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Beat frequency detection of bridges using ground-based radar interferometry

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Abstract

Ground-based radar interferometry offers an opportunity to record dynamic responses of bridge spans. High frequency of data records and measurement of multiple points on the span at given time enables to detect problems related to span susceptibility to dynamic excitation. One of the manifestations of such susceptibility are beat frequencies. This publication will provide some examples where the analysis of radar data has successfully identified the phenomenon of beat frequency, which poses a problem both to the new structures as well as to the existing ones.

Keywords: signal processing, radar interferometry, load testing.

Wykrywanie częstotliwości zdudnieniowej mostów za pomocą naziemnej interferometrii radarowej

Streszczenie

Naziemna interferometria radarowa daje możliwość rejestracji odpowiedzi dynamicznej przęseł mostowych. Duża częstotliwość rejestracji oraz pomiar wielu punktów przęsła na raz umożliwia detekcję problemów związanych wrażliwością na wzbudzenie dynamiczne. Jednym z przejawów takiej wrażliwości są dudnienia częstotliwości. Prezentowana publikacja przedstawi przepadki w których na podstawie analizy danych radarowych udało się zidentyfikować problem dudnień zarówno dla obiektów nowych jak i będących w użytkowaniu. Publikacja prezentuje cele wykonywania takich pomiarów, przedstawia zastosowane metody pomiarowe oraz ich ograniczenia. W szczególności omawia problemy związane z cyfrową, a więc skwantowaną w czasie i amplitudzie, reprezentacją analogowego sygnału drgań obiektów mostowych. Praktyczne przykłady analiz obejmują dwa przypadki, pierwszy dotyczy identyfikacji dudnień podczas pomiarów odbiorczy, drugi natomiast omawia analogiczne zjawisko które ujawniło się podczas badań obiektu mostowego pod obciążeniem użytkowym.

Słowa kluczowe: cyfowe przetwarzanie sygnału, interferometria radarowa, obciążenia próbne.

1. Introduction

One of the primary objectives of carrying out research studies of bridge structures under test loads is to identify potential risks to the safety of the structure. Measurements of this type should be carried out by accredited research laboratories. The focus of this article is to check the dynamic behavior and the response to static loads. In Polish conditions, the entity receiving the test results is the General Directorate for National Roads and Motorways [5, 2].

As part of the studies under the static load, measurements are performed which do not require a high sampling rate. With certain exceptions, they may be implemented with well-known and described measurement technologies. Then, the deflections and twisting of the bridge spans, settlement of the supports with the bearing control checks, horizontal displacement and tilting of the pylons are usually determined. Naturally, not all of these conditions are checked for each of the bridges, as due to the structural reasons they simply may not exist (e.g. pylons for column-and-girder bridge structures) [6].

During the testing under variable loads, time series of displacements of structural elements are recorded (vertical displacements of bridge decks, vibration of cable stays, vibration of pylons). Research under variable loads can be divided into dynamic tests and tests under operational loads [1, 2]. In this publication, the author presents one example for each of the cases. For new structures, the studies are carried out during the load testing. In such a case, the study program is clearly defined, preceded by a theoretical analysis. Then, we have the comfort of performing tests on a structure which is free of loads other than the predicted ones of a dynamic character. The only exceptions include the wind load or water pressure acting on the bridge supports. Very often, however, they are recorded and analyzed as well. The research program usually involves several different dynamic schemes. For the existing structures a need may arise to complete the information on the dynamic behavior, or to check whether the parameters have not changed during its use.

In each of these cases described above, the final effect is determining dynamic parameters of the structure and therefore, inter alia, the amplitude spectrum or damping decrements for each mode of vibration. The results of calculations are treated as experimentally determined measure of rigidity. Since each structure is different, the load level is adopted for each structure individually.

During the tests carried out in Poland, after the input force causing vibration has ceased to act, for example, a lorry driving over a threshold, we record free vibrations, based on which the vibration parameters are calculated.

2. Purpose of the measurements, applied methods and factors affecting the results

In most cases, particular attention will be paid to the amplitude spectrum ranging from 0 to 20 Hz. This is due to the fact that it covers the first few, most frequently revealed natural modes of vibration of the structure.

There are numerous surveying methods that may carry out such measurements. In this publication, the results were obtained based on the surveys performed with ground-based radar interferometry. It has been exhaustively described in numerous monographs and publications [3, 7]. According to the standard [4], while conducting the measurements of mechanical vibrations, it is recommended to use devices which directly record changes in the distance: “The use of the appropriate transducer to measure the required quantity directly and avoid the process of integration or differentiation is recommended”.

Similarly to other digital devices, interferometric radar carries out measurements by converting the source analog signal into a digital representation. Analog signals are continuous in time and have a continuous range of amplitudes. Thus, the signal is sampled according to the sampling frequency f_s, and the occurring mechanical vibration amplitude is quantized. Such a procedure is not without consequences, which one should be aware of when planning the measurement.

According to the theory of digital signal processing, the analog signal (the actual work of a structure) and the digital one (in this case, the effect of recording with a radar) are considered to be equivalent when, based on the digital signal, we are able to fully restore the original signal. Such a condition can be satisfied only for those signals which have a limited spectrum width. Figure 1 demonstrates that carrying out measurements with a device with limited sampling frequency can result in inability to identify the actual frequency (blue), and may lead to the identification of a different frequency (red).

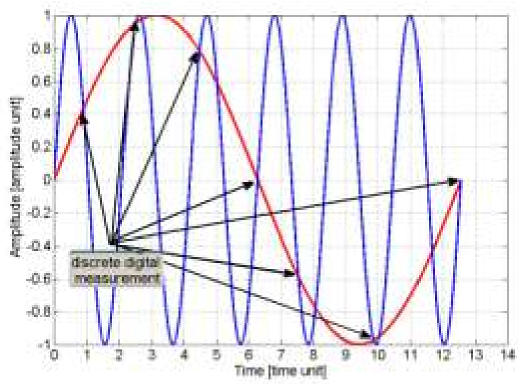

Fig. 1. The ambiguity of discrete sampling
Rys. 1. Niejednoznaczność próbkowania

In general, it should be assumed that it is required to have a device which would allow for the sampling with a frequency of at least twice the value of the highest sought component. This is a direct consequence of Shannon-Kotelnikov theorem. For the analyzed examples, radar sampling frequency was f_1=49.05 Hz (for the first example) and f_2=200.08 Hz (for the second example).

Thus, the maximum frequency of the signal spectral components that can be analyzed (the so-called Nyquist frequency) is as follows:

$$f_{max} = \frac{1}{2T_s} = \frac{f_s}{2} \tag{1}$$

On the basis of the equation (1), in the first case, without any major deformations, we can analyze the vibrations of the structure reaching up to 24.5 Hz, and in the second case - up to 100 Hz.

The difference in the sampling frequency results from the manner in which the IBIS radar (FMCW radar) carries out surveys. The relationship between resolution of images, sampling frequency and the range has been specified in the monograph [3]. The period and the sampling frequency are very stable, and based on the analysis of the data captured for the lines of sight of the length of 30 meters, the instability sampling error amounts to ±0.03 ms. It means that the relative error is only 0.05%. Therefore, for the analysis of the captured data, it is possible to successfully use algorithms which require a uniform sampling, including Fast Fourier Transform (FFT).

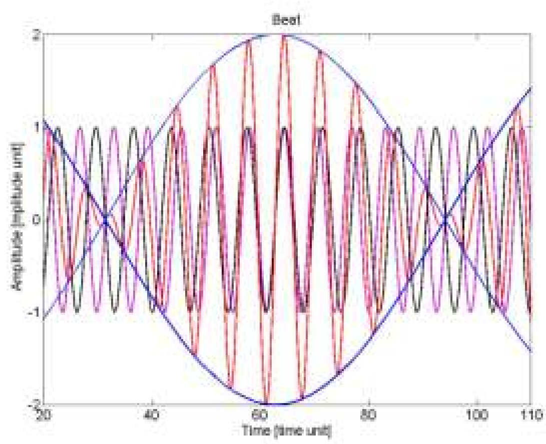

Fig. 2. Beat frequencies
Rys. 2. Dudnienie częstotliwości

Figure 2 presents a combination of two artificially generated signals, for which the vibration period varies relatively by 10%. Such a phenomenon occurs on some bridge structures, where two or more structural elements have close, but not identical, natural vibration frequencies. This phenomenon is damaging, since such a structure damps longer, as a whole it is subjected to vibrations of a greater amplitude and, consequently, such vibrations may lead to failure due to the wear of structural elements. The analysis of such cases, identified during check and acceptance surveys, has been presented below by the author.

3. Example of the beat frequency for a new bridge structure

The first example includes the results of the surveys carried out for a suspended steel bridge, combined with a concrete bridge deck. During the load testing, 22 dynamic load schemes were performed. Figure 3 demonstrates four examples of recorded time series, for which the adverse phenomenon of beats was revealed in a manner which was especially well-defined.

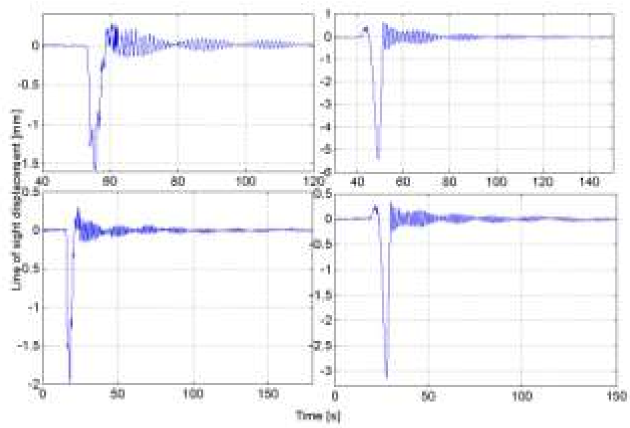

Fig. 3. The recorded beat frequency for various levels of excitation
Rys. 3. Zarejestrowane dudnienie częstotliwości przy różnym poziomie

The above diagram illustrates a response of the span to the excitation of a single 40-tonne vehicle, or two identical vehicles driven next to each other at the same time. The distance between the radar unit and the measurement point was 30.5 m. Table 1 presents a description of the manners of excitation, which have been shown as time series in Figure 3.

Tab. 1. Factors which force vibrations
Tab. 1. Czynniki wzbudzające drgania

Position in Fig. 3	Load	Speed, km/h	Direction
Top left	1 truck, 40 t	70	S
Top right	2 trucks, 2 x 40 t	60	N
Bottom left	1 truck, 40 t	60	S
Bottom right	1 truck, 40 t	60	N

Spectral analysis, which aims at determining the natural vibrations, requires calculations to be performed on the time series representing the free vibrations. Therefore, prior to calculating the amplitude spectrum, a subset of the time series representing these vibrations was selected, as schematically illustrated in Figure 4.

With the various factors causing the occurrence of vibrations, the rate of damping was different for this structure. The length of the analyzed samples ranged from 3075 to 9712 samples. In each of the cases for this structure, radar sampling frequency was constant at 49.05 Hz. Since the objective is to compare beat frequency detection in each of the four cases, thus it is important to have the spectra with the same resolution. The spectral resolution depends, inter alia, on the length of the analyzed dataset vector and the sampling frequency. The conducted analyses were performed based on a vector of the length of 216. Therefore, a technique of zero-padding was used to obtain the spectrum interpolation for a greater number of points. This technique is well described in the literature regarding digital signal processing [9].

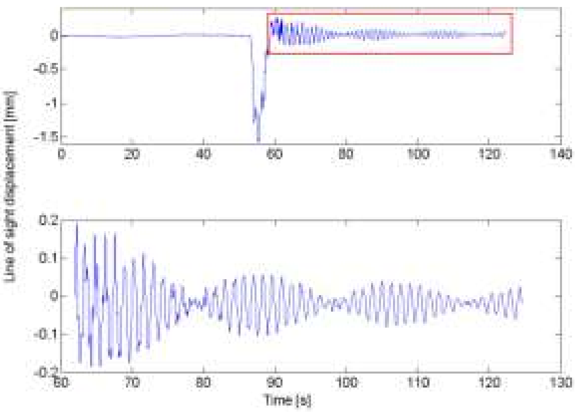

Fig. 4. A subset of the time series representing the free vibrations
Rys. 4. Podzbiór szeregu czasowego reprezentujący drgania swobodne

This operation was possible because the energy of vibrations transmitted in the modes of the frequency of 0.72 Hz and 0.77 Hz was large. Therefore, there is no fear of losing this information in the measurement noise. Figure 5 illustrates the amplitude spectra calculated by the FFT algorithm. Spectral resolution of the presented results is high (the neighboring points are interpolated at 0.007 Hz). It can therefore be noted without any major concerns, that, regardless of the excitation, the structure is characterized by two frequencies which are close to each other: f_1=0.72 Hz and f_2=0.77 Hz.

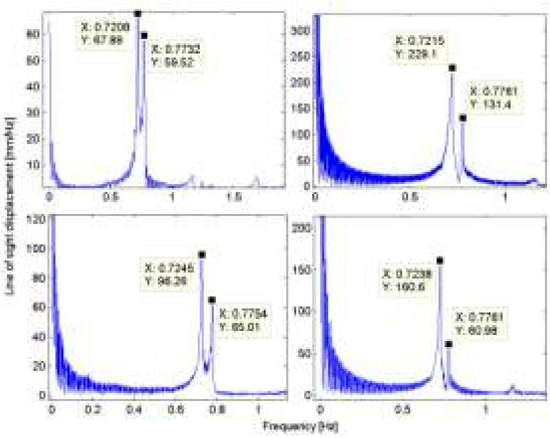

Fig. 5. The amplitude spectrum of the time series representing the free vibrations
Rys. 5. Widmo amplitudowe drgań swobodnych

4. Example of the beat frequency for the existing bridge structure

The second analyzed example includes the assessment of a possibility to capture information on the potentially occurring beat frequencies for a bridge structure subjected to current use. The author conducted two such studies for the flyovers located in Murckowska road junction in Katowice – for the eastern and the western one. The peculiar dynamic behavior of these bridge structures was the subject of structural analyses conducted by the specialists in the field of construction engineering. One of the recommendations resulting from the analyses is some change in the bearings of the structure. It was suggested in particular to leave the unmovable bearing and the sliding one unchanged, while the bearings located on the other end of the flyover should be replaced by elastomeric ones. Also, the geometry of the flyover, for example, in terms of suspensions, is unfavorable. Altering their arrangement should result in a change in the mode of vibrations [8].

Independently, these two bridge structures were subjected to measurement experiments, described, inter alia, in section 7.3 of the monograph (Gocał et al., 2013). The carried out calculations compared the amplitude spectrum, obtained depending on the location of the radar relative to the span, and they pointed to the consistencies between the results obtained from the interferometric radar and from the set of accelerometers.

At this point, the author would like to examine the consistency of beat frequency detection based on the operating excitation of random character. Figure 6 demonstrates the time series representing the free vibrations of the flyover. They were recorded with a radar located directly under the flyover (see: Fig. 7.18, [3]).

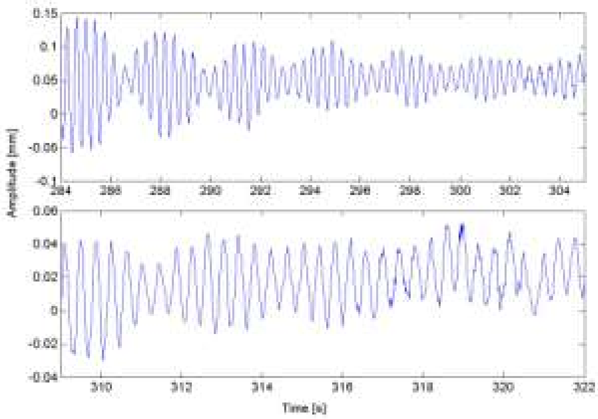

Fig. 6. The analyzed time series obtained during the work of the flyovers under operational load
Rys. 6. Analizowany szereg czasowy wiaduktu pracującego pod obciążeniem użytkowym

Due to such a location of the radar unit in relation to the span, we are not talking about the line of sight displacement here, but directly about the vibration amplitude. Another difference relative to the calculations based on the data from the load testing are the lengths of vectors. During the planned surveys, the length of the analyzed time series depends on the speed at which the structure damps. Thus, we record the whole phenomenon from the moment the factor causing vibration ceases to act, which for example is the lorry driving off the test span, until the moment when the vibration amplitude is smaller than the measurement sensitivity of the surveying system used.

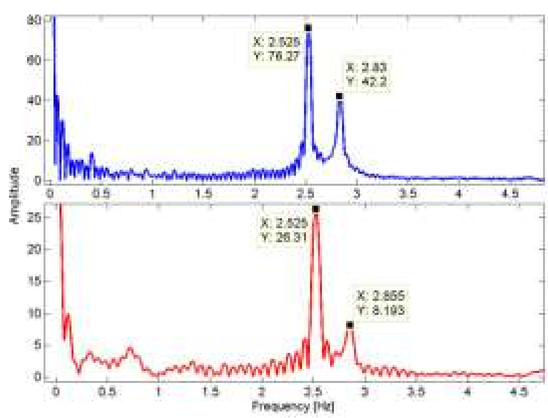

Fig. 7. The spectrum of the time series
Rys. 7. Widmo amplitudowe

During the load testing procedures, the recorded time series are additionally limited due to the road traffic. The analyzed time series include 4201 and 2600 samples, respectively. The sampling frequency was f_s=200.08 Hz. Figure 7 illustrates a spectral analysis of the recorded vibrations of the span. As in the first case, in order to compare both results, the vectors were completed to the length of 214 seconds.

5. Conclusions

The presented examples demonstrate that using the technique of ground-based radar interferometry enables to detect beat frequencies of bridge structures of the amplitude of vibration, towards the vector connecting the radar with the studied element of the span, of the value even as low as 0.03 mm. The applied sampling frequency was sufficient for the time series of the length not exceeding 14 seconds to identify neighboring frequencies distant only by about 0.31 Hz for the tests carried out under the operational load, and 0.05 Hz for the tests carried out under the load testing, in the amplitude spectrum.

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