# The Contribution Of Shaking Tables To Earthquake Engineering

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**SUMMARY**

A study is presented of how practical needs in earthquake engineering have been satisfied since 1900 by the development of shaking tables. Until the occurrence of the 1933 Long Beach earthquake - the first to be recorded - many types of mechanical input were used to provide vibratory motion in one direction, but that event clearly showed the real form of earthquake motion, introducing the search for electro-mechanical systems which would reproduce it. By 1965 this had been achieved for 1-DOF tables, and for 6-DOF by 1980. Since then, new control methods, utilizing fast computation, have produced 6-DOF real-time control for non-linear behaviour. For many tests, scale-models introduce difficulties in representing mass and structural details, leading to current research in dynamic substructuring, where actuator dynamics introduce control issues in the synchronization of force and displacement. The paper ends with comments on the use of electrical actuators.

*Keywords: Shaking tables; History; Automatic control; Substructuring; Electrical actuators.*

## 1. INTRODUCTION

Our objective is to show that shaking tables have made an essential contribution to earthquake engineering since the subject was first studied in c.1890. For those who use these experimental facilities as an aid to design, or to give support to a theoretical study, there must be an understanding of the errors that can occur. This is basically a matter of controlling the shaking table to ensure that the intended motion is actually imposed on the testpiece, uncorrupted by the electro-mechanical system which is used to produce it.

During the period 1890-1950 practical needs of the construction industry produced a variety of shaking tables to answer immediate problems. Manpower to move testpieces in a to-and-fro manner along a pre-set track was soon replaced by an electric motor to produce harmonic motion. More realistic motion was later provided by a pendulum impacting the table at one end, resisted by a set of springs at the other, producing an initial sharp peak followed by decaying vibration. A variation here was springs at both ends, one set being compressed and released, reacting against the other set.

Although the idea of an electrically controlled oil-filled cylinder containing a piston that acted on the table was introduced in the early 1930s, accompanied by the use of an actual earthquake record as input, the development of the necessary supporting technology was interrupted by the 1939-45 war. It was not until the mid-1960s that electro-hydraulic actuators, accompanied by digital computers began their dominance of actuation systems used in shaking tables, resulting today in the use of adaptive control systems which allow the study of non-linear behaviour. Even so, the size of the table that could be built restricted their use to the study of scale models for which scaling laws could seldom be satisfied completely. This issue has recently been resolved in the US and Japan by the building of very large tables capable of testing full-scale systems. More generally, great attention has been paid on a worldwide basis to the 'substructuring' approach, where the crucial, often relatively small, part of the structure is tested on the shaking table (or otherwise), and the larger part modelled numerically in a computer. However, control issues are still a matter of worldwide concern.

## 2. THE EARLIEST SHAKING TABLES, 1890-1950

The first shaking table was devised in c.1890 in Japan (Muir Wood 1988). It was driven along rails manually by turning a wheel connected to an eccentric crank to produce a to-and-fro motion. No records are available concerning its use. After the 1906 Californian earthquake the State Investigation Commission funded Rogers (1906) at Stanford University to build a similar table, but now driven by an electric motor turning the wheel at controllable speeds. As a contribution to earthquake engineering it investigated the problems encountered in the 1906 event, in particular the greater destruction of structures built on soft ground than those built on firmer foundations – an issue which even today exercises advanced soil mechanics research. Roger's work using sand layers containing different amounts of water, sometimes separated by an impervious layer of oil-cloth, was inconclusive, as were theoretical attempts to explain the observations.

The 1930 Tokyo earthquake prompted renewal at Stanford of shaking table development by Jacobsen (1930) whose table also ran on rails, with motion produced either by a pendulum striking one end of a box against a reaction spring at the other (Figure 1), or by rotating an unbalanced wheel attached firmly to the table. The pendulum produced an initial shock followed by a decaying vibration, whereas the unbalanced wheel gave a harmonic motion with frequency depending on speed of rotation. Jacobsen's experiments continued the soil dynamics studies which Rogers had started, but his response measurements consisted of very small and inaccurate displacements in the soil, prompting him to remark wisely that experiment not guided by a theoretical background were unlikely to be useful.

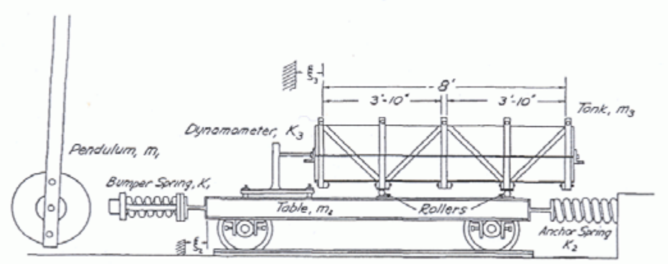


**Figure 1**. The Jacobsen (1930) shaking table

Concern about earthquake-induced dynamic pressure on dams resulted in the publication by Westergaard (1933) which was restricted to the two-dimensional problem of a vertical face vibrating with simple harmonic motion in an infinitely long reservoir. Experimental validation of this theory was taken up by Hoskins and Jacobsen (1934) using the latter's shaking table, who introduced his own 2D theory for a box of finite length, but unlike Westergaard he ignored compressibility, arguing that it was not significant. Because his theory included only the first derivatives of the two displacements, it was valid only for the motion induced by the pendulum immediately after impact. Even so, both the piezometer measurements on the end of his tank, and his theory, supported Westergaard's water-pressure profile as being of parabolic shape.

In 1934 the topic of structure/fluid interaction was taken up at M.I.T. by Ruge (1938), responding to damage to elevated water tanks during the 1933 Longbridge, California, earthquake, which is noteworthy in that it was the first earthquake to have its motion recorded. Ruge's shaking table was of novel design, being suspended by wires and controlled from rotation by others attached to the ground, but it is to be remembered for his use of an oil-filled actuator (Figure 2) for the first time (Ruge 1936), and an attempt to control the shaking table input to apply a defined motion to the testpiece on the shaking table. Ruge made use of the Long Beach records by doubly integrating the acceleration to obtain displacement, which he then proceeded to cut into the periphery of a large disc that was rotated by an electric motor. The second innovative nature of Ruge's work was his use of a concentrated light beam which was caused to follow the indentations on the disc, by what would now be called an 'error-drive' system, to control the movement of the actuator connected to the table. In order to secure the stability of his control, Ruge found that that it was necessary to accompany the error itself by its first derivative in order to achieve satisfactory responses. The fact that Ruge's initiative was not followed by others is due to the state of the art in electrical systems in the late 1930s, and to the demands of the 1935-45 world war.

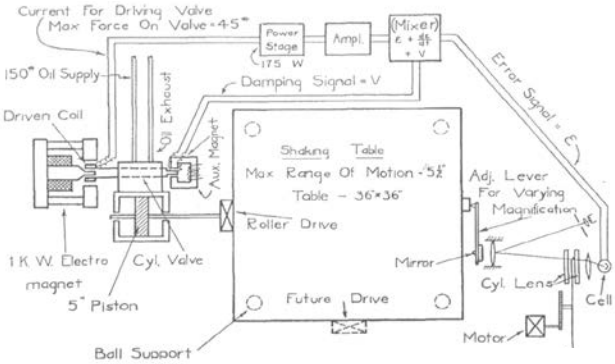


**Figure 2**. Ruge's table driven by an oil-filled actuator

### 3. SHAKING TABLES IN THE US, JAPAN AND ROMANIA, 1950-1970

The mid-1950s saw a return to the Jacobsen style of shaking tables by one built at the University of California, Berkeley, by Clough and Pirtz (1958) for a study of rockfill dams, the principal difference being that instead of running on rails it was supported by a number of flexible steel columns. For input, it continued to use a pendulum. This research suffered from many practically relevant shortcomings but its innovatory nature consisted of the use of acceleration spectra, introduced by Biot in 1933, to show that for levels of damping which are assumed for rockfill dams, spectral curves obtained from measured motion of the table were very close to those obtained from the N-S component of the 1940 El Centro earthquake.

A 1-DOF shaking table driven by the release of a set of compressed springs at one end, and reacted by a similar set at the other, producing 2*g* acceleration, was used in Japan (Muto et al., 1962) to test a small-scale model of the graphite core of the proposed nuclear power station at Tokai Mura. It was decided that, due to its importance, the design of the reactor-core would be dictated by seismic considerations requiring testing. Despite their simplicity it was claimed that the tests provided useful information on the arrangement of the graphite blocks, particularly that seismic loads acting on the core were carried by the restraint structure, with no transfer of shear between layers.

One positive outcome of the 1939-45 war relating to shaking tables was that it produced major advances in control of mechanical systems required by the armed services, amongst which was the oil-filled actuator. With assistance from the newly-created (1966) MTS System Corporation, and utilization of early forms of the digital computer, the University of Illinois (Sozen et al., 1969) constructed a 1-DOF table attached to a rigid base by columns similar to those used by Clough and Pirtz (1958). It was driven by a single actuator which could produce three kinds of input – steady state motion, real or simulated earthquakes and an arbitrary waveform. The input parameter could be either displacement, velocity or acceleration, but it was realized that displacement must be the preferred option to prevent damage to the table. However, the important question, not positively answered, was how closely did the motion applied to the testpiece correspond to the real earthquake? The acceptance of the Illinois table as an advance in shaking table development must also be qualified by the fact that the size and shape of the testpiece was deliberately arranged so that it did not excite to any measurable extent the other 5-DOF which would have attracted some of the input energy.

An innovative 10x10m, 1-DOF shaking table with input provided by 2 electro-hydraulic actuators having acceleration capability of 0.4*g*, was built at Jassy in Romania in the early 1960s, in order to test building structures at full-scale. The table itself was supported by a system of 16 nozzles fed by a 10m high external water tank, so arranged that they could be used to produce, or resist, pitch and roll.

## 4. SHAKING TABLES IN THE US AND JAPAN, 1970-80

MTS were also involved in the 1972 construction of the 6x6m shaking table at the University of California, Berkeley. Its 3 horizontal actuators, all acting in the same direction, were positioned to provide resistance to the yawing motion, and 4 vertical actuators were controlled to produce a common vertical motion, although they, like the horizontal actuators, did allow small pitch and roll motions to occur.

The table was designed to produce controlled motion in the vertical and one horizontal direction , but capacity of the servo-valves was not sufficient for the simultaneous achievement of their maximum values. The aim of the control system was to reduce the three rotations to zero and the two displacements to their specified values, by an adjustment process which required much skill from the operator, involving knowledge of the dynamic characteristics of the table and the testpiece, and a stepwise progression towards the specified input so as to ensure that maximum allowable values, particularly of displacement, were not exceeded. Because this process exceeded the duration of the actual earthquake record being used, the control was said to be 'out-of-real-time'.

By 1970 Japan had begun its industrial recovery from the 1939-45 war, including the building of shaking tables, in universities, manufacturing companies, and Research Institutes. An example of the last of these was the 15x15m table at the National Centre for Disaster Prevention in Tsukuba Science City built by Mitsubishi Industries (Sawada et al., 1970) particularly for the study of soil liquefaction which had caused great damage in the 1964 Niigata earthquake. Driven by 4 servo-hydraulic actuators in the vertical direction and 4 in one horizontal direction, it was fabricated from a grid of I-beams, supported by hydraulic bearings, and guided by rollers at the sides. It was capable of vibrating payloads of 500T and 200T in the horizontal and vertical directions, respectively, but with output being that measured at the testpiece. In the late 1970s the Public Works Institute in Tsukuba City produced a 6x8m table having a maximum load capacity of 100T, but of greater interest it constructed four 2x2m linked tables for what is now referred to as 'multiple –support excitation'. Most of the large Japanese companies continued until the mid 1980s to build their own, usually vary large, tables on the same principles, an example being the 15x15m Nuclear Power Corporation table completed in 1982, which, with a capacity of 1000T could excite one horizontal and the vertical direction simultaneously. For obvious commercial reason such companies were reluctant to publish details of the performance of their facilities.

## 5. SHAKING TABLES WITH 6-DOF CONTROL.

In a review of international earthquake engineering research by the US National Research Council published in 1982, it was recorded that no controlled 6-DOF shaking tables were available anywhere in the world at that time, but that the urgent need for such facilities came from the support which they could give to design and theoretical studies in many areas, not least of which was nuclear power. Here, the word ‘controlled’ signifies the ability to supply the appropriate current to each servovalve to drive its actuator along the correct trajectory.

### 5.1 Linear Controllers.

A linear controller is one in which the control system can be based on a model consisting of a set of simultaneous linear differential equations, whose parameters are assumed to be known *a priori* and which remain the same during the test. In principle, to achieve controlled motion in all 6 axes requires a minimum of 6 actuators and such tables, usually referred to as Stewart Platforms, have since found much use in the aerospace and automobile industries, where rotation is as important as displacement. But the practical needs of earthquake engineering require that motion in the vertical and two horizontal directions is paramount, with as much as possible of the available actuator energy directed to them, The 3 rotations are of much less importance, and their control often requires them to be reduced as close as possible to zero. Such requirements for earthquake engineering necessitates the use of at least 8 actuators disposed as in Figure 3, and the consequences of such an arrangement has been presented in Crewe and Severn (2001).

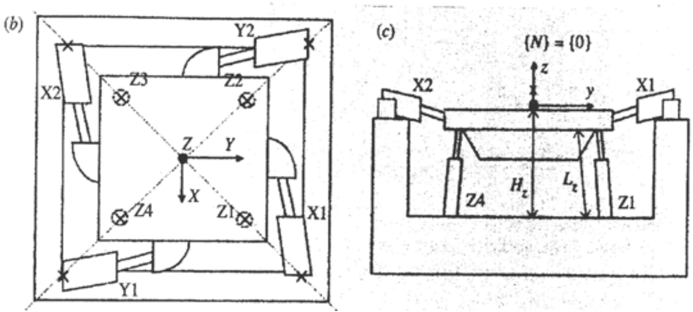


**Figure 3**. The disposition of the actuators in an 8-actuator table; (b) plan, (c) elevation.

A first difficulty here is the computational load imposed by what is referred to as ‘the inverse kinematic solver’ which transforms the reference vector (i.e. the 3 prescribed displacements and 3 rotations) into an 8-element vector, one element for each of the actuators. Also required at each step is the converse calculation, referred to as the 'direct kinematic solver', which converts 8 actuator values into the existing (6-DOF) position of the table. A second difficulty was that the linear controllers being used depended on the system dynamics being known, an unlikely situation which resulted in it being assessed by an incremental procedure at the beginning of the test, starting from low input values being increased incrementally until the desired input was achieved. Considerable skill was required by the shaking table operator to achieve this, particularly if, as became common, all three variables of displacement, velocity and acceleration were used to achieve control. The third significant shortcoming of a linear controller is the assumption, already noted, that the system being controlled can be represented by a set of time-invariant linear differential equations. This is unlikely to be the case, especially if the testpiece experiences any change during the test.

### 5.2 Adaptive Controllers – The Minimal Control Synthesis (MCS) Algorithm.

The search for a control system which could adapt to changing characteristics of the testpiece developed progressively in many industries during the last quarter of the 20th century, but not for earthquake engineering until 1992 when Stoten and Gomez (2001) applied Stoten's adaptive Minimal Control Synthesis (MCS) algorithm to a group of European shaking tables within a European Commission - funded research programme.

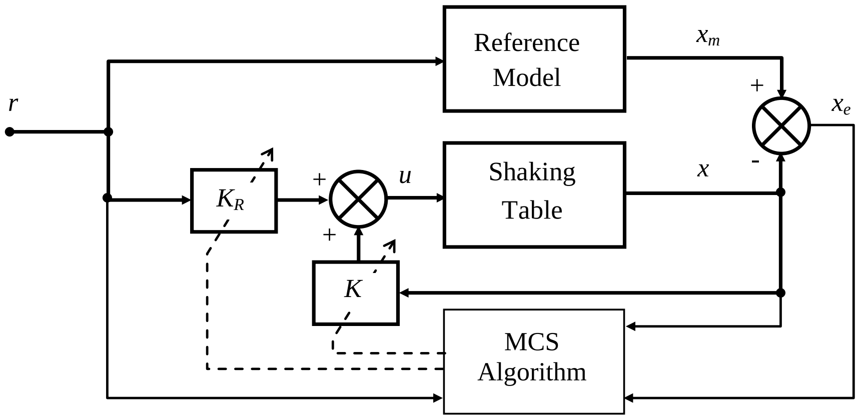


**Figure 4** Configuration of the basic MCS algorithm

The configuration of the basic MCS is shown in Figure 4, the salient features being:

1 a reference model, defining the ideal response, $x_m$, to a given reference signal, *r*.
2 the table to be controlled, with the response, *x*, to a control signal, *u*.
3 generation of adaptive time-varying gains, $K_R$ and *K*, via the MCS algorithm.
4 the error, $x_e = x_m - x$, which is the essential driving signal for the adaptive gains.

The adaptive gains are generated at every sampling instant in the closed-loop system in order to drive the error, $x_e$, asymptotically towards zero, despite the presence of unknown (though bounded), time-varying parameters and disturbances. In general, all signals are vector quantities and the MCS gains are time-varying matrices with arbitrary initial conditions – these could be values determined from a previous test run, for example. During a test, the MCS gains can be locked automatically when the magnitude of errors are less than a given tolerance and then released again, should the errors exceed the tolerance. Details, concerning the stability of MCS are dealt with in (for example) Hodgson and Stoten (1996).

A number of variants of MCS have been developed, primarily to improve functionality, to normalise adaptive effort over a range of operating conditions and to prevent drift of the adaptive gains in environments with noisy signals. Examples relevant to the control of shaking tables, including that at E-Defense, are described as decentralised MCS, MCS with integral action, error-based MCS, feedforward MCS; Stoten and Shimizu (2007).

In implementations of the MCS algorithm for shaking-table control, it is normally a requirement that existing (commercial) control hardware and software are retained, since they provide standard control algorithms, kinematic compensation, safety features, hydraulic drives, data processing capabilities, reference signal generators and graphical user interfaces. The earliest implementation of MCS on a shaking table was in 1993, on the 8-actuator, 6-DOF table at the University of Bristol. The 8-DOF adaptive controller was implemented via a standard PC, with a sampling frequency of 1000Hz and 12-bit analog conversion. This early design was an *inner-loop* configuration, where the adaptive controller was placed in parallel with an existing PID-based analogue control system, so that their control signals summed at one point. Inner-loop configurations have the advantage that should one of the controllers fail, the other will still be available to complete the control task. For tables where there are kinematic constraints between the actuator and table motions, another advantage of the inner-loop configuration is the ability to directly control each actuator. Also, the 8x6 inverse kinematic solver can be run off-line, to produce the actual actuator reference signal. A minor disadvantage is that 8 control loops are required, one for each actuator.

However, if it is not possible to access the control signal summing junction an alternative *outer-loop* scheme can be used (Figure 5) Direct control of the measured (or derived) table motion is now required and the MCS control signal becomes a modified reference signal. Although the outer-loop configuration does not offer the integrity of the inner-loop configuration, the majority of MCS implementations have been executed in this manner, since a relatively straightforward interface to the existing plant is possible. Also, the adaptive controller makes use of table response signals, so that only 6 control loops are necessary. A disadvantage is that both inverse and forward kinematic solvers must be implemented on-line, within the existing control loop.

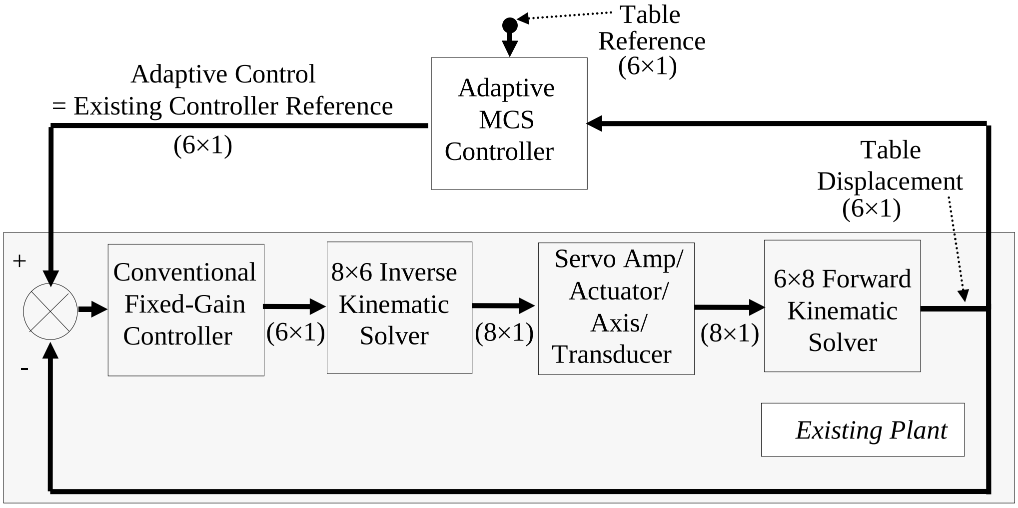


**Figure 5** Outer-loop MCS control of the Bristol shaking table, showing signal dimensions

## 6. RECENT DEVELOPMENTS

The 3 recent developments in shaking table testing are, the networking of several facilities, the limited construction of very large tables, and investigations using dynamically substructured systems.

### 6.1 Networking and very large systems

Examples of networking are the well-known NEES project in the US, and attempts in Europe to organize a similar activity. For very large tables, included in NEES is a 7.6x12m platform at San Diego capable of testing some types of full-scale structures, but the more significant example is the 20x15m table at E-Defense in Japan (Tagawa and Kajiwara, 2007). It is the only existing facility capable of shaking a full-scale 5-storey building in 3 dimensions, and since it was constructed in 2005, 47 structures have been tested, including full-scale reinforced concrete structures, wooden houses, soil foundations, and steel skeleton buildings and bridges. In the Tohoku earthquake of 11th March 2011 several tall buildings in Tokyo had serious problems from long-period motion which are difficult to reproduce in shaking tables because of shortage of oil capacity. The E-Defense table is currently being upgraded in this respect so as to generate large displacements at low frequency.

### 6.2 Dynamically substructured systems (DSS)

The DSS method, sometimes referred to as the 'hybrid' approach, is a testing technique that provides responses of full-scale engineering systems within the laboratory. In principle, the approach enables a large-scale system to be tested as an ensemble of constituent substructures, each represented in either physical or numerical form. A physical substructure is the more important part of the whole, which is difficult to represent in numeric form, but which can be tested at full-scale in a conventional laboratory. The numerical substructures represent less critical parts, which are can be modelled with sufficient accuracy. In DSS tests both the physical and numerical parts are run in real-time. One of the most demanding challenge here is to ensure that the substructures are synchronised at their interfaces so that, ideally, each set of interface displacements will be identical and the corresponding forces will satisfy Newton’s third law. This problem can be solved via synchronous control of interface displacements, whilst constraining interface forces to be identical (or vice versa). For good conditioning of both signals and control parameters, inertial-forced substructures are often synchronised in displacement and reaction-forced substructures in force.

Thus, a typical shaking table test with an unconstrained specimen, acting as a DSS physical substructure, is often synchronised in displacement. An early DSS experiment on the Bristol table is shown schematically in Figure 6. The emulated system is a simple mass-spring-damper system, subjected to base excitation *d*, with displacement response, *y*. The DSS interface is arbitrarily chosen at the base of the mass and it is the mass that constitutes the physical substructure, itself excited by the vertical motion of the shaking table.

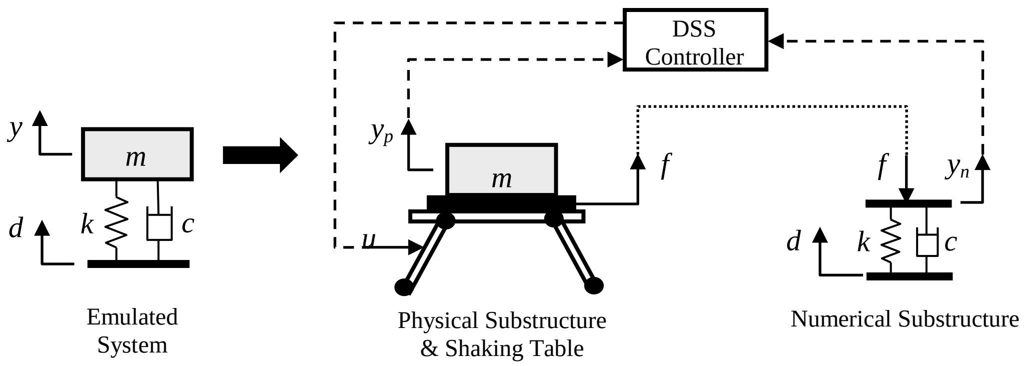


**Figure 6** An early Bristol shaking table DSS test for a simple mass-spring-damper system

The measured force constraint, *f*, is imposed on the numerical substructure consisting of the parallel spring/damper. The numerical and physical substructure responses, respectively $y_n$ and $y_p$, are then synchronised via the action of the control signal, *u*, from the DSS controller. With accurate parameter values for the system (including the shaking table), experimental results showed that a linear substructuring control scheme could synchronise the DSS, ensuring that both $y_n$ and $y_p$ closely followed the ideal emulated response, *y*. However, an MCS-based component was required if parameter values were not well-known; Stoten et al (2002). A valuable contribution to DSS has been made by Tu et al (2010) in comparing results for a base-isolated steel frame, using a shaking table for the complete structure, a DSS approach in which the physical structure is the base isolation device only, and a purely numerical simulation for the whole system. The conclusions reached, comparing maximum displacements, was that DSS produced values close to those of the shaking table, whereas the purely numerical approach was significantly in error.

## 7. SHAKING TABLE INPUT – COMPOSITE FILTERING

From a control engineering perspective, it is more natural to control the displacement of a shaking table, rather than its acceleration or velocity. But since it is normally acceleration data that is recorded from earthquake activity, it is the acceleration that should be reproduced on the shaking table. However, simply using acceleration data as the reference signal to a shaking table controller is not a viable option, because uncontrolled table drift will normally occur.

There are techniques for transforming acceleration to displacement (noting that simple double-integration will usually cause drift), so that displacement control can be used instead of acceleration. But due to resolution problems, displacement feedback alone can be problematic with a combination of high frequency/low amplitude reference signals. In such cases, the addition of acceleration feedback from the table would be a distinct advantage. Composite filtering is a technique that offers the advantages of using both displacement feedback at low to intermediate frequencies and acceleration feedback at intermediate to high frequencies, without incurring signal bias and drift associated with direct double-integration; Stoten (2001). The method mixes displacement and acceleration data in an ‘optimal’ manner, based on just one parameter (the break frequency), to yield a displacement signal that has high resolution across the frequency spectrum, which is referred to as the *ad2d* scheme shown in Figure 8.

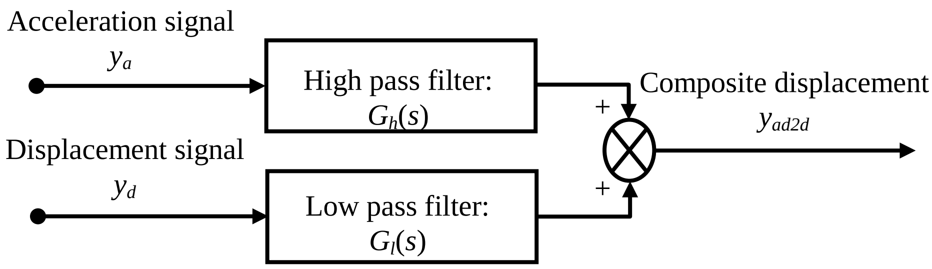


**Figure 7** Schematic representation of the composite displacement technique (*ad2d*)

Composite filtering can also be taken much further, so that different combinations of acceleration, velocity or displacement can be employed to give a filter output of either displacement, velocity or acceleration.

## 8 CONCLUSIONS AND POSSIBLE DEVELOPMENTS

It is argued above that shaking tables, used in conjunction with theoretical analysis, have made an essential contribution to the practice of earthquake engineering during the past 100 years, their use now being mandatory in many Codes. At first, construction was based on mechanical systems, as were the instruments used to record the behaviour of the structures being studied and no analysis was available to help assess the results. Major enhancements from 1950 onwards, were oil-filled actuators, electronic control and measuring systems. The introduction of digital computation affected not only control of input, but the creation of theoretical methods for comparison. Foreseen development of faster computation will bring greater success in the substructuring process in matching interface displacements and forces when using models, allowing comparisons to be made with full-scale testing. The simplicity of using electricity, rather than oil, as a power source has been recognized and has prompted research into electrical actuators, particularly in Japan, but adverse power-to weight ratios have delayed their introduction into earthquake engineering.

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