typu extradosed

Table 1 presents the obtained values of deflection of the studied long span during excitation with the speeds of 10 to 90 km/h. Despite significant deflections of the span (the table contains values reduced for the vertical direction), after the input force has ceased, the amplitude of free vibration of the span is of the order of the radar sensitivity.

Tab. 1. Span deflection values during passages in the process of dynamic load testing
Tab. 1. Ugięcia przęsła podczas przejazdów w czasie obciążeń dynamicznych

Direction of the passage	**Speeds**				
	10 km/h	**30 km/h**	**50 km/h**	**70 km/h**	**90 km/h**
Towards the village of Kopytkowo	11.84 mm	10.63 mm	10.56 mm	10.74 mm	4.68 mm
Towards the town of Kwidzyn	11.86 mm	11.79 mm	11.66 mm	11.84 mm	6.40 mm

From the point of view of the radar interferometry measurement and of the following process of signal processing, such a bridge structure has the following characteristics:
a) very good, clear radar profile. Identification of individual cross-bars, as well as cable stays and pylons, does not pose a big problem;
b) the amplitude of vibration caused by the excitation passage is significant, static deflection is very large;
c) explicit dynamic vibration, a possibility of the occurrence of beats.

The last of the presented examples is a bridge in Grudziądz over the Vistula River. It is the longest reinforced concrete bridge in Poland. The total length of the structure, calculated in the axis of the extreme supports, amounts to 1954 meters (Fig. 9). The record main bridge spans has the length of 180 meters. The length of the overpass is 991 meters, and it is the longest structure implemented in the incremental launch technology in Poland.

Fig. 9. Dynamic load tests of long reinforced concrete spans exemplified by a bridge near Grudziądz
Rys. 9. Dynamiczne obciążenia próbne przęsła żelbetowego mostu w Grudziądzu

In contrast to the previously presented examples, the radar profile of such a structure is not easy to analyze. In order to correctly identify the field position of radar measurement points (Rbin) presented in Figure 10, one of the two methods should be used. The first one includes the performance of the accurate as-built measurement, for example, using the method of laser scanning. This would allow for an identification of the elements by comparing them to the radial distances from the radar profile (Fig. 10).

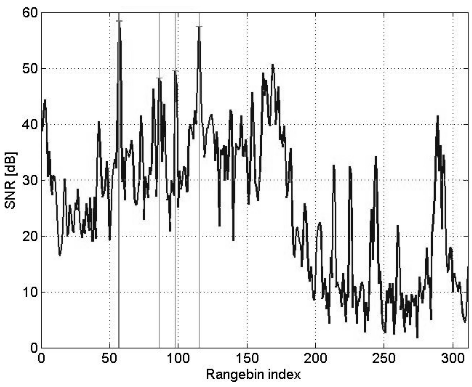

Fig. 10. Radar profile of the bridge near Grudziądz
Rys. 10. Profil radarowy przęsła mostu w Grudziądzu

The second method includes positioning radar reflectors in the specific places. Their presence will be revealed in the profile, allowing to analyze exactly those locations which are of interest to us. Signal analysis for such a massive bridge structure is feasible, just as it is in the case of extradosed bridge structures.

Tab. 2. Deflections of the span during dynamic load tests
Tab. 2. Ugięcia przęsła podczas przejazdów w czasie obciążeń dynamicznych

Direction of the passage	**Speeds**				
	10 km/h	**30 km/h**	**50 km/h**	**70 km/h**	**90 km/h**
Gdańsk	6.9 mm 7.5 mm	6.6 mm	6.4 mm	6.3 mm	6.2 mm
Grudziądz	7.0 mm	6.5 mm	6.3 mm	5.3 mm	6.2 mm

The deflections both in static and dynamic modes are easily measured (Table 2). In contrast, the amplitude of free vibration is at the detection limit of the measurement system. In this specific case, the studied span was characterized by critical damping, which additionally complicated the spectral analysis.

From the point of view of radar interferometry and signal analysis, large, heavy reinforced concrete spans have the following characteristics:

a) a need may arise to signal special points with radar reflectors;
b) the amplitude of vibration caused by the excitation passage is small, the deflection of the span is of a few millimeters;
c) critical damping may occur.

3. Conclusions

The use of ground-based radar interferometry techniques gave positive results in each of the studied cases. The results of the analyses allowed to significantly enrich the surveying information about the examined structure. Moreover, in most cases, it was the primary source of information about the dynamic behavior of the main bridge spans. From the point of view of structural mechanics, each of the presented structures has different characteristics, which naturally translates into the type and quality of the measurement material which is captured using radar technology. In each of the cases described above, the material is very rich and will be the subject of separate publications.

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4. References

[1] Łaziński P., Salamak M.: O badaniach mostów pod próbnym obciążeniem. Inżynieria i Budownictwo, No. 5–6/2010, pp. 300–303, 2010.
[2] Salamak M., Radziecki A., Łaziński P., Pradelok S.: Analysis of the results from the load testing of steel through arch bridges. 7th International Conference on Arch Bridges ARCH 2013, Trogir - Split, Croatia, 2-4 October2013, pp. 187-194, 2003.
[3] GDDKiA. Zalecenia dotyczące wykonywania badań pod próbnym obciążeniem drogowych obiektów mostowych. Załącznik do Zarządzenia Nr 35 Generalnego Dyrektora Dróg Krajowych i Autostrad, Warszawa 2008.
[4] Gocał J., Ortyl Ł., Owerko T., Kuras P., Kocierz R., Ćwiąkała P., Puniach E., Sukta O., Bałut A.: Determination of displacement and vibrations of engineering structures using ground-based radar interferometry, AGH University of Science and Technology Press 2013; ISBN: 978-83-7464-645-1.
[5] Owerko T., Ortyl Ł., Kocierz R., Kuras P., Salamak M.: Investigation of displacements of road bridges under test loads using radar interferometry – case study. Bridge maintenance, safety, management, resilience and sustainability. Proceedings of the 6th International Conference. Stresa 2012.

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