

INFORMATION AND DIAGNOSTIC SYSTEMS

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Bridge structure test results with using different types of dynamic force have been considered. It has been shown, that the developed technique of registering and processing vibration signals allows obtaining thin spectrum structure. The analysis of its change that is defined by the type of structure loading applied has been carried out. Key parameters of the vibration signals registered have been defined.

Introduction

When creating complex engineering systems (structures) the problem of securing their reliability which is solved not only at a structure stage, but also at a stage of their operation, is one of basic problems. In the latter case the periodic (regulation) study and technical diagnostics of structures with condition estimations and decision-making as for the possibility of their further operation is carried out. Bridge structures which technical diagnostics assumes conducting a complex of researches, including static and dynamic tests [1; 2], refer to complex and load-bearing structures like these.

When carrying out dynamic tests of bridge structures, registration of their own and forced vibrations, analysis of their parameters underlying the development of technical diagnostics techniques, is carried out.

Vibration excitation is realized by methods of dynamic force on a structure, which is applied in one point, moved and others [2]. To register vibrations various types of sensors (induction, capacitor, piezoelectric and others) which provide transformation of mechanical vibrations into an electric signal [2] are used; and its post-processing allows defining parameters of originating vibrations.

In spite of a wide range of parameters [3] which can be obtained by results of processing registered signals, the analysis of frequency (period) of vibrations, originating after dynamic force is applied to a structure, and coefficient of their attenuation [4; 5], has won the greatest prevalence. It is connected, first of all, with the ways of registering and processing originating vibrations, and also with the absence of precise interconnections of signal parameters, obtained in the tests, with the parameters describing structure condition. In the majority of existing diagnostics (control) techniques, based on a

frequency analysis of vibration signals, comparison of experimentally defined values of resonant frequency and attenuation coefficient with magnitudes obtained by results of theoretical calculations [5; 6] is regularly conducted.

However, as experimental results show, signals of registered vibrations have a sufficiently complex form, and at their processing and constructing spectra, mainly algorithm of fast Fourier transformation, when the permission on frequency, determining sensitivity to spectrum variations, depends on a number of points, rather than on a time interval of registered signal sample capture, is used. Thus, in low-frequency zone, characteristic of bridge structure vibrations, the spectrum is found to have discrete type, that considerably complicates its analysis, and moreover, definition of vibration parameters. Therefore, such spectra can be used only for qualitative comparison of numerical values of frequency magnitudes obtained. Thus definition of the registered vibration attenuation coefficient in such spectra with all necessary calculations being accomplished, is rather problematic. It should be also noted, that spectra obtained in such a way do not possess sufficient sensitivity to changes of a dynamic load type.

In the given work the results of experimental research of natural and forced vibrations of a bridge structure at its dynamic loading, using mobile system of technical diagnostics will be considered. When analysing frequency characteristics of registered vibrations the Fourier transform with a fine pitch of a discrete frequency increment defining length of digital sample of a signal, is used. As it will be shown, this approach possesses high sensitivity to vibration modifications when the type of dynamic loading that allows discriminating close laying resonant frequencies well, is changed.

Research technique

Research of the vibration signal frequency characteristics have been carried out when testing a bridge structure, after the construction work is finished. The general view of a tested bridge is shown in fig. 1, *a*. It represents a structure consisting of six metal bearing T-beams, connected among themselves by rigid transverse metal joints (fig. 1, *b*).

*a**b**c**d*

Fig. 1. Fragments of the bridge structure testing:
a – general view of the bridge structure; *b*– arrangement of bearing metal T-type beams (bottom view); *c* – KRAZ-type loaded lorry is moving across the threshold; *d* – disposing the induction sensor on the bottom T-surface of the T-type metal bearing beam of the bridge

Continuous concrete and then asphalt coverings have been laid on top of the metal bearing beams. Sizes of the bridge tested made: length of 58 m and width — 17 m.

Loading of the bridge for excitation of forced and natural vibrations was carried out with using two standard types of dynamic force: when the KRAZ-type loaded lorry was moving along the central part of the bridge with different speed, and also the KRAZ-type loaded lorry was moving with different speed across the threshold 100 mm high (fig. 1, *c*). In the first case excitation of forced vibrations of bridge structure was realized, and in the second case at dynamic impact its natural vibrations were energized as well. The weight of the loaded car made 250 kN, and its speed was ranging from 5 to 20 km/h.

For registering and transforming originating mechanical vibrations of the bridge structure into electric signal a standard SV-10Z-type induction sensor of vertical displacement speed with resonant frequency 10 Hz was used. The sensor was placed in the bottom part of the second bearing T-type beam from the edge of a bridge structure and rigidly fixed on it by a clamp (fig. 1, *d*). The principle of transforming mechanical vibrations into the electric signal by the induction sensor is considered in papers [7; 8]. Registration and processing the parameters of electric signals of originating low-frequency vibrations was carried out by using mobile system on the basis of a personal computer, aimed at examining dynamic characteristics of structures. The measuring system allows transforming electric signal from the induction sensor exit into numerical codes at a definite time interval of a sample, storing in a mobile computer and carrying out their subsequent processing by using applied program software.

The program software allows processing parameters of speed and shift signals of the originating vibrations and also to construct spectra with processing their parameters, which are considered in the paper [9]. Thus processing parameters of speed and shift signals and their spectra was carried out with correction of a conversion coefficient of the primary induction sensor used, which is considered in papers [3; 9].

Experimental results

Results of the research carried out according to the program of bridge loading, have shown, that spectra of registered vibration speed signals have a complex character of their change (fig. 2). It refers both to the data obtained when the car was moving along the bridge with constant speed, and to the data obtained when the car was crossing the “threshold” fixed in the middle of the bridge with preset speed.

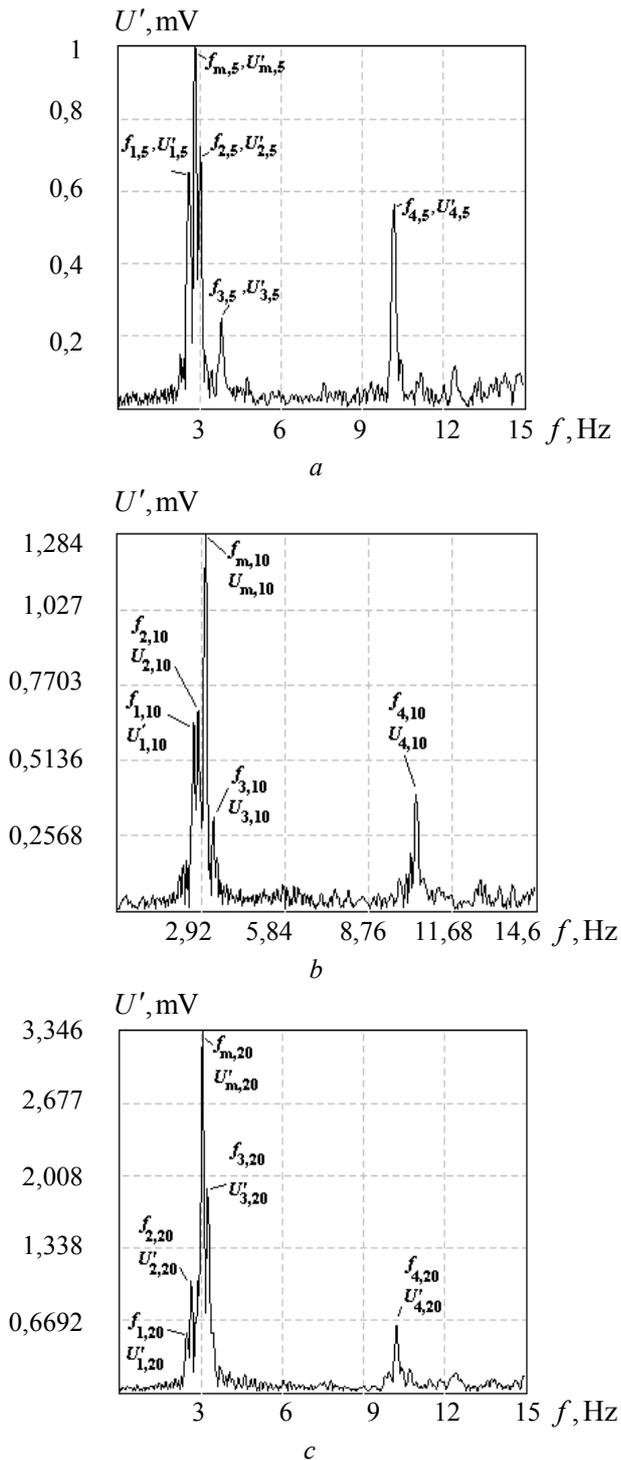


Fig. 2. Spectra of vibration speed signals when the car is moving on the bridge:
 a – car speed 5 km/h; b – car speed 10 km/h; c – car speed 20 km/h

The amplitude spectrum obtained when the car was moving at speed 5 km/h, is shown in fig. 2, a. The fig. 2 shows, that the greatest contribution into vibrations falls on frequencies of about 3 Hz. In this area the spectrum consists of three closely positioned narrow lines. Thus the resonant frequency which corresponds the maximum amplitude of a

vibration speed signal, which equals $U'_{m,5} = 1 \text{ mV}$, makes $f_{p,5} = 2,82 \text{ Hz}$ (vibration period $T_{c,5} = 0,3546 \text{ s}$). The logarithmic attenuation decrement defined along the width of a resonance peak curve, equals $\delta_5 = 0,1404$, and the mechanical shift amplitude $x_{m,5} = 0,21 \text{ mm}$. Next to this peak two more additional peaks with frequencies $f_{1,5} = 2,6 \text{ Hz}$ and $f_{2,5} = 3,0 \text{ Hz}$ are observed. Their amplitudes, accordingly equal to $U'_{1,5} = 0,6528 \text{ mV}$ and $U'_{2,5} = 0,73 \text{ mV}$. Further, on the curve of changing the spectrum of bridge vibration speed signal two more additional narrow peaks with frequencies in a $f_{3,5} = 3,8 \text{ Hz}$ and $f_{4,5} = 11,17 \text{ Hz}$ and with amplitudes $U'_{3,5} = 0,2514 \text{ mV}$ and $U'_{4,5} = 0,5636 \text{ mV}$ are fixed.

Vibration spectrum modification takes place when speed of the car is increasing. Thus in the 3 Hz frequency zone the increment of vibration speed resonant amplitude is observed. Reorganization of a peak frequency state in the given spectrum area with redistribution of their amplitudes also takes place. So, when the car moves at speed 10 km/h, resonant frequency (with maximum amplitude) of a bridge vibration speed signal makes $f_{p,10} = 3,09 \text{ Hz}$ (vibration period $T_{c,10} = 0,3262 \text{ s}$), i.e. has increased by 0,27 Hz, and the corresponding amplitude has increased by 0,284 B and made $U'_{m,10} = 1,284 \text{ s}$ (fig. 2, b).

The logarithmic attenuation decrement, defined along the width of a resonance peak curve equals $\delta_{10} = 0,1365$, and the mechanical displacement amplitude $x_{m,10} = 0,24 \text{ mm}$.

Thus, unlike the previous movement of the car at speed 5 km/h where two close laying peaks were to the left and right from the resonant one, at speed 10 km/h two close laying peaks are to the left of the resonance peak. Their frequencies have values $f_{1,10} = 2,65 \text{ Hz}$ and $f_{2,10} = 2,8 \text{ Hz}$, with amplitudes, accordingly, $U'_{1,10} = 0,6469 \text{ mV}$ and $U'_{2,10} = 0,6939 \text{ mV}$. So, under testing with movement speed 10 km/h of the position of peak frequencies has not changed considerably, but their amplitudes have changed in such a way, that the amplitude of peak with greater frequency has become maximum. Moreover, relative decrease of peak amplitudes with respect to the peak with the maximum amplitude also takes place. The peak well seen in tests at 5 km/h with frequency 3,8 Hz became less expressed and it was displaced into a low frequency zone. The same happened with the highest frequency peak, too. Their frequencies are equal to $f_{3,10} = 3,33 \text{ Hz}$ and $f_{4,10} = 10,46 \text{ Hz}$, i.e. have decreased, accordingly, by 0,47 Hz and 0,71 Hz, and amplitudes have made $U'_{3,10} = 0,3235 \text{ mV}$ and $U'_{4,10} = 0,3965 \text{ Hz}$ which have also decreased.

When the speed of the car was equal 20 km/h, the type of spectrum in zone 3 Hz appeared similar to the spectrum obtained in the test with the speed of car 10 km/h. Thus, the position of resonant frequency which value is equal to $f_{p,20}=3,06$ Hz, has not practically changed (vibration period $T_{c,20}=0,3268$ s). Vibration amplitude at this frequency has grown almost three times in relation to its value in the previous tests: the gain of amplitude has made 2,098 V, so its magnitude has made $U'_{m,20} = 3,346$ V (fig. 2, c). Logarithmic attenuation decrement, defined along the width of a resonance peak curve, is equal to $\delta_{20}=0,1402$, and amplitude of mechanical displacement $x_{m,5}=0,49$ mm. However in the test with speed 20 km/h there was a displacement into the low frequency zone of the positions of the first and second peaks which frequency values are equal to $f_{1,20} = 2,45$ Hz and $f_{2,20}=2,63$ Hz with amplitudes, accordingly, $U'_{1,20}=0,559$ mV and $U'_{2,20}=1,038$ mV. At the same time, position of the third peak has not practically changed, and the position of the fourth peak has moved on 0,21 Hz. Their frequencies and amplitudes have made $f_{3,20} = 3,25$ Hz, $U'_{3,20}=1,876$ mV, $f_{4,20}=10,25$ Hz, $U'_{4,10} = 0,636$ mV. Thus, significant (almost twice) increment of peak amplitude with frequency $f_{3,20} = 3,25$ Hz is observed.

The results obtained show, that when vibrations, originating during the car's movement on the bridge at different speed, are registered, two special frequency zones are observed in the signal spectrum: close to 3 Hz and close to 10–11 Hz. In low-frequency zone the spectrum has complex thin structure in it four resonant frequencies being distinguished, whereas in high-frequency zone there is only one peak present. The type and position of spectrum frequencies depends on speed of the car. Spectrum amplitudes increase when speed increases. However, such amplitude increment occurs in rather specific manner. For example, when speed increases from 5 up to 10 km/h the amplitude of high-frequency peak has changed a little and when speed became equal 20 km/h the amplitude has increased almost twice. Change of amplitude in low-frequency zone is even more difficult. If at 5 km/h the amplitude of the second peak (fig. 2, a) had the frequency 2,82 Hz, then at the speed 10 and 20 km/h then the third frequency in the spectrum becomes the maximum. It is interesting, that the position of this peak does not change much when the car speed changes a little. At the same time, at the speed equal to 20 km/h the frequency of the first two and the fourth peaks shifts into the low frequency zone.

In principle the magnitude of logarithmic attenuation decrement, defined on the peak with the highest amplitude in the low-frequency zone, practically does not change when the car speed changes. In other words loading experienced by the bridge, appears linear and far from critical area of mechanical overloading of the bridge.

Changing the mode of bridge loading, particularly when the car is running over the "threshold" with different speed, and when dynamic impact is happening, leads to change of spectra of vibration speed registered signals. First of all, significant increment of peak amplitude in a spectrum is observed. For example, when the car has speed 5 km/h and is running over the "threshold", for the greatest peak with frequency $f_{p,5}=2,52$ Hz its amplitude is equal to $U'_{m,5} = 4,737$ mV.

Next to this peak two close laying peaks which have accordingly equal frequencies and amplitudes: $f_{1,5} = 2,75$ Hz, $U'_{1,5}=1,838$ mV and $f_{2,5}=3,0$ Hz, $U'_{2,5}=2,178$ mV (fig. 3, a) are also fixed. Fig. 3, a, shows, that the arrangement of these peaks appears the same, as the one when the car was crossing the bridge with speed 5 km/h without "threshold". It points to the fact, that the peak amplitude increment is connected with occurring dynamic impact when running over the "threshold". Frequency of the fourth peak, its value being equal to $f_{3,5} = 3,8$ Hz with amplitude $U'_{3,5}=0,8905$ mV, coincides with frequency of the previous test without running over the "threshold" as well. However, the essential change of the spectrum in high-frequency area takes place. Two peaks with frequency values $f_{4,1,5}=10,05$ and $f_{4,2,5}=10,3$ Hz are fixed, their values are less, than at the first type of bridge tests (fig. 2, a). Their amplitudes are equal, accordingly, $U'_{4,1,5} = 2,027$ mV and $U'_{4,2,5} = 1,402$ mV.

Appearance of a new high-frequency peak with frequency $f_{5,5}=14,6$ Hz and amplitude $U'_{5,5} = 1,648$ mV is observed. We should also note that in the given type of loading the increase of resonance peak width happens. Thus logarithmic attenuation decrement magnitude is found equal to $\delta_5=0,179$, and magnitude of the mechanical shift amplitude, adequate to greatest peak frequency, makes $x_{m,5}=1,9$ mm.

When the car is running moving over the "threshold" with the speed equal to 10 km/h, redistribution of the position of the basic resonant frequency, frequency peaks, and also the change of their amplitudes occurs.

Resonant frequency fits the maximum amplitude pick, both in the tests without obstruction (fig. 2, b), and equal to $f_{p,10}=3,0$ Hz (period of vibrations $T_{c,10}=0,3333$ s), with amplitude – $U'_{m,10} = 8,264$ mV (fig. 3, b).

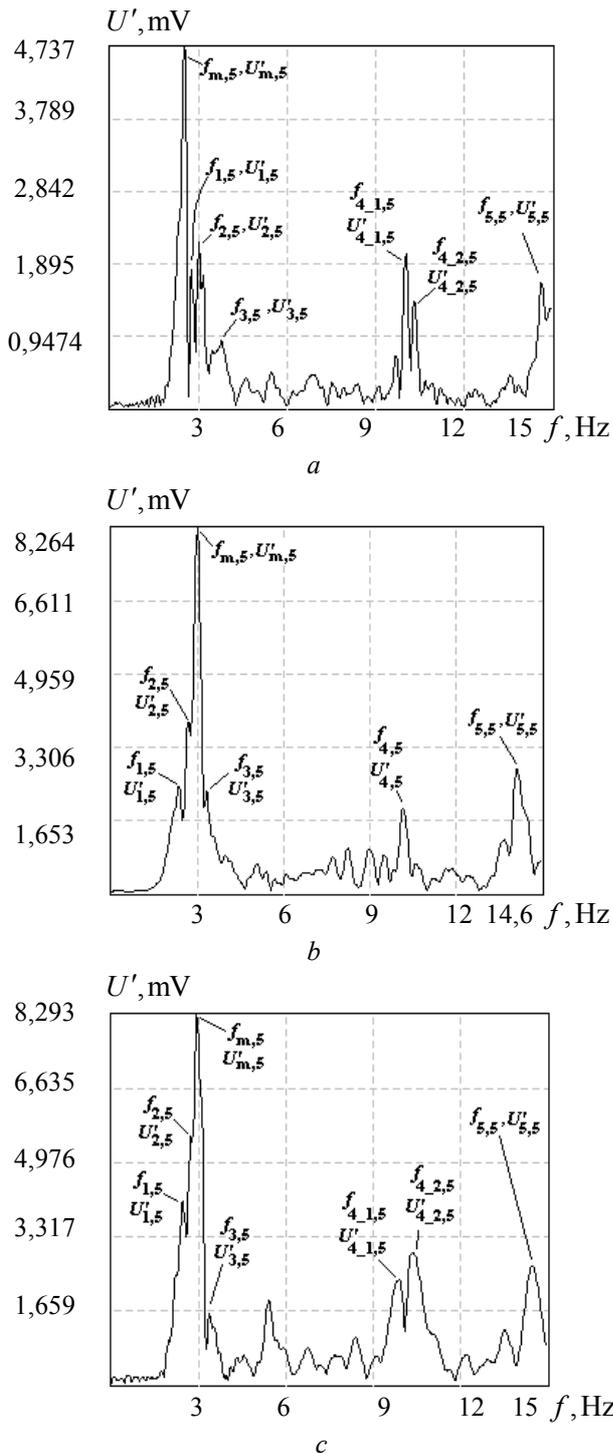


Fig. 3. Spectra of vibration speed signals when the car moves along the bridge with moving across the “threshold”:

a – car speed 5 km/h; b – car speed 10 km/h; c – car speed 20 km/h

The first and second low-frequency are found also to be disposed to the left of the peak with the greatest amplitude. Values of their frequencies and amplitudes, accordingly, are equal to: $f_{1,10} = 2,3$ Hz, $U'_{1,10} = 2,413$ mV and $f_{2,10} = 2,72$ Hz, $U'_{2,10} = 3,868$ mV. Thus the shift of other peaks into the low frequency

zone is observed, their frequencies and amplitude being, accordingly, equal to: $f_{3,10} = 3,35$ Hz, $U'_{3,10} = 2,314$ mV, $f_{4,10} = 10,15$ Hz, $U'_{4,10} = 1,917$ mV, $f_{5,10} = 14,15$ Hz, $U'_{5,10} = 2,81$ mV.

When the car moves with the speed 10 km/h, with moving over the “threshold”, the increase of the peak width with the maximum amplitude is observed. The magnitudes of logarithmic attenuation decrement and the mechanical shift amplitude, defined by it, are equal to $\delta_{10} = 0,2067$ and $x_{m,10} = 2,4$ mm.

The further increase of speed when the car was moving across the “threshold” up to 20 km/h has not led to increment of the basic peak amplitude in low-frequency area. Its position remains practically constant with frequency and amplitude being equal to $f_{p,20} = 2,94$ Hz (period of vibrations $T_{c,20} = 0,3401$ s), $U'_{m,20} = 8,293$ mV (fig. 3, c). In the given frequency zone the amplitudes of other peaks do not change significantly, either. In high-frequency zone of 10 Hz two peaks are observed, as well as in the case, when the car is moving across the “threshold” with the speed of 5 km/h. Values of the first, second, third, fourth and fifth frequencies and the magnitudes of their amplitudes are equal to:

$f_{1,20} = 2,4$ Hz, $U'_{1,20} = 4,14$ mV, $f_{2,20} = 2,65$ Hz, $U'_{2,20} = 5,54$ mV, $f_{3,20} = 3,45$ Hz, $U'_{3,20} = 1,592$ mV, $f_{4,1,20} = 9,9$ Hz, $U'_{4,1,20} = 2,385$ mV, $f_{4,2,20} = 10,4$ Hz, $U'_{4,2,20} = 2,986$ mV, $f_{5,20} = 14,45$ Hz, $U'_{5,20} = 2,654$ mV.

At the same time one more peak with frequency 5,4 Hz and amplitude 1,924 mV appears. Thus expansion of peaks on all frequencies is observed. However the peak of the second frequency $f_{2,20}$ has no obviously expressed character. It should be noted, that the expansion of a resonance peak takes place, too. Value of the logarithmic attenuation decrement, defined on this peak, is equal to $\delta_{20} = 0,2894$, and the mechanical shift amplitude for it makes $x_{m,20} = 3,43$ mm.

Thus, the result obtained shows, that when the car moves across the “threshold” with different speed the type of spectra of vibration speed signals differs from the spectra obtained in the previous tests. Thus the increase in amplitudes of registered spectra, as well as splitting and appearance of additional peaks in high-frequency zone at every speed are fixed. Besides the expansion of resonance curves in low-frequency zone is observed, when, actually, with increase in speed, a thin structure in the resonance zone with one peak formed is absent. This is, obviously, connected with the action of an additional shock dynamic load. It should be noted, that when the car speed changes from 10 up to 20 km/h there is no sharp change of vibration spectrum amplitudes,

and the expansion of resonance curves is fixed. It is equivalent to change of counted value of logarithmic attenuation decrement that cannot characterize oscillatory system under investigation, and is connected with the type of its dynamic loading, that leads to merging together close laying peaks in low-frequency zone. However, calculation of the structure mechanical shift amplitude for this frequency shows its increase when the car speed increases, that corresponds the real magnitudes defined on shift signals. For example, for speed 20 km/h the shift amplitude of the bridge, defined on a speed signal spectrum, makes 3,43 mm, and on a shift signal 3,75 mm.

Conclusion

The use of technique of registering and processing vibration signals, based on the Fourier transform with a fine pitch of a discrete increment of the frequency defining the sample interval, has allowed to reveal a spectrum thin structure in low-frequency zone and to carry out the examination of its modification. The results obtained have shown, that the type of dynamic force, particularly when the car moves along the bridge at constant speed or when it moves across the “threshold”, defines the character of changing the originating vibration spectra. Thus the use of the second type of loading results in merging together close laying peaks in the low frequency zone and in the resonance curve expansion. Its analysis has shown that similar expansion of resonance curve negatively affects such parameter as the logarithmic attenuation decrement, and reduces its self-descriptiveness. This points to the fact, that when carrying out the bridge tests the choice of the type of the dynamic effect, especially for the bridges under operation, when the presence of covering roughness or pits, will correspond introducing the “threshold”, is important. Its presence, as the carried out researches have shown, results in the abrupt change of amplitude-frequency characteristics of originating vibrations, and, naturally, in decision-making mistakes by the results of bridge structure technical diagnostics.

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В.П. Бабак, С.Ф. Филоненко, В.М.Калита, И.К. Корниенко-Мифтахова
Дослідження характеристик коливань мостової конструкції

Розглянуто результати випробувань мостової конструкції з використанням різних видів динамічного впливу. Показано, що розроблена методика реєстрації та обробки сигналів коливань дозволяє отримувати тонку структуру спектра. Виконано аналіз його відозміни, що визначається видом використаного навантаження конструкції. Визначено основні параметри реєстрованих сигналів коливань.

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Исследование характеристик колебаний мостовой конструкции

Рассмотрены результаты испытаний мостовой конструкции с использованием различных видов динамического воздействия. Показано, что разработанная методика регистрации и обработки сигналов колебаний позволяет получать тонкую структуру спектра. Проведен анализ его видоизменения, что определяется видом используемого нагружения конструкции. Определены основные параметры регистрируемых сигналов колебаний.