The scaled-time test as an alternative to the pseudo-dynamic test

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ABSTRACT: The stepped and excessively slow execution of pseudo-dynamic tests has been found to be the source of some errors arising from strain-rate effect and stress relaxation. In order to control those errors, a new continuous test method which allows the selection of a more suitable time scale factor in the response is proposed in this work. By dimensional analysis, such scaled-time response is obtained theoretically by augmenting the inertial and damping properties of the structure, for which we propose the use of hydraulic pistons which are servo-controlled to produce active mass and damping, nevertheless using an equipment which is similar to that required in a pseudo-dynamic test. The results of the successful implementation of this technique for a simple specimen are shown here.

1 INTRODUCTION

Probably due to the incompleteness of the available mathematical models for the behavior of the elements, connections, loading, etc., experimentation plays currently an important role in the research on Earthquake-Resistant Design. While the real-time shaking-table test and the quasi-static test are rather well established techniques, the Pseudo-Dynamic (PsD) test --which should provide the realistic response of the former technique, but using the simple equipment of the latter— is still under development.

1.1 *Pseudo-dynamic test*

The PsD test (Takanashi 1975) is based on an effective approach for reproduction of dynamic motion. Within this method, for a discrete DoF structure, the rate-dependent forces (inertial and viscous) are generated analytically, while the rate-independent restoring forces are obtained by performing a quasi-static test for each step of deformation. The equation of motion is then integrated by means of a step-by-step algorithm without the need of any other assumptions regarding the restoring forces since they are directly measured at every step. Using this testing method, the required load or displacement capacities of the equipment are not lower than those needed for a real time test; however, the power requirements at the installation and the velocity capacity are drastically diminished because of the expanded time scale.

In spite of that, the magnification of the time scale may sometimes be the source of errors which appear in PsD tests (Shing & Mahin 1988). For some materials, this is mainly due to a rate-dependent character of the restoring forces which cannot correctly be described by viscous damping. In fact, for a MDoF specimen, the duration of a PsD test may be three or four orders of magnitude larger than the duration of the simulated earthquake, which is clearly unnecessary in terms of savings of pumping capacity, but is rather a consequence of the stepped nature of the method. On the one hand, the time increment for the integration algorithm has to be sufficiently small to fulfill the stability and accuracy conditions. On the other hand, the execution of a given time step takes one second or so because it comprises a hold period (actuator settling, data acquisition, solution of the equation of motion) and a ramp period (movement to the new displacement value) which are subject to technological limitations (Mahin & Shing 1985).

1.2 *Scaled-time test*

The Scaled-Time (ST) test method proposed herein is motivated by an elimination of the stepped nature of the PsD test method. This could result into two major improvements. Firstly, the velocity of the test would be selected as large as possible accounting only for the physical limitations of the equipment and not for those of any integration algorithm; as a consequence, strain-rate effects might be diminished. Secondly, the continuous character of the movement would produce a more linear behavior in the actuators which might result in lower cumulative errors. Additionally, the complexity in the programming of a PsD step with its mentioned stages would by suppressed.

The force-control (FC) active version of the ST test, its passive version and, more recently, its displacement-control (DC) active version are respectively described in Molina & Alarcon 1991, 1992 and 1994b. Due to the fact that said formulations do not require a stepping algorithm and consequently are simpler than the PsD test, it is not strange that other researchers may have considered or published about them before us. Namely, that is the case of Thewalt & Mahin (1987), who proposed the FC version and called it "rapid testing technique", and also of Kaneta and Nishizawa (1983, in Japanese, abstracted by Takanashi and Nakashima 1986), who arrived at the DC version and called it "on-line hybrid simulation system".

The focus of this paper will be on the formulation and experimental verification of the DC active version of the ST test method as it seems to be the only one which offers, in principle, the most practicable possibilities of implementation.

2 BASIC FORMULATION OF THE ST TEST

Considering a discrete prototype system with mass m, viscous damping c and rate-independent restoring forces r, we will write its equation of motion as

ma(r) + cv(/) + r(d(0) = q(0, (2.1)

where / is the time, d, v and a are the relative displacements, velocities and accelerations respectively and q are the total equivalent loads including the effect of the shaking at the base (Clough 1993).

Now, a model will be built for which the response will be *X* times slowed down, i.e.,

$$\mathbf{d}_m(t) = \mathbf{d}(\frac{t}{\lambda}), \qquad (2.2a)$$

$$\mathbf{v}_m(t) = \frac{d}{dt}\mathbf{d}_m(t) = \frac{1}{\lambda}\mathbf{v}(\frac{t}{\lambda}) \qquad (2.2b)$$

and

$$\mathbf{a}_m(t) = \frac{d}{dt}\mathbf{v}_m(t) = \frac{1}{\lambda^2}\mathbf{a}(\frac{t}{\lambda}), \qquad (2.2c)$$

where the subscript *m* is used to denote magnitudes associated with that model.

To obtain such a ST response (2.2), the properties and excitation of the model will differ from those of the prototype, except for the restoring forces, so that the original structural elements can be used for the test specimen. The equation of motion for the model will be written as

$$\mathbf{m}_m\mathbf{a}_m(t) + \mathbf{c}_m\mathbf{v}_m(t) + \mathbf{r}_m(\mathbf{d}_m(t)) = \mathbf{p}(t), \qquad (2.3)$$

where

$$\mathbf{r}_m(\ ) = \mathbf{r}(\ ). \qquad (2.4a)$$

where

The simplest way to make functions (2.2) satisfy equilibrium (2.3) is by adopting for the model a scaled damping

$$\mathbf{c}_m = \lambda\mathbf{c} \qquad (2.4b)$$

and a second-order scaled mass

$$\mathbf{m}_m = \lambda^2\mathbf{m} \qquad (2.4c)$$

and applying the load at a scaled rate, i.e.,

$$\mathbf{p}(t) = \mathbf{q}(\frac{t}{\lambda}) \qquad (2.4d)$$

Now, introducing expressions (2.2) and (2.4), it is clear that eq. (2.1) implies also eq. (2.3).

The same conclusion can be arrived at by using similarity methods (Molina & Alarcon 1992), that is to say, in a ST test, we have:

- a real-scale model,
- a *X* -times enlarged duration,
- real-scale displacements and forces,
- *X* -times reduced velocities as well as *X* -times increased viscous damping and
- *X* Mimes reduced accelerations as well as *X* Mimes increased inert mass.

Particularly, the power requirements are A, -times diminished with respect to a real-time test. If the specimen is linear, natural frequencies are *X* -times reduced, while viscous damping ratios are not altered.

In the same way as in the PsD test, the structural hysteretic damping forces, which are dependent solely on the deformation and not on its rate, are correctly maintained in the model.

The implementation of the ST test by means of real added physical mass and damping (passive version of the method) presents important problems for which we have proposed some solutions (Molina & Alarcon 1992). However, as far as we understand it now, the most practical way of application of the method is by means of its DC active version which is covered in subsection 3.2.

3 IMPLEMENTATION BY ACTIVE CONTROL

The implementation of the ST test by means of active control consists in using force and movement transducers as well as actuators which are closed-loop controlled in order to simulate the additional mass and damping required in the model (Fig. 1). For this purpose, we have studied FC and DC strategies.

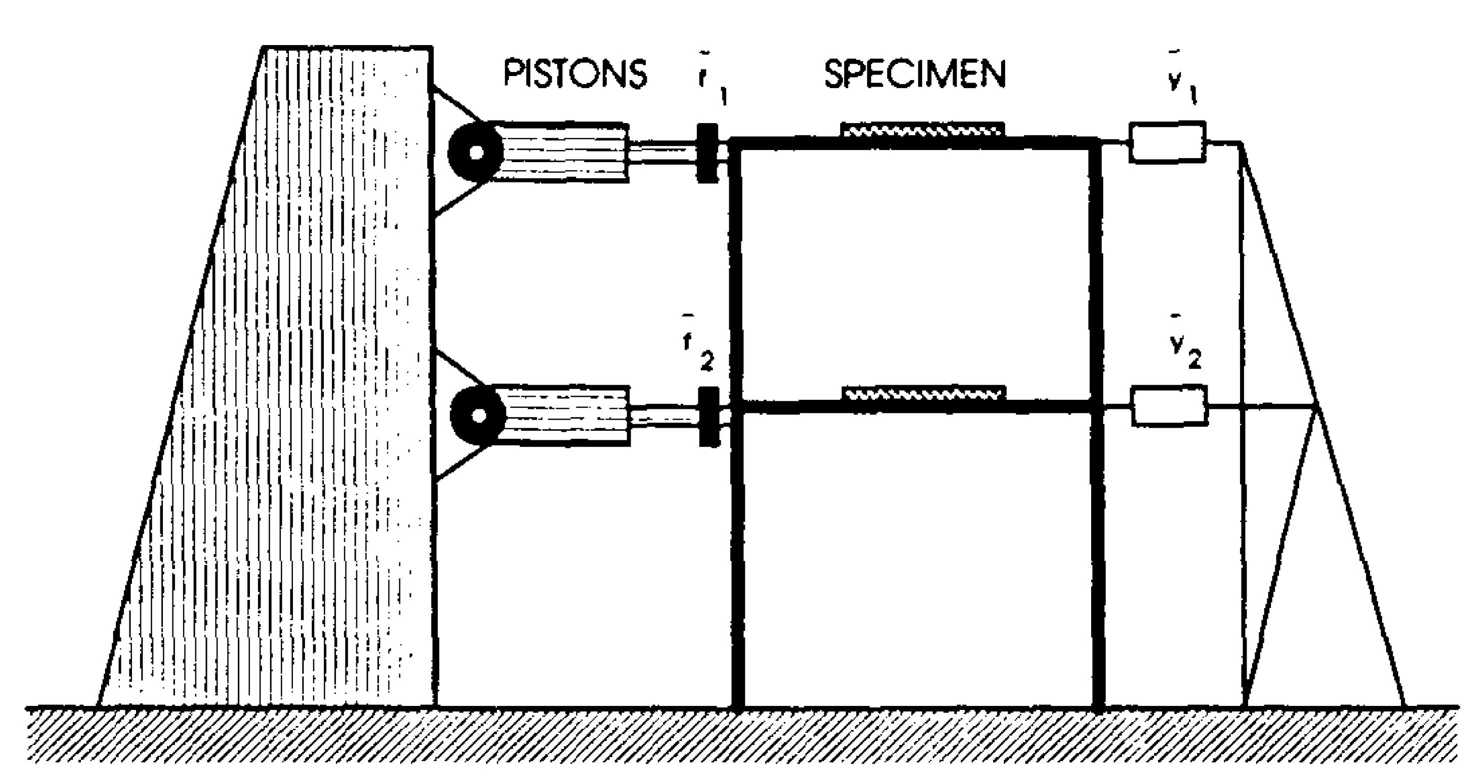

Figure 1. Active version of the ST test.

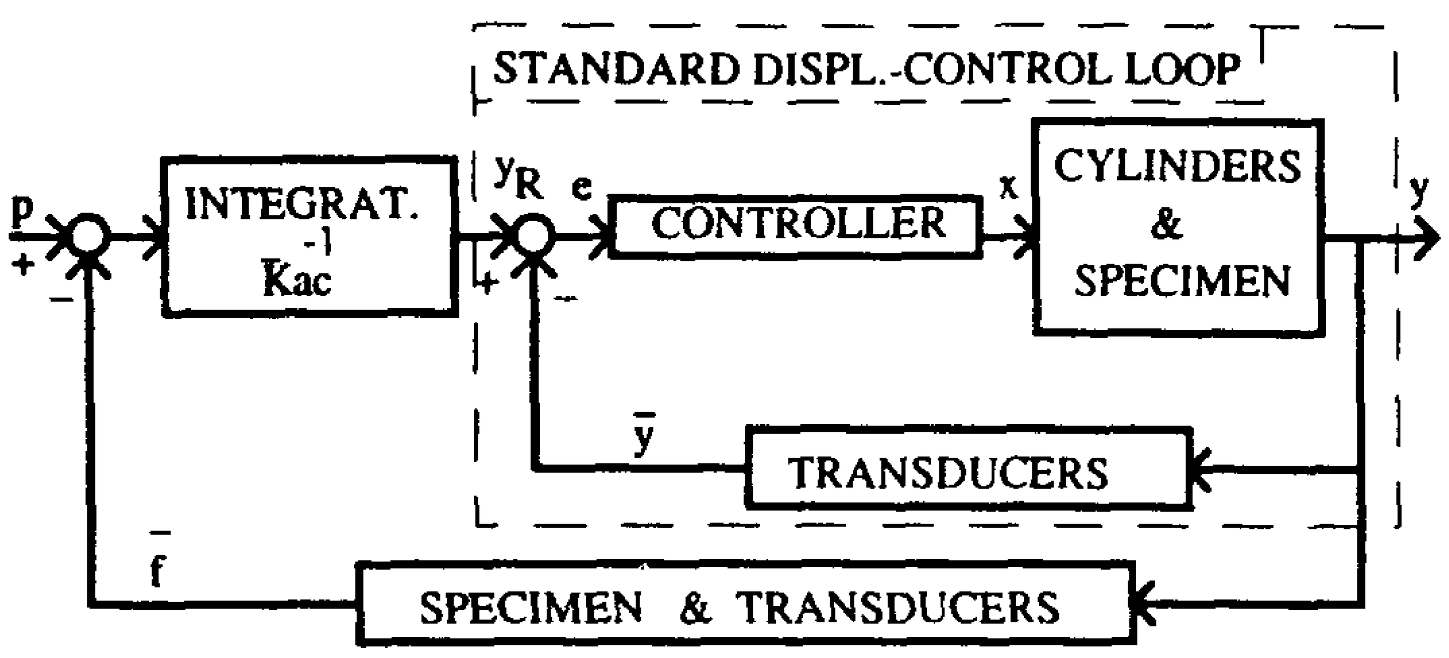

Figure 3. Displacement-control strategy of the ST test.

combined with small values of the time scale factor — which are not of practical interest in principle since they imply high power equipment.

33 PsD test as a particular case of ST test

It is interesting to observe that for a classical explicit PsD test we may define an equivalent particular case of DC ST test under the following conditions:

- the time scale *X* is defined as the ratio between the physical time spent in performing one step of the PsD test —which is assumed constant— and the corresponding time step in the original phenomenon and
- the integrator device KJ is digital and its sampling period equals that physical time step,

so that, due to the large value of *X*, eq. (3.15) may be approximated for convenience by

$$\mathbf{m}\frac{d^2}{d(t/\lambda)^2}\mathbf{y}_R + \mathbf{c}\frac{d}{d(t/\lambda)}\mathbf{y}_R + \bar{\mathbf{f}} \approx \mathbf{p} \qquad (3.16)$$

where, due to the low velocities and accelerations, the two first terms of the internal forces (3.2) can be neglected which makes f result in a direct measure of the rate-independent restoring forces r. Since eq. (3.16) coincides then with the step-by-step integrated one in the PsD test (tM, being the real time instant in the earthquake), the only additional condition for a total equivalence is the coincidence of the integration algorithms which are used in both techniques. However, even in the case of using the same time scale for both tests, the DC ST test has the advantage of allowing the use of a much shorter sampling period in the integrator device (0.001 sec. or so instead of the 1 sec. or so of a PsD step) which would result in a better accuracy for the numerical integration and practically a continuous response.

4 PRACTICAL EXAMPLE

4,1 Experimental set-up

The tests presented herein were conducted on a hydraulic testing machine commanded in the displacement-controlled mode. The closed loop control was performed using a standard PID controller and on-board LVDT displacement transducer as equipped by the manufacturer. The load was measured with a load cell having a range of 1 ton. The specimen and most of the experimental equipment has already been described in detail in a previous publication (Magonette 1991). It consists of two steel sheets of 2 mm thickness, clamped between steel chucks at both ends and anchored to the testing machine. The load cell (itself attached to the loading piston) is bolted through a third set of clamping chucks; in essence it is a cyclic three-point bending test.

In accordance with Fig. 3, the load is read form the cell and introduced as the input signal into the integrator. The numerical integration is performed by a PC equipped with a data acquisition card running at 30 kHz. The integration process forms part of a routine of a data acquisition program developed in-house. The software also supports peripheral, on-line, parameter visualization, thus the effective data update was running at 500 Hz; the smallest time increment that could be chosen was, therefore, 2 ms. The time integration technique chosen was the explicit, forward Euler method applied in two stages. Certainly, more sophisticated methods can be chosen, but, for the purposes of this investigation, this technique was considered adequate. The equation solved in this manner is (3.15). The result of the integration is the command signal to the piston controller. The parameters are, the mass, m, the damping coefficient c, and *the* time-expansion parameter A, As mentioned earlier, this specimen type had been used in previous investigations. It had been designed to carry add-on masses of up 18 Kg in such a manner that when the mass of the structural parts was also included, the total mass was deemed to be 27.2 Kg. For the tests presented herein, the ad-on masses were not present and, given that most of the structural specimen mass is held by the testing machine, it was decided to disregard the physical mass of the specimen in (3.15), so that the inertial term is weighted by X^2 only, and not $(A^2 - 1)$. This is a valid approximation if *X* is relatively large; for example, if all the theoretical mass were actually present inertially and *X* = 10, the error would only be 1%. In addition, it was known that the stiffness was 123 kN/m and that the equivalent viscous damping for free oscillations about small displacements was of the order of 0.3 %. The test program (Table 1) was as follows: the excitation consisted of either white noise or a simple spring-back test. All the motions occurred in the linear range, but although some form of hysteretic damping was present, viscous damping (expressed as a percentage of critical) was also included.

Table 1. Performed tests (damping %).

λ	white noise	spring-back
10	5%	5%
100	5%	5% and 0%

Figs. 4 and 5 represent the response of the system to white noise excitation provided by an FFT analyzer. The transfer function is that of the input noise level to that in the load cell. It can be seen that for the initial frequency values, the gain is close to one. In both case the behavior is that of a SDoF system. Having that the original natural frequency of the specimen was 10.7 Hz, in the case of X = 10 the peak gain is found at a scaled value of 1.067 Hz, while for the case of X = 100 the peak value is at 0.107 Hz. Clearly both results are consistent with the predicted behavior.

Figs. 6 to 8 show the displacement response for the snap-back tests. Figs. 6 and 7 clearly demonstrate the effect of including the viscous damping term. It seems that the damping in Fig. 7 (X = 100) is marginally greater than in Fig. 6 (X = 10). This effect is thought to be due to the fact that in the latter case, the data sampling, integration processes and piston control deficiencies, may cause a phase lag in the imposed displacement versus the corresponding load in the specimen. This may generate small negative equivalent damping effects which tend to disappear when the time scale is increased. This is also observed in Fig. 8 where the case for X = 100 has been repeated but with no viscous damping terms. As can be seen, the response is stable, moreover, there is some damping (of the order of 0.5%) which is thought to be caused by the small levels of hysteresis which are always present in the specimen and loading joints. This value of damping matches very well that observed for the real dynamic snap-back test conducted with the full mass (Magonette 1991). The mechanism and analysis of the nature of the negative damping terms alluded to above and how they can be compensated is currently the subject of investigations. For the present, and in the case of SDoF systems, it is important to say that, if the time expansion is large (X > 100) this effects can be disregarded.

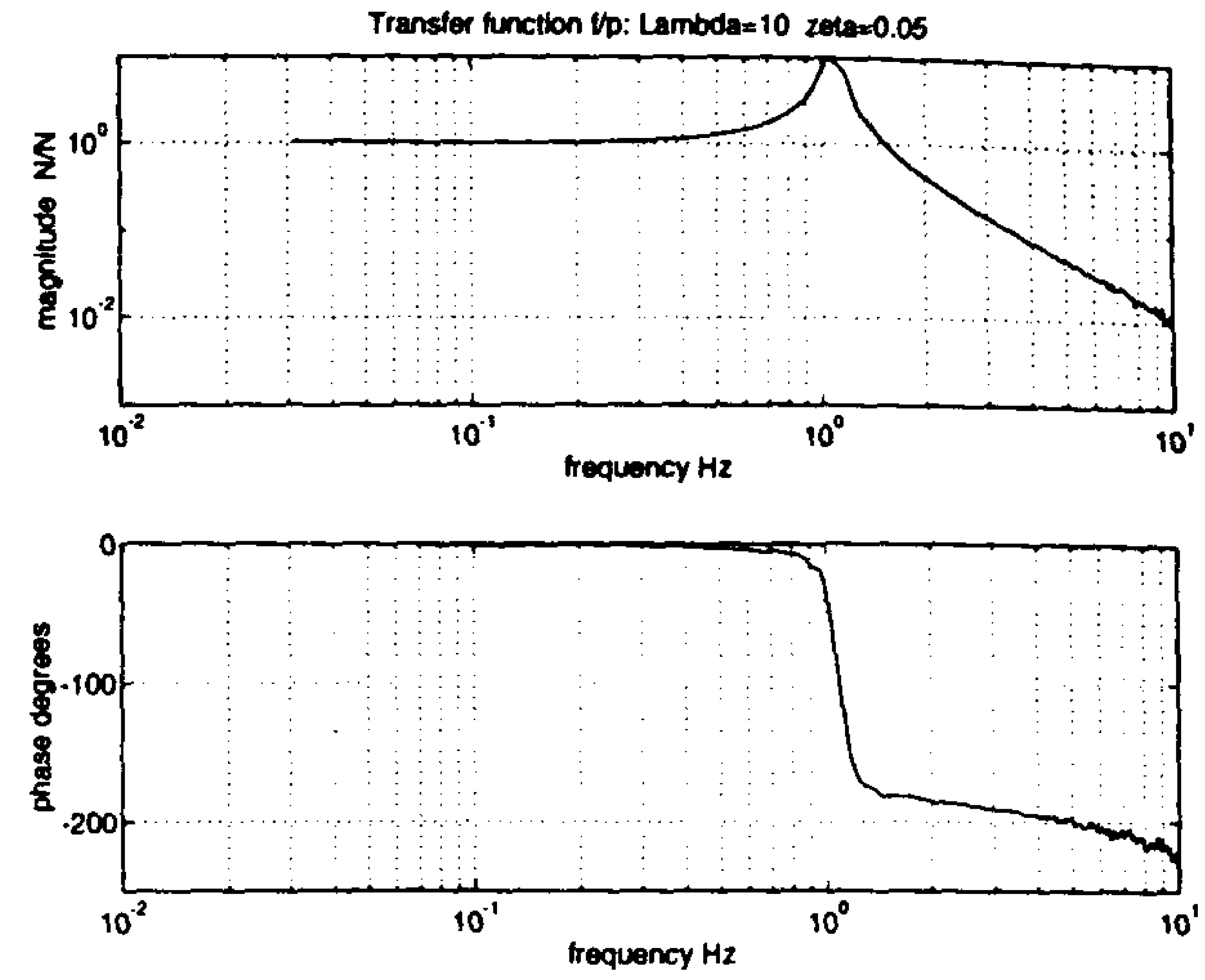

Figure 4. Experimental transfer function (λ =10).

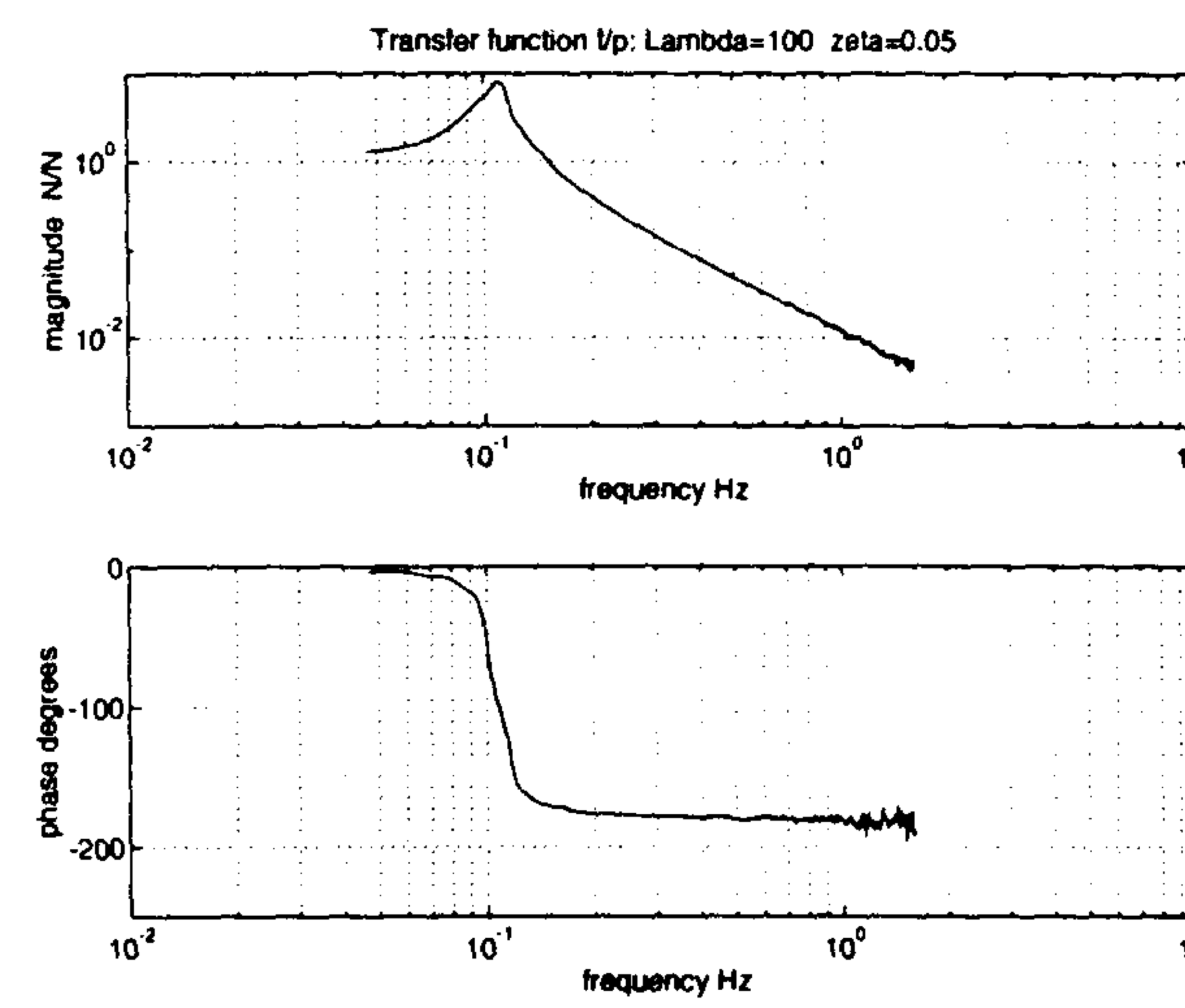

Figure 5. Experimental transfer function (λ =100).

5 CONCLUSIONS

The possibility of performing continuous slowed-down tests with a high flexibility in the selection of the time scale has been shown by means a displacement-controlled system provided a simple time-integration device. For the experimentally verified case of a SDoF system, this DC ST test method outperforms the PsD test method and is simpler to implement because the former does not involve the stoppages and complex piston command subprocesses of the latter, which are also the origin of stress relaxation effects. Presumably, in the case of strain-rate-sensitive materials, the ST test may even result in improved accuracy by using a loading rate faster than the highest admissible one for the PsD test.

The fact that, as we have shown, the standard PsD test can be understood as a particular case of the DC ST test for the corresponding time scale implies, in principle, two interesting consequences:

- Firstly, any successful performance of the PsD test might be reproduced by the equivalent DC ST test.
- Secondly, in those cases in which the DC ST test may present instability limitations due to a combination of relatively small time scale and damping, no better behavior should be expected for the PsD test.

Our preliminary theoretical studies about the feasibility of the DC ST test for MDoF specimens, which are not included here, have predicted no important difficulties for the performance of the method. Currently, a 3-DoF experiment is planned for the near future.

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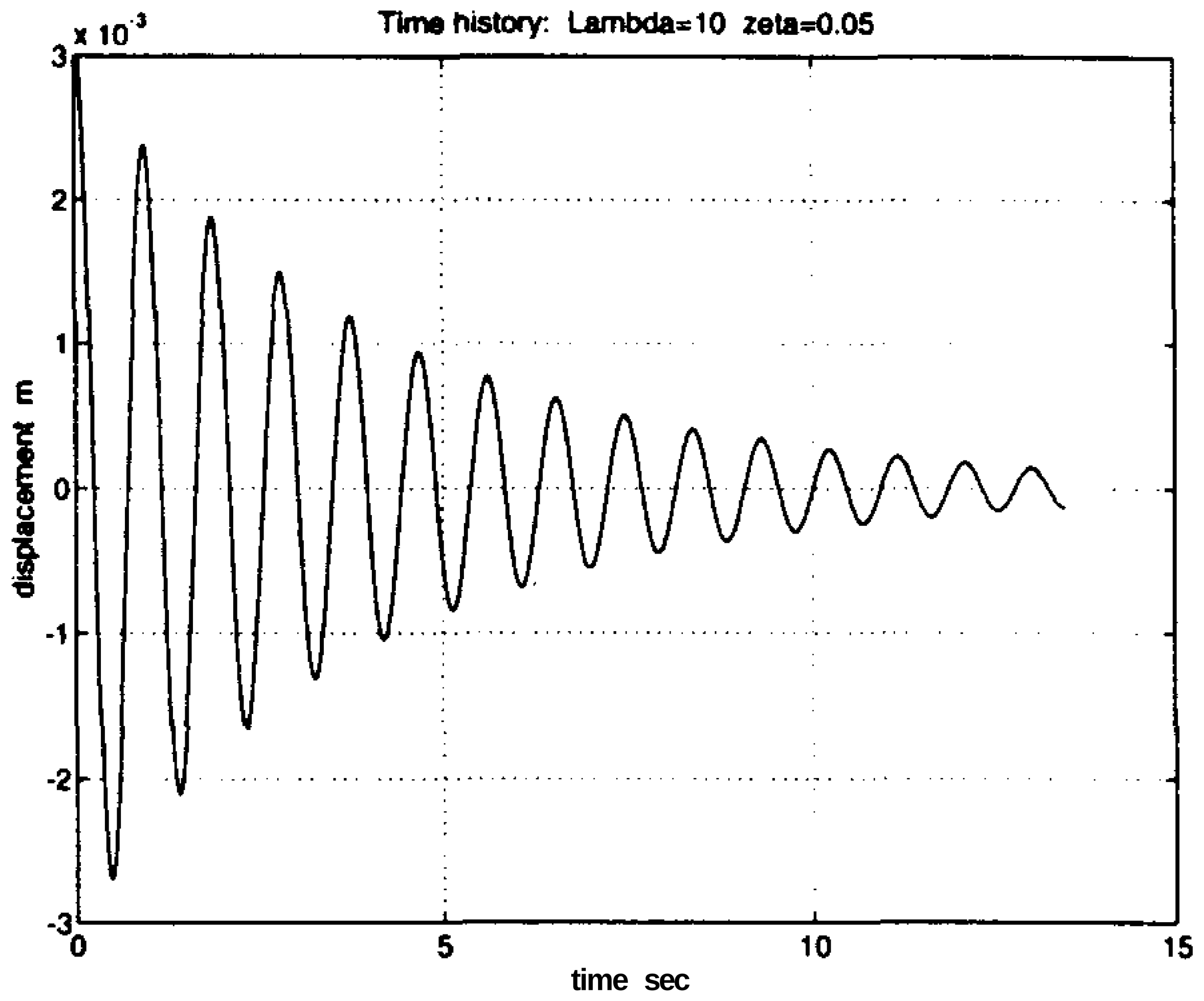

Figure 6. Experimental time history (λ =10, ζ =0.05)

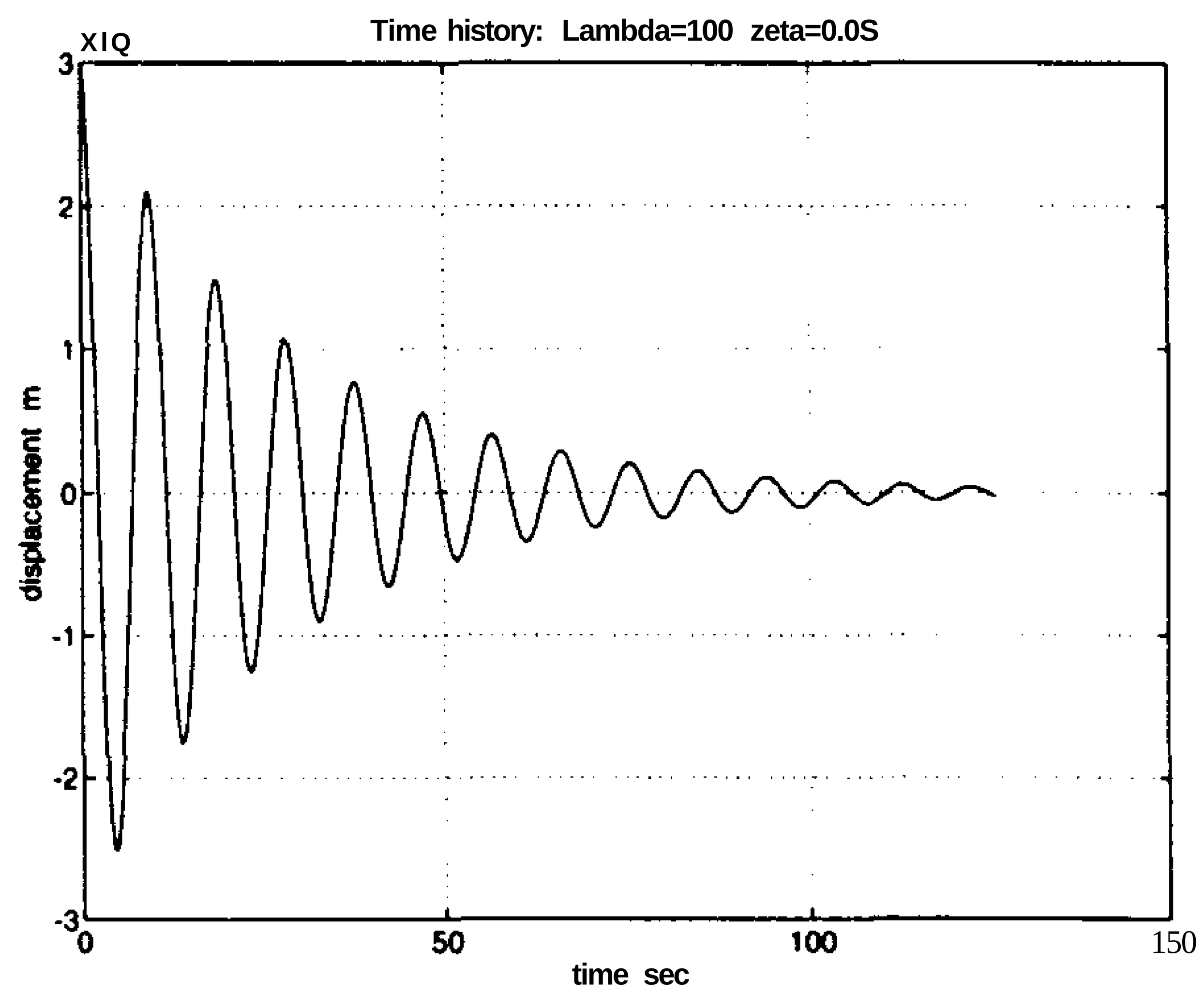

Figure 7. Experimental time history (λ =100, ζ =0.05)

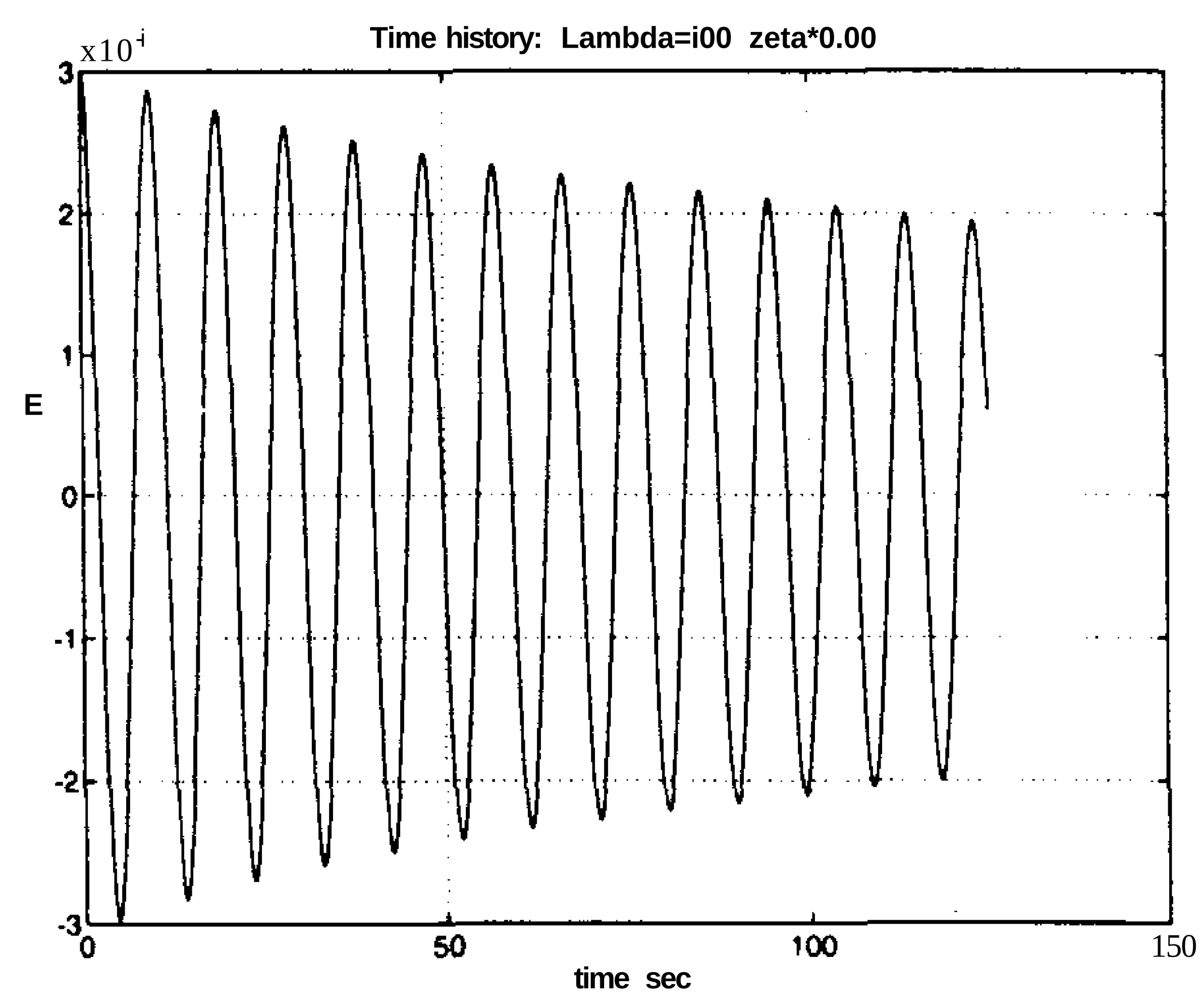

Figure 8. Experimental time history (λ =100, ζ =0.00)

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