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A NOVEL EXPERIMENTAL SETUP TO MODEL EARTHQUAKE EXCITED ELASTIC-PLASTIC STRUCTURES

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SUMMARY

An acceleration controller for an electrodynamic shaking table is presented. It is designed for experimental investigations of small-scale civil engineering structures subject to earthquake excitations. For obtaining excellent tracking performance over a wide frequency range a robust control algorithm is proposed which ensures that the amplitude of the random excitation is equal to the reference signal. The well known interaction problem between the shaking table and the structural model is integrated in the controller design making the experimental setup appropriate for a variety of structural models. Theoretical basis, practical considerations and implementation of the proposed controller is described in detail. Good acceleration control characteristics of the designed shaking table is demonstrated by experimental results.

INTRODUCTION

At the Institute of Rational Mechanics, Civil Engineering Department of the Technical University of Vienna, a uniaxial shaking table has been developed in order to perform experimental investigations on small-scale civil engineering structures subject to large base accelerations, such as earthquake loadings. A typical small-scale model consists of a multi-storey shear frame composed of steel columns or alternatively soft aluminium columns and rigid aluminium beams, designed both for unlimited elastic and elastic-plastic structural behaviour. For example, the dynamic interaction between primary and secondary structures has been studied experimentally in [2]. In another study [1] the influence of passive vibration absorbers on the structural response of elastic-plastic shear buildings has been investigated. The shaking table is an essential component of the test equipment. Due to limited space in the laboratory an electrodynamic shaker, Brüel&Kjær Type 4808, is employed. It is easy to handle and cheap in operation. However, it has the disadvantage of frequency dependent acceleration output, especially in the low frequency range. Moreover, there is always an unwanted interaction between the structural model and the shaking table assembly. The acceleration output of the shaking table is altered, often decreased, at frequencies close to the natural frequencies of the structural model. As a consequence the reference excitation signals does not match the actual acceleration signal measured during the experiment. One of the key objectives of this work is to ensure the consistent repetition of predefined acceleration signals or earthquake samples at the shaker, despite the significant diversity of dynamic parameters of the structures to be investigated. Until now, several control method have been developed for shaker systems, see e.g. Chen and Liaw [3] and Stoten and Gómez [6]. However, the procedures reported in the literature cannot be implemented into the existing small-scale shaking table without difficulty.

This particular paper focuses on the development of an active control strategy which minimises the effects of interaction and frequency dependence of the acceleration output. Measurements of the absolute acceleration are used to adjust the control force in a feedback loop. The design of the controller is supported by the software package MATLAB and SIMULINK. The system identification procedure applied to determine the parameters of the mathematical model is discussed.

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A detailed description of the hardware and software employed for the controller implementation is provided, including a discussion of the supervisory features of the control system. The experimental results indicate the significant improvement of the dynamic response achieved by the outlined feedback control.

EXPERIMENTAL SETUP

Tests are conducted at the laboratory of model dynamics at the Institute of Rational Mechanics, Technical University of Vienna, where a uniaxial earthquake simulator is designed and built and placed in the laboratory. The simulator, shown in Fig. 1, consists of an electrodynamic actuator assembly (Brüel&Kjær PM Vibration Exciter Type 4808) which drives an aluminium foundation mounted on flexible columns. A power amplifier (Brüel&Kjær Power Amplifier Type 2712) is providing the shaker's input voltage. The shaker has a maximum output force of 112N. For acceleration measurements a piezoelectric accelerometer is fixed to the foundation and connected to a low noise charge amplifier (Brüel&Kjær Charge Amplifier Type 2635) with band limited filtering features. Data acquisition is done by means of the dSPACE ACE (advanced control educational) Kit which consists of a DS 1102 DSP controller board and software for control application development. The DSP system is fully programmable from the SIMULINK block diagram environment with the Real Time Interface (RTI) [7] and ideally suited for rapid control prototyping. The dSPACE ACE-Kit is a perfect tool for controller design and implementation because is works together with MATLAB and SIMULINK, a state-of-the-art software package for scientific calculation and research, see again [7]. A Texas Instruments C31 Digital Signal Processor and various I/O are integrated on the controller board, which plugs into a PC's expansion port. The TI C31 DSP chip can achieve a nominal performance of 60 MFLOPS. The onboard A/D system provides 4 channels, two 16 and two 12-bit precision and a maximum sampling rate of 250 kHz. Furthermore, ready-to-use units for pulse width modulation (PWM) generation, frequency generation/measurement, and an incremental encoder interface are available on the DSP board.

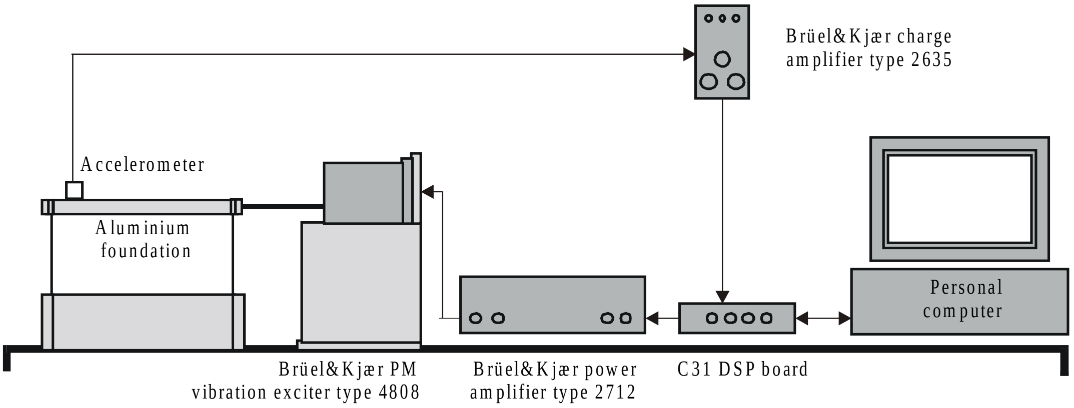

Figure 1: Experimental setup with all components

The capabilities of the simulator are: maximum displacement: ±6 mm, maximum acceleration of ±5 g but limited by the stroke at lower frequencies, with a 2 kg test load. The operational frequency of the simulator is 5-150 Hz, allowing to conduct laboratory experiments for variety of different types of buildings. Up to now several steel frame type buildings have been tested, including experiments with linear and nonlinear vibrations due to elastic and elastic-plastic column deformations. The experimental setup turned out to work reliably, independent of the number of floors and the distribution of the natural frequencies of the structure of interest.

SYSTEM IDENTIFICATION AND CONTROLLER DESIGN

An important phenomenon that should be integrated into the identification process and controller design is the interaction between the shaking table and the structural model. Unfortunately, this is impossible for a general purpose shaking table setup because the dynamics of the test structure is not known. A feasible approach would be the application of an adaptive control strategy as proposed in [6]. Another method, which is utilised in the current paper, is to separate shaking table and structure and develop a *robust control strategy* for the acceleration of the shaking table without any test structure fixed to it. If a well designed controller is capable of handling disturbances like the force exerted by the structure the design will be successful. Whichever control strategy is employed the development of an accurate mathematical model of the dynamic system is one of the most important and challenging components in control design. There are several methods to accomplish this task. One is to derive the input/output characteristics analytically by modelling the plant physically. However, this method often leads to models that do not correlate well with the observed response of the physical system due to modelling inaccuracies and simplifications. An alternative approach is to measure the input/output relationship of the physical system and to construct a mathematical model that can replicate the behaviour. This method is called system identification in the control systems literature. The steps in a typical system identification procedure are: (i) the collection of accurate input/output data, (ii) the computation of the best model within a class of systems considered, and (iii) the evaluation of the quality of the identified model. All three steps are supported by the Identification Toolbox of MATLAB/SIMULINK. The system identification procedure models the system as a ratio of two polynomials in the frequency domain ($s = j\omega$), thereby applying a least squares method, see e.g. [9]. Because some of the model parameters are difficult to obtain the input/output relationship of the physical system is measured and a subsequent least squares identification is performed. The system dynamics can be described by a transfer function G_{ua} relating the input voltage u to the table acceleration a:

$$G_{ua} = -\frac{2268\,s^2}{s^3 + 798\,s^2 + 93580\,\mathrm{s} + 5237000}\,. \tag{1}$$

The double differentiating character of the plant is due to the output being an acceleration. A constant voltage input will cause the velocity as well as the acceleration to be zero in steady state.

CONTROLLER DESIGN

The earlier discussed separation of shaking table and structure leads to plant inaccuracies, which can have strong adverse effects on control systems. One control strategy dealing with model uncertainty is robust control. A possible approach to robust control is the so-called sliding mode control (SMC). Such a design can be regarded as a high speed switched feedback control. The purpose of the switching control is to drive the (nonlinear) plant trajectory onto a specified surface σ in state space and maintain the plant's trajectory on this surface for all subsequent time. Details of sliding mode designs can be found in [5]. In summary, a SMC design breaks down into two phases. The first is to design or choose a switching surface so that the plant's state, restricted to the surface, has desired dynamics. The second is to design a switched control law that will drive the plant's state to the switching surface and maintain it there.

The switching surface can be determined analytically or intuitively. An intuitive choice is to demand that the actual table acceleration a_{table} and the reference input acceleration a_{ref} are equal which is achieved if

$$\sigma = a_{table} - a_{ref} = 0\,. \tag{2}$$

All other state variables are not taken into account which simplifies the implementation enormously because no state estimation algorithm has to be designed. A sufficient condition for the sliding surface to be globally attractive, see [4], is that the control input u is chosen so that

$$\sigma^T\left(\frac{\partial\sigma}{\partial t} + f_{plant} + f_{dist} + u\right) < 0. \tag{3}$$

f_{plant} denotes the plant dynamics, f_{dist} is due to the disturbance dynamics and is proportional to $1/m_{foundation}$. For further details see again [4]. Obviously, a massive foundation can reduce the disturbing influence of the test structure. On the other hand it also decreases the maximum possible acceleration of the entire setup due to the limited shaker force.

A simple control structure is obtained if the control input is chosen to be

$$u = \alpha\,\mathrm{sgn}(\sigma)\,, \tag{4}$$

which is commonly known as relay controller with constant gain, where α has to be chosen so that eqn. (3) is fulfilled. This implies that, for given f_{plant} and f_{dist}, α can be determined that stability is guaranteed. A schematic view of the entire system, consisting of the relay controller, the shaking table and the model is shown in Fig. 2.

The SMC concept assumes infinite fast switching for perfect tracking behaviour. However, numerical simulations with the previously determined shaking table dynamics and the relay control law reveal an excellent system behaviour even under the presence of strong disturbances if the sampling rate is chosen to be larger than 30 kHz. Because of the simple controller structure the controller is implemented on an analogue circuitry after a short period of testing the feedback design with the DSP board system.

It is obvious that this control law is independent of the actual structure, shaker or amplifier dynamics. Robustness is achieved if a high input voltage is guaranteed. Good tracking behaviour is realised if the control algorithm works as fast as possible. The choice of $\alpha = U_{\max}$ ensures good performance and high disturbance attenuation, even in the presence of strong disturbing forces, at the price of high frequency chattering. However, this high frequency acceleration can be accepted because it is of small amplitude and well separated from the natural frequencies of the test structure.

Although the actual actuator, structure and model dynamics are not reflected in the control law an accurate identification is very important for the overall understanding of the plant behaviour and crucial during the control design, because a great deal of numerical simulations, including the test structure dynamics, is carried out before an adequate control law is found.

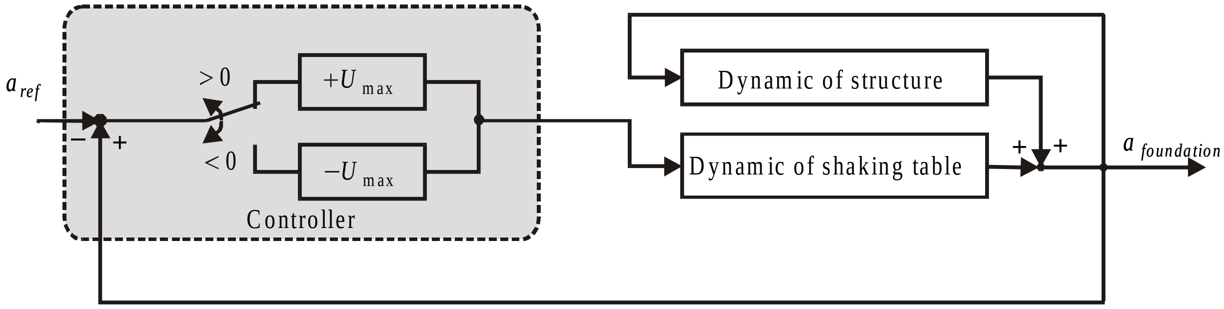

Figure 2: System with relay controller

It has to be mentioned that the aim was to improve an existing shaking table assembly by a feedback control setup. All aspects concerning energy conversion efficiency were neglected due to the light weight small scale models and short testing periods. Obviously, the analogue power amplifier used could be replaced by a much simpler pulsewidth modulated amplifier as presented in [3], or even by a switching amplifier, thereby overcoming some energy related drawbacks.

The proposed control algorithm is designed to perfectly track the acceleration signal. Because of the limited stroke of the electrodynamic shaker it is essential to limit the maximal reference displacement x_{ref} obtained by double integrating the acceleration input a_{ref}. For this reason the desired ground acceleration is high pass filtered before it is used as acceleration input signal. Whenever it is physically possible to follow the acceleration input signal the tracking performance of the overall system is excellent. For good results the input signal should be restricted to frequencies between 5 and 150 Hz and the maximum required acceleration force must be less than 100 Newton due to shaker limitations. This implies that if the building is acting as a perfect absorber than the control will fail. However, in such a situation no control strategy will be successful, because of the almost infinite force which would be required to obtain the desired ground acceleration. In the case of elastic-plastic deformations the results are much better due to energy absorbing behaviour of elastic-plastic shear frames. The maximum force transmitted by a column is limited resulting in limited forces exerted on the foundation.

RESULTS AND IMPROVEMENTS

The described shaking table setup is tested for a typical laboratory experiment where the object of investigation is a three floor shear frame building, consisting of steel columns whose deformations are purely elastic. The beams are modelled by aluminium bars, and weight a total of 3.0 kg, distributed evenly between the three floors.

The time scale factor is about 0.1 making the natural frequencies of the model 8.0, 21.0 and 29.0 Hz, approximately 10 times those of a real structure. The building frame has a total height of 58 cm. As shown in Fig. 3, accelerometers positioned on each floor measure the absolute accelerations of the model, and an accelerometer located on the base measures the ground excitation. Additionally, a laser based measurement equipment can be used to obtain displacement information. Only the base acceleration of the structure is employed for the purpose of ground acceleration control.

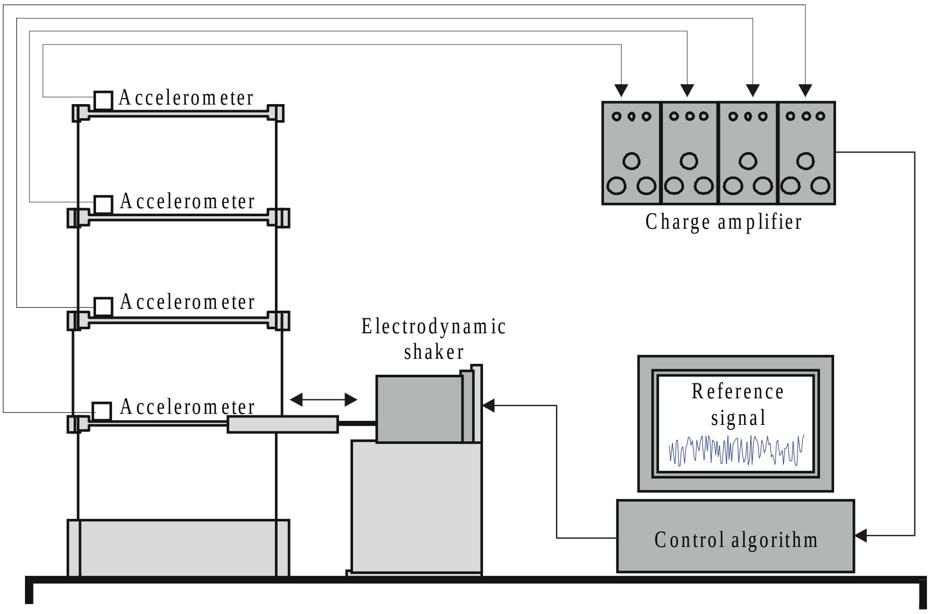

Figure 3: Experimental setup

The structure is excited with artificially generated 5 to 50 Hz band limited white noise. The measured frequency responses of the ground accelerations are shown in Fig. 4 and Fig. 5 for both, the controlled and the uncontrolled (original) experiment. The acceleration in the controlled experimental setup has the typical white noise characteristics. Even the unwanted input acceleration losses at frequencies close to the structure's natural frequencies (see Fig. 6) due to the absorbing behaviour have been eliminated entirely, compare Fig. 4 and Fig. 5.

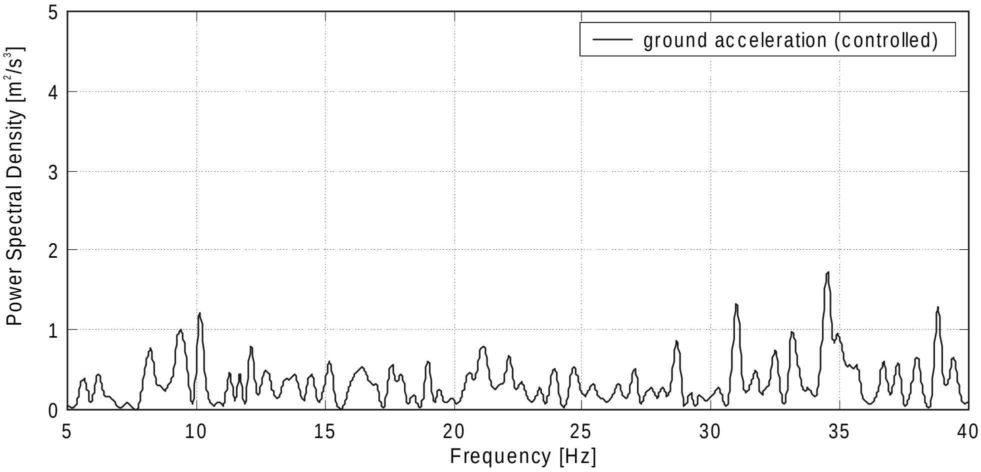

Figure 4: Controlled ground acceleration input

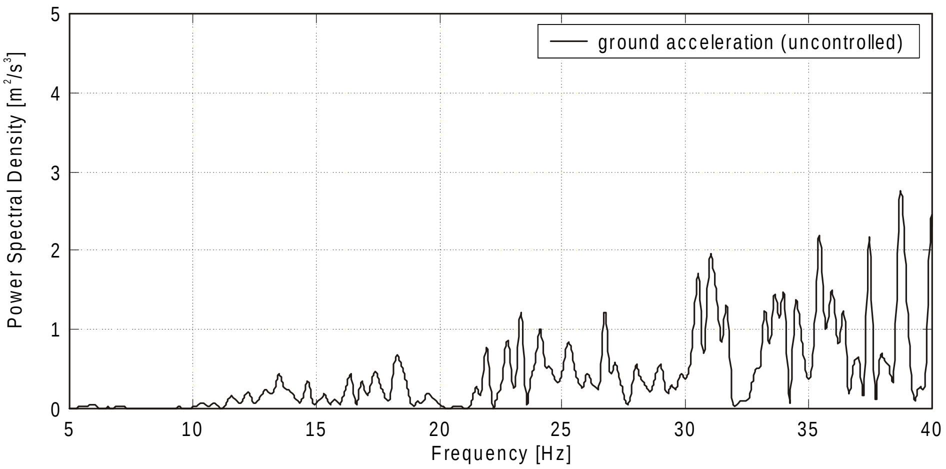

Figure 5: Original ground acceleration input

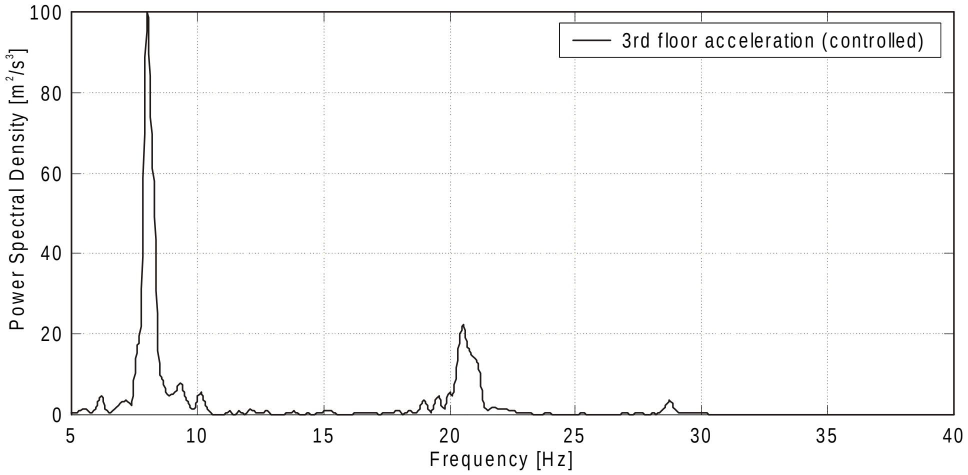

Figure 6: Third floor response, ground acceleration controlled

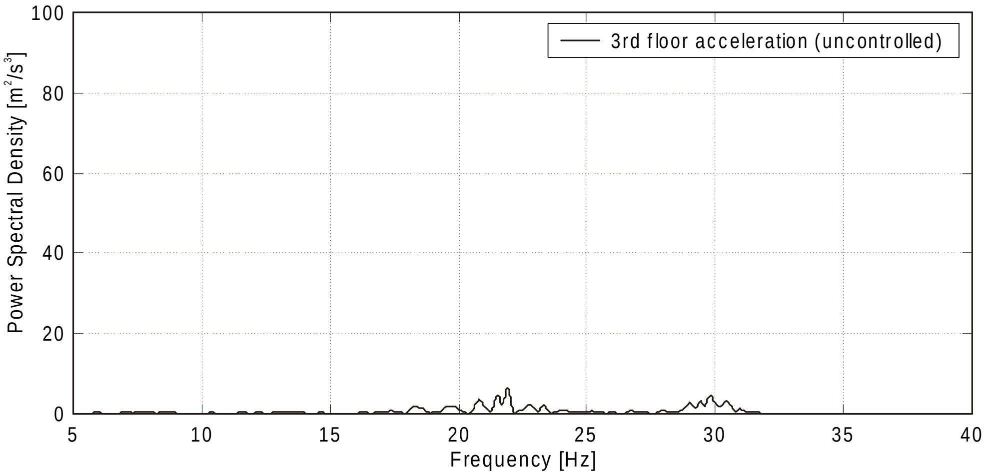

Figure 7: Third floor response, ground acceleration uncontrolled

Fig. 6 and Fig. 7 show the measured acceleration at the third floor for the same input signal. The peaks in Fig. 6, typical for a structural response signal, indicate excitation in the entire frequency spectrum whereas the absence of these peaks in Fig. 7 show that the lower natural frequencies are not excited in the uncontrolled experimental setup.

For further demonstrating the effectiveness of the proposed controller Fig. 8 and Fig. 9 show the tracking performance of the original and the improved acceleration controlled setup. Almost perfect behaviour is achieved, but a high frequency chattering can be found in the measured acceleration input signal. This chattering effect can be reduced by the introduction of a so called boundary layer, a method well established in sliding mode control. However, this also decreases the tracing performance as reported in [8]. Because the chattering frequency (more than 1 kHz) is well separated from the highest natural frequency of all investigated structures it does not influence the building dynamics and can therefore be accepted.

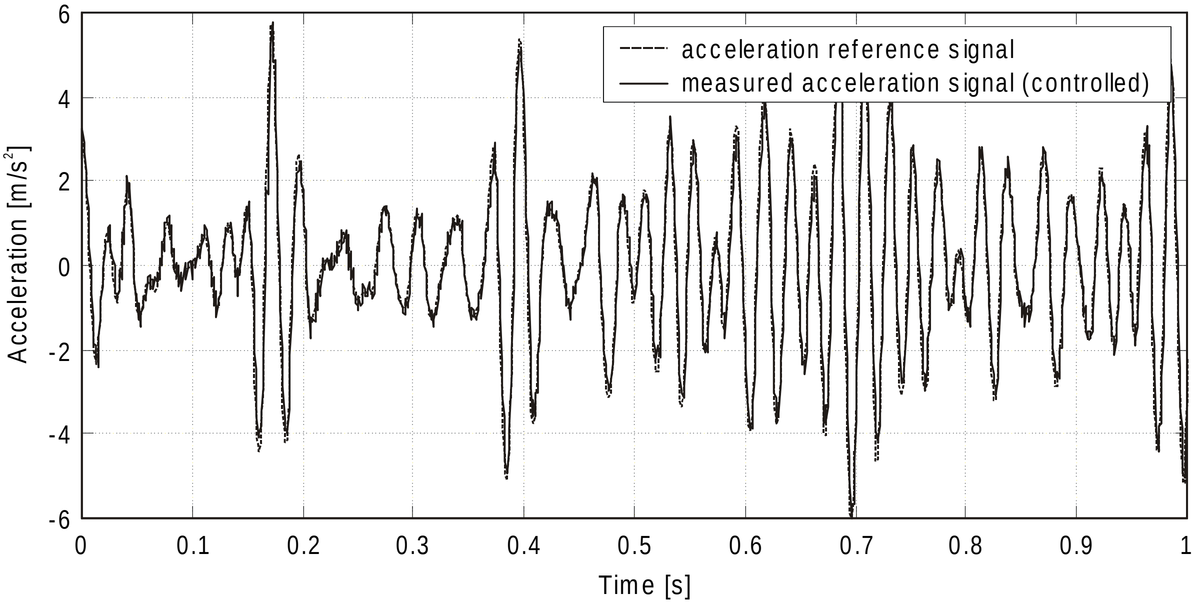

Figure 8: Reference and measured signal with feedback control

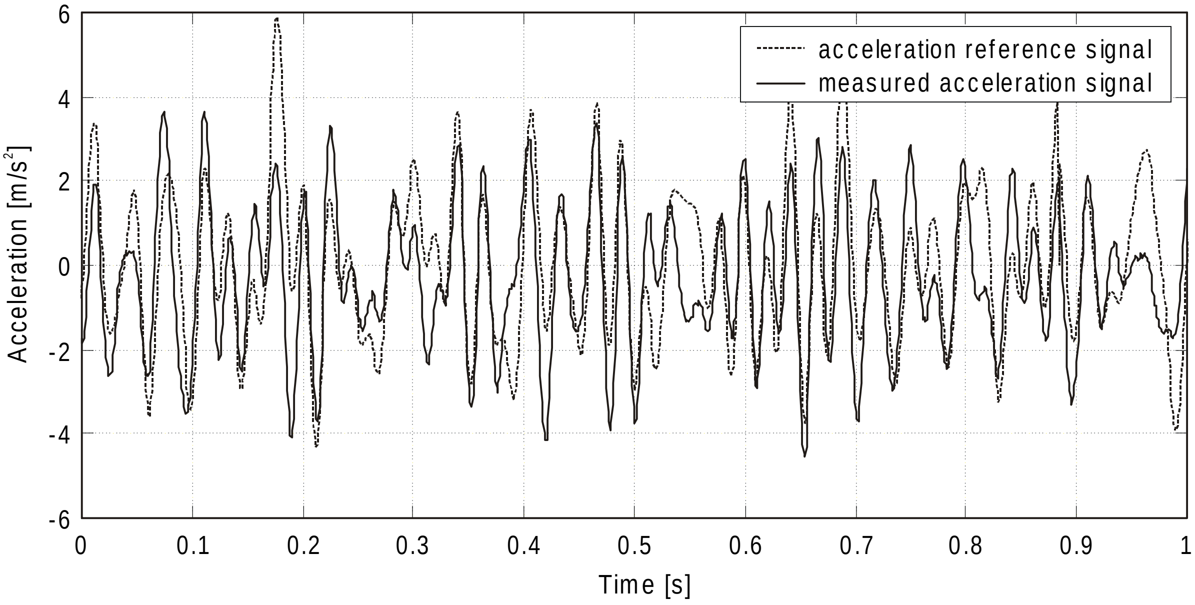

Figure 9: Reference and measured signal without feedback control

The same experiments are also performed with a slightly modified structure in which the elastic steel columns of the second floor are replaced by elastic-plastic ones. The results are very much the same but it has to be mentioned that the performance is even better due to the energy absorbing characteristics of elastic-plastic vibrations. This reduces the maximum force in the foundation allowing a small electrodynamic shaker to generate stronger acceleration inputs. As mentioned in the previous section the proposed control design which is independent of the actual plant characteristics works perfectly up to a maximum acceleration input which is limited by the shaker.

CONCLUSIONS

This paper reports the development of a controlled shaking table setup, its successful implementation and verification on several multi storey test structures. Although difficult to achieve, an accurate ground acceleration is essential for reliable and accurate testing of structural models used for the prediction of the behaviour of real structures. A possible acceleration control law is presented guaranteeing high robustness and easy implementation into existing shaking table setup. The frequency dependent, dynamic effect of actuator-structure interaction is eliminated by the introduction of a feedback control loop.

Experiments are conducted for both, elastic and elastic-plastic structures with varying degrees of freedom and natural frequencies spread over a wide frequency range. The results show the improvement over the original setup and prove the system to work stable and reliably.

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