DYNAMIC INVESTIGATIONS ON REINFORCED CONCRETE BRIDGES

Tamás Kovács[1]
Technical University of Budapest, Department of Reinforced Concrete Structures
1521 Budapest, Hungary

SUMMARY

As a part of the comprehensive supervision of bridges, the most frequent way of the statical examinations is the load test in required frequency. The idea of the continuous inspection of the condition and corrosion state of reinforced concrete bridges by measuring the dynamic characteristics of the structure is an existing theory and more and more gaining ground in engineering practice. In the followings these dynamic characteristics and their measuring modes will be the focus. At the end the above-mentioned behaviour will be demonstrated by practical examples.

Keywords: natural vibration, natural frequency, damping, excitation, amplitude-spectrum, phase-spectrum

1. INTRODUCTION

The main requirement of maintenance and renovation of bridges is the continuous inspection of the condition and corrosion state of the bridges during the whole lifetime. The required mode, depth and frequency of inspections is defined in regulations. Carrying out these investigations is rather costly apart from the simple visual supervision. The most commonly accepted method in Hungary of examining the statical behaviour of the structure at regular supervisions is the load test.

The load test is carryed out by placing known concentrated forces on given points of the bridge and measuring the displacements. By increasing the number of the positions of load and points of measuring the „weak cross-sections" can be determined with approximate accuracy. Comparing the results of measurement and statical calculations provides informations about the behaviour of the structure. Single measuring, however, is not appropriate to determine the cause of deviations: whether it comes from the differences between the supposed and real statical model or from the changes in the condition of the bridge. To determine the cause repeated measurements are needed, but doing it frequently is too expensive.

Therefore there is need for developing measuring modes being relatively cheap, simple, and applicable without special equipment. Measuring in practice the dynamic characteristics of the structure such as natural frequency and the damping can also be carryed out by using simple devices. The methods differ from each other only in the

[1] PhD Student

mode of excitation. In practical cases these measurements are relatively cheap and fast, because there is no need for real exciter, because the normal traffic is used for generating vibration. In this way the changes in the state of the structure can continually be inspected by frequent measurements.

In the followings we give a brief summary of the theoretical and practical possibilities of the existing measuring modes of these dynamic characteristics. We also deal with the possible modes of excitation and with suitable modes of elaborating the results. The efficiency of the method is shown on practical examples.

2. MEASURING MODES

2.1 Examined characteristics

In dynamic tests of reinforced concrete bridges two main characteristics are measured: the natural frequency and the damping coefficient.

In a real structure the natural frequency depends on several parameters such as the geometry of the structure, material characteristics, load effects, extent and pattern of cracks, effects of post-tensioning, etc. Therefore it is impossible to define it as a limit value for a certain bridge-type (in contrary to the general detailing practice, where the adequacy of the structure can be shown by comparing the given variables with their limit values), but can be accepted as an informing characteristic of a given structure.

The extent of structural damping – if there is no vibration absorber used – depends mainly on the structures energy absorbation capability, which is similarly effected by several parameters, but the material characteristics has a considerable effect. In this regard the range of material continuity or discontinuity can significantly influence the structural damping. This effect usually has great importance in reinforced concrete structures, where the material discontinuity must always be taken into account in practice due to the unavoidable occurrence of cracks. For the lack of more accurate investigations the Hungarian Code 1984 defines the value of logarithmic decrement in dynamic calculations as 0.05 for concretes without cracks and 0.15 for concretes with cracks (Szalai, 1984).

Generally the objective of dynamic tests on bridges is the measuring of the process of changes in the above-mentioned characteristics, which occur mainly as a result of changes in the condition of the bridge.

2.2 Mode of measuring

Before the measurements vibration is generated on the structure with an exciter effect. The road traffic also can be used for this generation. The registration of the response to the excitation of a structure can be based on the measurement of the time-dependent amplitude A(t) or acceleration a(t) functions of movement in given points of the vibrating system. Because of its higher intensity due to the second derivation of the function of the amplitude the measurement of the accelerations is technically easier. The disadvantage of this method is that the range of measurement must be accurately adjusted due to the higher intensity of the registrated signals. The measurement of displacements is carried out with use of electrical displacement transducers. The registrated and amplified signals are recorded by an instrumentation tape recorder.

If there is a need for determining the eigenfunctions beside the natural frequencies more displacement transducers are to be applied. The eigenfunctions are determined by the phase difference in the vibration of the measuring points. To be able to distinguish the different vibration modes (in bridges mainly flexural and torsional) the number of measuring points in the cross-sections must be increased as far as possible in symmetrical arrangement. For characterization of the eigenfunctions an increased number of measuring points must be applied in longitudinal direction at the same cross-sectional points if possible. Applying more measuring points also has the advantage of getting more data for the determination of the natural frequency. If the measuring points are chosen properly the eigenfunction of the structure can adequately be determined even by three applied points. It has a great importance not to place the measuring devices into the supposed nodal points of the eigenfunction or near to them, because it can be resulted in false data.

2.3 The principle and modes of excitation

The solution of a harmonically excited vibrating system's differential equation is given by the following expression (Vértes, 1972):

$$x = \left[C_1 \cdot \sin(\omega_0 \cdot t) + C_2 \cdot \cos(\omega_0 \cdot t)\right] + \frac{\frac{P_0}{c}}{1 - \left(\frac{\omega}{\omega_0}\right)^2} \cdot \sin(\omega \cdot t)$$

where: x – the displacement of the system in the plane of vibration
ω - the radian frequency of the exciter force
ω_0 - the radian frequency of the system
P_o - the maximum value of the exciter force
c – spring constant
t – time
C_1, C_2 - constants

The homogenous part of the solution is the natural vibration, the particular part is the excitation. In case of strictly harmonic excitation the natural frequencies quickly diminish from the vibration pattern at the beginning of the vibration due to the generally occurring damping effects. Further on the structure vibrates at the frequency of the excitation. In case of non-harmonic excitation both the natural and the exciter frequencies exist in the vibration pattern. The actual natural frequency in the vibration pattern depends on the frequency range of the initial excitation.

If the determination of more than one natural frequency of the system is necessary the exciter effect must be chosen in such a way that it could cause excitation in the examined frequency ranges, so it must comprehend as wide frequency range as possible. As a general rule it can be stated that at real vibrating systems the occurrence of the first natural frequency in the vibration pattern is the most strikingly marked. Measuring natural frequencies after the third mode mainly depends on the type of the initial excitation.

The ideal excitation in this respect is called „white noise”. Its exciter function is on Fig.1:

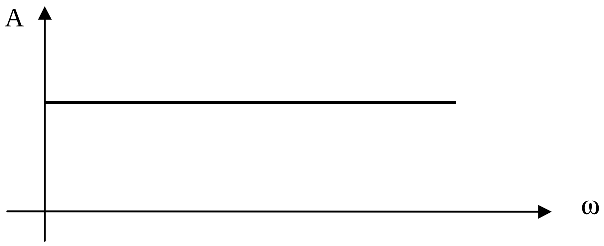

Fig. 1 Exciter function of the „white noise”

Its advantage is the fact, that it excites across the whole frequency range with the same amplitude, which means that it emphasizes every natural frequency in the same way. But on the other hand it can be made only theoretically.
The influence of the wind in several frequency ranges approximates the white noise excitations. Its exciter function is on Fig.2:

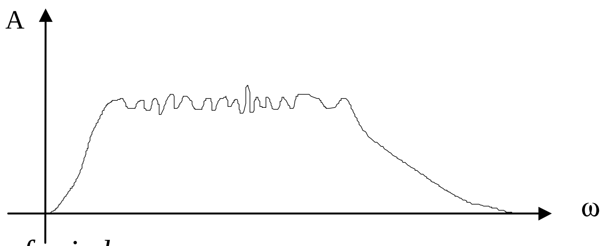

Fig. 2 Exciter function of wind

It can be applied as an exciter effect on condition that the frequency range - in which the A-ω function is nearly constant – contains also the structure’s natural frequencies (or some of them) which are supposed to measure. Wind as an exciter effect also can be used for dynamic analyses mostly for larger structures (e.g. skew-cabled bridges).
For highway bridges the road traffic is frequently used for excitation. The wide amplitude-spectrum of the exciter effect comes from the different vehicles’ non-uniform running-properties, therefore it is essential to examine a sufficiently long time interval to reach an appropriately wide frequency range. In this case excitations, which are not close enough to any of the natural frequencies will occur in random manner and can be sifted out from the vibration pattern. Excitations, which are close to them will amplify the natural vibration of the bridge enabling the determination of the natural frequencies (Kálló, 1997)

For excitation the so-called Dirac-δ impulse can also be used. Its exciter function is on Fig.3:

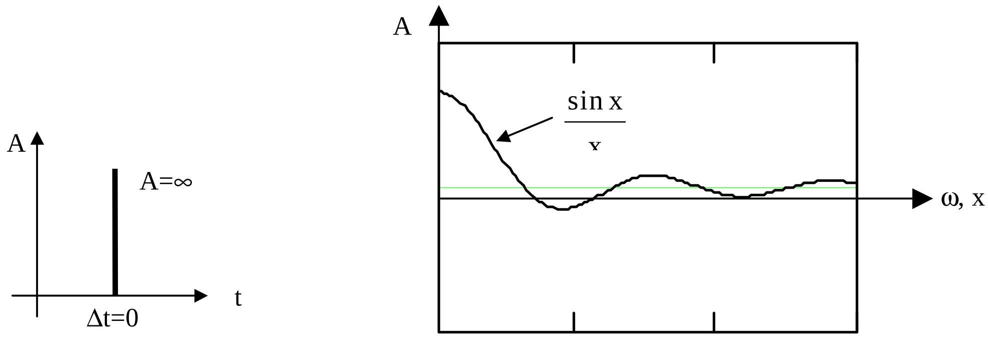

Fig. 3 Exciter function of the Dirac-d impulse

For impulses in practical cases (e.g. impact effects) A≠∞ and dt≈0 naturally. In this case the A-ω function of the excitation has a sin(x)/x –like shape.

Another possibility for excitation of the bridge is the so-called diminishing impulse (or its inverse). The exciter function is on Fig.4:

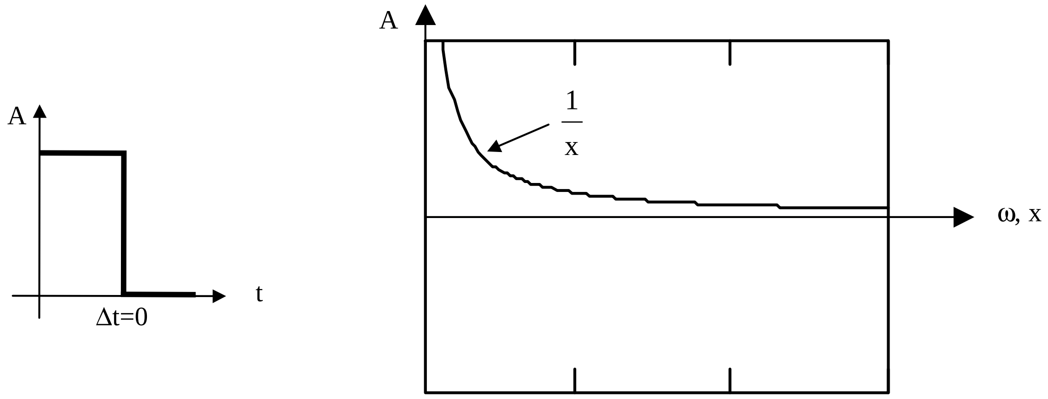

Fig. 4 Exciter function of the diminishing impulse

In practical applications this impulse diminishes in dt≈0 time. Its A-ω function has a shape similar to the 1/x function. The disadvantage of the impulse is that it over emphasizes the first natural frequencies, but excites the others only with too small amplitude.

The most sophisticated method for exciting bridges is the excitation with a generator, which emits harmonic signals. In this case the measurement is carryed out at varied frequency values for certain times with standard signal emission or with continually changing ω =f(t) signal emission. The exciter function is entirely known in both cases. Applying this method for bridges generally requires special equipment, which usually entails considerable extra cost.

At practical applications the Dirac-δ impulse is usually generated by the impact effect of the crossing vehicle's wheels on the bridge. The measurement contains many disturbing effects in this case because the vehicle continues exciting the bridge with an unknown function.
Placing a huge mass on the bridge and cutting the suspender cable is a well proved method for generating „clear" diminishing impulse in practice.
A disadvantage of the two above methods that the larger frequencies are generated with considerably smaller amplitude and consequently the measurement of them is more difficult. Therefore most frequently the real traffic is used in practice as an exciter effect due to its above detailed advantages and less costs.

Damped vibrations at natural frequencies can be used for measuring the structural damping after the exciter effect has stopped operating. This natural vibrations are the „clearest" when the initial excitation is also harmonic. In other cases the natural vibration is influenced by the „inherited" non-harmonic signals of the initial vibration.

2.4 Evaluating the registrated signals

The natural frequencies can be determined in the easiest way if the exciter signals A(ω)-(ω) function is constant in the examined frequency range. In this case the analysis can be accomplished purely according to the response functions, because every natural frequencies in the excited range appear in the measured data with the same weight. It is fulfilled if we apply road traffic as excitation. In the followings we discuss only this case.
The amplitude-spectrum (A(ω)-(ω)) and the phase-spectrum (Φ(ω)-(ω)) of the vibration can also be worked out from section to section by sectionalizing the amplitude-time (A(t)-t) or amplitude-acceleration (A(a)-a) functions at the measuring points and applying a Fourier-transformation. The transformation is carryed out by an analysator or by a computer programmed for this.
After averaging the amplitude-spectrums the weights of the natural frequencies will increase, while the weights of the frequencies from the random-typed excitation will decrease. In this average spectrum the natural frequencies are represented by significant peaks and can easily be identified, but after the averaging the phase informations will be lost and the eigenfunctions cannot be determined.
The „derived spectrum" method determines the amplitude-spectrums for the difference and the sum of time-functions measured at two different measuring points. This way the natural frequencies will be even stronger in one of the spectrums and also the phase informations remain. Applying sufficient number of measuring points the eigenfunctions can also be determined.

The logarithmic decrement of the damping is directly calculated from the A(t)-t function of the registrated natural vibration and given by the following expression:

$$D = \frac{1}{n} \cdot \ln \frac{A_1}{A_n}$$

where: A_l – the first amplitude of the vibration in the examined range
A_n – the last amplitude of the vibration in the examined range
n – the number of waves in the examined range

For eliminating the random disturbing effects generally a value of 15 is proposed for n. A relatively accurate average value can be calculated for the logarithmic decrement if we determine it at several points from the time-function.

3. PRACTICAL EXAMPLES

In the followings the above detailed theory will be illustrated on practical examples.

The first example examines two highly cracked reinforced concrete, where the effect of strengthening by additional post-tensioning on the natural frequencies of the bridges was analyzed bridges (Farkas, 1998). Both were continuos two-span bridges with beam-slab superstructures. The longitudinal section of the bridges and the scheme of post-tensioning are shown on Fig.5:

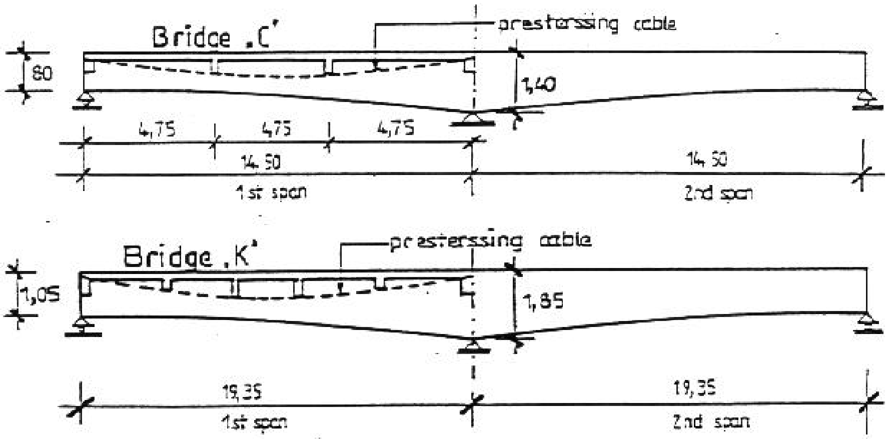

Fig. 5 Longitudinal section of the examined bridges with beam-slab superstructures

The acceleration-time functions were registered at 6 measuring points before and after the strengthening under the effect of normal traffic (Dalmy, 1995). The results are given in Table 1:

Bridge	Mode	Natural frequencies [Hz]		Change [%]
		before strengthening	after strengthening	
C	bending	8.15	8.74	7.2
	torsional	11.62	11.87	2.2
K	bending	4.2	4.39	4.5
	torsional	6.59	7.08	7.4

Tab. 1 Change of natural frequencies before and after the strengthening

The increase in the natural frequencies was due to the post-tensioning which resulted in enhancing the stiffness of the structure by closing the initially large cracks .

The second example shows the supervision of a reinforced concrete arch bridge with prestressed slab deck by using dynamic method (Farkas, Szalai, 1998). The supervision was initiated by the preliminary observations of broken prestressing cables. The scheme of the bridge is on Fig.6:

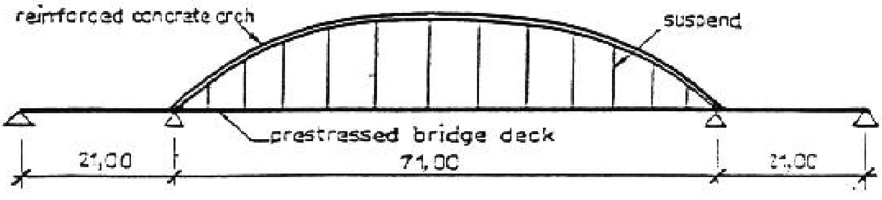

Fig. 6 Scheme of the arch bridge

The excitation was carried out with a 20 ton-vehicle, which crossed the bridge at a given speed. An impact effect was caused by clashing the wheels of the vehicle with an obstacle in the middle of the bridge. The time-functions was registrated at measuring points in the middle of both spans at fixed cross-sectional coordinates. The first two natural frequencies calculated by averaging the acceleration-amplitude-spectrum and the determination of the damping coefficient is shown on Fig.7:

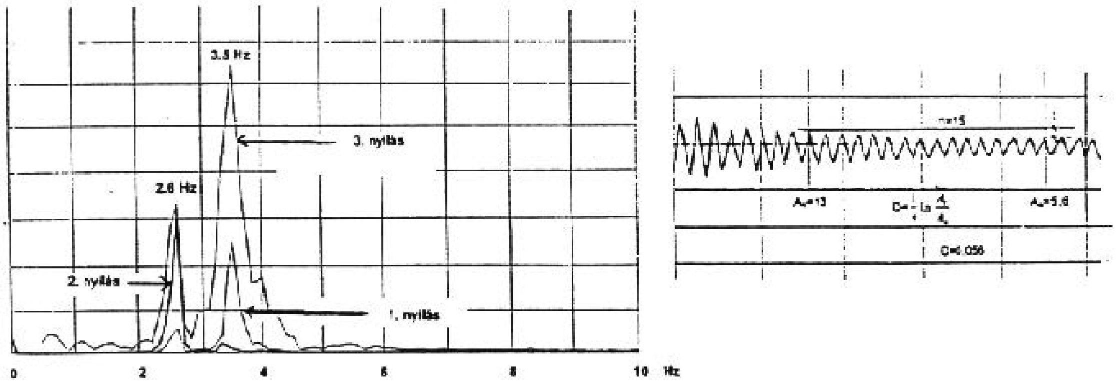

Fig. 7 Acceleration-amplitude spectrum and the damping coefficient

The value of damping coefficient from the dynamic analysis is in accordance with the results of the statical calculations. These calculations have shown that the immediate strengthening of the bridge is not necessary mainly because it was originally designed for uncracked condition. The natural frequencies from this analysis can be used for comparing them with the results of later supervisions and for drawing conclusions about the corrosion process.

4. CONCLUSIONS

The above detailed dynamic tests are well applicable in regular supervisions of reinforced concrete bridges. It has also been proved by practical examples. There are several modes of measurements and evaluation of the data. Beside their sufficient accuracy these measurements can be carried out in practice easily, quickly and they are not cost demanding. These characteristics are the biggest advantages of dynamic methods.

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