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A COMPARATIVE STUDY OF THE ADAPTIVE MCS CONTROL ALGORITHM ON EUROPEAN SHAKING-TABLES

Eduardo G GOMEZ[1] And David P STOTEN[2]

SUMMARY

This paper summarizes the results achieved using a form of adaptive control known as the Minimal Control Synthesis algorithm, on shaking tables across Europe. The responses of tables are improved and the dynamic changes introduced by the specimen are dealt with by the adaptive controller. The implementation details have already been published elsewhere and a general overview and some of the results of the testing programme are given here.

INTRODUCTION

The first attempts to reproduce seismic motion using experimental techniques date back to the beginning of the 20th century. However, Earthquake Engineering did not experience significative advances until the second half of the century when new developments in electronics and dynamics allowed researchers to use the recently introduced dynamic simulators.

During the 1980's, many shaking tables were constructed in order to analyze the result of seismic motion on structures. They were fitted with the latest available technology, represented by analog linear controllers. These kind of devices have now been superseded by more advanced digital equipment and by new control algorithms. Linear controllers work by assuming that the plant under control can be modelled by a linear equation, which does not change in time. Although it is possible to find such a model for a shaking table using approximations, its real dynamics are of non-linear nature. Furthermore, the dynamics are determined by not only the platform and the actuator placements, but also by the specimen under test. The specimen often weighs far more than the table and can exhibit plastic behaviour. During the course of the experiment the specimen can collapse, producing a drastic change in the table-specimen model parameters.

The use of analog electronics makes the control of the table more difficult. Analog devices are affected by electrical noise. Their behaviour is modified by temperature and humidity conditions and, if part of the controller is replaced due to a component fault, the whole system has to be recalibrated. In addition to this, complex calculations cannot be carried out and elaborate algorithms cannot be implemented, due to technological limitations.

All these restrictions make it very difficult to do experiments when the specimen dynamic parameters are unknown (the usual scenario), when it enters the plastic regime or when it partially collapses. Over the past two decades, several techniques have improved the testing procedures. Included in these techniques are:

- The use of a combination of acceleration, velocity and displacement control. This allows the table transfer function to be fine-tuned by varying the weight of each component and the parameters in each control loop.
- The use of iterative matching procedures. These pre-compensate the reference signal in accordance with the output of the table. The process is iterated until a good level of agreement is reached.

[1] *Automatic Control Laboratory. Department of Mechanical Engineering. Faculty of Engineering. University of Bristol*
[2] *Automatic Control Laboratory. Department of Mechanical Engineering. Faculty of Engineering. University of Bristol*

Both methods can improve the control of the table. However, they do not provide an answer to the changes in the dynamic parameters during the test or to non-linear regimes of the specimen. In the case of iterative procedures, they have to be carried out with the specimen placed on the table. This is not always feasible, or desirable, as the specimen can break during the process. The time for convergence can be excessive and sometimes this convergence cannot be achieved.

During the 1990’s a Pan-European network of shaking table facilities, the ECOEST consortium [Severn 1996], was set up in order to promote co-operation between these facilities. As part of this co-operation, a comparative exercise between shaking table performances was carried out [Crewe 1998]. The results highlighted the control deficiencies mentioned above and gave rise to the creation of the program CESTADS (Control Enhancement of Shaking Tables from Analog to Digital Systems), supported by the European Union. The main aims of CESTADS were to upgrade the existing analog controllers to digital technology and to research into new control techniques able to meet the demanding requirements of shaking table dynamic testing.

CEDSTADS has been based upon two main pillars: digital technology and the use of the Minimal Control Synthesis (MCS) algorithm [Stoten 1993]. The latter is a form of adaptive control researched at the University of Bristol since 1990. The achievements of this program have prompted the creation of FUDIDCOEEF (Further Developments In Dynamic COntrol of Earthquake Engineering Facilities), also supported by the European Commission. FUDIDCOEEF investigates improvements to the testing processes that can be carried out based on the new table control capabilities.

OVERVIEW OF THE MCS ALGORITHM

The MCS algorithm is derived from a general Model Reference Adaptive Control (MRAC) algorithm. Adaptive control provides capabilities that can be used to counteract the effect of dynamic changes and parameter variations. MRAC needs a good degree of knowledge of the nominal plant dynamics but this is not the case with MCS. The former must use some form of system identification in order to adapt the gains of the controller. MCS, on the other hand, does not require any parametric information and can start with zero gains. The main characteristics that make MCS able to improve shaking table control are:

- No knowledge of the plant dynamic parameters is necessary.
- The stability and robustness of the algorithm have been formally proved and tested.
- The algorithm can cope with parameter variations and external disturbances as well as non-linear regimes.
- It offers a high speed of response to disturbances.
- The adaptive gains can be started from zero or be given an initial value to speed up convergence.
- The adaptive gains can be locked transforming the algorithm into a virtual fixed-gain controller with automatic tuning.
- A linear controller can be used in parallel, allowing the algorithm to be implemented as a retrofit to an existing controller.

A block diagram of the algorithm is depicted in figure 1. The demand signal is modified by a reference model that produces the ideal close loop response. This response is compared to the output of the table and the adaptive gains are modified in order to achieve a good matching between the output of the table and the output of the reference model. The voltage bias usually present in analog devices (or servovalve bias) can be removed using a third gain, which is computed based on the integral of the table output error. This is known as the integral action (MCSIA) version and is described in [Stoten 1995].

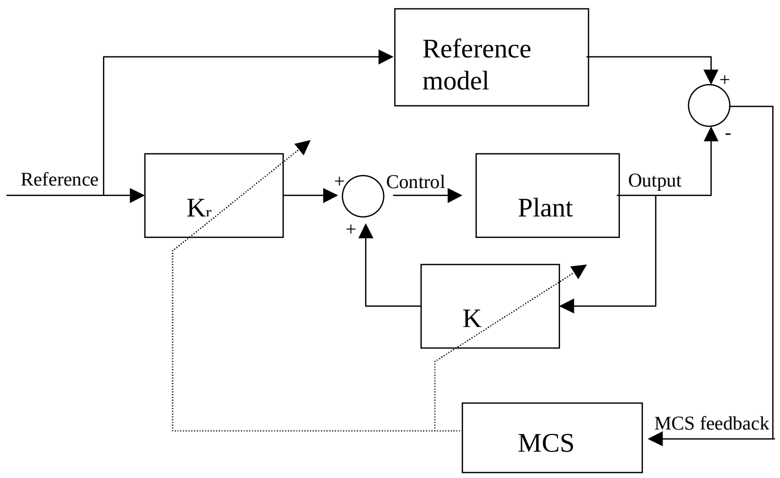

Figure 1 – Block diagram of MCS.

IMPLEMENTATION OF ADAPTIVE CONTROL ON SHAKING TABLES

The traditional control scheme of a shaking table has been reproduced in figure 2. The demand contains the position and orientation of the table defined by the three spatial co-ordinates and the three orientation angles (roll, pitch and yaw). This six-component demand vector has to be decomposed into an eight-component driving signal, one per actuator. Each component of the driving signal is then fed to the control loop of each actuator. The transformation between position/orientation of the table and driving signal for the actuator is carried out by the block named "inverse kinematic solver". This element computes the length of the actuator based on the geometric parameters of the table. In a similar manner, the position of the table can be recovered from the measured length of the actuators by the direct kinematic solver. Although this conversion is not strictly necessary for the control scheme, it provides information in order to ensure that the experiment has been performed as expected.

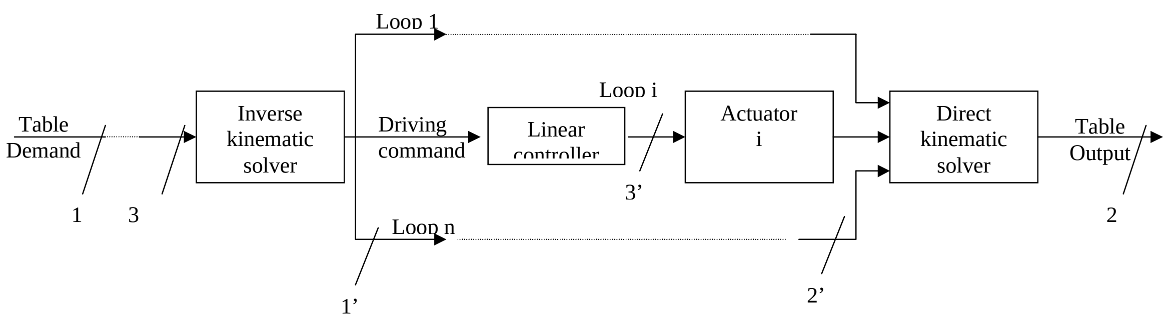

Figure 2 – Shaking table control scheme.

The inverse kinematic solver must be implemented in real time, as it is part of the control scheme. [Stoten and Gomez 1998a] describes an inverse kinematic algorithm suitable for real-time. The direct kinematic problem, on the other hand, has to be solved using iterative methods. Although there are general analytic solutions to the problem, they require large amounts of computing power. An iterative algorithm that works off-line is provided in [Stoten and Gomez 1998b]. There are other direct algorithms which are suitable for real time, such as the one described in [Etemandi-Zanganeh and Angeles 1995]. However, they require the use of extra transducers.

The adaptive controller can be implemented following two different strategies. The first one, labelled as "inner loop", requires access to the summing junction of the servo-valve (point 2' in figure 2). It applies the control directly on the actuators, thus preserving the loop integrity, since both the conventional controller and the actuator are treated as the plant to be controlled. For each actuator, the driving command (point 1') is used as the MCS reference, the output (point 2') is used as the MCS feedback and the MCS control signal is added to the actuator control signal (point 3'). This strategy has been implemented and tested at the shaking table of the University of Bristol, where a new digital controller was commissioned as part of CESTADS and an access to the summing junction was provided.

A second strategy, labelled as "outer loop", was designed in order to incorporate MCS in shaking tables where direct access to the actuators is not possible. This is the case in most of currently operative analog shaking tables. In the outer loop control scheme the adaptive control signal is fed at point 3 of figure 2. In practical terms, this involves using the external reference input of the table. The demand of the table (point 1) is fed to MCS and compared to the output of the table (point 2). The control signal produced is used as the new demand for the table and fed at point 3. This strategy resembles the matching process (the demand is modified according to the output), although here it is carried out in real time and stability issues are addressed by MCS stability proofs. Both inner and outer loop strategies are described in detail in [Stoten and Gomez 1998a].

The shaking table can be controlled in displacement or in acceleration. The preferred option is displacement, since the acceleration is unique for a given displacement but not *vice versa* (due to bias). Control in displacement also avoids unwanted drift of the table and ensures that the demand is within the physical limits. However, in certain cases, such as high frequency motions, it is desirable to use acceleration control. MCS has been implemented and tested in both configurations.

The displacement transducers (LVDT) are limited in bandwidth and this reduces the range of frequencies that can be controlled under displacement using traditional approaches. A solution to combine acceleration from accelerometers and displacement from LVDTs into the so-called "composite displacement" signal has been developed by one of the authors (DPS) and used in tests involving high frequencies. This solution is based on an optimal combination of both signals and is described in [Stoten and Gomez 1999].

RESULTS OF DISPLACEMENT CONTROL

The first experiment presented in this section corresponds to a uniaxial test carried out at Bristol in the summer of 1998. The table was loaded with a steel frame with an approximate mass of 7000kg (the table mass is 3000kg). The adaptive control was active on the six axes in spite of having demand for only one of them. This allowed the spurious pitch to be bounded. This spurious motion is produced as a consequence of the considerable mass and the high centre of gravity of the specimen (approximately 3m above the surface of the table). The results for the *X* axis are reproduced in figure 3, where they can be compared with the results achieved using linear control only.

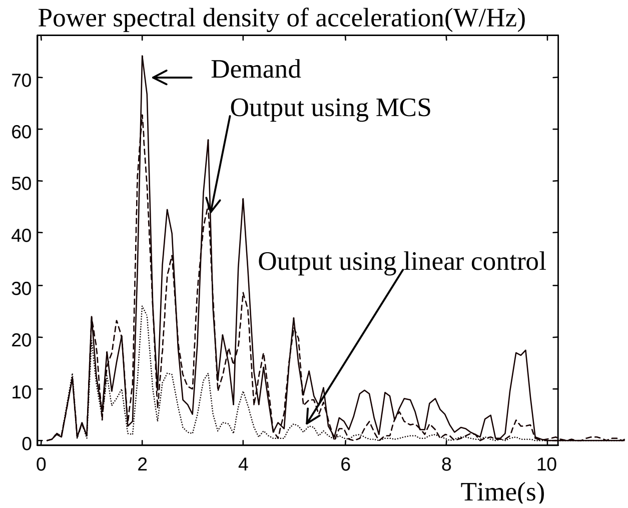

Figure 3 – Bristol test. Demand compared with output using linear control and with output using MCS.

The results produced with the linear controller working alone can be improved only after a complex process of iteratively modifying the demand and after fine-tuning the controller gains. This process usually produces large pitch spurious motion. On the other hand, MCS did not require any previous tuning and the adaptive gains were started from zero. The adaptive algorithm automatically increased the control signal supplied to the vertical actuators in order to counteract the effect of the specimen on the pitch motion. Figure 4 reproduces the control signal send by MCS to the vertical actuator Z_1 when the table is empty and when the payload is present. The frequency contents of the latter are around the resonant frequency of the model as they are cancelling the effect of the specimen-table interaction in the pitch and roll motions. Figure 5 shows the pitch spurious motion in both cases. The maximum stroke of this motion is bounded within the resolution limits of the system. The actuator displacement responsible for this pitch is under 0.3mm, i.e. well under the 1mm resolution limit of the system.

There is no data available from the results of the linear controller. The matching procedure necessary to obtain a similar result, i.e. good matching in the excited degree of freedom and close to zero motion in the remaining ones, was too problematic to be carried out and it is highly unlikely that it would have been successful.

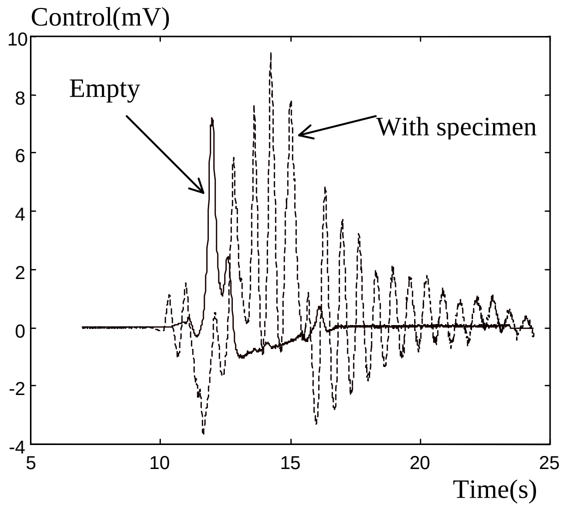

Figure 4 – Bristol test. Control adaptive signal sent to the vertical actuator Z_1 in order to counteract the spurious pitch motion when the table is empty and when a specimen is present.

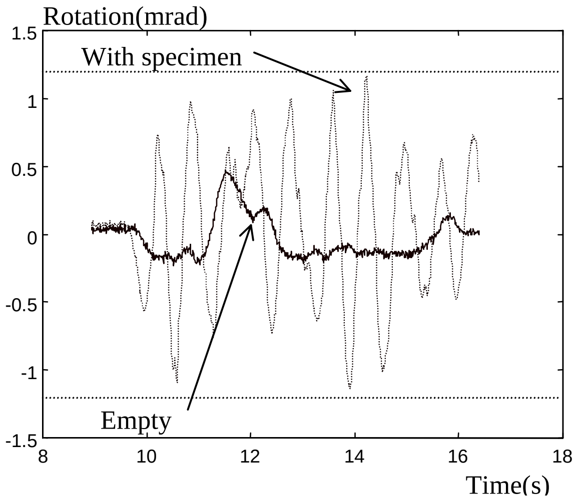

Figure 5 – Bristol test. Pitch spurious motion with specimen compared to spurious motion on the empty table. The horizontal lines show the estimated resolution limits of the system.

The second test presented in this section was carried out at ISMES (Bergamo, Italy) using the six axes MASTER table and MCS in the "outer loop" configuration. A two-storey model of a building was placed on the table and a demand was send to the three translation axes. Figure 6 reproduces the Integral Square Error (ISE) found in the *X* axis. The results for the Y axis are similar and in the case of the Z, the improvement was more reduced. The figure shows a reduction of the ISE when MCS is employed.

Some results from the experimental work carried out on the shaking table at LEE (Athens, Greece), are also presented. MCS was permanently installed as part of the table's control system in the outer loop configuration. Figure 7 shows the improvements in control achieved with MCS. The adaptive control was active on the six axes, although demand was only supplied for the *X* motion. The MCS response fully matched the amplitude of the demand. This can be compared with the amplitude of the output achieved by the linear controller, which resulted in a relative error of 30%.

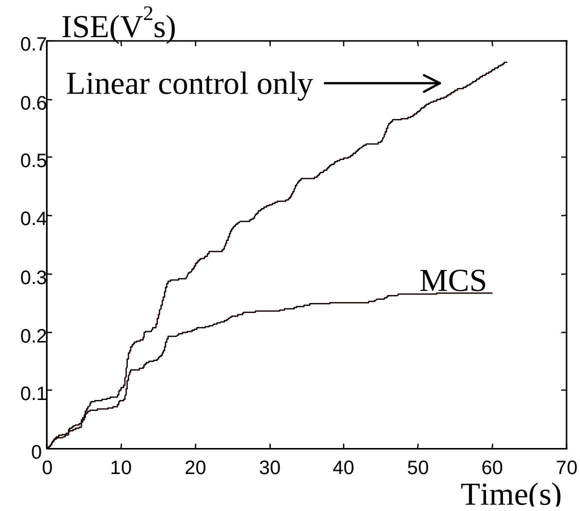

Figure 6 – ISMES test. Integral Square Error (ISE) for the X axis using MCS and using linear control.

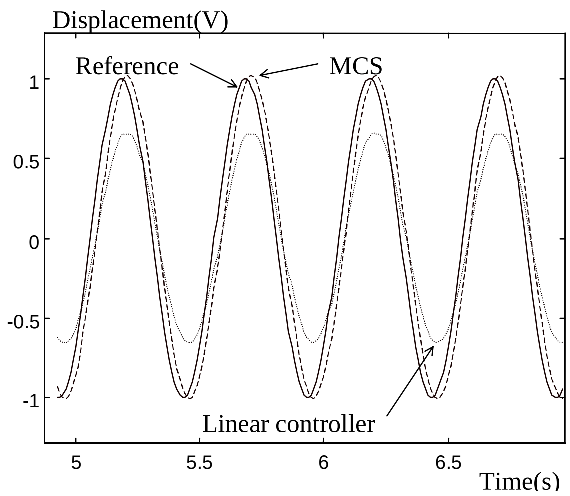

Figure 7 – Athens test. X demand compared to the output of MCS and the output of a linear controller.

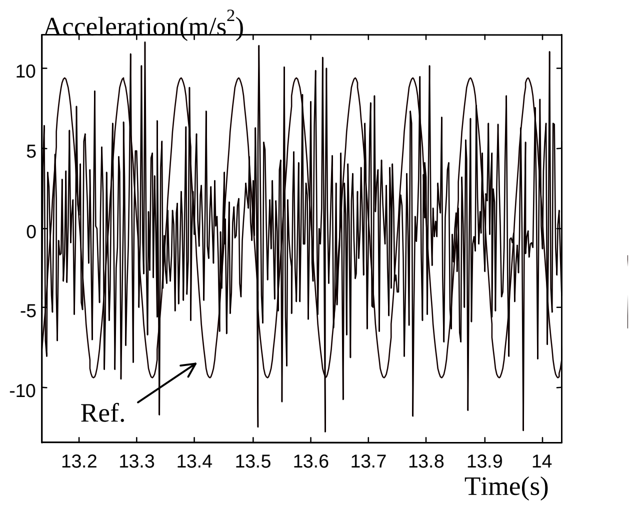

Figure 8 – Reference and output using MCS without composite filters. Target signal: 10Hz, 10m/s^2.

Finally, an example of the results achieved with composite filters is given. In this experiment, the shaking table was driven at 10Hz with amplitude of 1m/s^2. This is equivalent to a displacement of 0.3mm, well below the resolution achievable with displacement control at Bristol. The test could not be repeated without composite filters and therefore the amplitude was increased. Figure 8 shows the results without composite filters using an amplitude of $10 m/s^2$. The reproduction is worse and the quality of the feedback signal is poor. Figure 9 shows the results produced using MCS and the composite filters with the $1 m/s^2$ target. The output matches very closely to the demand and the quality of the signal is much better due to the use of composite filters. The results were also monitored using accelerometers and a good agreement between acceleration derived from composite displacement and acceleration measured by the accelerometers was observed.

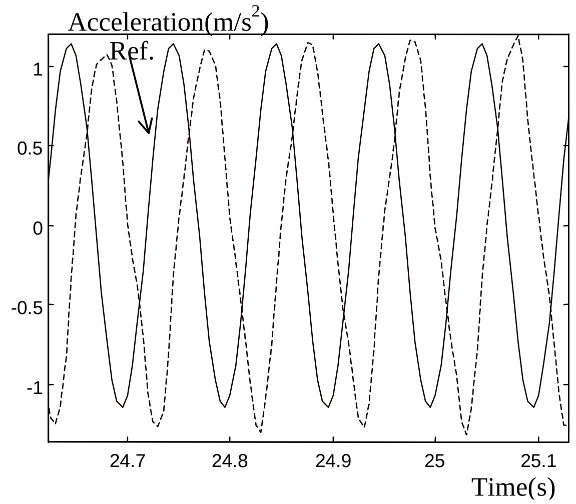

Figure 9 – Reference and output using MCS and composite filters. Target signal: 10Hz, $1 m/s^2$.

RESULTS OF ACCELERATION CONTROL

The best results achieved under acceleration control correspond to a test carried out on the LEE shaking table in January 1998. The control set up was slightly limited due to electrical noise and due to the quantization effect of the analog to digital converters employed to transfer the signal into the computer which ran MCS. In spite of this, the control was improved over the frequency range shown in figure 10. In this case, the adaptive gains of the algorithm were initialized using the values from a previous test. This technique increases the speed of convergence and improves the results.

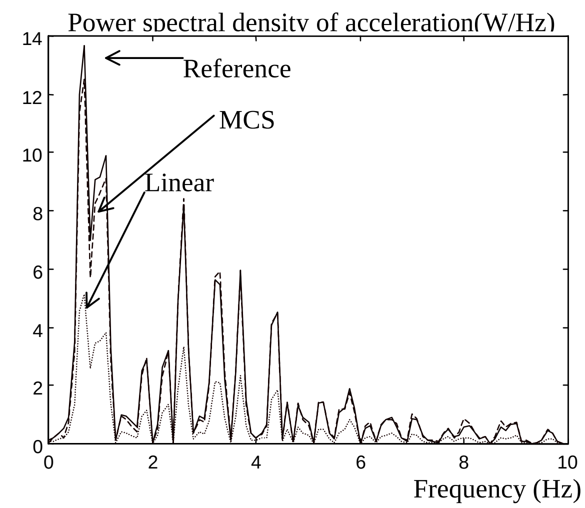

Figure 10 – Athens acceleration test. Demand compared to the output of MCS and the output achieved with a linear controller. MCS gains held from a previous experiment.

CONCLUSIONS

The results shown in this paper have been taken from the experimental work carried out over the past three years on three different shaking tables. They give a general overview of the variety of scenarios and circumstances tested. Based on the evidence presented, the conclusions can be summarized as follows:

- The control of the shaking table is improved by using adaptive control in the form of the MCS algorithm. The improvements can be achieved under both displacement and acceleration control.

- MCS has been used in its first order decentralized form. This is consistent with traditional methods of control where the actuators are controlled as independent devices.

- The adaptive algorithm can cope with specimens without further changes to the controller set up. The effects introduced by the specimen are also dealt with by MCS. This includes the dynamic effects of the specimen on non-excited degrees of freedom.

- The quality of the feedback signal and the frequency range in displacement control can be extended using the composite filters combined with MCS.

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