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Project “E-Defense”, Control System Architecture

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ABSTRACT: Project “E-Defense” now under construction in Miki, Japan will be the world’s largest 3 Dimensional seismic simulation table when completed in 2005. The scale of the shaking table requires 44 of the world’s largest servovalves powering 24 enormous actuators.

This paper describes the real time control architecture consisting of six separate and specialized controllers that was developed to meet the significant controller challenges of the Project “E-Defense” shaking table. Five of the real time controllers communicate through a fiber optic shared memory system. The primary controller is the 3 Dimensional (6 DOF) table controller that utilizes the latest table control methodologies. It communicates with the table through three specialized servovalve controllers located nearer the table that also collect the actuator feedbacks. The fifth controller is a specialized data output controller while the sixth controller is a totally separate data logger that records selected actuator and servovalve signals while also monitoring table operation to insure that the large scale shaking table remains stable within its operating parameters.

1 INTRODUCTION

Project “E-Defense”, (NIED Reference) what will soon be the world’s largest shaking table, presented a number of unique challenges for the design of it’s control system. First, it was essential that the best proven shaking table control techniques be incorporated into the controller in order to achieve the highest fidelity of wave form reproduction. Second, the large physical scale of the system means the large distances between the control room and the shaking table exceed the recommended range for noise free transmission of the feedback and control signals. Third, the large capacity of the system requires many more physical components than a usual shaking table to provide the huge forces and displacements necessary(Ogawa 1999,2000) (Rood, 2000). Finally, the any control design solution must make innovative use of only proven technologies such that reliability and maintainability of the system meets the needs of the research objectives for the shaking table through it’s planned operating life.

The controller design solution presented herein was developed by asking the age honored Engineering questions of “What do you want it to do?” and “How are you going to do it?” Since the answer to the second question is totally dependent on the answer to the first question, we first present the set of proven basic shaking table control techniques that have been shown to provide the best fidelity of earthquake wave for reproduction and were thus selected to be a part of the “Project E-Defense” control system design capabilities, then we present the advanced control techniques, and finally we will present the control hardware architecture necessary to implement those techniques.

2 BASIC CONTROL TECHNIQUES

The basic control techniques incorporated into the design are Degree of Freedom control, Three variable control, delta-P compensation, Servovalve Flow Linearization, Lead Terms, and Notch Filters. These control techniques have been presented elsewhere in the literature and/or patents and our discussion herein will be limited to the reasons why our selection of those techniques is appropriate for “Project E-Defense”

Degree-of-Freedom Control, or DOF, for controlling the table motion in the coordinate domain rather than the actuator domain. The table motion is a result of 24 independent actuators, (Ogawa 1999) which must be time synchronized to achieve the desired motion. While the desired motion of an earthquake shaking table is just the 3 linear degrees of freedom, (usually referred to as the X,Y and Z degrees of freedom) it is not efficient to mechanically constrain the rotational degrees of freedom (yaw, pitch, and roll). Degree-of-Freedom Control accomplishes this synchronization by transforming all individual actuator feedback signals into a degree-of-freedom feedback signal where in earthquake records, the rotational axes are controlled to zero. Each degree-of-freedom composite error signal is then transformed into individual actuator commands. Stability and tuning are greatly improved for systems operating in the coordinate domain as compared to the actuator domain.

Three Variable Control (TVC) allows for high fidelity reproduction across a wide frequency bandwidth. TVC includes a reference generator and velocity computer for deriving command and feedback signals in displacement, velocity, and acceleration. The wide frequency bandwidth associated with seismic time histories is best achievable by controlling for displacement at low frequencies, velocity at mid range frequencies and acceleration at the higher frequencies

Delta Pressure Stabilization (DPS) for effectively dampening oil column compliance to allow for higher gain settings across a wider bandwidth. As is true in virtually all servohydraulic shaking tables, the actuators will have an oil column resonance within the bandwidth of the earthquake motions. The ability to maintain high gain settings without decreased stability from this resonance is critical for high fidelity seismic waveform reproduction.

Servovalve Flow Linearization (SFL) for effectively removing the inherent non-linearities present in all servo hydraulic system. SFL significantly reduces the potential for errors in desired motion with respect to velocity and acceleration profiles.

Lead terms, in a seismic system, where there are large masses and high velocity and acceleration requirements, there is a maximum amount of gain that can be applied to the control loop and still ensure table stability. To enhance system response when it is not possible to apply more gain, high fidelity seismic test control systems contain lead terms. The displacement, velocity, acceleration and jerk (derivative of acceleration) lead terms effectively feed forward an operator-adjusted amount of the command (reference signal) into the composite error signal to provide system performance beyond the optimum stabilized response otherwise available.

Force balance compensation is required in systems where more than one actuator affects the control of any translational or rotational axis (that is, where systems are “over-constrained”). The seismic test system, with 24 actuators controlling the 6 degrees-of-freedom is an seriously over-constrained system. The force “imbalance” can seriously limit the force capability of the actuator system. If a table is considered a rigid body, three actuators completely define the plane of the table (one each for X motion, Y motion and Yaw control). A fourth actuator, if not perfectly balanced, may exert large forces to try to distort the stiff table into a shape out of the plane of the other actuators. In “Project E-Defense” there are 10 horizontal actuators, 7 of which are over-constraints on the system. Therefore, due to the high stiffness of a typical seismic table, small errors in the actuator position can cause large internal table forces to be generated. The Force balance function compensates for this effect by essentially adding more degrees-of-freedom, which are all controlled to zero using a PID controller.

Notch filter compensation provides the ability to tune the system for high gain over the entire operating frequency range by selectively adjusting gain at system and specimen resonant frequencies. The Notch filter technique employed is non-linear with adjustable peak amplitude and has linear phase.

All the above techniques can be implemented either in an all analog controller or in an analog/digital hybrid controller. Starting in the mid 1990's, success has been achieved using the hybrid analog/digital approach. This approach uses analog control for the innermost control loop, that of the intermediate servovalve control loop, while using digital control for all the outer control loops. The use of digital control for the outer loops, not only increases system control flexibility for the operator, it also allows for the use of some advanced control techniques.

3 ADVANCED CONTROL TECHNIQUES

The proven advanced control techniques included in the system control design are Amplitude Phase Control, Adaptive Harmonic Cancellation, and Adaptive Inverse Control. These are also described in the literature and /or patents and our discussion is limited to the reasons why they are included in the design of the "Project E-Defense" control system.

Amplitude Phase Control, or APC, provides a technique for the automatic correction of amplitude and phase errors during sine wave testing. A network of time domain digital filters measures the system input and output to detect errors in amplitude and phase. The input signal is than automatically scaled by the inverse of the amplitude error and shifted by the negative of the phase error. APC quickly reacts to changes in the system to maintain minimal error in amplitude and phase even when changing system dynamics are present. (Thoen 1992)

Adaptive Harmonic Cancellation, or AHC, provides a technique for the control and elimination of harmonic distortions during sine wave testing. AHC is based upon the technologies developed in the science of active noise cancellation. AHC automatically eliminates unwanted harmonics by adding a signal with exactly the right phase and amplitude such that the harmonic is cancelled. AHC automatically adjusts to changes in the system or specimen response. Note: Amplitude Phase Control and Adaptive Harmonic Cancellation can be used simultaneously for reducing linear and non-linear errors when performing sine wave testing.

Adaptive Inverse Control, or AIC, provides a technique for reducing linear distortions during random waveform testing. AIC uses a digital filter to measure the frequency response function of the system. The command signal is than scaled by the inverse of this function so that the overall frequency response is closer to unity. AIC automatically adjusts to changes in the system or specimen response. (Thoen 1994)

Finally, there are times when the shaking table control is desired to be further improved with iteration. The controller includes a built in On-Line Iteration approach and also provides the capabilities for implementing external iterative approaches. (Thoen 1995)

These control techniques were tested in the "Project E-Defense" prototype constructed in Shimonoseki Japan having 8 "E-Defense" actual sized actuators controlled by 16 actual sized high flow servovalves and were found to provide the necessary high fidelity control under a rigorous testing program.

4 CONTROL HARDWARE DESIGN CONSIDERATIONS

For "Project E-Defense" having answered the question what we want the control system to do, we are then faced with the question of "How to do it?" or more specifically, what hardware configuration can be used that provides the capability to reliably monitor all feedback signals and also provides the necessary capabilities to compute the needed command signals to achieve the high fidelity wave form reproduction.

In a more standard sized shaking table, this is done by putting a single controller in the control room. The distances to the feed back transducers are normally well within the allowable distances for low noise transmission of the feedbacks and the number of components (usually 8 actuators and 8 regular 3 stage servovalves) are well within the computational capabilities of a single controller.

The Shimonoseki prototype with 8 actuators but 16 high flow servovalves required an modifying the standard approach through the addition of a separate servovalve controller in the control room. Analog signals were used to transmit the feedback and the control signals between those 2 controllers.

For “Project E-Defense” however, even such a modified approach would not work. The distances involved from the transducers to the control room are commonly in the range of 200 meters, twice the accepted range for the low level feedback signals. Further, the number of transducers (165) is greatly in excess of those that can be conditioned in one or even two controllers.

5 SHAKING TABLE CONTROLLER HARDWARE DESIGN

The solution to these problems was the decision to have a second control room, located closer to the table, for the servovalve controller(s), and such a room has been designed and built into the foundation of “Project E-Defense”. It was also decided that the servovalve controllers would house the conditioners for the actuator and table transducers. This reduced the distance to the transducers to 100 meters +/-, the same distance that was effective for the control of the prototype system. As the room is within the concrete foundation, a remote on/off and the operators Graphical User Interface PCs (GUI) for all controllers in that room obviously must be located in the main control room.

The next decision was the type controller hardware to use. The prototype used a VME based system having imbedded GUI computers with control computations being done with multiple DSP processors and having separate conditioners and valve drivers. While this system was successful, it’s continued manufacture depends on using electrical sub-components that the components manufacturers have announced will be discontinued within the next few years. Therefore, using the prototype controller hardware was not a feasible option for the actual “Project E-Defense” system whose research life is expected to last well into this 21st Century.

Meanwhile, a new VME real time controller architecture had been developed using electronic components that are projected to be available during the life of “Project E-Defense”. The new hardware design uses an imbedded Power PC for control calculations, uses conditioners mounted on VME daughter cards and has a separate PC for the operators GUI. The new hardware appeared ideal for “Project E-Defense” but unfortunately, this design was only available in a 10 VME slot configuration which would have required 7 servovalve controllers, a large, uneven and confusing number of controller components. Our design indicated that if a 20 slot VME was available, it would have sufficient capability that we could utilize one servovalve controller for each principal axis (namely a X, a Y and a Z axis controller). Three controllers, one per axis, made good sense. Therefore, we developed such a 20 slot hardware configuration for use on the “Project E-Defense” servovalve controllers and have successfully tested it by implementing it to control existing and new 6 DOF shaking tables.

The actual table controller that receives the feedback signals, transforms them into DOF space, computes the corrections in DOF space, then transform said corrections into servovalve commands in actuator space will be located in the main control room.

The next major decision was how to transfer the transducer feedback signals from the servovalve controllers to the table controller and send the command signals out to the servovalve controllers. In the prototype, this transfer was done by transferring analog high level signals. For the actual “Project E-Defense”, this would have required over 2 kilometers of 2 pair wire, plus 400+ cable connections, each of which is a possible source of maintenance difficulties. Therefore, for the actual “Project E-Defense” we decided that all controllers will be interconnected with a proprietary, commercially available, shared memory network scheme called “Scram-Net” (TM, Systran Corporation) such that the command and feedback signals can be passed digitally between controllers. This not only increases the reliability of the whole controller architecture, it also reduced the latency of signal transmission.

The controller hardware architecture described above allows us to fully implement the desired basic and advanced shaking table control techniques while making maximum use of already fully developed and tested software for many of the controller functions.

6 ADDITIONAL CONTROLLERS

Given we had chosen a shared memory approach to interconnect the servovalve and table controllers, this introduced the option of adding another controller just for data output functions. During a test, various controller feedbacks and sometimes commands are desired to be recorded as part of the test record. Our experience during the prototype stage was that the time required for setting up that data recording function on the table controller conflicted with the smooth progression of the test sequence. Therefore we added a 5th controller whose only function is to serve as the analog outlet for all desired data from the table system during a test, said data being made available to that controller through the "Scram-Net".

Finally, a 6th independent controller was specified as part of "Project E-Defense" just for the purpose of logging separately obtained data on the movements of the shaking table for future analysis. This controller was specified to receive and convert independent analog data for 8 of the 24 actuators. During the design process, it was decided the scope of this controller could be increased to include a separate independent check of the velocity and displacement limits during of the dynamic operation of the table as well as an operational check on the status of all the other controllers. In effect creating a master safety controller.

7 CONCLUSIONS

We propose that the shaking table controller design presented herein has met our four design challenges. First, it does incorporate the best shaking table techniques while minimizing the effects of the large distances and number of components and it is accomplishing all this with innovative use of only proven technologies.

Final judgment, of course, must await commissioning of "Project E-Defense" in 2005 but we are confident this design will be successful and will be instrumental in "Project E-Defense" providing years of valuable large scale test results to the research community.

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