Design of instrumentation and vibration testing programs of structures through analytical investigations

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Abstract

For the estimation of the dynamic properties of structures, forced vibration tests are often used. Various methodologies for the predetermination of the force level and the position of the shaker have been developed. In the present work the methodologies of field-testing and analytical evaluations of the structural response are defined through an interactive procedure. During field-testing, a group of parameters may vary, such as the position and the direction of the excitation force, and the amount, eccentricity and frequency of the rotating mass. These parameters should be defined and estimated before the actual testing, in order to perform an effective test plan. For this purpose, the structure under investigation is analytically modeled and its dynamic properties (mode shapes and frequencies) are estimated. Parametric analyses follow, by considering a vibrating mass on the analytical model for the simulation of the vibrator action. These analyses are performed for various positions of the vibrator on the analytical model and for various excitation levels and frequencies of vibration in order to evaluate the activated, in each case, dynamic properties of the structure and hence to better design the testing vibration program. The suggested methodology is applied for a specific bridge on Egnatia Highway, which crosses Northern Greece in an E–W direction. Also, a methodology for the installation of the vibrator on an actual structure is proposed, aiming towards the optimum transfer of forces from the vibrator to the structure.

Keywords: R/C bridges, forced vibrations, dynamic analyses, vibration testing, vibrator installation.
1 Introduction

In the present paper a methodology is presented, in which the design of forced vibration tests of structures is determined through the results of analytical parametric investigations. During the last years, significant progress has been achieved in the field of non-destructive, in-situ testing of existing structures. Portable equipment, such as rebound hammers, sonometers, vibrators, accelerometer arrays etc., have become available, by use of which it is possible to evaluate experimentally both static (e.g. concrete strength, quality, quantity and location of reinforcement bars) and dynamic (e.g. eigenvalues, eigenmodes) properties of the structures. For the case of dynamic testing, use of high-sensitivity sensors and high capacity recording systems is necessary Harris [1]. Apart from the necessary equipment and know-how that is necessary in order to conduct a forced vibration test of a structure and to record its response, the determination of its dynamic characteristics from the recordings is by itself a highly complicated procedure, based on advanced mathematical concepts. The methodology proposed in this paper is applied for the design of a forced vibration test of an actual bridge, located on the Egnatia highway, which transverses Northern Greece in an E-W direction. Analytical models of the bridge are developed, and its dynamic characteristics (eigenvalues, eigenmodes) are evaluated. Parametric analyses are also conducted, in order to simulate the excitation of the bridge by a uniaxial, eccentric mass vibrator system. The results of the analytic investigations help determine the actual test procedure that must be followed on site, as well as the necessary specifications (e.g. resolution, dynamic range etc) of the sensors that are to record the response of the bridge during the testing. Finally, a transition plate system that was designed for anchoring the shaker to the bridge is presented.

2 Description of the Polymylos bridge

The proposed methodology is applied for the case of bridge Γ9 on section 5.1 of the Egnatia Highway in Northern Greece (‘Polymylos’ bridge) (Figures 1,2,3). The bridge has a total length of 170 m and is T-shaped, with the central pier consisting of a pair of wall-like columns monolithically connected to the deck, while the support at the two abutments is achieved through elastomeric bearings. The cross section of the bridge deck is a hollow girder box with a variable height from 4.0m at the abutments to 9.0 m at the pier. The deck is circular in plan, with a radius of 757.55 m. The width of the deck is 13.5m at the top, while the corresponding width at the bottom part of the box cross section is 7.00m. The bridge was constructed by the asymmetric cantilever procedure with in situ cast of the RC cantilever parts. For the deck, C35/40 category concrete was used, and for the pier columns C30/35. The deck cross section is prestressed in the longitudinal direction. Each of the two pier columns has a rectangular cross section of 2.00 x 7.00 m, has a height of 26.28 m, and their vertical axis – to -vertical axis distance is 7.00 m. The elastomeric bearings at the two abutments
allow free movement along the longitudinal direction of the bridge deck and are activated only in the transverse (radial) direction. The bridge is founded on rocky subsoil.

![Bridge Diagram](image)

**Figure 1:** The Polymylos bridge (plan view).

### 3 Modal analysis of the Polymylos bridge

For the analytical investigation of the dynamic properties of the bridge, finite element models were developed, using the beam and shell elements of the SAP2000-v9.0 [2] general-purpose program (Figure 2). Since, during the actual testing of the bridge, linear response behaviour is expected, appropriate element stiffnesses and viscous damping values were assumed in the models, as is discussed in detail in the following chapter. The total activated mass of the bridge is estimated at 6200 t. The first six computed shape-modes of the bridge are presented in Table 1. The first shape-mode is essentially a torsional one about the vertical axis of the pier. Also, no significant coupling is observed among the various shape-modes.

<table>
<thead>
<tr>
<th>Eigen-mode</th>
<th>Modal effective mass (%)</th>
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<tbody>
<tr>
<td></td>
<td>$\omega$ (rad/sec)</td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>1.41</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>0.33</td>
</tr>
<tr>
<td>Total</td>
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**Table 1:** Analytical shape-modes of Polymylos bridge.
Analytical investigation of the forced-vibration test procedures

4.1 Estimation of the viscous damping of the bridge

The level of the excitation force produced by a vibrator is considerably lower than the one that a bridge is designed for, thus leading to small response amplitudes. As a result, the value of the viscous damping ratio during a forced vibration test is considerably smaller than that of $\zeta=5\%$ which is usually assumed for the seismic design of a bridge. For the same reason, since the dynamic behaviour of the bridge is essentially linear during the test, in any analytical models that are developed in order to simulate the forced vibration tests, it is the geometric stiffness of the structural elements that must be used and not an effective stiffness that takes into account a non-linear behaviour (cracking) of the elements. For the needs of the present research effort, the proposition of Gulkan & Sozen [3] was adopted for the equivalent damping ratio:

$$
\zeta_{eq} \approx 0.02 + 0.2 \times \left(1 - 1/\sqrt{\mu}\right)
$$

where $\mu$ is the displacement ductility of the bridge.

For a linear response of the structure, eq. (1) leads to an equivalent damping ratio of $\zeta \approx 0.02$. Two analytical models of the bridge were developed for the present research needs:

a. Analytical model with an equivalent damping ratio of $\zeta=1.5\%$ and use of initial (geometric) stiffness for the uncracked structural elements, corresponding to the linear behaviour of the bridge during the forced vibration tests.

b. Analytical model with an equivalent damping ratio of $\zeta=5\%$ and use of effective stiffness for the structural elements, corresponding to the nonlinear behaviour of the bridge when subjected to the design seismic forces.
For the actual tests, a uniaxial eccentric mass vibrator system is to be used. The vibrator is to be placed on the elastic center of the bridge, which can be computed after Makarios et al. [4]. An indicative position of the vibrator and the accelerometers within the girder box of the deck is shown in Figure 3.

![Indicative position of the vibrator and the accelerometer sensors within the girder box of the deck.](image)

**Figure 3:** Indicative position of the vibrator and the accelerometer sensors within the girder box of the deck.

### 4.2 Analytical investigations of the bridge response during the forced-vibration tests

For the analytical investigations of the bridge response, both analytical models, as described in the previous chapter, were used in order to estimate the linear and nonlinear response of the bridge. A series of parametric dynamic analyses were performed for each model, assuming the harmonic vibrator force applied at the elastic center of the bridge (see Figure 3) and acting first along the x-axis and then along the y-axis of the bridge (Figure 4), with different rotation speeds $\Omega$ of the excitation mass.

![Application of the horizontal harmonic dynamic force on the elastic center along the x and y axes of the bridge.](image)

**Figure 4:** Application of the horizontal harmonic dynamic force on the elastic center along the x and y axes of the bridge.

The results of the analyses are presented in Figure 5 for the x-axis and in Figure 6 for the y-axis. The dynamic coefficients $D_x$ and $D_y$ plotted in the figures are defined as:
\[ D_x = \frac{u_{x,max}(t)}{u_{x,st}}, \quad D_y = \frac{u_{y,max}(t)}{u_{y,st}} \] (2a,b)

where

- \( u_{x,max}(t) \) is the maximum dynamic displacement of the elastic center along the x-axis for a sinusoidal excitation force of amplitude \( F \) along the same axis.
- \( u_{x,st} \) is the maximum static displacement of the elastic center along the x-axis for a static excitation force of amplitude \( F \) along the same axis.

and analogous definitions hold for \( u_{y,max}(t) \) and \( u_{y,st} \) along the y-axis.

From Figures 5 and 6 the following conclusions can be deduced:

a. During the forced vibration test along the x-axis, the maximum bridge response \( u_{x,max} \) takes place for a frequency of the dynamic force of \( \Omega = 1/1.42 = 0.70 \text{Hz} \).

b. During the forced vibration test along the y-axis, the maximum bridge response \( u_{y,max} \) takes place for a frequency of the dynamic force of \( \Omega = 1/0.58 = 1.72 \text{Hz} \), with a second peak for a frequency of \( \Omega = 1/1.16 = 0.86 \text{Hz} \).

Figure 5: Variation of dynamic coefficient \( D_x \) vs. frequency \( \Omega \) of excitation force.

It should be noted that the maximum dynamic force that a vibrator can produce depends on the frequency of its rotating masses. For lower frequencies, the applicable dynamic force is considerably smaller than the nominal maximum value. Taking into account the specifications of the vibrator that is to be used for the tests, two sets of analytical investigations were also conducted, in which the maximum
dynamic force that can be produced by the vibrator at each frequency was considered. In the analyses, the model corresponding to the linear response of the bridge was used. The expected response of the bridge is presented in Figures 7 and 8. From the figures, it is noted that the bridge displacements that are expected to be produced by the vibrator are rather small, thus indicating the need of a high-resolution network of accelerometers in order have a reliable recording of the response.

Figure 6: Variation of dynamic coefficient $D_y$ vs. frequency $\Omega$ of dynamic force.

Figure 7: Maximum bridge displacement $u_{x,max}(t)$ along x-axis for various frequencies $\Omega$ of the dynamic force in the same direction. The corresponding static displacement $u_{x,st}$ and maximum dynamic force $F_{max}$ produced by the vibrator are also plotted.
From the analytical investigations the following test procedure has been decided:

a. **Enforced vibration test along the x-axis of the bridge:** Excitation within the frequency range of \( \Omega = 0.50 \div 1.20 \) Hz, with a 0.05 Hz step and expected peak at \( \Omega = 0.70 \) Hz.

b. **Enforced vibration test along the y-axis of the bridge:** Excitation within the frequency range of \( \Omega = 0.70 \div 2.40 \) Hz, with a 0.05 Hz step and expected peaks at \( \Omega = 0.86 \) Hz and \( \Omega = 1.72 \) Hz.

5 **Anchoring system for the vibration generator**

The vibrator that is to be used for the test is a portable, uniaxial dual counter-rotating shaker, which can be operated from 0.1 to 20.0 Hz and can produce a maximum force of 5 tons from 10.5 to 20 Hz. The direction of the uniaxial force produced by the shaker is variable and can be set to any horizontal direction by the user. The actual force-producing capabilities of the vibrator were taken into account for the analytical investigations. It is very important to properly anchor the shaker to the test structure. Insufficient or improper anchorage can lead to vibration loosening of the attachment hardware. Most structures require anchoring the shaker to concrete. The anchoring can be achieved either directly (by thru-bolting using epoxy anchors), or by use of a suitably designed transition plate. The use of epoxy anchors presents several disadvantages, among which one can mention the need for a perfectly level mounting surface in order to prevent any deformation of the shaker and the nature of the epoxy anchors, which demands a minimum drilling depth and a curing time that depends on the
existing temperature conditions. Also, the unique pattern of the holes provided for the thru-bolting demands a very precise drilling procedure, which might fail when reinforcing bar or sheet metal pouring frame is encountered.

![Diagram of anchoring system for the eccentric mass vibrator]

Figure 9: Anchoring system for the eccentric mass vibrator.

For all these reasons, a special transition plate system has been designed in order to facilitate the anchoring of the shaker to the concrete mounting surface. The system (Figure 9) comprises a tough aluminum transition plate, larger than the shaker in plan and with many holes on its perimeter, through which mechanical bolts can be used for anchoring to the concrete. Only a small number of the provided perimetric holes need to be used for anchoring, thus providing the possibility of alternative bolting patterns, in case reinforcing bars are encountered. The plate has permanently welded anchor rods through which the shaker is attached. Apart from the anchors, special stop devices (‘stoppers’) are provided in order to hinder any differential displacement between the shaker and the transition plate.

6 Conclusions

A methodology has been developed for the proper design of forced-vibration tests on structures, and is applied for the case of an actual bridge. Analytical models of the structure to be tested are developed, and parametric dynamic analyses are performed. Various models are developed in order to simulate the linear or nonlinear behaviour of the structure, while the vibrator action is properly simulated by a harmonic, uniaxial dynamic force. The linear models are used for the simulation of the force-vibration tests, since the expected structural response during the tests is essentially linear. The nonlinear models, in the contrary, describe more accurately the seismic response of the structure for the design earthquake. From the dynamic coefficient curves $D_x$ and $D_y$ that are obtained for different frequencies $\Omega$ of the vibrator force, the proper testing procedure (frequency range and step of the excitation force) can be determined.
for each test direction. Taking into account the force-producing capabilities of the shaker that is to be used, the expected response can be determined from the analytical models, and this information is used in order to determine the necessary specifications of the sensors, so that the actual structural response during the test will be accurately recorded. For the case of the bridge under examination, a high-resolution array of sensors is necessary, since the expected response during the actual tests, especially for the first eigenmodes, is very small. The proper anchoring of the shaker to the concrete mounting surface is very important for the proper transfer of the shaker force to the test structure. For the anchoring, a special transition plate system has been designed, which, by permitting the use of mechanical bolts, facilitates the whole anchoring procedure and avoids all the disadvantages of trying to anchor the shaker directly to the test structure by use of chemical anchors.

References