HYBRID TESTING OF SEISMICALLY ISOLATED BRIDGES

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by

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Abstract

Elastomeric bearings have long been employed in bridge structures and their response under horizontal loading action has been experimentally studied by applying – slow or real-time – displacement cycles to failure. The experimental study of the actual response of bridges on elastomeric bearings under earthquake action presents difficulties due to the required size of the test specimens and thus one resorts to substructuring methods.

In this report a pre-test characterization procedure for determining the rate-dependent response of bearings - to be accounted for in non-real-time, sub-structured hybrid testing - is presented. The results of this phase are then employed to calculate an additional force term that is taken to depend on certain parameters of the response (level of bearing deformation, velocity, force and force rate). The latter force term is added to the restoring force measured at each step during hybrid testing, so that the displacement to be applied at the next step (at a slow rate) encompasses an approximate estimation of the effect of rate on material response.

The procedure was applied to commonly used isolation bearings and results from a testing campaign on a series of isolators are presented. It is shown that the rate-dependent response of bearings can be approximately accounted for in non-real-time testing and that in isolated bridges the deformation demand placed on plain low damping elastomeric bearings may exceed their capacity under actual earthquakes.
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1 Introduction

1.1 General

Seismic isolation of bridges aims at lengthening the fundamental period of the system to reduce force and strength demands, adding often energy dissipation to reduce further the force demands and limit the increase in displacement demands brought about by the longer period. Flexible or sliding bearings are normally sufficient for the period lengthening. Viscous dampers, elasto-plastic devices or high damping bearings provide the additional energy dissipation. There is no consensus yet on whether lengthening of the period is sufficient or additional energy dissipation is required.

The present report focuses on the first strategy of seismic protection of bridge structures via period lengthening with the use of low damping elastomeric bearings. The main interest lies in the experimental investigation of the response of such structures and the associated techniques. The technique used is the hybrid (pseudo-dynamic, PsD) testing of the idealized structural model with the addition of a force-correction step accounting for the effect of loading rate on the behaviour of the isolation devices.

1.2 Hybrid testing of bridge structures

Owing to their large size bridges do not lend themselves to seismic testing at full or even realistic scale. Their seismic response has been studied experimentally either via cyclic testing of piers, or through shake table tests on scaled models (Casirati et al., 1996, Correal et al., 2007). The development of hybrid techniques based on sub-structuring, combining pseudo-dynamic physical testing of part of the system with – linear or nonlinear – mathematical simulation of the rest, has made possible testing of bridges at nearly full scale (Pinto et al. 1996, Pinto et al. 2004, Spencer et al 2006, Johnson et al. 2006). So far in studies of this type physical testing has been limited to the piers, while simulating the deck and any bearings numerically. On the other hand, in experimental work to-date isolation devices or systems have been tested individually, mainly under imposed
cyclic displacement histories. In this study attention is exclusively focused on the physically tested isolation system that belongs to a bridge subjected to seismic ground motions.

### 1.3 Description of the prototype bridge structure

The prototype bridge used as reference for the experimental program is a 12-span highway bridge at the valley of river Nestos in northern Greece. The bridge is part of recently completed Egnatia highway (E-90). The elevation view of the bridge is depicted in Fig. 1.1. The piers are located on average 38 m apart and their net height (from valley ground level up to the cap beam) is approximately 5.8 m (see Fig. 1.2). The cross section of all the piers (shown in Fig. 1.3) is identical and constant along their longitudinal axis (height). On the top of each pier lies a 2.6 m high transverse cap beam that serves as support for the deck. Each deck span consists of five simply supported, precast, prestressed concrete girders (Fig. 1.4), topped by an in-situ cast concrete slab. Each girder is supported at both ends by plain elastomeric pads and, additionally, each end the central girder of a span is connected to the cap beam with a pair of viscoelastic dampers – one in the longitudinal and one in the transverse direction. The foundation of the bridge consists of pile groups reaching as far as the underlying bedrock.

![Fig. 1.1 Elevation view of prototype bridge](image-url)
Fig. 1.2 Schematic of typical pier

Fig. 1.3 Typical pier cross-section (dimensions in m)

Fig. 1.4 Geometry of prestressed concrete deck girders
2 Experimental setup

2.1 General

The experimental program started with characterization tests in order to determine the mechanical properties of the elastomeric bearings at levels of rubber shear deformation up to 100% and at frequencies close to the dominant frequencies expected of the response of the bridge during an earthquake event. The characterization tests were followed by a series of pseudo-dynamic tests using the substructuring technique. The pseudodynamic (PsD) tests are generally performed quasi-statically (i.e. at very slow rates). In reality, the strain rate during the dynamic (seismic) response of the structure significantly affects the response of isolation systems. This is the reason why a special procedure must be followed (described in Section 3.2) for the determination of the strain rate effect on the mechanical properties of the isolators and the correction of the restoring forces measured during pseudodynamic testing.

2.2 Modelling of the bridge structure

The size of the studied bridge renders the construction of a full-scale (or even a realistic scaled) model impossible. Nevertheless, the fact that the superstructure (deck) and the piers are expected to exhibit elastic behaviour during a seismic event makes the use of the substructuring method appropriate. More specifically the bridge is discretized into an experimental substructure comprising the isolation system (elastomeric bearings), and a numerical substructure consisting of the piers and the deck. Taking advantage of the symmetry of the prototype bridge in the longitudinal and the transverse direction, each span can be modelled as a two-degree-of-freedom (2-DOF) system where the first degree of freedom corresponds to the horizontal displacement of the top of the pier and the second degree of freedom corresponds to the horizontal displacement of the deck (Fig. 2.1).
Assuming that the piers are fixed at the level of the top of the piles’ cap, the stiffness of the pier, its mass, as well as the mass of the deck correspond to the 10 bearings that support the deck girders on the cap beam of the pier. The deck itself is modelled as a rigid mass. For the given pier dimensions, the moments of inertia of the pier cross-section are $I_{xx} = 7125 \text{ m}^4$ and $I_{yy} = 44103 \text{ m}^4$ for the longitudinal and the transverse directions, respectively. Additionally, with the assumption that the pier functions as a cantilever and taking into consideration the contribution of the rotation of the pile cap to the pier stiffness, the latter is calculated as follows:

$$K_{xx}^p = \frac{3EI_{xx}}{h^3\left(1+1.5\frac{h}{h}\right)} \quad K_{yy}^p = \frac{3EI_{yy}}{h^3\left(1+1.5\frac{h}{h}\right)}$$

The calculated values for the pier stiffness are $K_{xx} = 2200 \text{ MN/m}$ (longitudinal direction) and $K_{yy} = 13600 \text{ MN/m}$ (transverse direction). No shear deformations were considered. It should also be noted that the aforementioned prototype bridge was used just as a basis for a realistic experimental simulation and that the actual hybrid setup slightly deviates from the prototype geometry and properties. The total mass of the deck was calculated at 917000 kg, while the mass of the pier was calculated as the sum of the mass of the pier section per se (213000 kg) and the mass of the transverse cap beam (217300 kg). The stiffnesses and the masses for the real structure (per 10 bearings) numerical substructure (per pair of bearings) are summarized in Table 2.1.
Table 2.1 Properties of the prototype structure and of the corresponding numerical model

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Per 10 bearings (prototype)</th>
<th>Per pair of bearings (numerical model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pier stiffness (longitudinal) $K_{xx}$</td>
<td>2200 MN/m</td>
<td>440 MN/m</td>
</tr>
<tr>
<td>Pier stiffness (transverse) $K_{yy}$</td>
<td>13600 MN/m</td>
<td>2720 MN/m</td>
</tr>
<tr>
<td>Deck mass</td>
<td>917000 kg</td>
<td>183400 kg</td>
</tr>
<tr>
<td>Pier mass</td>
<td>430300 kg</td>
<td>58200 kg (effective)</td>
</tr>
</tbody>
</table>

2.3 Properties of elastomeric bearings

The bearings used during testing were low damping rubber bearings manufactured by ALGA (Type NB4 with an external diameter of 350mm). Each bearing consists of 7 layers of rubber with a layer thickness of 11 mm and 6 steel shim plates with a thickness of 6 mm each (Fig. 2.2). The steel end plates of the bearings have significant thickness (15 mm) in order to provide the required stiffness for the connection with the pier and the deck of the bridge. The end plates are vulcanized with the rubber and have 15 mm deep recesses in which cylindrical shear pins of 30 mm length are inserted. The protruding ends of the pins are inserted into the corresponding holes of external, 400 mm-square connection plates. The external connection plates are bolted or welded to the pier (at the lower side) and the deck (at the upper side). The total height of the bearing, including the external connection plates, is 181 mm, while the total rubber height is 77 mm.

![Fig. 2.2 Photograph of ALGA low damping rubber bearing (left) and typical section showing the steel reinforcements (right)](image-url)
The prescribed shear modulus of the rubber is 0.99 MPa. The horizontal and vertical stiffness of the bearings is:

\[ K_H = \frac{GA}{t_r} \]  \hspace{1cm} (2.2)

and \[ K_V = \frac{E_c A}{t_r} \]  \hspace{1cm} (2.3)

respectively, where \( G \) is the shear modulus of the elastomer (rubber), \( A \) is the cross-section area of the bearing, \( t_r \) is the total height of the rubber and \( E_c \) is the instantaneous compression modulus of the rubber-steel composite under a specified level of vertical load. For a single pad in the form of a complete circle the compression modulus is given by

\[ E_c = 6GS^2 \]  \hspace{1cm} (2.4)

where \( S \) is a shape factor which is defined as the ratio of the loaded area to the force-free area of a layer. In the case of a circular bearing:

\[ S = \frac{\text{loaded area}}{\text{force-free area}} = \frac{\text{diameter}}{4t_r} \]  \hspace{1cm} (2.5)

Substituting the geometry and mechanical properties into Eq. (2.2) to Eq. (2.5) it is obtained that for the test bearings: \( K_H = 1237 \text{ kN/m} \), \( K_V = 469.6 \text{ MN/m} \), \( S = 7.95 \) and \( E_c = 375.8 \text{ MPa} \).

### 2.4 Elastomeric bearings test setup

It has already been mentioned in Section 2.2 that the bridge structure (more accurately, a span of the bridge) is modelled as a 2-DOF system with a translational DOF corresponding to the effective pier mass and a second translational DOF corresponding to the deck mass. The stiffness of the pier and the masses are introduced into the pseudodynamic algorithm that controls the test and is executed in the controller. The relative displacement of the deck with respect to the pier (i.e. the algebraic difference of the values of the DOF’s) corresponds to the displacement of the isolation
system which is imposed by the experimental setup. A vertical force that simulates the weight of the deck is simultaneously applied to the bearings.

The experimental setup is designed in such a way that an (nearly) constant vertical load is applied to the isolators, regardless of the level of applied shear deformation. It also ensures that the endplates of the bearings remain parallel to each other during testing, in order to avoid influence of the relative rotation of the end plates to the bearings’ response. The basic characteristic of the adopted setup is that a pair of bearings is tested each time in a back-to-back configuration (i.e. one bearing on top of the other with the relative displacement applied by an actuator at a middle plate between the bearings). A schematic of the experimental setup with the actuator and the restraining mechanism is presented in Fig. 2.3.

![Fig. 2.3 Plan view (top) and side view (bottom) of the bearing test setup](image)

The target displacement calculated by the pseudodynamic algorithm is applied to the pair of elastomeric bearings by means of a servo-hydraulically controlled actuator (MTS Model 244.41S...
dynamic actuator) with a maximum stroke 500 mm, equipped with a 3-stage, 1500 lt/min servovalve (MTS Model 256.40). The measured reaction force of the bearings is recorded by a load cell and is fed back to the algorithm for the calculation of the next target displacement etc. The load cell (MTS Model 661.23F) has a capacity of 500 kN in tension or compression and is part of the actuator assembly, located between the rod and the end swivel. An LVDT displacement transducer is mounted within the actuator body, coaxially with the rod and provides feedback on the relative position of the rod. The actuator is anchored to the reaction wall of the laboratory on one side and to the middle plate between the bearings on the other side. A restraining mechanism consisting of two 36 mm threaded bars with a transverse steel hollow beam is used to provide restraint against lateral motion of the actuator. The MTS actuator assembly and its connection to the reaction wall and the bearing test device is presented in Fig. 2.4.

![Fig. 2.4 MTS Model 244.41S dynamic actuator assembly](image_url)

The external connecting plates of the pair of isolators are bolted and welded to two 1250 mm by 750 mm steel slabs with a thickness of 100 mm. The bottom slab is embedded into a 20 cm high concrete base which is post-tensioned to the strong floor of the laboratory by means of 10 Dywidag ø 25 mm threadbars with a total vertical force of 1500 kN. The top slab of the setup is connected to the strong floor with 4 pinned rods consisting of steel circular hollow sections with
an external diameter of 60 mm. The rods can be extended or contracted using a combination of clockwise and counter-clockwise threads and their main function is to ensure the transfer of shear force from the top of the setup to the laboratory floor, while keeping the top slab level and in its initial position. The middle plate which is moved by the actuator is located between the two bearings and moves parallel to the top and bottom plates as long as the latter do not rotate (significantly), thus ensuring that the bearings are deformed in shear during testing.

The vertical load is set to 900 kN and is applied to the top slab by 6 ENERPAC hydraulic jacks with a capacity of 300 kN each. Oil is supplied to the jacks through a manifold connected to a manually controlled pump. The oil pressure remains almost constant during testing and is always the same for all six jacks. The manifold is equipped with a total of four pressure transducers for recording the fluctuation of the vertical force during testing.

For the measurement of the actual displacement of the bearings an optical digital displacement transducer (HEIDENHAIN) is employed. The HEIDENHAIN transducer has a nominal precision of the order of 3-4 \( \mu m \) and is fixed to a rigid column that is completely independent from the rest of the setup and provides a fixed reference point. This is deemed necessary for two main reasons (i) the high precision required for displacement measurements in pseudodynamic testing and (ii) the fact that the displacement feedback provided by the internal LVDT transducer includes the influence of possible minute displacements and deformations within the experimental setup.

A total of six linear potentiometers (WAYCON) are used for recording the relative displacements between selected points on the top slab and an external reference frame that are eventually used for calculating the translations and rotations of the top slab, thus enabling the monitoring of the overall performance of the setup during pseudodynamic testing.

The good overall performance of the experimental setup is verified by test data (to displacement and rotation histories and diagrams of the variation of the vertical load) presented in APPENDIX C. The back-to-back bearing configuration as it was implemented is presented in Fig. 2.5 while a
general view of the experimental setup with the HEIDENHAIN transducer on the right hand side is illustrated in Fig.2.6.

**Fig. 2.5** Experimental setup for testing of elastomeric bearings

**Fig. 2.6** General view of the experimental setup
2.5 Calibration of equipment

The pre-testing preparation of the experimental setup involves the calibration of the main equipment (i.e. the actuator). The LVDT sensor is calibrated by means of a high precision electronic caliper. The load cell calibration is performed by transferring and connecting the actuator assembly to a special calibration beam that is equipped with a prototype 500 kN capacity HBM load cell. The offsets of the LVDT sensor and the load cell are annulled by trimming potentiometers embedded in the main controller system. Finally the resulting linear calibration factors are calculated by regression analysis and used as input in the controller.

The calibration and control of the 3-stage MTS 256.40 servovalve is a more complicated procedure (outlined in APPENDIX A) that requires a special external control module for the inner (3rd-stage) displacement control loop.
3 Testing program and results

3.1 General

Two main categories of tests were executed within the context of the experimental program. The first category are the characterization tests that are necessary for determining the mechanical properties of the bearings at different rates of deformation and for calculating the strain rate correction parameters to be used at subsequent pseudodynamic (PsD) testing for each pair of bearings. The second category are the PsD tests that simulate the response of the numerical substructure and the experimental substructure for a given ground acceleration input.

3.2 Effect of strain rate on bearings’ response

Seismic isolators (in this case, elastomeric bearings) are devices whose behaviour varies significantly according to the rate of applied strain. Since pseudodynamic tests are normally performed at a “dilated” time scale (i.e. slower than in real-world conditions), it is necessary to devise a procedure so that at every test step the restoring force of the isolators (which is a function of their stiffness) is corrected so that it corresponds to the actual restoring force that would have been measured had the test been executed at real-time speed.

The algorithm used for the pseudodynamic tests is the PSDCYC03.DLL version of the ELSA-PSD testing algorithm (Zapico and Molina, 2008a & 2008b). This algorithm is a continuous pseudodynamic algorithm which means that a number of \( N \) points are interpolated between two successive points of the input acceleration record. The equation of motion of the pseudodynamic test is solved \( N \) times at a frequency equal to the internal clock frequency of the controller (500 Hz or 2ms time step), taking \( N \) measurements of the restoring force and executing \( N \) substeps for each step of the acceleration record. If \( \Delta T \) is the time increment of the acceleration record, \( \Delta t \) is the internal sampling time increment of the controller and \( N \) is the chosen by the user number of substeps, the time scaling factor \( \lambda \) is

\[
\lambda = \frac{\text{laboratory time}}{\text{prototype time}} = \frac{N \cdot \Delta t}{\Delta T} \quad (3.1)
\]
For example if \( \Delta T = 0.01 \) s (typical for acceleration records), \( \Delta t = 0.002 \) s (as in the case of the controller used in the tests) and \( N \) is chosen equal to 500, then the calculated value of time scaling factor is \( \lambda = 100 \), which practically means that the PsD test is 100 times slower than in real-time conditions. The above mentioned procedure creates a smoother displacement target history for the actuator which is important for control stability and, additionally, filters the noise inherent in load cell measurements because it takes \( N \) more measurements of the restoring force at each step, with respect with the traditional discrete PsD method.

In order to obtain correction factors for compensating for the low strain rates of pseudodynamic tests with respect to real-time tests, one must resort to a series of strain rate characterization tests during which the isolators are subjected to a predefined (usually harmonic) displacement history including a desired frequency band. The dominant frequency of the displacement history should be close to the first eigenfrequency of the structure. Also, the achieved level of strain should be similar to that expected during the subsequent pseudodynamic test. The characterization test is run successively at multiple “speeds” corresponding to different values of the time scaling factor \( \lambda \), starting with \( \lambda = 1 \) (real-time) and proceeding with lower rates (\( \lambda = 10, \lambda = 100 \) etc. ). Eventually a set of force vs. displacement curves is obtained, such as the ones presented at the lower half of Fig. 3.2 and Fig. 3.3. From the loops it is evident that the response of the elastomeric bearings varies according to test speed with a consistent tendency for less stiff response as speed (and strain rate) drops.

A force correction procedure proposed by Magonette et al. (1998) and Molina et al. (2002) and modified by Palios et. al (2007) has been implemented in the ELSA-PSD testing algorithm (Zapico & Molina, 2008a). The basic assumption of the strain rate compensation procedure is that the correction of the measured force at the isolator (for a specific value of the time scaling factor \( \lambda \)) is used in the algorithm after adding a force term which is a function of the measured force, displacement, force rate and displacement rate (speed). This can be expressed as follows

\[
F_{SRAdd} = F_0 \cdot F_{meas} + D_0 \cdot u_{meas} + F_1 \cdot \dot{F}_{meas} + D_1 \cdot \dot{u}_{meas}
\] (3.2)
where $F_{SRAdd}$ is the additional force term that compensates for the strain rate effects which is added to the measured restoring force and the sum being fed back to the PsD algorithm; $F_{\text{meas}}$, $u_{\text{meas}}$, $\dot{F}_{\text{meas}}$, $\dot{u}_{\text{meas}}$ are the measured restoring force, the measured displacement, the first time derivative of the force and the first time derivative of the displacement (i.e. speed); $F_0$, $D_0$, $F_1$, $D_1$ are parameters that need to be determined. The latter are calculated as follows: let $[A]_{\text{meas}}$ be a vector where the load cell force is recorded for the real-time test with $\lambda = 1$ (dimension $n$ is the number of the data points) and let $[C]_{\text{meas}}$ be a matrix where the load cell force and displacement are recorded (at the first and second column, respectively) for the test with $\lambda = x$ (where $x = 10, 100$ etc.). The least square regression method is employed to calculate a vector $[B]_{4\times 1}$ that satisfies the following equation

$$A(i,1) = \begin{bmatrix} C(i,1) & C(i,2) & C(i-1,1) & C(i-1,2) \end{bmatrix} \cdot \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix}, \text{ for } i = 2 \text{ to } n$$

(3.3)

Given vector $[B]$ the unknown parameters can be calculated as follows

$$A(i,1) = \left[ C(i,1) - C(i-1,1) \right] \cdot (-B_3) + C(i,1) \cdot (B_1 + B_3) + \left[ C(i,2) - C(i-1,2) \right] \cdot (-B_4) + C(i,2) \cdot (B_2 + B_4)$$

(3.4)

which can be rewritten as

$$A(i,1) = \begin{bmatrix} \dot{F}_{\text{meas}} \cdot \Delta t \\ \dot{u}_{\text{meas}} \cdot \Delta t \end{bmatrix} \cdot (-B_3) + F_{\text{meas}} \cdot (B_1 + B_3) + \left[ \dot{u}_{\text{meas}} \cdot \Delta t \right] \cdot (-B_4) + u_{\text{meas}} \cdot (B_2 + B_4)$$

(3.5)

Thus:

$$F_0 = B_1 + B_3$$

$$F_1 = -B_1 \cdot \Delta t$$

$$D_0 = B_2 + B_4$$

$$D_1 = -B_4 \cdot \Delta t$$

(3.6)
If the parameters determined with the above mentioned procedure (for a given value of $\lambda$, say $\lambda = 100$) are used to calculate an additional force term that is added to the measured force from the slow test with $\lambda = 100$, then new force vs. displacement loops are obtained that are almost identical with the loops recorded during the real-time test ($\lambda = 1$), as shown in the upper half of Fig. 3.2 and Fig. 3.3.

3.3 Characterization tests

From the information presented in Section 3.2 it becomes evident that each set of elastomeric bearings needs to be subjected to a series of characterization tests, in order to determine the respective sets of parameters that will subsequently be used for force correction during PsD testing.

From the dynamic characteristics of the simplified 2 degree-of-freedom model presented in Section 2.1 it was calculated that the fundamental eigen-frequency of the system would be around 0.67 Hz. It was thus decided to build a displacement history (Fig. 3.1) composed of a harmonic function (at 0.67 Hz frequency) and a band-limited random motion part. The harmonic function consists of successive sinusoid cycles, starting at an amplitude of 80mm (corresponding to 104% rubber shear strain in the bearings) diminishing gradually to 64 mm (83% strain), 48 mm (63%), 32 mm (42%), 16 mm (21%), 8 mm (10%) and 4 mm (5%). A total of four cycles are executed at the 104% strain level (80 mm) to allow for the stabilization of the behaviour of the bearings and mitigate the effect of scragging which is more intense during initial deformation cycles.

The random motion part was constructed using a random number generator and then applying a low-pass Butterworth filter of 4th polynomial order with a cut-off frequency at 2Hz. The peaks of the random part were kept under 40 mm (52% strain). As a result the total displacement history contains a band of frequencies up to 2 Hz with a “peak” in the frequency domain at 0.67 Hz.
The results of two characterization test series are presented in Fig. 3.2 (test series CH14) and Fig. 3.3 (test series CH17) in terms of corrected (top) and uncorrected (bottom) force vs. displacement loops. The characterization tests were run for values of the time scaling factor equal to $\lambda = 1$, $\lambda = 10$ and $\lambda = 100$. By comparison of the corrected vs. the uncorrected force-displacement loops it is clear that the correction procedure produced responses in very good agreement with the real-time response. The values of the calculated correction parameters are presented in Table 3.1 and Table 3.2 for test series CH14 and CH17, respectively.
Fig. 3.2 Corrected (top) and uncorrected (bottom) force vs. displacement loops for characterization test series CH14.
Fig. 3.3 Corrected (top) and uncorrected (bottom) force vs. displacement loops for characterization test series CH17.
Table 3.1 Strain rate effect correction parameters for characterization test series CH14

<table>
<thead>
<tr>
<th>Correction Parameter</th>
<th>( \lambda = 10 ) (4 param.)</th>
<th>( \lambda = 10 ) (2 param.)</th>
<th>( \lambda = 10 ) (1 param.)</th>
<th>( \lambda = 100 ) (4 param.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_0 )</td>
<td>0.1768</td>
<td>0.1242</td>
<td>0.0725</td>
<td>0.2518</td>
</tr>
<tr>
<td>( F_1 )</td>
<td>-0.0036</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.0031</td>
</tr>
<tr>
<td>( D_0 )</td>
<td>-0.264</td>
<td>-0.1303</td>
<td>N/A</td>
<td>-0.2896</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>0.0027</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

Table 3.2 Strain rate effect correction parameters for characterization test series CH17

<table>
<thead>
<tr>
<th>Correction Parameter</th>
<th>( \lambda = 10 ) (4 param.)</th>
<th>( \lambda = 10 ) (2 param.)</th>
<th>( \lambda = 10 ) (1 param.)</th>
<th>( \lambda = 100 ) (4 param.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_0 )</td>
<td>0.2003</td>
<td>0.1368</td>
<td>0.0852</td>
<td>0.2757</td>
</tr>
<tr>
<td>( F_1 )</td>
<td>-0.0022</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.0019</td>
</tr>
<tr>
<td>( D_0 )</td>
<td>-0.3483</td>
<td>-0.1573</td>
<td>N/A</td>
<td>-0.3692</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>-0.0023</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.0013</td>
</tr>
</tbody>
</table>

For the calculation of the correction parameters, the first 3 cycles of the response (at 104% strain level) were ignored because it was observed that scragging was predominant and affected the response much more than the strain rate. The response was considered stabilized thereafter. Another important observation is that the correction factors must be always calculated for the specific strain rate sensitive device just before PsD testing and are dependent on previous loading history. They are not globally valid and their values depend on the displacement history selected for the characterization tests (i.e. on strain levels and rates included therein). This is the reason why the input displacement history should be carefully selected, so that it matches the predicted PsD response in terms of strain level and frequency content.
It is also noted that in both test series, for the cases where the time scaling factor is \( \lambda = 10 \), alternative but similar correction procedures were employed, using two-parameter correction (with \( F_0 \) and \( D_0 \)) and one-parameter correction (\( F_0 \) only). This was done because the online (synchronous with the PsD test) calculation of the additional force term \( F_{SR,add} \) using Eq. (3.1) with 4 parameters involves the evaluation of (two-point) numerical derivatives of the force and displacement which is very prone to numerical error and caused problems (high numerical “noise”) when used in PsD tests run at speed \( \lambda = 10 \). No such problem was observed when \( \lambda = 100 \). In terms of accuracy, the 2-parameter correction produced corrected loops practically identical to those computed with the 4-parameter correction, always in good agreement with the “real-time” loops. Nevertheless, if the test setup included devices such as viscous dampers where the force depends primarily on the displacement derivative, the 2-parameter and 1-parameter correction techniques would obviously not be applicable. Finally, the 4-parameter correction method of Section 3.2 cannot capture and compensate for effects such as heating of isolators in cases where the seismic response includes many “large” cycles.

A typical input command script for the ELSA-PSD algorithm (version PSDCYC03.DLL) used during cyclic characterization tests is presented in APPENDIX B.

### 3.4 Pseudodynamic tests

The earthquake input used for the pseudodynamic tests is an artificial accelerogram which was obtained by modifying a real record from the April 15, 1979 Montenegro earthquake, so that its spectrum matches the design spectrum of Eurocode 8 (CEN, 2004) for soil type C. The acceleration time history (with a maximum peak ground acceleration of 11.28 m/s\(^2\)) is presented in Fig. 3.4 while the pseudo-acceleration response spectrum is shown in Fig. 3.5. The accelerogram consists of 1500 points with a time discretization of 0.01 s, adding up to a total prototype time duration of 15 s.
The pseudodynamic tests were performed with a time scaling factor $\lambda = 10$ (i.e. 10 times slower than the prototype time) and a two-parameter ($F_0$, $D_0$) force correction was used, as explained in Section 3.3. The numerical substructure is the two degree-of-freedom simplified model presented in Section 2.2. The experimental substructure is the pair of elastomeric isolators and the applied (by the actuator) displacement corresponds to the relative displacement of the two DOF’s (i.e. the
displacement of the isolation system. The command script for a typical PsD test is presented in APPENDIX B.

Two pairs of isolators were used for the pseudodynamic testing. Prior to the PsD tests, each pair was subjected to characterization tests for the determination of the force correction parameters. It is noted that the PsD tests were run with scaled-down acceleration input with a factor of 25% maximum, as it was not expected that the specific type of elastomeric bearings would withstand higher intensities. The test series is summarized in Table 3.3.

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Description</th>
<th>Bearing Pair #</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH14</td>
<td>Characterization test, $\lambda = 1, 10 &amp; 100$</td>
<td>2</td>
</tr>
<tr>
<td>PD01</td>
<td>PsD test, $\lambda = 100$, intensity 7.5% of record (test-run)</td>
<td>2</td>
</tr>
<tr>
<td>PD04</td>
<td>PsD test, $\lambda = 10$, intensity 7.5% of record (test-run)</td>
<td>2</td>
</tr>
<tr>
<td>PD06</td>
<td>PsD test, $\lambda = 10$, intensity 25% of record &gt; bearing failure</td>
<td>2</td>
</tr>
<tr>
<td>CH17</td>
<td>Characterization test, $\lambda = 1, 10 &amp; 100$</td>
<td>3</td>
</tr>
<tr>
<td>PD08</td>
<td>PsD test, $\lambda = 10$, intensity 7.5% of record</td>
<td>3</td>
</tr>
<tr>
<td>PD09</td>
<td>PsD test, $\lambda = 10$, intensity 15% of record</td>
<td>3</td>
</tr>
<tr>
<td>PD10</td>
<td>PsD test, $\lambda = 10$, intensity 20% of record &gt; bearing failure</td>
<td>3</td>
</tr>
</tbody>
</table>

The main purpose of the testing program was to verify the ability to perform fast, large amplitude characterization tests, in order to determine force correction parameters for subsequent use in PsD testing. The speed selected for the pseudodynamic tests ($\lambda = 10$) is approximately one order of magnitude faster than that used in similar testing of rate-dependent systems (see Molina et al., 2002, Bousias et al., 2005).

Characteristic results of the higher intensity PsD tests PD06 and PD10 are presented from Fig. 3.6 to Fig. 3.11. More specifically, for test PD06 (rubber bearings pair #2), the response histories of the measured restoring force (load cell), the additional strain-rate correction force and the total computed corrected force are plotted in Fig. 3.6. The bearing measured force vs. strain loops (for a
single bearing – not the pair) are presented in Fig. 3.7. The top bearing of the pair ruptured at a shear strain level equal to 155% and the test was interrupted at 11 s of prototype time, approximately. It is obvious that the loops exhibit pinching behavior at strain levels more than 100%. The displacement response histories of the two degrees of freedom (pier and deck) are illustrated in Fig. 3.8.

![Graph showing force vs. time](image)

**Fig. 3.6** Test PD06: history of measured isolator restoring force (dashed line) and force correction (dotted line)
Fig. 3.7 Test PD06: Bearing force vs. strain loops

Fig. 3.8 Test PD06: Displacement response histories of the 2 DOF’s
In the case of PsD test PD10 (rubber bearings pair #3) the maximum achieved intensity was 20% of the artificial record. The response histories of the measured restoring force (load cell), the additional strain-rate correction force and the total computed corrected force are plotted in Fig. 3.9. The bearing measured force vs. strain loops (for a single bearing – not the pair) are presented in Fig. 3.10. The top bearing failed at a strain level equal to 145% at prototype time 12.2 s but it did not disintegrate (local un-bonding of rubber from shim plate), which permitted the completion of the test. Pair #3 was generally rather stiffer than pair #2. The displacement response histories of the two degrees of freedom (pier and deck) are illustrated in Fig. 3.11. A photograph depicting the deformed state of the bearings during test PD10 is presented in Fig 3.12. Note that the bottom bearing of the pair has already started failing, as can be seen from the small tear in the cover rubber layer on the right-hand side.

![Figure 3.9](image-url)  
**Fig. 3.9** Test PD10: Isolators’ measured restoring force history (red) and force correction (green)
Fig. 3.10 Test PD10: bearing reaction force vs. strain

Fig. 3.11 Test PD10: Displacement response histories of the two DOF’s
Comparative plots from initial PsD tests PD01 ($\lambda = 100$, “slow” test) and PD04 ($\lambda = 10$, “fast” test) are presented from Fig. 3.13 to Fig. 3.17. Both tests were run at 7.5% intensity of the artificial accelerogram and employed a 4-parameter online force correction scheme. A comparison of the measured (by the load cell) forces is presented in Fig. 3.13. As expected, the measured force is larger for the case of the faster test PD04. Conversely, the additional strain-rate compensation force is higher for the case of the slower test PD01 (Fig. 3.14). As a result, the total corrected forces are practically identical (Fig. 3.15). Comparisons of force vs. displacement loops (for the pair of bearings) and of the deck displacement response histories are presented in Fig 3.16 and Fig. 3.17, respectively. It is obvious that the force correction procedure produces equal results for PsD tests with time scaling factors differing by an order of magnitude, as is the case with tests PD01 and PD04. A small numerical oscillation is observed in the additional strain-rate compensation force plot for the faster test PD04; this oscillation is due to the numerical differentiation algorithm used for the force correction and can be completely avoided if a 2-parameter correction is used (Section 3.2).
Fig. 3.13 Comparison of measured (load cell) forces (PD01 – PD04)

Fig. 3.14 Comparison of additional strain-rate compensation forces (PD01 – PD04)
Fig. 3.15 Comparison of corrected forces (PD01 – PD04)

Fig. 3.16 Comparison of corrected force vs. displacement loops (PD01 – PD04)
Fig. 3.17 Comparison of deck (DOF 2) displacements (PD01 – PD04)
4 Conclusions

An experimental setup was constructed enabling the execution of high velocity and high strain characterization tests on elastomeric bearings. The characterization tests were used for determining force correction parameters in order to compensate for the strain-rate effect in slower than real-time pseudodynamic (PsD) tests. The force correction parameters were calculated on the basis of a least squares regression method, in which force vs. displacement loops obtained from “slow” tests are fitted to “real-time” loops. It was found that the force correction parameters differ for each pair of bearings and, in order to accurately represent the intended response, should be evaluated immediately prior to the respective PsD test and at comparable strain levels and frequencies with those to be developed during the actual PsD test.

The calculated parameters were used in a series of PsD tests that demonstrated the ability to use a time scaling factor equal to 10, which is at least an order of magnitude faster than similar previous tests. In terms of performance of the isolation system, it was concluded that the tested configuration which employed only low damping elastomeric bearings was inadequate for the seismic protection of the bridge structure, as failure occurred at relatively small shear strain (around 150%) for seismic input with peak ground acceleration ranging from 20% of $g$ to 25% $g$. 
REFERENCES


APPENDIX A – Servovalve Calibration

Calibration of the 3-stage MTS Type 256.40 Servovalve

The MTS 244.41S dynamic actuator is equipped with a 3-stage, 1500 lt/min capacity servovalve. This servovalve consists of a typical MTS 2-stage servovalve (Fig. A.1) with the addition of a larger third-stage spool with an in-built LVDT displacement transducer that provides feedback on the position of the aforementioned spool, thus implementing an inner control loop (Fig. A.2). In order for the 3-stage servovalve to be effectively controlled by the pre-existing controller of Structures Laboratory (Fig. A.3), the addition of a 3rd stage control module is necessary (Fig. A.4). This 3rd stage control module receives as input (i) the servovalve command (setpoint) from the controller and (ii) the LVDT (feedback) signal of the 3rd stage and produces a new command that is sent to the servovalve of the actuator. The 3rd stage control module consists of two sections: the first section is the oscillator-demodulator of the LVDT while the second section is a servoamplifier that calculates the error signal as an algebraic sum of the setpoint and the feedback signals, provides a new setpoint based on a proportional control law and carries out a voltage-to-current conversion of the new setpoint signal, in order to control the current-driven MTS servovalve.

The calibration of the 3rd stage control module consists of two main phases. The first phase is the calibration of the 3rd stage LVDT transducer. Pilot hydraulic pressure of about 150 psi is applied to the servovalve. Then the controller is set to “manual” mode and a command signal between +10 V and -10 V is sent to the servovalve by means of a potentiometer. The variable command signal forces the 3rd stage spool to move and this motion variates the output of the 3rd stage LVDT transducer. When the command is 0 V then the LVDT output should also be 0 V and this is
achieved by adjusting an offset trimmer. When the command signal is set to 10 V then the output of the LVDT should also increase to 10 V and this is achieved by adjusting a gain trimmer (this is repeated for a command of -10 V). The procedure (offset and gain trimming) is repeated until a linear behaviour is achieved for the response of the 3\textsuperscript{rd} stage LVDT to the manual command signal.

At the second phase, the offset and the gain of the servoamplifier section are adjusted. The actuator is connected to a main pressure of about 1000 psi and is set to “automatic” displacement control with feedback from the \textit{main} LVDT. With a target displacement equal to zero and the actuator remaining motionless, the servoamplifier offset trimmer (different than the one used in the first phase) is adjusted until the zero position target corresponds to 0 V servovalve command. Then the actuator is disconnected from main pressure and only pilot pressure is applied to the servovalve. Subsequently, the 3\textsuperscript{rd} stage control module is disconnected from the controller and set to receive a command signal from an external generator (square wave with amplitude of 0.5 V and 0.3 Hz frequency). The response of the 3\textsuperscript{rd} stage LVDT is then monitored by means of an oscilloscope and the servoamplifier gain is adjusted until the 3\textsuperscript{rd} stage LVDT output satisfactorily matches the generated command. Eventually the actuator is connected to main pressure and the 3\textsuperscript{rd} stage control module is connected to the controller; the system can now be set to automatic control.
Fig. A.1 Functional diagram of a 2-stage MTS servovalve (MTS Corporation)

Fig. A.2 Typical closed-loop control system with an inner loop
Fig A.3 The main controller computer used for PsD testing (MOOG Corporation)

Fig A.4 The 3rd stage control module (MOOG Corporation)
APPENDIX B – Command Scripts

Input command script for characterization test CH17

>>>Data of the test
>>>psdcyc03.DLL: JRC-ELSA general PsD and/or cyclic algorithm at one master
>>>User comment lines are started with a #
# Example of user comment line
>>>----------------------------------General Data----------------------------------

>TEST NAME: CH17
>TITLE DESCRIBING THE TEST:
Decreasing cycles 0.67Hz -max 80mm- Random History, cutoff=2Hz

>NUMBER OF SLAVE CONTROLLERS CONSIDERED AT THIS MASTER NCon>0:
  4
>EXTERNAL BOARD NUMBER OF EVERY SLAVE CONTROLLER CtrNum (1,NCon):
  1 2 3 4
>PISTON SECTION1 (TENSION CHAMBER) AT Con1 Con2 ... Section1 (1,NCon) kN/Bar:
  2.75 2.75 2.75 2.75
>PISTON SECTION2 (COMPRESSION CHAMBER) AT Con1 Con2 ... Section2 (1,NCon) kN/Bar:
  2.75 2.75 2.75 2.75
>NUMBER OF PATTERN INPUT FILES NPatt>=0:
  1
>NUMBER OF PSD DEGREES OF FREEDOM NDof>=0:
  0
>IF NDof>0, NUMBER OF GROUND ACCELERATION INPUT FILES NGAcc>=0:
>IF NDof>0, NUMBER OF STRAIN-RATE DEPENDENT DEVICES TO BE COMPENSATED AT THE RESTORING
  FORCES NSR>=0:
>PROTOTYPE TIME INCREMENT BETWEEN TWO RECORDS AT THE PATTERN AND GROUND ACELERATION
  INPUT FILES TimeRecIncr s:
  0.01
>NUMBER OF INTERNAL CONTROLLER 2ms SAMPLINGS BETWEEN TWO RECORDS InterRec:
  5
>>>Time scale lambda = InterRec*0.002/TimeRecIncr = RealTime/PrototypeTime

>PROTOTYPE TIME FOR NEXT TEST STOP TimeStop s:
  29.085
>>>
>-------------------------------Pattern Data-------------------------------

>>>Formula for computation of every pattern 1<= M <=NPatt:
>>>IntM(Rec)=IntM(Rec-1) + PattISpanM/100 * PattFileM(Rec-1) * TimeRecIncr
>>>PattM(Rec) = PattSpanM/100 * PattFileM(Rec) + IntM(Rec)
>IF NPatt>0, PROPORTIONAL SPAN PERCENTAGE MULTIPLIER PattSpan (1,NPatt) %:
  80
>IF NPatt>0, INTEGRAL SPAN PERCENTAGE MULTIPLIER PattlSpan (1,NPatt) %/s:
  0
>IF NPatt>0, FILE NAME FOR EVERY PATTERN (UP TO 4 CHARACTERS PER NAME) PattName (NPatt, 4):
  CH17
>IF NPatt>0, INFLUENCE MATRIX FROM PATTERNS TO TARGETS Patt2Targ (NCon,NPatt) (mm OR kN)/(mm OR
  kN):
    1
    0
    0
    0
>INFLUENCE MATRIX FROM HEIDENHAIN TO TARGETS Heid2Targ (NCon,NCon) (mm OR kN)/mm:
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
>INFLUENCE MATRIX FROM TEMPOSONICS TO TARGETS Temp2Targ (NCon,NCon) (mm OR kN)/mm:
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
>INFLUENCE MATRIX FROM LOAD CELLS TO TARGETS LCell2Targ (NCon,NCon) (mm OR kN)/kN:
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
>INFLUENCE MATRIX FROM FORCE2 CHANNEL TO TARGETS Force22Targ (NCon,NCon) (mm OR kN)/unit:
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
>INFLUENCE MATRIX FROM SPEED CHANNEL TO TARGETS Speed2Targ (NCon,NCon) (mm OR kN)/unit:
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
>INFLUENCE MATRIX FROM LVDT CHANNEL TO TARGETS Lvdt2Targ (NCon,NCon) (mm OR kN)/unit:
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0

>TO AVOID RESTORING-FORCE OFFSET COMPENSATION INTRODUCE NFSAMPL=0

>IF NDof>0, NUMBER OF SAMPLINGS TO AVERAGE FOR RESTORING FORCE OFFSET COMPUTATION NFSAMPL:

>IF NDof>0 AND NFSAMPL>0, PRESCRIBED RESTORING FORCE VALUE FOR OFFSET COMPUTATION ResInit(1,NDof) N:

>IF NGacc>0, PROPORTIONAL SPAN PERCENTAGE MULTIPLIER GAccSpan(1,NGacc) %:

>ACCELEROMETER TIME INCREMENT MUST BE EQUAL TO PROTOTYPE TIME INCREMENT

>IF NGacc>0, FILE NAME FOR EVERY GROUND ACCELEROMETER (UP TO 4 CHARACTERS PER NAME) GAccName(NGacc,4):

>IF NDof>0 AND NGacc>0, INFLUENCE MATRIX FROM GROUND MOTION TO DOF GAcc2Dof(NDof,NGacc) (m/s/s)/(m/s/s):

>IF NDof>0, INFLUENCE MATRIX FROM LOAD CELLS TO RESTORING FORCES LCell2Res(NDof,NCon) N/kN:

>IF NDof>0, INFLUENCE MATRIX FROM DOF DISPLACEMENTS TO TARGETS Dis2Targ(NCon,NDof) mm/m:

>IF NSR>0, INFLUENCE MATRIX FROM FORCE2 CHANNEL TO FSR Force22FSR(NSR,NCon) kN/unit:

>IF NSR>0, INFLUENCE MATRIX FROM SPEED CHANNEL TO FSR Speed2FSR(NSR,NCon) kN/unit:

>IF NSR>0, INFLUENCE MATRIX FROM LVDT CHANNEL TO FSR Lvdt2FSR(NSR,NCon) kN/unit:
IF NSR>0, INFLUENCE MATRIX FROM FORCE2 CHANNEL TO DSR Force22DSR(NSR,NCon) mm/unit:

IF NSR>0, INFLUENCE MATRIX FROM SPEED CHANNEL TO DSR Speed2DSR(NSR,NCon) mm/unit:

IF NSR>0, INFLUENCE MATRIX FROM LVDT CHANNEL TO DSR Lvdt2DSR(NSR,NCon) mm/unit:

Formula for strain-rate-compensation additional force at every device:
FSRAdd = SRFacF0*FSR + SRFacD0*DSR + SRFacF1*FSRdot + SRFacD1*DSRdot

IF NSR>0, FORCE CORRECTION FACTOR SRFacF0(1,NSR) kN/kN:

IF NSR>0, DISPLACEMENT CORRECTION FACTOR SRFacD0(1,NSR) kN/mm:

IF NSR>0, FORCE-DERIVATIVE CORRECTION FACTOR SRFacF1(1,NSR) kNs/kN:

IF NSR>0, DISPLACEMENT-DERIVATIVE CORRECTION FACTOR SRFacD1(1,NSR) kNs/mm:

IF NSR>0, INFLUENCE MATRIX FROM FSRAdd TO RESTORING FORCES FSR2Res(NDof,NSR) N/kN:

--- Algo Alarm Data ---------------------

ALGO_ALARM SUPERIOR LIMIT AT HEIDENHAIN HeidMax (1,NCon)
200 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT HEIDENHAIN HeidMin (1,NCon)
-200 -1e10 -1e10 -1e10

ALGO_ALARM SUPERIOR LIMIT AT TEMPOSONICS TempMax (1,NCon)
200.0 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT TEMPOSONICS TempMin (1,NCon)
-200.0 -1e10 -1e10 -1e10

ALGO_ALARM SUPERIOR LIMIT AT TEMPOSONICS ABS TempAbsMax (1,NCon)
1e10 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT TEMPOSONICS ABS TempAbsMin (1,NCon)
-1e10 -1e10 -1e10 -1e10

ALGO_ALARM SUPERIOR LIMIT AT LOAD CELL FORCE LCellMax (1,NCon)
450 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT LOAD CELL FORCE LCellMin (1,NCon)
-450 -1e10 -1e10 -1e10

ALGO_ALARM LIMIT AT ABSOLUTE ERROR ErrorMax (1,NCon)
5 1e10 1e10 1e10

ALGO_ALARM LIMIT AT ABSOLUTE ERROR AVERAGE ErrAvMax (1,NCon)
5 100 100 100

ALGO_ALARM LIMIT AT ABSOLUTE ENERGY ERROR AVERAGE EneErAvMax
1e10 1e10 1e10 1e10

ALGO_ALARM SUPERIOR LIMIT AT LVDT LvdtMax (1,NCon)
250 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT LVDT LvdtMin (1,NCon)
-250 -1e10 -1e10 -1e10

ALGO_ALARM SUPERIOR LIMIT AT PRESSION1 Press1Max (1,NCon)
1e10 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT PRESSION1 Press1Min (1,NCon)
-1e10 -1e10 -1e10 -1e10

ALGO_ALARM SUPERIOR LIMIT AT PRESSION2 Press2Max (1,NCon)
1e10 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT PRESSION2 Press2Min (1,NCon)
-1e10 -1e10 -1e10 -1e10

ALGO_ALARM SUPERIOR LIMIT AT SERVOVALVE ServoMax (1,NCon)
1e10 1e10 1e10 1e10

ALGO_ALARM INFERIOR LIMIT AT SERVOVALVE ServoMin (1,NCon)
-1e10 -1e10 -1e10 -1e10
Input command script for pseudodynamic test PD10

>>> Data of the test
>>> psdcyc03.DLL: JRC-ELSA general PsD and/or cyclic algorithm at one master
>>> User comment lines are started with a #
# Example of user comment line
>>>----------------------General Data-------------------------------
>>> TEST NAME: PD10
> TITLE DESCRIBING THE TEST:
Rubber Bearings, PsD, L=10, 20%g, 02/04/2012
> NUMBER OF SLAVE CONTROLLERS CONSIDERED AT THIS MASTER NCon>0:
1
> EXTERNAL BOARD NUMBER OF EVERY SLAVE CONTROLLER CtrNum (1,NCon):
1
> PISTON SECTION1 (TENSION CHAMBER) AT Con1 Con2 ... Section1 (1,NCon) kN/Bar:
2.75
> PISTON SECTION2 (COMPRESSION CHAMBER) AT Con1 Con2 ... Section2 (1,NCon) kN/Bar:
2.75
> NUMBER OF PATTERN INPUT FILES NPatt>=0:
0
> NUMBER OF PSD DEGREES OF FREEDOM NDof>=0:
2
> IF NDof>0, NUMBER OF GROUND ACCELERATION INPUT FILES NGAcc>=0:
1
> IF NDof>0, NUMBER OF STRAIN-RATE DEPENDENT DEVICES TO BE COMPENSATED AT THE RESTORING
FORCES NSR>=0:
1
> PROTOTYPE TIME INCREMENT BETWEEN TWO RECORDS AT THE PATTERN AND GROUND ACCELERATION
INPUT FILES TimeRecIncr s:
0.01
> NUMBER OF INTERNAL CONTROLLER 2ms SAMPLINGS BETWEEN TWO RECORDS InterRec:
50
>>> Time scale lambda = InterRec*0.002/TimeRecIncr = RealTime/PrototypeTime
> PROTOTYPE TIME FOR NEXT TEST STOP TimeStop s:
25.005
>>>-------------------------Pattern Data----------------------------
>>> Formula for computation of every pattern 1<= M <=NPatt:
>>> IntM(Rec)=IntM(Rec-1) + PattSpanM/100 * PattFileM(Rec-1) * TimeRecIncr
>>> PattM(Rec) = PattSpanM/100 * PattFileM(Rec) + IntM(Rec)
> IF NPatt>0, PROPORTIONAL SPAN PERCENTAGE MULTIPLIER PattSpan (1,NPatt) %:
> IF NPatt>0, INTEGRAL SPAN PERCENTAGE MULTIPLIER PattSpan (1,NPatt) %/s:
> IF NPatt>0, FILE NAME FOR EVERY PATTERN (UP TO 4 CHARACTERS PER NAME) PattName (NPatt, 4):
> IF NPatt>0, INFLUENCE MATRIX FROM PATTERNS TO TARGETS Patt2Targ (NCon,NPatt) (mm OR kN)/(mm OR
kN):
>>> Other Influence Matrices----------------------
>>> INFLUENCE MATRIX FROM HEIDENHAIN TO TARGETS Heid2Targ (NCon,NCon) (mm OR kN)/mm:
0.0
>>> INFLUENCE MATRIX FROM TEMPOSONICS TO TARGETS Temp2Targ (NCon,NCon) (mm OR kN)/mm:
0.0
>>> INFLUENCE MATRIX FROM LOAD CELLS TO TARGETS LCell2Targ (NCon,NCon) (mm OR kN)/kN:
0.0
>>> INFLUENCE MATRIX FROM FORCE2 CHANNEL TO TARGETS Force22Targ (NCon,NCon) (mm OR kN)/unit:
0.0
>INFLUENCE MATRIX FROM SPEED CHANNEL TO TARGETS Speed2Targ (NCon,NCon) (mm OR kN)/unit: 0.0
>INFLUENCE MATRIX FROM LVDT CHANNEL TO TARGETS Lvdt2Targ (NCon,NCon) (mm OR kN)/unit: 0.0

>>>
>>>----------------------PsD equation data---------------------------
>>>>
>IF NDof>0, THEORETICAL MASS MATRIX Mass(NDof,NDof) kg:
58200.0 0.0
0.0 183400.0
>IF NDof>0, THEORETICAL ADDITIONAL STIFFNESS MATRIX StiffAdd(NDof,NDof) N/m:
440000000.0 0.0
0.0 0.0
>IF NDof>0, THEORETICAL ADDITIONAL DAMPING MATRIX DampingAdd(NDof,NDof) Ns/m:
0.0 0.0
0.0 0.0
>IF NDof>0, INITIAL DISPLACEMENT DisInit(1,NDof) m:
0.0 0.0
>IF NDof>0, INITIAL VELOCITY VelInit(1,NDof) m/s:
0.0 0.0

>>>To avoid restoring-force offset compensation introduce NFSampl=0

>IF NDof>0, NUMBER OF SAMPLINGS TO AVERAGE FOR RESTORING FORCE OFFSET COMPUTATION NFSampl: 0
>IF NDof>0 AND NFSampl>0, PRESCRIBED RESTORING FORCE VALUE FOR OFFSET COMPUTATION ResInit(1,NDof) N:
>IF NGacc>0, PROPORTIONAL SPAN PERCENTAGE MULTIPLIER GAccSpan(1,NGacc) %: 20.0

>>>Accelerogram time increment must be equal to prototype time increment

>IF NGAcc>0, FILE NAME FOR EVERY GROUND ACCELEROGRAM (UP TO 4 CHARACTERS PER NAME) GAccName(NGAcc,4):
BOSN
>IF NDof>0 AND NGAcc>0, INFLUENCE MATRIX FROM GROUND MOTION TO DoF GAcc2Dof(NDof,NGAcc) (m/s/s)/(m/s/s):
1.0 1.0

>IF NDof>0, INFLUENCE MATRIX FROM LOAD CELLS TO RESTORING FORCES LCell2Res(NDof,NCon) N/kN:
-1000.0 1000.0
1000.0 -1000.0
>IF NDof>0, INFLUENCE MATRIX FROM DoF DISPLACEMENTS TO TARGETS Dis2Targ(NCon,NDof) mm/m:
-1000.0 1000.0
1000.0 -1000.0
>IF NSR>0, INFLUENCE MATRIX FROM FORCE2 CHANNEL TO FSR Force22FSR(NSR,NCon) kN/unit: 1.0
>IF NSR>0, INFLUENCE MATRIX FROM SPEED CHANNEL TO FSR Speed2FSR(NSR,NCon) kN/unit: 0.0
>IF NSR>0, INFLUENCE MATRIX FROM LVDT CHANNEL TO FSR Lvdt2FSR(NSR,NCon) kN/unit: 0.0
>IF NSR>0, INFLUENCE MATRIX FROM FORCE2 CHANNEL TO DSR Force22DSR(NSR,NCon) mm/unit: 0.0
>IF NSR>0, INFLUENCE MATRIX FROM SPEED CHANNEL TO DSR Speed2DSR(NSR,NCon) mm/unit: 1.0
>IF NSR>0, INFLUENCE MATRIX FROM LVDT CHANNEL TO DSR Lvdt2DSR(NSR,NCon) mm/unit: 0.0

>>>Formula for strain-rate-compensation additional force at every device:
>>>FSRAdd = SRFacF0*FSR + SRFacD0*DSR + SRFacF1*FSRdot + SRFacD1*DSRdot
>IF NSR>0, FORCE CORRECTION FACTOR SRFacF0(1,NSR) kN/kN: 0.1368
>IF NSR>0, DISPLACEMENT CORRECTION FACTOR SRFacD0(1,NSR) kN/mm: -0.1573
>IF NSR>0, FORCE-DERIVATIVE CORRECTION FACTOR SRFacF1(1,NSR) kNs/kN: 0.0
>IF NSR>0, DISPLACEMENT-DERIVATIVE CORRECTION FACTOR SRFacD1(1,NSR) kNs/mm: 0.0
ALGO_ALARM SUPERIOR LIMIT AT HEIDENHAIN HeidMax (1,NCon) 250
ALGO_ALARM INFERIOR LIMIT AT HEIDENHAIN HeidMin (1,NCon) -250
ALGO_ALARM SUPERIOR LIMIT AT TEMPOSONICS TempMax (1,NCon) 1e10
ALGO_ALARM INFERIOR LIMIT AT TEMPOSONICS TempMin (1,NCon) -1e10
ALGO_ALARM SUPERIOR LIMIT AT TEMPOSONICS ABS TempAbsMax (1,NCon) 1e10
ALGO_ALARM INFERIOR LIMIT AT TEMPOSONICS ABS TempAbsMin (1,NCon) -1e10
ALGO_ALARM SUPERIOR LIMIT AT LOAD CELL FORCE LCellMax (1,NCon) 500
ALGO_ALARM INFERIOR LIMIT AT LOAD CELL FORCE LCellMin (1,NCon) -500
ALGO_ALARM LIMIT AT ABSOLUTE ERROR ErrorMax (1,NCon) 5
ALGO_ALARM LIMIT AT ABSOLUTE ERROR AVERAGE ErrAvMax (1,NCon) 5
ALGO_ALARM LIMIT AT ABSOLUTE ENERGY ERROR AVERAGE EneErAvMax 1e10
ALGO_ALARM SUPERIOR LIMIT AT LVDT LvdMax (1,NCon) 250
ALGO_ALARM INFERIOR LIMIT AT LVDT LvdMin (1,NCon) -250
ALGO_ALARM SUPERIOR LIMIT AT PRESSION1 Press1Max (1,NCon) 1e10
ALGO_ALARM INFERIOR LIMIT AT PRESSION1 Press1Min (1,NCon) -1e10
ALGO_ALARM SUPERIOR LIMIT AT PRESSION2 Press2Max (1,NCon) 1e10
ALGO_ALARM INFERIOR LIMIT AT PRESSION2 Press2Min (1,NCon) -1e10
ALGO_ALARM SUPERIOR LIMIT AT SERVOVALVE ServoMax (1,NCon) 1e10
ALGO_ALARM INFERIOR LIMIT AT SERVOVALVE ServoMin (1,NCon) -1e10
APPENDIX C – Testing Setup Performance

Fig. C.1 Vertical force fluctuation time-histories (CH17)
Fig. C.2 Top slab displacement time-histories (CH17)

Fig. C.2 Top slab rotation time-histories (CH17)