ADVANCED TESTING TECHNIQUES AT THE ELSA-JRC REACTION WALL

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Abstract

This paper presents the state-of-the-art of the hybrid simulation method with substructuring developed at the European Laboratory for Structural Assessment (ELSA) at JRC-Ispra. The Continuous Pseudo Dynamic (PsD) test method is implemented by means of a synchronous process with short control period (2 ms) and small time step. This introduces some challenging difficulties for the implementation of substructuring. These difficulties have been overcome by using the stable parallel inter-field procedure presented hereafter allowing to robustly performing continuous PsD testing with non-linear substructuring. Details are also given on the software and hardware implementation with emphasis on the specific distributed control architecture designed at ELSA.

INTRODUCTION

Since its inauguration in 1992, the ELSA Laboratory has a leading position in pseudo-dynamic (PsD) testing of Large-scale civil engineering structures. The full-digital implementation of the PsD method was a key feature, which contributed to the successful completion of several tests on buildings and bridges and models of monumental structures. The test campaigns on bridges using substructuring techniques are considered as pioneer at international level. In spite of this confirmed success, ELSA is continuously improving its tools. In particular, there is a substantial effort on the development and implementation of the so-called continuous PsD testing method with substructuring which is outlined in this paper. In fact, this new technique is now systematically and successfully applied to the testing of a variety of structures ranging from full-scale multi-storey structures to structural subassemblies. By sustaining a smooth motion and a continuous loading of the structure, it avoids restoring force relaxation and provides very accurate experimental results. In many cases it extends the applicability of the conventional PsD. When coupled with the new analytical substructuring procedure also presented here, the continuous technique can be applied to test structural subassemblies and can be easily upgraded to carry out fast on-line substructuring tests of structures sensitive to the rate of loading.

The continuous PsD relies on significant improvements in both the hardware design of the servo-control system and the software to pilot the motion of the actuators. In addition to the development of new controller unit, a new system architecture is currently developed in order to integrate the controllers and to distribute all the activities related to data visualization, storage and elaboration on different hardware of the network.

AN ADVANCED IMPLEMENTATION OF PsD METHOD: THE CONTINUOUS PsD TESTING

The conventional PsD test procedure requires a considerable time to complete a test run, because the actuator motion is stopped (pause period) when the test specimen reaches the target displacement so that the reaction force can be measured and the next target displacement computed. These pause periods, of the order of some seconds, prevent the smooth movement of the structure and introduce spurious load relaxation. Instead of stopping the actuator, in continuous PsD testing, the servo-controller moves the actuator in such a way that the specimen follows very accurately the target displacement, due to the lack of discontinuity in the motion. The forces are measured at every sampling period of the digital servo-controller and the equations of motion are integrated on the fly (without hold period) at the sampling rate. The next target displacement is determined and the motion proceeds without any interruption.

This novel implementation has been achieved by providing substantial modifications in the hardware architecture of the testing system. The challenge is to synchronise and complete inside the control sampling time (typically 1 or 2 ms), the main tasks of a PsD cycle: measurement, motion computation and displacement control. An advanced hardware configuration has been set up to ensure a strong coupling and a very high-speed data communication between the servo-controllers and the main computer solving the equations of the motion. Furthermore, the control algorithm has been enhanced to guarantee a very small control error {Magonette *et al.* 1998}.

Although both methods, conventional and continuous, use the same integration scheme (typically the explicit Newmark integration scheme), a significant departure is that in the continuous PsD technique, for each discrete value g_i of the ground acceleration (**g**) read from the acceleration file (recorded with a sampling time ΔT), a sequence of n_{ss} acceleration values $g_{i+k/n_{ss}}$ ($0 < k < n_{ss}$) is computed by interpolation between g_i and g_{i+1}. After completion of computation of these n_{ss} intermediate acceleration values, the PsD procedure is executed n_{ss} times at the sampling rate Δt_{st} of the controller (typically 1 or 2 ms) performing n_{ss} sub-steps inside one conventional PsD step as indicated in Figure 1. Thus the time scale expansion factor λ of the PsD test is given by: $\lambda = n_{ss}\Delta t_{st} / \Delta T$. For a continuous PsD test performed on large scale multi-floor structures, one may have $n_{ss} = 500$, $\Delta t_{st} = 2\text{ms}$, $\Delta T = 5\text{ms}$ giving $\lambda = 200$ which means that 1 second of the real earthquake takes 200 seconds in the test.

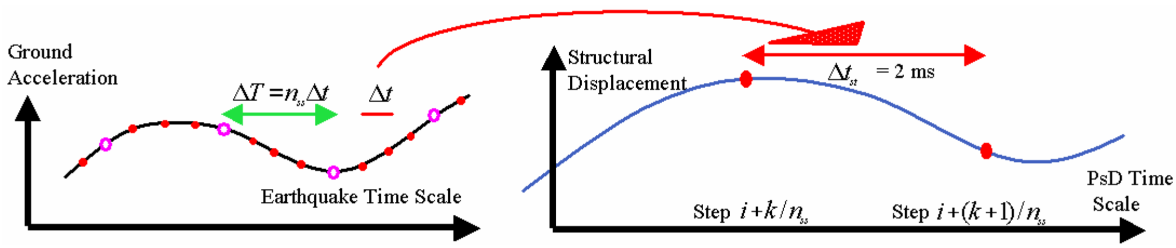

Figure 1. The continuous PsD method.

For a specified test, Δt_{st} and ΔT are constant, so the time scale expansion can be increased or decreased interactively simply by changing n_{ss} during the experiment. As a rule, λ is decreased until the control error exceeds prescribed tolerance limits depending on the nature and complexity of the test. In any case, by similitude with the conventional PsD theory, these errors must always remain very small and it is worth noting that the smooth motion of the continuous PsD certainly contributes in this sense. Practically the value of λ can range from value near 1 for simple substructuring tests with negligible inertial effect in the experimental set-up, to value as large as 100 or 200 for tests on full-scale multi-storey buildings. Moreover, in continuous PsD the restoring force measurements are updated at the sampling rate of the controller (typically 500 or 1000 Hz). This procedure not only generates a smooth displacement of the structure and a continuous load application avoiding relaxation, but also performs an excellent noise filtering of the analogue signals with respect to a conventional PsD test in which much less measurements enter in the integration algorithm.

SUBSTRUCTURING FOR CONTINUOUS PSD TESTING

When the behaviour of a part of the structure can be represented analytically, it is possible to extend the field of PsD application by using the substructuring technique. Taking profit of the hybrid character of the PsD method, this technique combines the numerical simulation of the known part of the structure with the effective laboratory testing of the remaining part of the structure. The possibilities offered by the substructuring technique have already been highlighted (Nakashima *et al.* 1990), and pilot tests have been performed (Dermitzakis & Mahin 1985, Vannan 1991). Furthermore, conventional PsD testing with substructuring has been successfully applied at ELSA to test four large-scale models of bridges. The physical part of the test was limited to the piers, while the deck, which was supposed to remain elastic, was treated as a numerical substructure. An integration scheme derived from the Operator Splitting algorithm has been implemented using two processes running in parallel (Buchet & Pegon 1994, Pegon 1996). More details on the tests results are given in Pinto 1996 and Pegon & Pinto 2000. It should be underlined that in such a configuration, the introduction of non-linearity is not a difficulty in itself because in the conventional method, the experimental and analytical processes are asynchronous and the pause period is long. As a consequence, the process responsible for the non-linear problem is usually able to reach convergence before the end of the pause, and if it is not the case, the experimental process may even wait for it.

The mixed implicit-implicit integration scheme adopted for conventional substructure PsD tests can still be implemented in the continuous PsD method, but unfortunately, the resulting parallel implementation uses the same integration time step for the computation of the experimental part as well as for the computation of the analytical part of the model. If the analytical structure is complex, the analytical process is unable to perform even an elastic computation during a control period of the experimental process. Different time steps are likely to be used by the two processes.

In fact it is not desirable to compute the analytical part with the very short time step used in the integration of the experimental part by the continuous method. The alternative to this fully coupled approach is to partition the model into analytical and experimental element groups and to use two different codes to solve the system of discrete equations for the analytical and the experimental part, respectively. The two codes are tied together by an interface on which continuity of force and displacement should be ensured. The analytical and experimental parts may have different time steps. In such a situation it is interesting to subcycle the experimental computation: while the analytical part is advanced in one time step ΔT, the structure is updated with n_{ss} subcycle steps.

The principal drawback of this approach, denoted as ***simple inter-field***, is that the force coming from the analytical structure is not well synchronized with the external loading of the experimental part, which is updated at the end of each subcycle. This delay is known to introduce damping, as it has been put in evidence with numerical simulations. This scheme has been improved with the introduction of a more uniform data flow shown in figure 2, called ***improved inter-field***. Basically the analytical structure is integrated with a time step 2ΔT, which is the double of the usual one. This allows knowing the location of the analytical structure one time step ΔT in advance with respect to the experimental structure. Then, an approximation of the additional force f_{i+1} generated by the analytical structure and acting on the experimental part at time t_{i+1} is known before starting the subcycling between t_i and t_{i+1}. It is thus possible to drive the experimental structure with more updated information than with the basic scheme. The best approximation of the force $f_{i+k/n_{ss}}$ that is used in the experimental process at each subcycle level is given by the interpolation $f_{i+k/n_{ss}} = f_i + (k/n_{ss})(f_{i+1} - f_i)$.

If *two* analytical processes (instead of one) can run in parallel for representing the analytical structure, a further improvement can be proposed. While the first analytical process computes the state at time t_{i+2}, the second analytical process performs the correction of what have been obtained at the previous time step by the first process. Then a better approximation of the additional reaction force will be available for the experimental structure for the next step. This further improvement is represented by means of dashed arrows in figure 2. The coupling of the different schemes and the stability issue are addressed in Pegon & Magonette 1999.

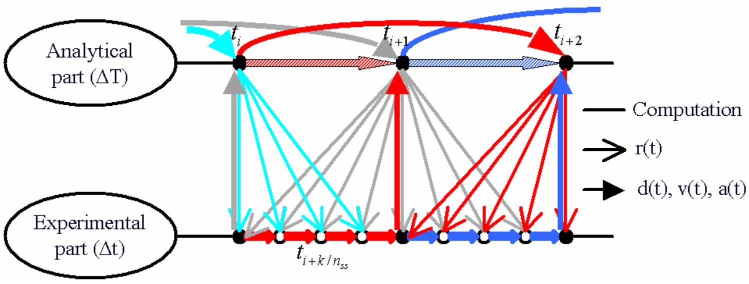

Figure 2. The synchronous multisubstep substructuring with improved inter-field communication.

THE CONTROL SYSTEM

Hardware

When tests involving multiple actuators are performed, an accurate synchronisation between individual actuators needs to be accomplished. This requires additional refinement in the architecture of the control system (Dorka & Heiland 1991). Because of the very high speed needed for computing and communicating, the computational capacity of the ELSA controllers has been increased and a novel high speed communication system has been designed, assuring the "strong coupling" of all the controllers with the main computer which solves the equations of motion of the experimental part as well as of the analytical part (in the case of substructure PsD test). In fact, the new computer hardware has been designed at ELSA. As indicated in Figure 3 the controller is made of 3 parts (Signal processing, Data acquisition and Data exchange). On one side it can control in real time the motion of the associated actuator with a time sampling of 1 or 2ms and on the other side it is connected via the PC bus to the Windows NT environment.

Software

The MCS control algorithm

In PsD tests, accurate displacement control has been found to be of prime importance to ensure reliable response; otherwise, displacement error propagation and eventual severe distortion in response will prevail in the test. Moreover, in a test performed on a structure whose restoring force is highly velocity-dependent, accurate velocity control is also a necessity to measure the velocity-dependent restoring force correctly. Unfortunately, the parameters of the tested object are poorly known and the controllers operate in environments where unpredictable large system parameter variations and unexpected disturbances are possible. In such situations, for position-tracking control, the usual fixed-gain PID control is inadequate to achieve the requested performances in the entire range over which the characteristics of the system may vary.

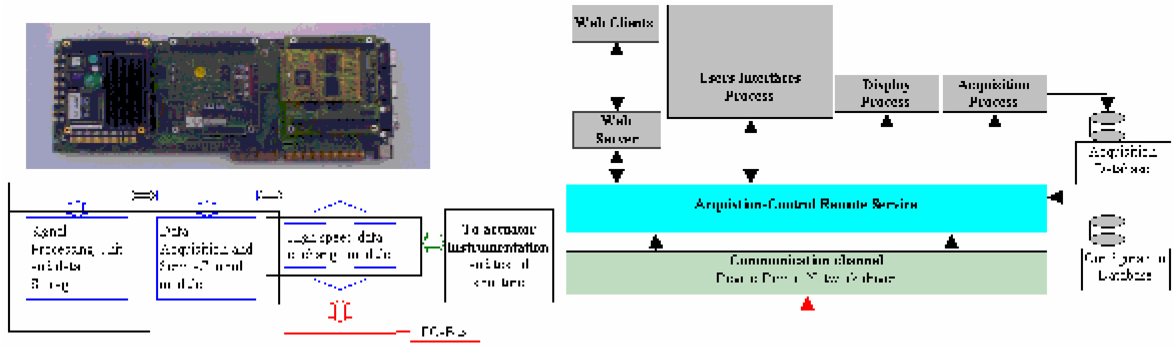

Figure 3. The new controller hardware and the new system architecture.

Instead, in the above circumstances, an adaptive control algorithm must be used. To achieve the necessary accuracy in both displacement and velocity of our servo-hydraulic actuators and guarantee an accurate PsD simulation, the novel minimal control synthesis (MCS) control algorithm developed at Bristol University, which possesses excellent adaptive capabilities, has been incorporated into our digital controllers. A full description of the MCS algorithm is given in Stoten & Benchoubane 1990 and experimental results can be found in Stoten 1992 or in Magonette *et al.* 1998. The basic premises behind the formulation of this control law can be summarised as follows:

- No plant parameter estimates are required of- or on-line. Control calculations do not require adaptive observers or full state feedback.
- Plant parameters (although unknown) may vary with time, and with relatively high bandwidth (MCS does not assume slow changes in parameters).
- Similarly, unknown high bandwidth external disturbances can act on the plant, and MCS will compensate for these disturbances.
- The implemented form of MCS requires a minimal amount of coding.

Further extension to high speed on-line testing of components and devices

Recently, a variety of new devices have been introduced in structures in order to mitigate vibrations. Most of them operate on principles such as frictional sliding, phase transformation in metals deformation of viscoelastic solids or fluid orificing. These have properties that are very velocity-dependent and thus require experimental substructuring testing performed in continuous mode and at high speed (possibly near real-time). By implementing an improved servo-control law, the PsD testing system described above can be upgraded to carry out fast on-line substructuring tests of structures outfitted with components made of materials exhibiting velocity dependent behaviour.

In fact, the problem to face is to maintain a very small error and a very small phase shift (delay) between the computed displacement (target) and the structural displacement (measured feedback). As the speed of the PsD test increases, the phase lag appearing in the higher vibration modes becomes more important. Imposed displacements consistently lag behind command values and as a result, the measured restoring forces are delayed. These force-feedback errors tend to exhibit energy adding force-displacement hysteresis so that, in the integration of the motion equations, the cumulative errors in the higher modes can grow indefinitely in a resonance-like fashion.

To face this problem a supplementary feed-forward circuit has been inserted below the servo-control algorithm (Magonette *et al.* 2000). Its action aims to provide an anticipatory action and minimize the tracking phase lag. The feed-forward part intends to provide the necessary input for following the specified motion trajectory. It is responsible for reducing and eliminating the tracking errors. The feedback part then stabilises the tracking error dynamics. The feed-forward transfer function is the inverse of the servo-loop transfer function combined with a low pass filter to avoid amplification of the high frequency noise. By feed-forwarding frequency components (in the range from 0Hz to about 5Hz) of the desired trajectory, a better tracking has been achieved and the amplification of the higher vibration modes (about 5 Hz) of the structure has been avoided. The vibration modes with frequency higher than 5 Hz, if they exist, can be dumped (or cancelled) numerically, because their contribution in the degradation of the structure is generally negligible.

Finally, It must be warned that the substructure fast on-line method is designed to test components or devices developing low inertial forces during the experiment. In fact, care must be taken for the measurement of the reaction forces since, in the dynamically applied loading, the load cell measurement includes the inertial force of the test specimen and apparatus and, therefore, does not necessarily represent only the reaction force of the specimen.

THE NEW DISTRIBUTED SYSTEM ARCHITECTURE

The new acquisition/control system is integrated in a wider distributed architecture (figure 3). In fact, this system can be seen as an object with which it is possible to dialog from any computer of the local area network. Thus, processes such as visualization, data base storage, data elaboration and data transfer through web can access the object and get properties and data. Inversely, the object get from a configuration database all the information it needs about the instrumentation of the experiment. In such a way, it is intended in one hand to favour the distribution and the use of the experimental data and on the other hand to increase the reliability of the measurement system.

CONCLUSION

An important research effort has been undertaken to improve the testing capabilities of the ELSA laboratory. New procedures and numerical algorithms are in development to fully take advantage of the potentialities of the substructuring testing method. A new hardware architecture was designed and several control units have been used to assess the system robustness as well as the hardware and software reliability. Over the past few years, many pseudodynamic tests have been achieved demonstrating the superior capabilities of the continuous techniques. These tests are classified in three categories:

- Continuous PsD tests on large-scale structures, also called global tests: This procedure is now fully effective and is systematically applied to investigate the dynamic response of the large civil buildings tested at ELSA.
- Continuous PsD (CPsD) tests on large-scale structure with substructuring: These tests are conducted on large specimens at low speed with non-linear substructuring. They are especially designed to assess the behaviour of bridges submitted to asynchronous motions.
- High-speed CPsD tests with substructuring in which the critical sections or components of a structure are tested at full scale and the surrounding edifice is modelled numerically. The main objective of this method is to perform parametric analysis of the response of strain rate sensitive passive or semi-active devices (installed in the laboratory) used to protect a structure (modelled numerically). This technique is still in development, but the preliminary results are very promising.

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