NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

State University of New York at Buffalo

ACTIVE ISOLATION FOR SEISMIC PROTECTION OF OPERATING ROOMS

by

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NOTICE

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PREFACE

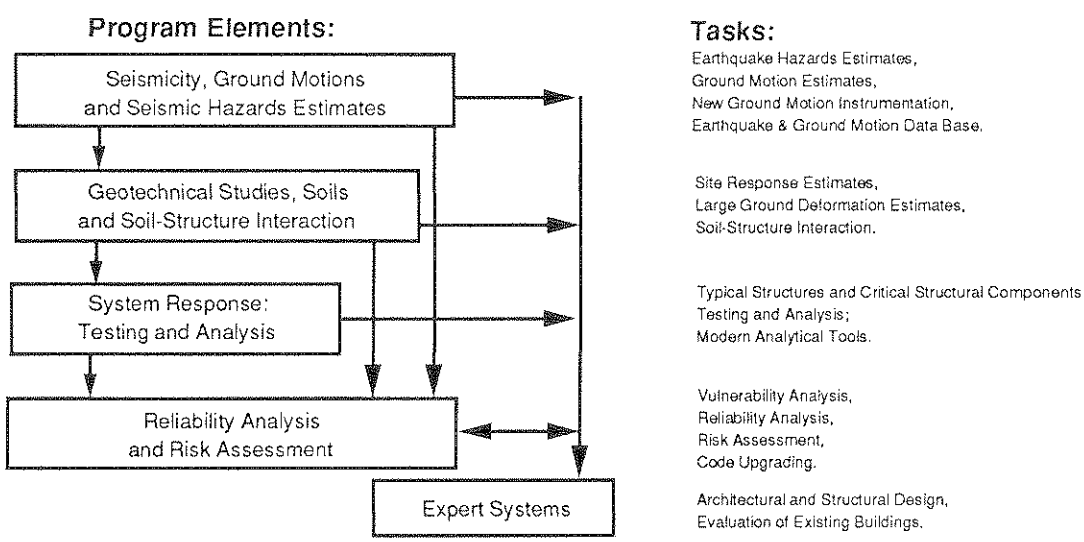
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 1, Existing and New Structures, and more specifically to reliability analysis and risk assessment.

The long term goal of research in Existing and New Structures is to develop seismic hazard mitigation procedures through rational probabilistic risk assessment for damage or collapse of structures, mainly existing buildings, in regions of moderate to high seismicity. This work relies on improved definitions of seismicity and site response, experimental and analytical evaluations of systems response, and more accurate assessment of risk factors. This technology will be incorporated in expert systems tools and improved code formats for existing and new structures. Methods of retrofit will also be developed. When this work is completed, it should be possible to characterize and quantify societal impact of seismic risk in various geographical regions and large municipalities. Toward this goal, the program has been divided into five components, as shown in the figure below:



Reliability analysis and risk assessment research constitutes one of the important areas of Existing and New Structures. Current research addresses, among others, the following issues:

1. Code issues - Development of a probabilistic procedure to determine load and resistance factors. Load Resistance Factor Design (LRFD) includes the investigation of wind vs. seismic issues, and of estimating design seismic loads for areas of moderate to high seismicity.
2. Response modification factors - Evaluation of RMFs for buildings and bridges which combine the effect of shear and bending.
3. Seismic damage - Development of damage estimation procedures which include a global and local damage index, and damage control by design; and development of computer codes for identification of the degree of building damage and automated damage-based design procedures.
4. Seismic reliability analysis of building structures - Development of procedures to evaluate the seismic safety of buildings which includes limit states corresponding to serviceability and collapse.
5. Retrofit procedures and restoration strategies.
6. Risk assessment and societal impact.

Research projects concerned with reliability analysis and risk assessment are carried out to provide practical tools for engineers to assess seismic risk to structures for the ultimate purpose of mitigating societal impact.

This study shows that the seismic integrity of an operating room can be enhanced by implementing a hybrid control device and that by doing so, the risk associated with delicate operations being jeopardized by minor to moderate earthquakes can be reduced. Without such a device, surgeons and nurses may not be able to respond properly to the floor motion caused by these low level but more frequent earthquakes.

ABSTRACT

The fields of physiology and psychology do not often overlap with that of structural engineering, but research on the protection of operating rooms from earthquakes is a common ground for these and other disciplines. An evaluation of the protection of operating rooms from microtremors and frequent low-level earthquakes must take into consideration the threshold limits of the human response to vibration. In this paper, these threshold limits are adopted from a 1978 International Organization for Standardization (ISO) Standard on human response to vibration and are used as maximum limits for the evaluation of the performance of an active isolation device. The active isolation device, which is used to minimize the effects of the input vibration on the operating room, is an actual 6DOF combined passive and active floor isolation unit designed by the Takenaka Corporation and known as TACMI. An idealized SDOF computer model of the TACMI device was tested using the accelerogram of the NS component of the 1940 El Centro earthquake. The active control is based on an open-closed loop instantaneous optimal control algorithm which was found to be more effective than either an open loop or a closed loop algorithm. The responses of the uncontrolled and controlled systems are compared to the human vibration perception levels in the ISO Standard, showing that the active isolation model is able to reduce rms acceleration to a level close to that of the human perception threshold. Based on these tests, it is proposed that active isolation devices like TACMI which, until now, have only been used to protect equipment or manufacturing processes, may also be installed in operating rooms or other areas where humans must perform delicate tasks.

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SECTION 1
INTRODUCTION

In areas with high seismic activity, such as Los Angeles, San Francisco, and Tokyo, inhabitants live with the constant threat of "the Big One," the expected great earthquake that will destroy entire cities and kill millions of people. In Tokyo, it is the fear of the recurrence of the Great Canto Earthquake of 1923, measuring 8.3 on the Richter scale. In California, it is the fear of a repeat of the 1906 San Francisco earthquake (M = 8.3). As evidenced by the comparatively minimal damage experienced in the San Francisco area from the October 17, 1989 Loma Prieta Earthquake (M = 7.1), large-scale destruction by these natural disasters can be avoided by carefully adhering to seismic design codes when planning any lifeline network system or structure. However destructive the awesome power of a large earthquake may be, each year millions of dollars are lost to damage caused by earthquakes that are not strong enough to cause structural damage at all. These frequent "weak" earthquakes (less than 5.0 on the Richter scale) disrupt processes that take place within structures, without directly damaging the structure itself. The operation of delicate computer equipment and sensitive manufacturing processes such as those employed by the silicon wafer manufacturing industry can be disrupted and damaged as a result of weak earthquake ground motion [30]. Even building codes which protect the buildings themselves cannot solve this problem. In order to greatly reduce the damage caused by weak earthquakes, new systems must be developed and explored. New technology being developed in areas of base isolation and active control of secondary systems such as operating rooms and laboratories may hold the answer to the protection of these delicate procedures in the event of an earthquake.

In 1985, T. Fujita developed the idea of "active isolation" as a proposed application for the protection of fragile silicon monocrystals during production [30]. Active isolation combines two aspects of seismic control: active control and passive base or floor isolation. While experiments by Fujita, et al. with a one-dimensional active isolation model were unable to overcome all shortcomings of the dual system, they were able in some instances to achieve a 5% greater reduction in acceleration and displacement over that realized with passive isolation alone [32]. As a continuation of research in this field several Japanese construction firms, including Takenaka, Kajima and Shimizu, have developed active floor systems for use in computer rooms. Up to the present time, the application of these systems has been primarily in the area of protection of computers or equipment for manufacturing products. The applicability for use in human surroundings has not been widely explored, primarily due to the high cost of such systems and because injury to humans during weak earthquakes is uncommon. However, in operating room conditions where the slightest extraneous movement during laser surgery, for example, could mean disaster, it is imperative that a system such as active isolation be used.

Base isolation is a method of protecting a structure from vibration in a passive sense, usually by mounting the structure on thick rubber pads and often by additionally supporting it with viscous oil dampers to absorb the vibration between the ground and the structure. The concept is based on the idea that the rubber pads, or isolators, are able to deform greatly elastically and will do so in an earthquake, thus allowing the structure to move as a rigid body, minimizing the damage. Isolation techniques are also used in floor systems, using stainless steel rollers in lieu of rubber isolators, in buildings where secondary systems and equipment such as computer networks are mounted and protected from potential damage from earthquake accelerations and displacements. These passive isolation techniques have been demonstrated to provide a significant decrease in the accelerations and displacements experienced by the equipment; however, even these reduced quantities may be too large to permit the continuation of some delicate manufacturing procedures during even weak earthquakes [32]. For this reason, active control combined with passive base isolation is proposed as a method of further reducing the earthquake effects and bringing them within a level acceptable for execution of these procedures. Active control provides a time-varying control force to a system to counteract the time-varying earthquake input, essentially cancelling the input force to minimize the force felt by the system. Although active control has been used in other fields for many years, the application of active control to civil engineering structures has developed within the last ten years. One model of a combined active isolation system is shown in Figure 1-1.

Because of their sense of balance, humans are able to automatically adjust themselves to certain types of external motion, typically, that of a floating structure or a moving train. However, there is a certain displacement and acceleration threshold beyondwhich humans cannot automatically adjust. Motion above this threshold disturbs humans to the extent that activities such as surgical operations are jeopardized. This human response threshold dictates the extent of applied control that is necessary during an earthquake to maintain standard operating conditions. Using the human response threshold as the basis for the maximum acceleration values that may be permitted, a control algorithm may be developed for control of the isolated operating room floor. By using this technique, the floor acceleration can be reduced to a level well below that of the human response threshold.

It is emphasized that these procedures are to be used in cases of weak earthquakes. In earthquake-prone regions, weak earthquakes (too weak to cause structural damage, but strong enough to disrupt a sensitive procedure) occur often, while stronger quakes are infrequent. It is expected that the larger quakes which cause damage will also cause an interruption of delicate procedures such as laser surgery. However, this control system is not expected to be required to counteract these strong, yet infrequent earthquakes. No control system can be expected to withstand the extreme forces experienced by ground shaking in a major earthquake. Even if a system were designed to try to counteract moderately strong quakes, the system would have to be very massive and would require a large energy input, because of the large magnitude of the control forces necessary. Since strong earthquakes occur infrequently (in some cases with a return period many times longer than the lifetime of the structure), the benefits from the higher cost of the expanded system may never be realized. This proposal for the use of combined active control and base isolation will render the majority of weak quakes innocuous, enabling operations to continue as normal.

This report is concerned with the definition of the human response factor and the implementation and feasibility of the active isolation system in conjunction with precision operating room work.

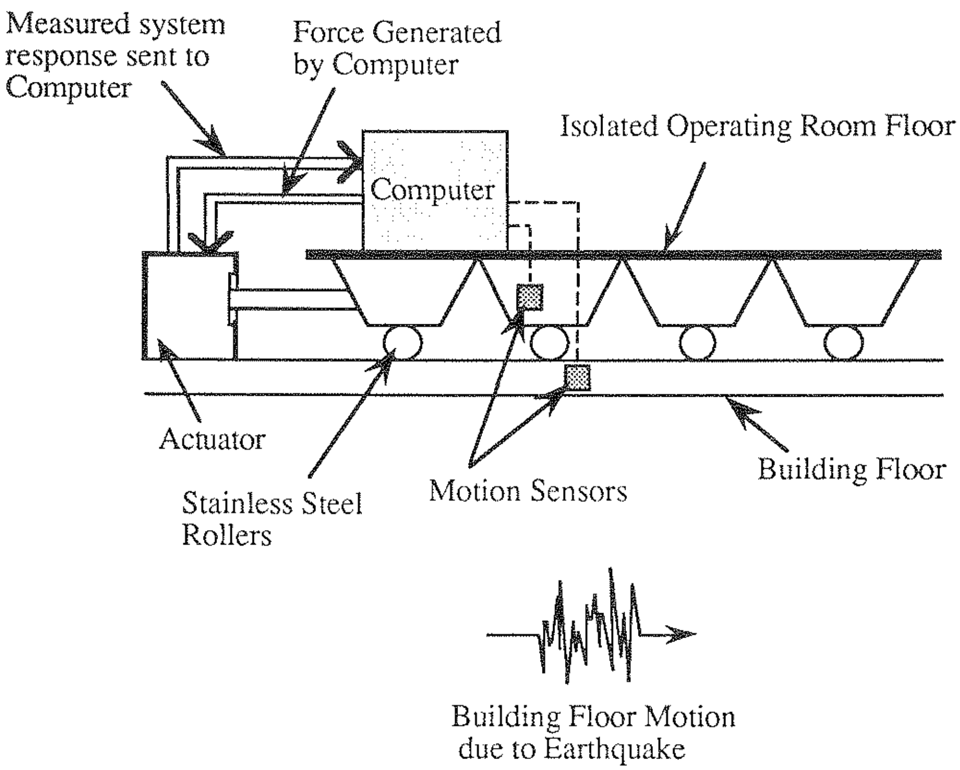


FIGURE 1-1 Model of active isolation system

SECTION 2
HUMAN RESPONSE TO VIBRATION

A primary concern in installing an active isolation floor system is the determination of parameters of the system: the maximum allowable levels of displacement, velocity, or acceleration. When using such a system to protect computers or equipment, it is relatively simple to determine these parameters, since, in most cases, the vibration exposure limitations of the individual pieces of equipment are given by the manufacturer. In the case of installation of an active isolation floor system in an operating room, however, the limiting parameters are not determined by the limitations of machines. They are instead governed by the physical vibration perception threshold levels of the humans working in the room.

2.1 Overview of Past Research

The study of human response to vibration has been a subject of concern for scientists in many fields for a variety of situations, and for many types of vibrations. In general, human beings are subjected to vibrations from three main types of sources: vibrations directly transmitted to a part of the body, such as through a hand-held tool like a pneumatic drill; vibrations simultaneously transmitted to the entire body when it is immersed in a vibrating continuum; and vibrations transmitted to the body through a supporting structure, such as a vehicle seat or a vibrating building [12]. The last source is representative of the type of vibration experienced by people in an earthquake-excited structure. Reiher and Meister initiated research on this subject with the publication of their experimental studies of the effects of both horizontal and vertical whole-body sinusoidal vibration on humans in 1931 [17]. They developed the idea of the constant comfort curve for use in correlating subjective levels of response with the vibration amplitude and frequency. Research in this area continued with experiments on human response to seat-transmitted vibration, beginning in the early 1950's with tests made by the United States Air Force on the effect of cockpit vibration on the visual acuity of the pilot and his ability to make decisions.

This research continued with several studies on the effects of vehicle vibrations on truck drivers, tractor riders, and heavy equipment operators [1]. In the late 1960's, as taller and thinner buildings were becoming more common, serviceability limit states of movement due to high wind became a concern of both engineers and psychologists [3]. Several experiments made to determine what effect the movement of buildings had on the occupants were the first in a series of tests on human response to vibration of structures [7]. In 1976, Shinozuka et al. continued these studies of human/structure interaction in a paper on human habitability of offshore structures subject to wave motion [20]. In the 1970's and 1980's many researchers attempted to repeat and expand upon the original Reiher and Meister experiments [4,14,16,18]. Many tests were performed on humans in standing, sitting, and reclining positions using a variety of vibrational input, including random vibration, impact vibration, and sinusoidal vibration. Specific papers cover a broad range of topics in this area, from perception of human footfall-induced vibration on wood floors [8], to annoyance caused by building vibration due to large wind turbine generators [19]. In 1978 and again in 1984, the International Organization for Standardization (ISO) developed a series of standards specifically devoted to the evaluation of human exposure to whole-body vibration [12]. As a corollary to these general standards, specific guidelines were composed to address the issue of the response of occupants in structures subject to horizontal motion, including earthquake motion [11]. Other types of vibration that affect structures include traffic, railroads, blasting, internal machinery, and wind [7,10].

The definition of human response threshold levels has posed an interesting problem to scientists. Most experiments on human response to vibration involve subjecting many people to varying levels of vibration and asking them to rate their comfort level, or ability to perceive motion, on a subjective scale. For example, in the original Reiher and Meister experiments, subjects seated on a vibrating seat were asked to rate the vibration as imperceptible, just perceptible, clearly perceptible, annoying, unpleasant or disturbing, or painful [17]. The psychological determination of personal comfort varies among individuals and is dependant on age, sex and health. However, there does exist a narrow envelope in which humans generally agree on the comfort level for a particular frequency or amplitude of vibration. Other factors which may affect the results of an experiment are expectation of motion and acclimatization of the subject to the experimental procedure. Careful attention must be paid to the exact duration and type of vibration when comparing results from different experiments, since no correlation may be drawn between those concerned primarily with long duration sinusoidal vibration and others concerned only with short impulse vibration. Since most civil structures, in particular, buildings, are not traditionally places in which occupants expect to experience motion, humans tend to express extreme concern over any perceptible building motion, even if it is well below the structural limitations of the building itself [13]. This psychological aspect of fear of collapse is an area that is seldom dealt with in studies devoted to human response to vibration of structures [5]. However, this aspect should be considered with respect to future research on overall human annoyance from vibrations.

2.2 The ISO Standard

Vibrations may affect humans with varying degrees of severity. On the most basic level, comfort and quality of life may be reduced [21]. Working efficiency can decrease, and in some extreme cases of long-term exposure, structural vibrations may pose a health hazard [17]. Vibrations of the duration and magnitude necessary to warrant a health hazard will undoubtedly cause damage to the building structure as well. The ISO Standards are concerned with the development of boundary curves related to three different vibration concerns: comfort, working efficiency, and health safety. The names given to the respective ISO threshold boundary curves are, "reduced comfort boundary" (RCB), "fatigue decreased proficiency boundary" (FDPB), and the "exposure limit" (EL) [11]. In the ISO Standard, experimental and practical data for both vertical and horizontal vibration is gathered in the frequency range from 1 to 100 Hz, and curves are developed for maximum allowable acceleration levels for each threshold boundary. Various vibration exposure times, from one minute to 24 hours, are examined.

The ISO Standard develops a method of determining the three threshold boundary curves, RCB, FDPB, and EL, in terms of the vibration frequency, acceleration magnitude, exposure time, and direction of vibration relative to the human torso [11]. Although the computer model used in Section 4 of this paper is a single degree of freedom model, taking into consideration only one horizontal component of the earthquake force, in actuality the earthquake ground acceleration is comprised of both vertical and horizontal accelerations. It is therefore important not to ignore the effects of vertical motion in the ISO Standard. In fact, ISO proposes using a combined curve which represents the weakest cases of both the horizontal and vertical response curves (see Figure 2-1).

The definition of the degree of the effect of structural vibrations on humans is dependent on the type of building and the kinds of tasks performed within the building. For example, workers in a warehouse will have different working efficiency requirements than do scientists in a laboratory. Both Splittgerber [21] and Ashley [2] discuss the proposed use of weighting factors to correlate building usage with the ISO boundary curves. Building usage is divided into major categories, and the weighting factors are given for both day and night usage, as shown in Table 2-I.

The base RCB curves of Figure 2-1, determined from experimental data in a proposed addenda to the 1978 ISO Standard [2], are multiplied by these weighting factors to yield corresponding curves for the various categories of building usage. As noted in Table 2-I, hospital operating rooms are considered to be the most critical working areas. The perception limits are multiplied by a factor of one, so that they remain at the minimum level. These limits are listed as appropriate for hospital operating room areas, even to those persons who are more sensitive to vibration [13]. This table appeared in a proposed addendum to the ISO Standard in 1978, and was adopted by the Standard in a subsequent revision.

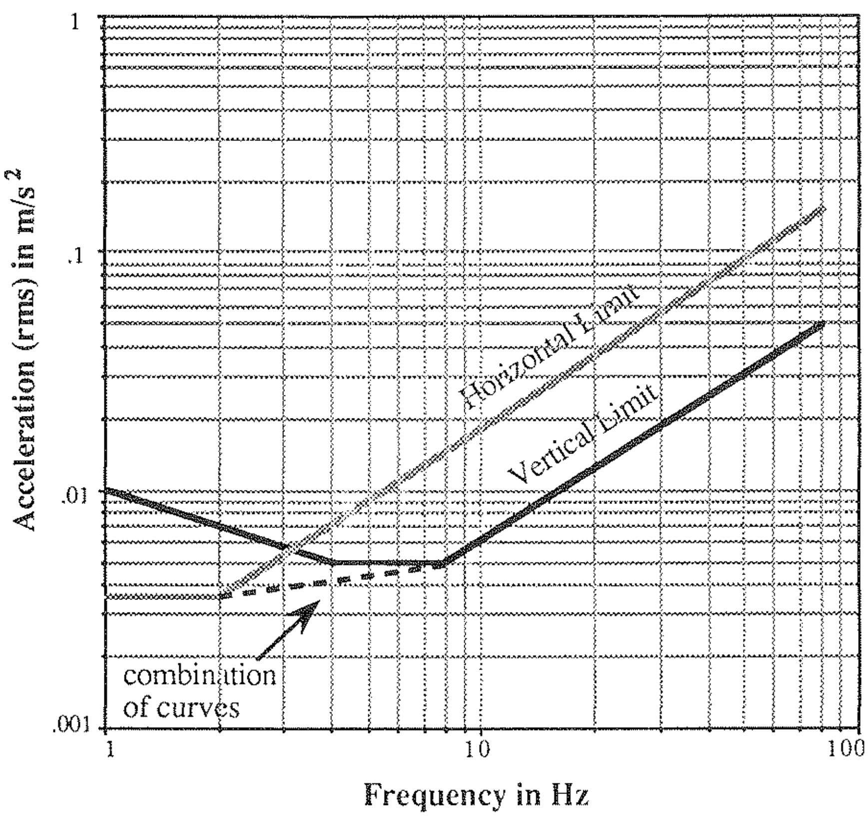


FIGURE 2-1 Base curves for human horizontal and vertical vibration perception limits in buildings, taken from [2], Fig. 2, p. 160.

TABLE 2-I Weighting factors for acceptable building vibration, corresponding to types of building usage. Taken from [21], Table 1, p. 150.

Building usage	Time	Weighting factor for Impulsive shock excitation (less than 3 times a day)
Hospital operating rooms and critical working areas	day night	1 1
Residential	day night	16 1.41
Workshop & Office	day night	128 128

2.3 Parameters

There is a disagreement among researchers over the proper parameter to express human perception of vibration. Displacement, velocity, acceleration, and jerk [the time derivative of acceleration) have all been proposed as appropriate parameters, and in some cases the use of different parameters for different frequency ranges has been suggested [13,15]. Acceleration is often used as a parameter because humans are sensitive to it and because it is easily measured by current equipment [13]. Acceleration is also a quantity that is often measured in determining the response of structures to vibration, and in this way studies on structural response and human response may be combined. In the ISO Standard, the root mean square (rms) value of acceleration in meters per second squared (m/s^2) is used to describe the intensity of the vibration environment. The rms value of acceleration is given as:

$$a_{rms} = \sqrt{\frac{\sum_{n=1}^{N} (a_n)^2}{N}} \tag{2.1}$$

where N is the number of measured acceleration points in the vibration time-history, and a_n is the value of the acceleration at each of those points. This measurement is representative of the vibration time-history for narrow-band or sinusoidal motion, although, for random or broad-band vibration (like earthquake vibration), often the rms acceleration does not reflect actual peak motion [6]. For this reason, the crest factor, defined as:

$$\text{crest factor} = \frac{\text{maximum peak acceleration}}{\text{rms acceleration}} \tag{2.2}$$

is used as a parameter characteristic of the input ground motion. For crest factors less than three, the proposed limits are acceptable. The ISO Standard recommends using the proposed limits only as a guideline for motion with crest factors greater than three, but it does state that in most cases the limits still hold for crest factors as high as six, with the evaluation underestimating the limits for crest factors greater than six [11]. In order to properly assess the feasibility of using an active isolation system in areas such as operating rooms where humans must perform delicate tasks, an evaluation of the rms acceleration of the isolation system must be compared with human perception limits like those in Figure 2.1. A description of this evaluation and an outline of the isolation system model is given in Section 4.

2.4 Summary

In order to determine the proper parameters needed for the development of an active isolation floor system in operating rooms, it is necessary to determine the threshold levels for human response to vibration. The threshold levels in rms acceleration, outlined by the ISO Standard, are adopted as the human perception threshold levels for this purpose. Measuring the rms acceleration of the model isolation system and comparing it to these threshold levels leads to a determination of the feasibility of the system for areas such as operating rooms where humans must carry out delicate tasks.

SECTION 3
ISOLATION & CONTROL

For as long as humans have lived in areas of high seismicity, there has been the need to design earthquake-proof structures, both for safety and for functionality. Design methods have experienced many improvements within the last 50 years, and new design concepts are emerging, including the use of passive and active control techniques. Traditional methods of earthquake-resistant design typically use large static lateral forces as design forces, making the structure itself strong enough in the horizontal direction to resist earthquakes. Other techniques involve the use of a "soft" or flexible story to dissipate energy, in which case steel is often favored over reinforced concrete as a building material, since steel has greater flexibility. In comparison with these traditional methods which rely heavily on the design codes and standards of the structure itself, modern design concepts advocate the use of passive and active control to supplement conventional building designs in order to protect the structures from earthquakes. Passive control is based on the use of passive energy dissipation systems, such as tuned mass dampers [50] or seismic isolation, while active control is concerned with active systems, such as active mass drivers and pulse control, which counteract the incoming earthquake forces by applying forces in the opposite direction. This section is devoted to an overview of the research in the fields of seismic isolation and active control as background for a discussion of the development of combined active-isolation floor systems.

3.1 Base Isolation

While seismic isolation techniques are now being used for both base isolation and for floor isolation, initial research was only concerned with base isolation. It is therefore important to study base isolation in order to fully understand the concepts behind floor isolation. Contrary to more traditional design techniques which strengthen the building in an effort to better withstand the powerful earthquake forces, the technique of base isolation, first of all, seeks to dissipate the ground motion energy before it enters the structure, eliminating the source of most damage. This is especially important for structures whose functions are crucial in the aftermath of a major earthquake [28]. Secondly, the technique of base isolation seeks to significantly reduce damage by moving the natural frequency of the isolated structure outside the frequency range of the ground motion, since the greatest damage to a structure occurs when the natural frequency of the structure is close to that of the incoming ground motion [27]. The theory of base isolation is that by mounting the structure on a system of "isolators" that have a high lateral flexibility, the structure may be uncoupled from the ground and its natural period increased by as much as two seconds, beyond that of the ground motion [40] (see Figure 3-1). Base isolation does not only protect a structure from earthquakes; it also offers protection from ground-transmitted ambient noise from other sources. Some of the first base isolated structures were built on springs, not only to protect against ground vibration, but against subsidences as well [36].

The idea of base isolation appears to have originated long ago, although the first implementation of base isolation systems has only been within the last twenty years. Early systems either were not practical or were not accepted by the engineering profession at large. Today, however, due to advances in materials science and isolation hardware, the use of isolation technology is rapidly becoming an accepted practice in the field of aseismic design. In Japan, several different companies have developed similar seismic isolation systems. Shimizu Corporation tested two structurally identical buildings at Tohoku University, one with base isolation and one without, and achieved a 75% reduction in acceleration in the building with the isolation [47]. Kajima Corporation has developed a combined isolator and damper system to protect an environmental engineering laboratory from earthquakes and other vibrations [38,39]. A building built by Takenaka Corporation using laminated rubber isolators and viscous dampers has already performed satisfactorily during several moderate earthquakes [35]. Other examples of base isolated structures include the USC hospital in Los Angeles, using lead-rubber and elastomeric bearings [22,49], and the Los Angeles County Fire Command and Control Facility, using natural

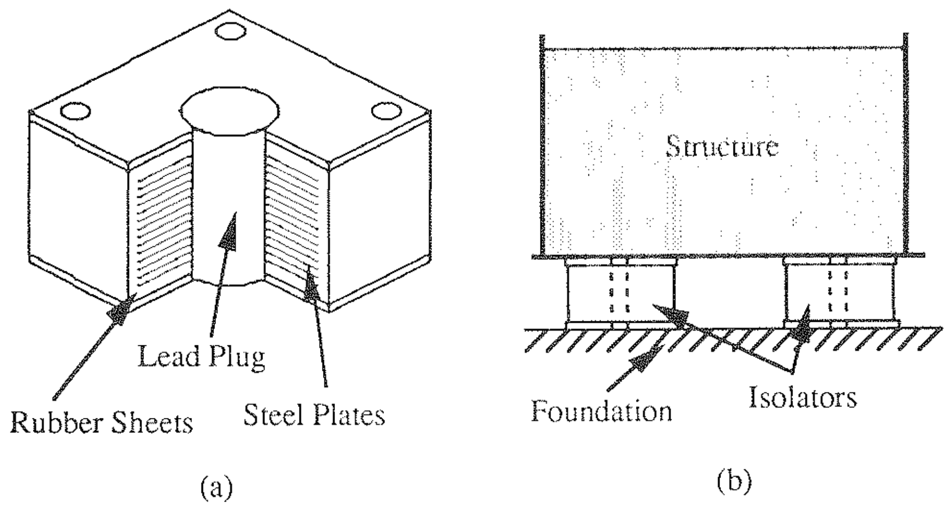


FIGURE 3-1 (a) Cut-away view of a typical lead-rubber isolation bearing, or isolator. (b) Isolators installed beneath a structure.

rubber isolation bearings [48], both of which are currently under construction. There have also been proposals for retrofitting an existing building in San Diego with base isolators [34]. In all, there are now over 100 structures worldwide that employ isolation techniques [24].

3.2 Research

Research in the field of base isolation appears to be concentrated in several major areas: experimental testing, computer simulation, and development of isolation theory. Experimental testing has often involved the use of shaking tables for large-scale testing of isolated structures. Bhatti et al. [23] developed standard shaking table experiments in 1980 to analyze and optimize base isolation system performance. In 1985, Chang et al. [25] performed preliminary shaking table tests on a proposed vertical and horizontal spring floor isolation system for use in computer rooms. Also in 1985, Fujita [30] used shaking table experiments to test floor isolation systems for use with heavy equipment and for use in the semi-conductor manufacturing industry. In 1988, Fujita et al. [29] tested various types of dampers and their properties as the basis for minimizing the response of internal equipment in seismically isolated buildings. In 1989, Kelly and Aiken [40] conducted extensive shaking table experiments at the Earthquake Engineering Research Center (EERC) at Berkeley, including comparison tests of types of isolators, namely, natural rubber bearings, lead-rubber bearings, and sliding bearings.

A large portion of the research in the field of seismic isolation has been devoted to theoretical analysis and computer simulation of isolation systems. One area in this type of research is concerned with the comparison of different types of isolators using various dynamic analysis techniques. Su et al. [52,53] compare the horizontal flexibility and the energy dissipative capacity of six different types of isolators, including rubber bearings, roller bearings, and frictional types, by developing and testing analytical models of each type. Ikonomou [37] proposes a "dual isolation system," with sliding bearings in the horizontal direction combined with steel or rubber springs in the vertical direction. This is proposed as a method of overcoming the buckling problem that limits isolator efficiency, often experienced by ordinary rubber isolators which simultaneously transfer forces in the vertical and horizontal directions. Similarly, Koh and Balendra [44] explore the relation of resistance to buckling with the effects of compression load on the performance of isolation bearings. Other comparative research is directed towards the performance of ordinary base isolators under random vibration [45] and the use of nonlinear isolators for random vibration input [43]. Several papers have been devoted to computer simulation and new analysis methods. Tsai and Kelly [54,55] propose a simplified method of perturbation analysis for laminated rubber base isolated systems with internal equipment. Constantinou [26] and Constantinou and Siddiqui [51] also propose similar simplified analysis methods for the evaluation of the dynamic response of base isolated structures. The difficulty of modeling complicated base isolated structures using conventional computer programs is addressed by Way and Jeng [57,58] in their development of a computer program specifically designed for use in evaluating the dynamic response of seismically isolated structures.

3.3 Floor Isolation

Other research involving computer simulation and dynamic analysis has been devoted to the protection of sensitive equipment in the microelectronics manufacturing industry [56]. Because the production of high-resolution semi-conductor chips involves sensitive manufacturing techniques, a vibration-free as well as dust-free environment is required in the manufacturing centers [33]. Fujita [30] and Nelson et al. [46] propose the installation of seismically isolated floor systems that separate the area where sensitive equipment is located from the rest of the manufacturing room. Isolated floor systems were first developed for use in computer rooms to protect computers from damage and interruption during strong earthquakes. The implementation of these floor isolation systems was initiated in Japan for air-traffic control computer systems, banking computer facilities, and other systems that are crucial to society [30]. The primary role of the seismic floor isolation with respect to these crucial computers is to keep them functioning in the event of a large magnitude earthquake. For the microelectronics industry, however, any level of vibration may cause a decreased yield in production. Therefore, adequate floor isolation systems for the microelectronics industry must protect against frequently occurring microvibrations as a greater concern than the infrequent large magnitude earthquakes [69]. For this reason, the original floor isolation systems used in computer rooms were found not to be effective for microelectronics manufacturing rooms, and they had to be redesigned [30]. As the requirements for vibration control in certain industries becomes more specialized, new types of floor isolation systems that are specific to the needs of each industry may have to be designed.

3.4 Building Codes

One issue which must be addressed as more structures incorporate seismic isolation in their designs is the acceptance and integration of design standards and practices in building codes. Presently one of the major disadvantages to choosing seismic isolation for a project design, besides the high initial hardware cost, is the time delay in obtaining design approval by the building code authorities [41]. If the building codes themselves actually included design standards and procedures relating to seismically isolated structures, there would be no delay. Currently, the Structural Engineering Association of California (SEAOC), is developing proposed standards for the design of isolated structures. Once these proposed standards are accepted in California, they may be incorporated into wider-reaching design codes such as the Uniform Building Code [42]. The eventual incorporation of these design codes may open the doors for the design of an entirely new generation of seismically isolated structures in the near future.

3.5 Active Control

While the concept of base isolation has become widely accepted and many seismically isolated structures have been built, the field of active control in civil engineering remains at the stage of theoretical and experimental research. Active control, the technique of measuring system variables to compute a control force and applying the control force to the system to counteract an input force, is a concept that is not new to engineering. It has been accepted and applied successfully in the disciplines of aeronautical, mechanical and electrical engineering for several decades [95]. However, the use of active control in civil engineering was not systematically researched until 1972 when Yao [99] first proposed the application of modern control theory to civil engineering structures. This proposal was created in response to the fact that as building techniques and the development of new methods of structural design allowed for the construction of taller, more flexible structures (which are vulnerable to increased movement due to environmental loads), a need was created for new methods of structural protection, such as active control [88].

Almost as soon as it was proposed, difficulties in the adoption of classical optimal control theory to civil engineering structures began to be realized. In 1975, Yang [97] recognized that one major difficulty in the application to civil engineering structures is that they are generally massive and heavy, thus requiring a very large control force. Martin and Soong [75] pointed out that for multi-degree-of-freedom (MDOF) systems, like most structures, the solution to the nonlinear Riccati matrix equation in classical optimal control theory becomes exceedingly complicated and computationally difficult. In addition, computation of control forces is complicated by the fact that environmental loads, such as seismic loads, are not known *a priori* [95]. For these reasons, classical optimal control theory must be modified before it may be applied to civil engineering structures. Another reason for the slow acceptance of active control techniques in civil engineering may be due to some potential disadvantages of active control when compared to passive control, as outlined by Masri [78,80]. The power requirements for a structural control system are very large. In addition, the demand for power would come at a time when failure of public utilities is imminent. Active systems that are designed to protect only against catastrophic events would have to be in a standby mode for many years and would therefore risk being unreliable. Finally, the psychological fears of the occupants of such a structure would have to be dispelled. Although these disadvantages are not to be taken lightly, at the same time active systems offer some advantages over passive systems. Kobori [70] points out that active control can maintain interior functions of a building, instead of merely protecting it from collapse, and it does not restrict the design of the building, thus preserving "high-value architectural space." Active control also offers the overwhelming advantage that it is definitely more effective than passive control, since it generates the counteracting forces by external means [83].

3.6 Research

The early work by Yao and Yang, mentioned above, opened the doors for an extensive amount of research in the 1980's on the subject of active structural control. When it was realized that classical optimal control theory did not address all the problems of civil engineering systems, several different branches of research were formed. One branch deals with simplifying structural control so that classical control theory can be used, while another addresses the development of a modern control theory that can be applied to structural systems without a significant increase in computation. A third branch of research is concerned with the details of actually applying the control forces to the structure. In the first branch of research, one method of simplifying the required control system is to use modal control [75,79,86,94]. By controlling only a select number of lower-order modes, the number of computations is greatly reduced. Ebrahimi [65,66] proposes a numerical optimization method to determine the modes which should be controlled. The optimality of modal control, however, requires that the number of controllers at least be equal to the number of controlled modes [88]. Another simplification involves treating the building as a SDOF or a 2DOF system [81]. This also reduces computation time, but it does not describe actual building motion adequately enough to draw conclusions for the behavior of real structures.

In the second branch of research, a considerable amount of experimental, analytical, and theoretical study has been devoted to the development of instantaneous optimal control algorithms for seismic response control. Yang [96,98] proposes three different algorithms which, contrary to classical control algorithms that require a known input time history, are based on the fact that while the ground motion is not known *a priori*, it is known up to the instant of calculation of the control force. Closed-loop, or feedback, control uses control forces that are regulated only by the measured response variables. Open-loop, or feedforward, control uses control forces that are regulated only by the measured ground excitation. Open-closed loop control is with control forces regulated by both the ground excitation and the response variables (see Figure 3-2). Yang, Soong, Reinhorn, et al. have done extensive experimental and computer simulation testing of these algorithms at the State University of New York (SUNY) at Buffalo. They have constructed a 1:4 scale model with active tendon control devices, and it has been tested for SDOF and MDOF response with the instantaneous optimal control algorithms [61,62,63,74,82,85]. These tests, along with computer simulations of the experiments, have proved successful, and continued studies on time delay and spillover effects are planned [63]. A rigorous derivation of this control theory is found in Section 4.

The third branch of research is concerned with the development and refinement of the control systems themselves. Many methods of active structural control have been researched, including active mass dampers (AMD) for seismic and wind response [60,64,67], active tendon control (at SUNY, see above), on-line pulse control [76,77,92,93], the use of aerodynamic appendages to suppress wind-induced oscillations of tall buildings [87], and the use of pressurized control [84] and disturbance absorbers [68] for floating structures. These studies range from experimental [84,87,89] to theoretical [65,66,67,86,96,98] and are an indication of the broad range of applications for active control. The most ambitious research on active control is that of Kobori et al. [71,72,73] in their plan for a "Dynamic Intelligent Building," which not only employs active control, but uses a satellite and sensor network to relay ground motion characteristics to the control force computer *before* the earthquake reaches the structure. In this way the computer control force can be calculated to exactly counteract the incoming earthquake force at the moment it arrives. Of

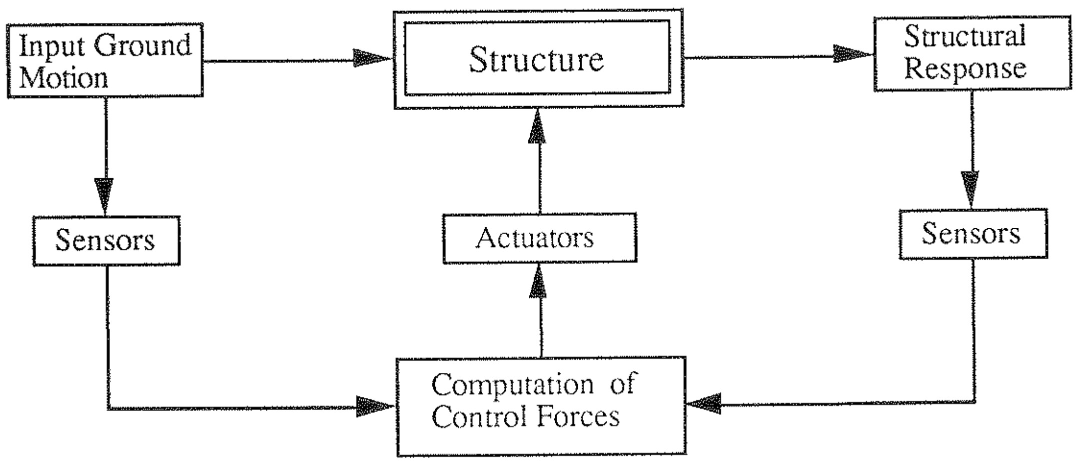


FIGURE 3-2 Diagram of Open-Closed Loop control system. Taken from [88], p. 2-2.

course this proposal is unlikely to be implemented in the near future, but it does highlight the extent of future possibilities for active control of civil engineering structures.

3.7 Active Isolation

As stated earlier, in certain industries such as microelectronics, monocrystal manufacturing, and biotechnology, there is an acute need for extreme vibration protection, even from microtremors. The use of passive isolation devices has become prevalent in computer rooms and areas with sensitive equipment since their introduction in 1984. However, it has been shown that in some cases the passive system alone is not sufficient [31]. In 1985, Fujita strongly emphasized the need for further research in the area of floor isolation [30]. In 1989, he presented some of that research with his concept of a combined passive and active,"active isolation," controlled floor system for use in microelectronics manufacturing facilities [31,32]. Although the idea of combined passive and active control had been proposed before [81], it had never before been used in a floor system, and never for microtremor protection in a manufacturing facility. Fujita conducted experiments on a SDOF model of an active-isolation device with equipment and found that the active-isolation device was at least as effective as the passive isolation alone, with the potential to yield even more encouraging results in future experiments [32]. Takenaka Corporation, in conjunction with Fujita's research, developed and built an active vibration control floor device, TACMI, in response to the needs of the semiconductor industry [89]. Using a linear motor actuator, the TACMI device, integrated into Takenaka's Precision Controlled Work Space Laboratory [90], actively controls vibration through six degrees of freedom and is able to reduce microtremors to within one tenth of their input magnitude [91]. Takahashi et al. [89] conducted rigorous tests, both experimental and analytical, to determine the effectiveness of TACMI and achieved consistently positive results for a variety of control algorithms. Although the parameters required for vibration control in the microelectronics industry may be different from those required to maintain a level below that of human vibration perception thresholds, there is no reason that systems like TACMI could not be designed to provide seismic protection to human work environments such as operating rooms.

SECTION 4
COMPUTER MODEL

4.1 The System

The computer model is a single degree-of-freedom (SDOF) system based on the parameters of the actual Takenaka Active Microtremor Isolation System (TACMI active isolation system) developed by Takenaka Corporation of Tokyo, Japan [91] (see Section 3). In actuality, this system is a six degree of freedom system (three translational and three rotational) since, however, the motion of the earthquake force in each component is taken to be independent of the motion in the other components, it is essentially six SDOF systems, superimposed on each other. In this way, motion in a single linear direction may be treated as being independent of the motion in any other direction. Takahashi et al. [89] tested a SDOF model of the TACMI System analytically and experimentally to determine its effectiveness over a frequency range of 0 to 10 Hertz. It was determined that, while the system is not as effective in the lower end of the frequency range (0 to 2 Hertz) as it is in the remainder of the range, in general, the actuator offers significant protection in the range from 0 to 70 Hertz for environments which may be threatened by low-amplitude vibration or microtremors. The experimental SDOF model used by Takahashi et al. consists of an isolation table, a vibration table for input, a sensor, a computer control unit, and an electromagnetic actuator (linear motor) to supply the control force (see Figures 1-1 & 4-1). The computer model neglects the dynamics of the actuator in the evaluation of the system behavior. The computer model used in this paper is a standard SDOF model with an added component of control, as shown in Figure 4-1.

4.2 Equations of Motion

The equations of motion for a linearly elastic SDOF system at any point in time, subject to an earthquake load and a control force, are given by the following:

$$M\left(\ddot{u}+\ddot{x}_g\right) + C\dot{u} + Ku = -F_{total} \qquad (4.1)$$

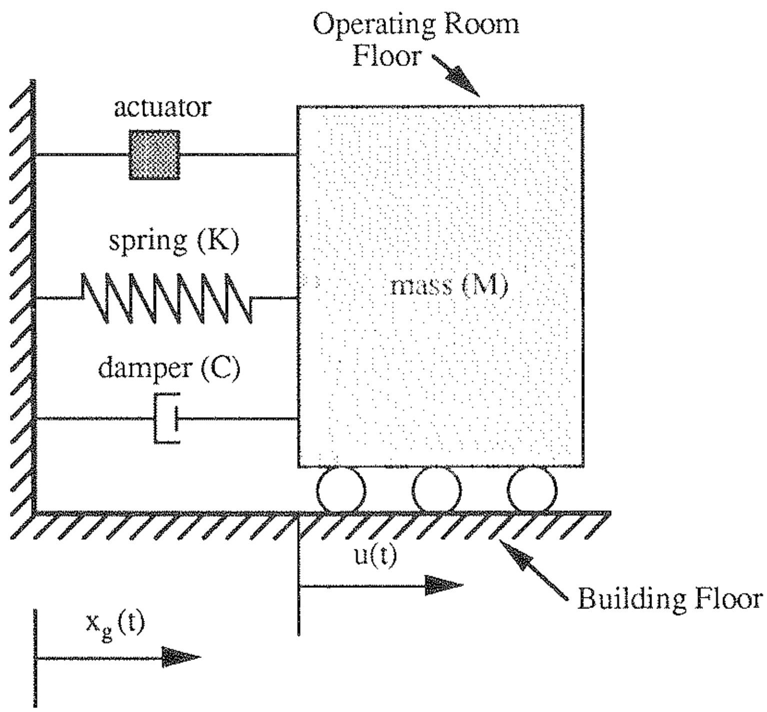


FIGURE 4-1 Idealized SDOF system used for computer modelling. Relative response, u(t), and input ground motion, $x_g(t)$, are indicated.

where overhead dots designate time derivatives and

M, C, K = mass, damping, and stiffness parameters of the system, respectively
u = relative displacement of the system
x_g = ground motion displacement
$u + x_g$ = absolute displacement

F_{total}, the total force on the model, may be rewritten as a combination of feedforward control force, and feedback control force, according to the following equations:

$$M(\ddot{u}+\ddot{x}_g) + C\dot{u} + Ku = F_{ff} + F_{fb} \tag{4.2}$$

where

F_{ff} = feedforward component of control force
$F_{fb} = -C_a(\dot{u}+\dot{x}_g) - K_a(u+x_g)$ = feedback component of control force

The feedback component is based on the absolute displacement and velocity response feedback control as given in Takahashi et al. [89], since it was determined in their paper to be the most effective. Equation (4.2) may be further refined and rewritten for any time t as:

$$M\,\ddot{u}(t) + C\dot{u}(t) + Ku(t) = U(t) + F_g(t) \tag{4.3}$$

where

$F_g(t) = -M\ddot{x}_g(t) - C_a\dot{x}_g(t) - K_a x_g(t)$ = function of the imput ground motion
$U(t) = -C_a\dot{u}(t) - K_a u(t) + B(t)$ = control force
$B(t) = F_{ff}$ = function of the ground force (feedforward component of control)
C_a, K_a = coefficients of the ground motion, related to absolute response

Assuming linear acceleration between time steps, the velocity and displacement may be derived from the definition of the acceleration, as given by:

$$\ddot{u}(t) = \ddot{u}(t-1) + \Delta\ddot{u}(t) \tag{4.4}$$

$$\dot{u}(t) = \dot{u}(t-1) + \frac{\Delta t}{2}[2\ddot{u}(t-1) + \Delta\ddot{u}(t)] \tag{4.5}$$

$$u(t) = u(t-1) + \Delta t\,\dot{u}(t-1) + \frac{\Delta t^2}{6}[3\ddot{u}(t-1) + \Delta\ddot{u}(t)] \tag{4.6}$$

where $\Delta\ddot{u}(t)$ is the incremental acceleration. Equations 4.4, 4.5, and 4.6 are substituted into equation 4.3 to solve for $\Delta\ddot{u}(t)$.

$$\Delta\ddot{u}(t) = C_4\left[-C_2\ddot{u}(t-1) - C_3\dot{u}(t-1) - Ku(t-1) + U(t) + F_g(t)\right] \tag{4.7}$$

where

$$C_2 = M + C\Delta t + K\frac{\Delta t^2}{2}$$
$$C_3 = M + K\Delta t$$
$$C_4 = \left[M + C\frac{\Delta t}{2} + K\frac{\Delta t^2}{6}\right]^{-1}$$

Equation 4.3 may be written for time (t –1) and can be solved for $\ddot{u}(t-1)$as given by:

$$\ddot{u}(t-1) = -\frac{C}{M}\dot{u}(t-1) - \frac{K}{M}u(t-1) + \frac{1}{M}U(t-1) + \frac{1}{M}F_g(t-1) \tag{4.8}$$

Equations 4.7 and 4.8 are substituted into both equations 4.6 and 4.5 to yield solutions for the relative displacement and velocity at the current time step as a function of the current ground and control forces and the equation of motion at the previous time step:

$$u(t) = C_9u(t-1)+ C_{10}\dot{u}(t-1)+ C_{11}U(t-1)+ C_{11}F_g(t-1)+ C_{12}U(t)+ C_{12}F_g(t) \tag{4.9}$$

$$\dot{u}(t) = C_6u(t-1) + C_5\dot{u}(t-1) + C_7U(t-1) + C_7F_g(t-1) + C_8U(t) + C_8F_g(t) \tag{4.10}$$

where

$$C_5 = \left[1 - \frac{\Delta tC}{2M}(2 - C_2C_4) - \frac{\Delta tC_3C_4}{2}\right] \qquad C_9 = \left[1 - \frac{\Delta t^2K}{6M}(3 - C_2C_4) - \frac{\Delta t^2KC_4}{6}\right]$$

$$C_6 = \left[-\frac{\Delta tK}{2M}(2 - C_2C_4) - \frac{\Delta tKC_4}{2}\right] \qquad C_{10} = \left[\Delta t - \frac{\Delta t^2C}{6M}(3 - C_2C_4) - \frac{\Delta t^2C_3C_4}{6}\right]$$

$$C_7 = \frac{\Delta t}{2M}(2 - C_2C_4) \qquad C_{11} = \frac{\Delta t^2}{6M}(3 - C_2C_4)$$

$$C_8 = \frac{\Delta t}{2}C_4 \qquad C_{12} = \frac{\Delta t^2C_4}{6}$$

Equations 4.9 and 4.10 can be combined into one expression by defining the state vector, $\mathbf{Z}(t)$, as:

$$\mathbf{Z}(t) = \begin{pmatrix} u(t) \\ \dot{u}(t) \end{pmatrix} \tag{4.11}$$

Substituting equations 4.9 and 4.10 into 4.11, $\mathbf{Z}(t)$ may be written as a function of $\mathbf{Z}(t-1)$ and the current and previous ground and control forces:

$$\mathbf{Z}(t) = \mathbf{D}(t-1) + A_3\,U(t) + A_3\,F_g(t) \qquad (4.12)$$

where

$$\mathbf{D}(t-1) = A_1\,\mathbf{Z}(t-1) + A_2\,U(t-1) + A_2\,F_g(t-1)$$

$$A_1 = \begin{bmatrix} C_9 & C_{10} \\ C_6 & C_5 \end{bmatrix} \qquad A_2 = \begin{bmatrix} C_{11} \\ C_7 \end{bmatrix} \qquad A_3 = \begin{bmatrix} C_{12} \\ C_8 \end{bmatrix}$$

4.3 The Algorithm

The selected algorithm is modelled after an open-closed loop system discussed by Yang, et al. [98] and was developed as part of their research on instantaneous optimal control algorithms. Open-closed loop control is used because it was shown to yield significantly better results than an algorithm based on closed loop control alone. Because earthquake forces and other natural vibrations cannot be known *a priori*, classical optimal control methods cannot be employed. Since, however, the input force is known up to the instant the control force is to be calculated, the theory of instantaneous optimal control can be applied (see Section 3). The advantages to the instantaneous control algorithms are that they are effective, relatively simple and can be calculated on-line.

The minimization of a time-dependant quadratic objective function, J(t), at every time step is proposed to be used in the development of the instantaneous optimal control algorithms [98]:

$$J(t) = \mathbf{Z}^T(t)\,\mathbf{Q}\,\mathbf{Z}(t) + U^T(t)\,R\,U(t) \qquad (4.13)$$

For a SDOF system, $\mathbf{Q}$ is a 2x2 matrix, $\mathbf{Z}(t)$ is a 2x1 state vector, and U and R are scalar quantities. $\mathbf{Q}$ and R are weighting factors, signifying the relative importance of the state vector and the control vector. The minimization of equation 4.13 subject to the conditions of equation 4.12 can be expressed by the introduction of a Lagrangian multiplier, λ, and the use of a Hamiltonian function, H:

$$H = \mathbf{Z}^T(t)\,\mathbf{Q}\,\mathbf{Z}(t) + U^T(t)\,R\,U(t) + \lambda[\mathbf{Z}(t) - \mathbf{D}(t-1) - A_3U(t) - A_3F_g(t)] \tag{4.14}$$

By taking the derivatives of H with respect to the three unknown quantities (state vector, control force, and Lagrangian multiplier), and by setting these derivatives equal to zero, three equations can be written to express the minimization of the quadratic objective function, J(t):

$$\frac{\partial H}{\partial \mathbf{Z}} = 0 = 2\mathbf{Q}\,\mathbf{Z}(t) + \lambda(t) \tag{4.15}$$

$$\frac{\partial H}{\partial U} = 0 = 2R\,U(t) - A_3{}^T\,\lambda(t) \tag{4.16}$$

$$\frac{\partial H}{\partial \lambda} = 0, \quad \mathbf{Z}(t) = \mathbf{D}(t-1) + A_3U(t) + A_3F_g(t) \tag{4.17}$$

For instantaneous open-closed loop control, the control force, U, is a function of both the state vector $\mathbf{Z}(t)$, and the ground force. Since the Lagrangian multiplier (Yang, et al. [98] call it "the co-state vector") is directly proportional to the control force, it also can be written as a function of the state vector and the ground force:

$$\lambda(t) = \Lambda\,\mathbf{Z}(t) + \mathbf{q}(t) \tag{4.18}$$

where Λ and $\mathbf{q}(t)$ are unknowns, to be determined from the above equations. Equation 4.18 is substituted into equation 4.16 and is solved for U(t):

$$U(t) = \frac{1}{2R}A_3{}^T[\Lambda\,\mathbf{Z}(t) + \mathbf{q}(t)] \tag{4.19}$$

This, in turn, is substituted into equation 4.17 where $\mathbf{Z}(t)$ is solved for in the following expression:

$$\mathbf{Z}(t) = \mathbf{D}(t-1) + A_3\frac{1}{2R}A_3^T\left[\Lambda\,\mathbf{Z}(t) + \mathbf{q}(t)\right] + A_3F_g(t) \tag{4.20}$$

Substituting equations 4.20 and 4.18 into 4.15 yields an expression containing $\mathbf{q}(t)$, $\mathbf{Z}(t)$, and Λ as unknowns:

$$\left[\mathbf{Q} + \mathbf{Q}A_3\frac{1}{2R}A_3^T\Lambda + \Lambda\right]\mathbf{Z}(t) + \left[\mathbf{Q}A_3\frac{1}{2R}A_3^T + \mathbf{I}\right]\mathbf{q}(t) + \mathbf{Q}[\mathbf{G}(t)] = 0 \tag{4.21}$$

where

$\mathbf{I}$ = 2x2 identity matrix

$\mathbf{G}(t) = \mathbf{D}(t-1) - A_3F_g(t)$

For $\mathbf{Z}(t) \neq 0$, and for $\mathbf{q}(t) \neq 0$, equation 4.21 gives solutions for the three unknown quantities:

$$\Lambda = -\left[\mathbf{Q}A_3\frac{1}{2R}A_3^T + \mathbf{I}\right]^{-1}\mathbf{Q} \tag{4.22}$$

$$\mathbf{q}(t) = \Lambda\,[\mathbf{G}(t)] \tag{4.23}$$

$$\mathbf{Z}(t) = \left[I - A_3\frac{1}{2R}A_3^T\Lambda\right]^{-1}\left[I + A_3\frac{1}{2R}A_3^T\Lambda\right]\mathbf{G}(t) \tag{4.24}$$

Substituting equation 4.22 into equation 4.19 results in an expression for U(t):

$$U(t) = -\frac{1}{2R}A_3^T\left[\mathbf{Q}A_3\frac{1}{2R}A_3^T + \mathbf{I}\right]^{-1}\mathbf{Q}\,[\mathbf{Z}(t) + \mathbf{G}(t)] \tag{4.25}$$

Once the state vector has been determined, the control force is calculated from equation 4.25 and is applied at the following time step as U(t–1).

Assuming $\mathbf{Q}$ is a diagonal matrix where $\mathbf{Q}(1,1) = \mathbf{Q}(2,2) = Q$, then, setting equation 4.25 equal to the definition of U(t) in equation 4.3, the coefficients C_a and K_a may be determined as:

$$K_a = -\frac{Q^2C_{12}}{2R}\left(\frac{(C_{12})^2}{2R} + 1 + \frac{(C_8)^2}{2R}\right) \tag{4.26}$$

$$C_a = -\frac{Q^2 C_8}{2R}\left(\frac{(C_{12})^2}{2R} + 1 + \frac{(C_8)^2}{2R}\right) \tag{4.27}$$

All coefficients can be determined off-line in advance of the time step loop, minimizing the actual on-line computation. A copy of the Fortran program employing this algorithm is included in the Appendix.

4.4 Parameters

The parameters used to test the computer model were taken to be equivalent to those of the experimental SDOF model developed by Takahashi et al. [89] in their testing of the SDOF system. These values are summarized in the following table.

Mass (M)	Damping coefficient (C)	Stiffness coefficient (K)	Natural frequency (ω)	Damping ratio (ξ)
20.0 kg	8.293 kg/s	3821 kg/s^2	13.82 rad/s	1.5%

The optimal values of the parameters Q and R were determined by assuming that **Q** is a 2x2 diagonal matrix with both diagonal entries equal to a single factor, Q. R was set equal to 1.0 while Q was varied and the acceleration and control force were recorded for each Q-factor level (see Figure 4-2). The Q-factor that simultaneously minimizes the acceleration and the control force is the optimal value. From the graph it was determined that Q = 1710 is the optimal value. The computer model was tested with the 1940 El Centro earthquake N-S accelerogram, which was scaled to a maximum peak acceleration of 300 cm/s^2 (≈ 0.3g). This peak value was used to demonstrate the effectiveness of the system for moderate earthquakes. The model was also tested with a maximum peak acceleration of 30 cm/s^2. The El Centro earthquake was selected because it is an earthquake whose energy is distributed over a relatively large frequency band. The time step used is 0.04 seconds and the total time-history length is 29.36 seconds, resulting in 734 time steps.

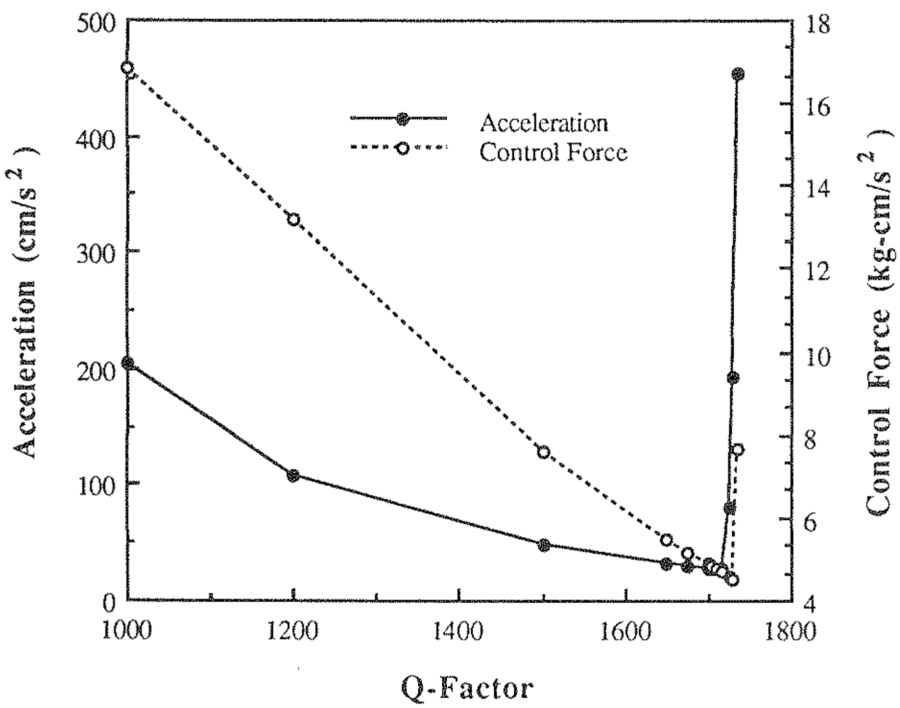


FIGURE 4-2 Graph of the absolute acceleration and the control force for various values of Q. The optimal value of Q is that which minimizes these two quantities.

4.5 Results

Using the above parameters, the computer model was analyzed both with an open-closed loop control system and with an uncontrolled system. The maximum values of relative displacement, relative velocity, and absolute acceleration for both systems were computed and the rms acceleration and the crest factor for each system calculated according to equations 2.1 and 2.2, respectively. The results are summarized in Table 4-I. Comparing the rms acceleration values above to the combined curve in the graph in Figure 2-1 for the frequency range of 1 to 10 Hz (predominant earthquake frequency), it can be seen that while the acceleration for the uncontrolled system surpasses the human perception limits by three orders of magnitude, the acceleration level of the controlled system is reduced to a level that is within the realm of human sensitivity limits (see Figure 4-3). Even the rms acceleration level of the controlled system is still almost ten times the level required for it to be below the threshold level. However, this magnitude is directly proportional to the maximum input acceleration level. The rms response acceleration of 0.06 m/s^2 for a 0.3g earthquake would be reduced to a 0.006 m/s^2 response for a 0.03g earthquake, achieving a response that is close to the human perception thresholds in Figure 2-1. A 0.03g earthquake is equivalent to a common microtremor of the magnitude tested by Fujita in 1989 [31]. See Figure 44 for a comparison of the relative magnitudes of the uncontrolled and controlled response acceleration time histories. Figure 4-5 shows a magnified graph of the controlled response acceleration and Figure 4-6 is a graph of the control force in $kg\text{-}cm/s^2$.

The crest factor of 4.53 for the controlled rms response acceleration, in comparison with the crest factor of 2.701 for the uncontrolled rms acceleration, shows that the control system does not reduce acceleration levels equally over the entire frequency range. Because a study of human response to vibration is concerned with the concept of a crest factor, and not simply with overall maximum acceleration levels which may be important when protecting equipment, the parameters

TABLE 4-I Response values of uncontrolled and controlled systems.

	maximum relative displacement (cm)	maximum relative velocity (cm/s)	maximum absolute acceleration (cm/s^2)	rms acceleration (m/s^2)	crest factor
uncontrolled system	6.549	86.04	1250	4.627	2.701
controlled system	0.02921	2.56	26.9	0.05983	4.53

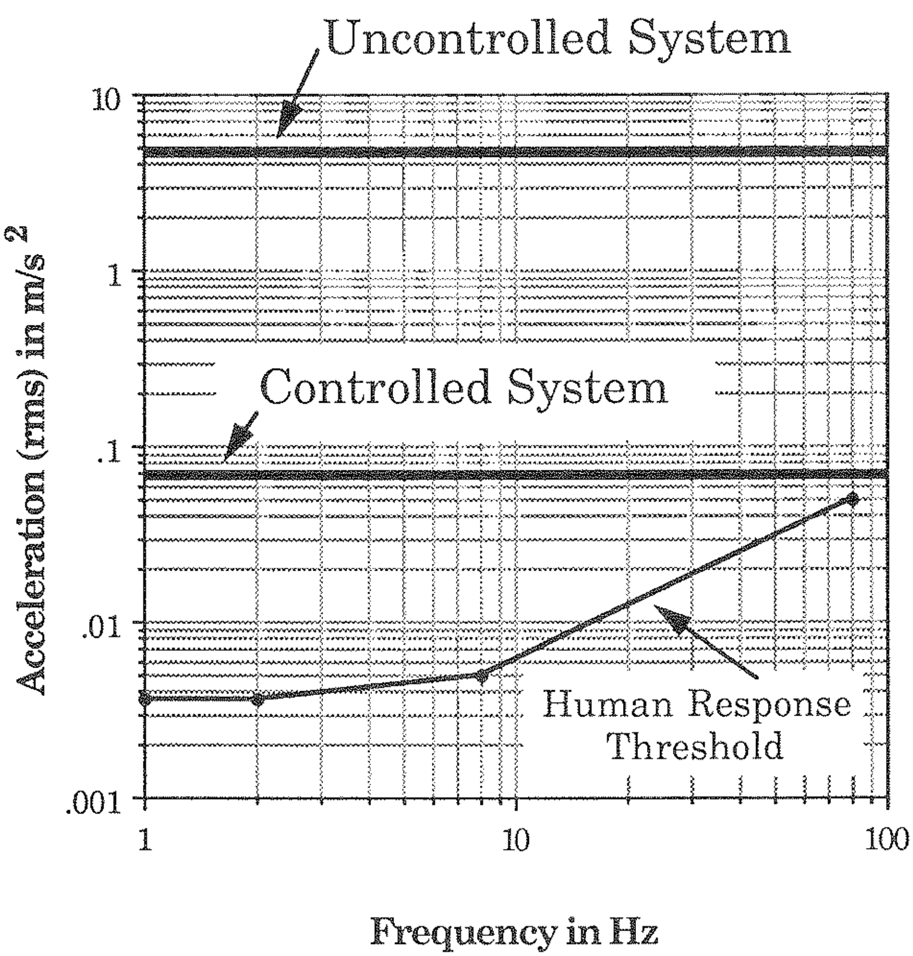
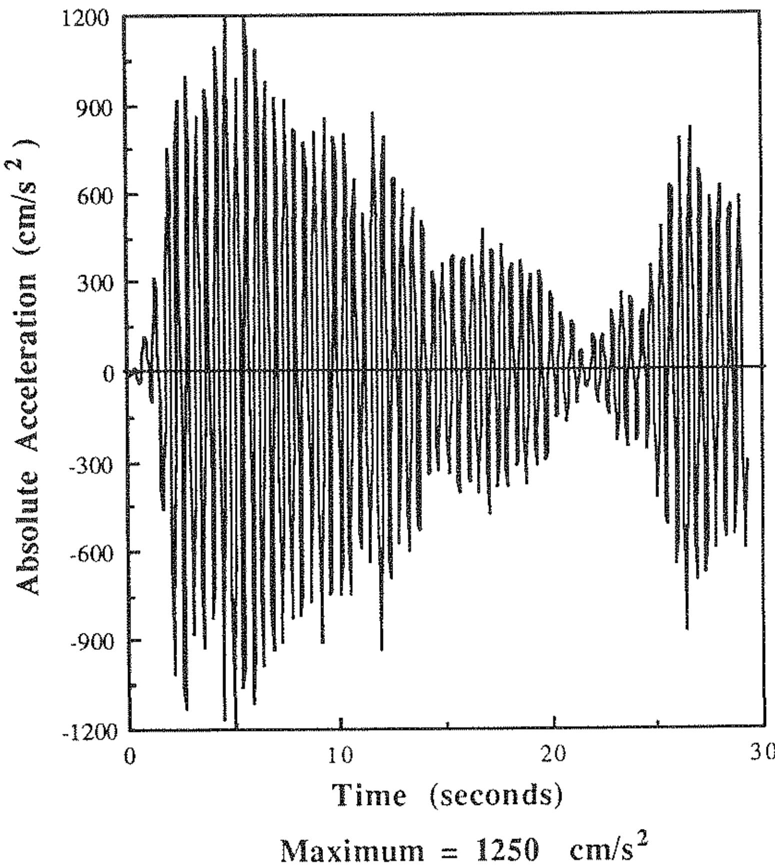


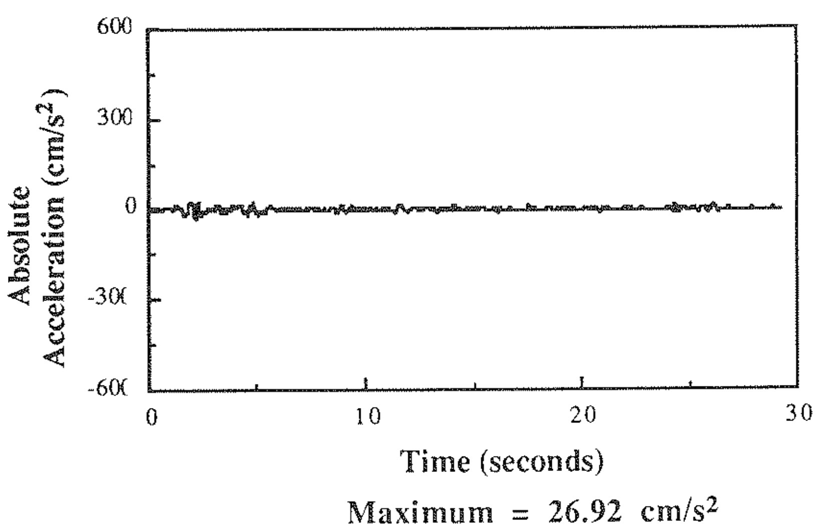
Figure 4-3 A comparison of the peak rms acceleration levels for the open-closed loop controlled system and the uncontrolled system in reference to the human response threshold using a peak ground acceleration imput of 300 cm/s^2.

of the control system should be adjusted to reflect this criterion. Since the computer program used in this paper was based on ideal assumptions that were not made by Takahashi et al. [89] in their SDOF model, and since the algorithm used was optimal rather than suboptimal, the effectiveness of the system realized by this program is much greater than that achieved by Takahashi et al. However, the results achieved in this paper are used merely to show the feasibility of using such systems in areas such as hospital operating rooms where humans must perform delicate tasks, and these ideal assumptions should not influence this evaluation.

In summary, the computer model with open-closed loop control has been proven effective in reducing the response of the SDOF system under weak earthquake excitation. The rms acceleration is reduced by two orders of magnitude from that of the uncontrolled system, to a level that is close to the threshold levels of human perception of vibration. By adjusting the parameters of the system so that they are more compatible with an evaluation based on a low crest factor value, it is reasonable to assume that active isolation devices such as the TACMI device may be a viable option for seismic protection of operating rooms and other human working environments.



a.



b.

FIGURE 4-4 Comparison of absolute acceleration for uncontrolled system (**a.**) and controlled system (**b.**) under excitation by the El Centro earthquake accelerogram with a peak ground acceleration of 300 cm/s^2.

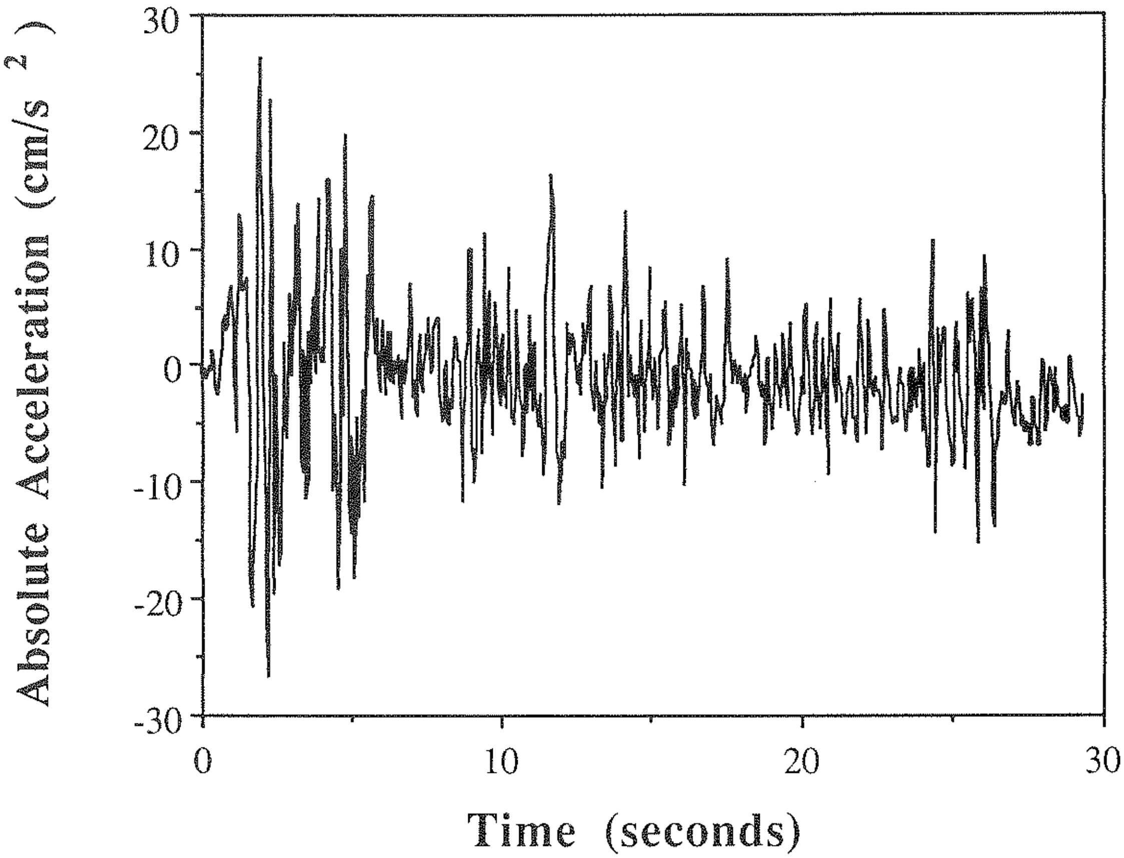


FIGURE 4-5 Reduced scale graph of the absolute acceleration response for the controlled system with a maximum acceleration of 26.92 cm/s^2.

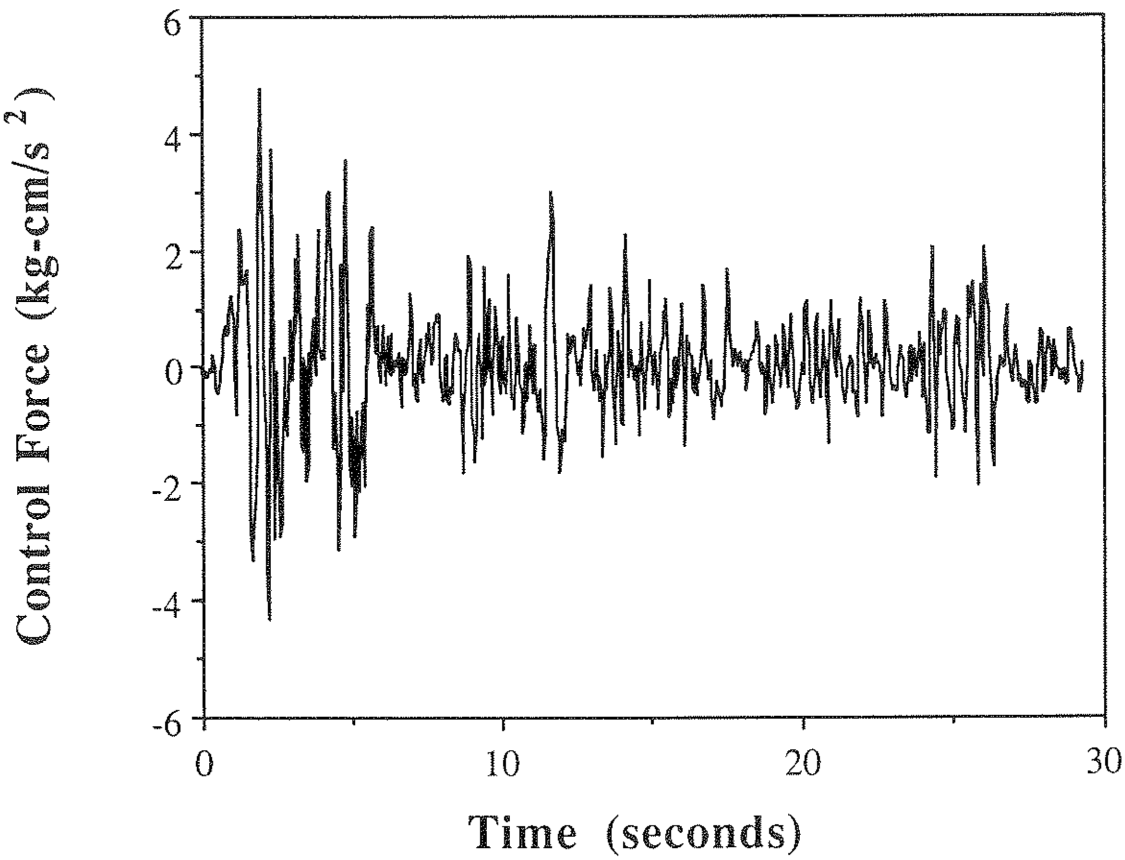


FIGURE 4-6 Graph of the control force time history (maximum = 4.75 kg-cm/s^2) using the instantaneous optimal open-closed loop control algorithm.

SECTION 5
CONCLUSION

Although in the past the field of human response to vibration and that of seismic protection of structures have not been well recognized as related fields of study, in this paper they have been combined into a single discipline. Scientists who study human response to vibration of structures should be aware of the state-of-the-art technology that is being developed in civil engineering. Likewise, the engineers who are designing the technology should become aware of the levels of human perception, comfort, and working efficiency, and they should incorporate these limits into their designs according to the purpose of the structure.

The ISO Standards for human response to vibration should incorporate a special section only devoted to earthquake response. Experiments should be developed and performed to explore the response of humans to random vibration of a short duration while they are engaged in delicate precision work. Until now, most studies have dealt with continuous sinusoidal vibration of various durations, and have been concerned with the development of curves which correlate response with exposure time or frequency of motion occurrence. Since earthquakes are of short duration and have a low frequency occurrence, these studies are not readily applicable. While the ISO Standard curves are adequate for use in a preliminary study such as this, more detailed research would require data specifically related to earthquake response.

Past research in earthquake engineering in the areas of seismic isolation and active control has concentrated on the protection of structures and facilities from collapse and damage. As the field became more specialized, the idea was introduced of not only providing protection from structural damage, but using isolated floors to protect equipment as well. An even higher level of protection involves maintaining the functioning of equipment during a seismic event. This is the purpose of an active isolation device. At the present time active isolation devices are overwhelmingly expensive. However, in the microelectronics industry, for example, the increase in yield gained due to the protection offered by the active isolation device may be sufficient to warrant the installation of the device. Similarly, studies must be made to determine the effects of the implementation of active isolation in hospital operating rooms in seismically active regions. If it is found that the enhancement of the working conditions, the psychological sense of security, and the protection of patients' lives is sufficiently improved to balance the cost of an active isolation device, then studies in this area should be at the forefront of seismic engineering research. If the benefits are found to be great, but not greater than the cost of the device, then methods of decreasing the cost should be explored before abandoning this proposed use of active isolation. In any case, as more active isolation devices are developed, the effectiveness of the control will improve and the cost of the devices will decrease. Even though active isloation devices may be slowly accepted in the field of earthquake engineering, their use in reducing vibrations that have more regular characteristics, such as wind-induced motion in high-rise buildings and wave-induced motion in floating structures, appears to be even more practical. In a few years they may even become standard devices in many different types of facilities. Although the initial active isolation devices such as TACMI have been designed for the protection of computers and equipment in the microelectronics industry, this report emphasizes their application to operating rooms and other human working environments as well.

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APPENDIX
COMPUTER PROGRAM

```
      PROGRAM CONTROL
C
C     *************************************************************
C     *                                                           *
C     *           MAIN PROGRAM FOR ACTIVE CONTROL OF SDOF         *
C     *           LINEAR SYSTEM UNDER EARTHQUAKE LOAD             *
C     *                                                           *
C     *           BY:   Margaret Talbott '90                      *
C     *                 Princeton University                      *
C     *                 FEBRUARY, 1990                            *
C     *                                                           *
C     *           Language:    Fortran 77                         *
C     *           Last edited: March 16, 1990                     *
C     *                                                           *
C     *************************************************************
C
C     PROGRAM DESCRIPTION:
C     This program reads a list of parameters and a ground
C     acceleration time-history from a list-directed input file
C     and outputs the response of a SDOF system to a list-directed
C     output file in the following format:
C
C           CONTROL <inputfilename> outputfilename
C
C     INPUT FILE:
C     The input file consists of two header cards followed by
C     NSTEP time-history cards.
C           CARD 1:     <NSTEP> <DT> <YAMAX>
C                 NSTEP = integer number of time steps in ground
C                 acceleration time-history.
C                 DT = length of time step between data points in
C                 time history.
C                 YAMAX = value given to peak value of the time-history
C                 after normalization.
C           CARD 2:     <SM> <C> <SK> <QSR>
C                 SM = mass coefficient of the SDOF system.
C                 C = damping coefficient of the SDOF system.
C                 SK = stiffness coefficient of the SDOF system.
C                 QSR = weighting ratio used in optimization of
C                 control force.
C           NEXT NSTEP CARDS: <YA(I)>
C                 each card contains a ground acceleration value,
C                 where I = 1, NSTEP.
C     Each card is read using unformatted input.
C
C     THE PROGRAM:
C     --    Data is read in and all constants and coefficients
C           are calculated.
C     --    The subroutine EQWAVE is called to normalize the
C           ground acceleration time-history and to determine
C           the total ground motion force, based on ground
C           acceleration, ground velocity, and ground displacement.
C     --    The subroutine ALGORI is called to process the input
```

```
C           ground force and to apply the open-closed loop control
C           algorithm to determine the control force and the
C           system response.
C     --    Subroutines for use in matrix manipulation are
C           also included.
C
C     OUTPUT FILE:
C     The subroutine ALGORI writes data to the list-directed
C     output file in the following format:
C
C     CARD 1:     <XMAX> <VMAX> <ABSMAX> <UMAX> <FGMAX>
C           XMAX = maximum value (+ or -) of system displacement
C           VMAX = maximum value (+ or -) of system velocity
C           ABSMAX = maximum value (+ or -) of absolute system
C           acceleration
C           UMAX = maximum value (+ or -) of control force
C           FGMAX = maximum value (+ or -) of ground force
C
C     NEXT NSTEP CARDS: <T(I)>,<X(I)>,<V(I)>,<ABSA(I)>,<U(I)>,<FG(I)>
C           where I = 1, NSTEP, and:
C           T = time-history of time values
C           X = time-history of system displacement
C           V = time-history of system velocity
C           ABSA = time-history of absolute system acceleration
C           U = time-history of control force
C           FG = time-history of ground force
C
C*********************************************************************
C
C*********************************************************************
C     MAIN PROGRAM CONTROL
C
C                 dimensioning of arrays and explicit
C                 declaration of all variables
C
      DIMENSION YA(10000),FG(10000)
C
      REAL A1(2,2),A2(2,1),A3(2,1),DII(2,2),Q(2,2),QR(2,2),
     *     A3T(1,2),D9(2,2),D92(2,2),D911(2,2),A3X(2,2),QQRN(2,2),
     *     D91(2,2),D10(1,2),QRA3ND(2,2),QRA3D(2,2),QRA3(2,2),
     *     QRA3I(2,2),QRA3IN(2,2),LAMDA(2,2),QRA3N(2,2),RA3(1,2)
C
      REAL*4 SM,C,SK,DT,QSR,YAMAX,R,C2,C3,C4,C5,C6,C7,C8,C9,C10,
     *       C11,C12
      INTEGER NSTEP
C
      COMMON C2,C3,C4,A1,A2,A3,D9,D10
C
C                 read in input from list-directed file
C
      READ(5,*) NSTEP,DT,YAMAX
      READ(5,*) SM,C,SK,QSR
C
C                 calculation of constants and coefficients
C
      R=1.
      C2=SM+C*DT+SK*DT*DT/2.
      C3=C+SK*DT
```

```
      C4=1./(SM+C*DT/2+SK*DT*DT/6.)
      C5=1.-(DT*C/(2.*SM))*(2.-C2*C4)-DT*C3*C4/2.
      C6=-(DT*SK/(2*SM))*(2.-C2*C4)-DT*SK*C4/2.
      C7=(DT/(2.*SM))*(2.-C2*C4)
      C8=DT*C4/2.
      C9=1.-(DT*DT*SK/(6.*SM))*(3.-C2*C4)-DT*DT*SK*C4/6.
      C10=DT-(DT*DT*C/(6.*SM))*(3.-C2*C4)-DT*DT*C3*C4/6.
      C11=(DT*DT/(SM*6.))*(3.-C2*C4)
      C12=DT*DT*C4/6.
C
C                         compute matrix coefficients
C
      A1(1,1)=C9
      A1(1,2)=C10
      A1(2,1)=C6
      A1(2,2)=C5
      A2(1,1)=C11
      A2(2,1)=C7
      A3(1,1)=C12
      A3(2,1)=C8
      Q(1,1)=QSR
      Q(1,2)=0.
      Q(2,1)=0.
      Q(2,2)=QSR
C
      DII(1,1)=1.0
      DII(2,1)=0.
      DII(1,2)=0.
      DII(2,2)=1.0
C
      CALL TRANS(A3,2,1,A3T)
      CALL MATMUL(A3,2,1,A3T,1,2,A3X)
      DO 88 I=1,2
            RA3(1,I)=(.5/R)*A3T(1,I)
                DO 77 L=1,2
            QR(I,L)=(.5/R)*Q(I,L)
77              CONTINUE
88    CONTINUE
C
      CALL MATMUL(QR,2,2,A3X,2,2,QRA3)
C
      CALL MATADD(QRA3,2,2,DII,QRA3I)
      CALL INVERS(QRA3I,QRA3IN)
      CALL MATMUL(Q,2,2,QRA3IN,2,2,QQRN)
      DO 111 I=1,2
          DO 99 L=1,2
            LAMDA(I,L)=-QQRN(I,L)
            QRA3N(I,L)=-QRA3(I,L)
99        CONTINUE
111   CONTINUE
C
C
      CALL MATMUL(RA3,1,2,LAMDA,2,2,D10)
      CALL MATMUL(QRA3N,2,2,LAMDA,2,2,QRA3ND)
      CALL MATADD(DII,2,2,QRA3ND,D91)
      CALL INVERS(D91,D911)
      CALL MATMUL(QRA3,2,2,LAMDA,2,2,QRA3D)
      CALL MATADD(DII,2,2,QRA3D,D92)
```

```
      CALL MATMUL(D911,2,2,D92,2,2,D9)
C
C
C                 call subroutines EQWAVE and ALGORI
C
C
      CALL EQWAVE(NSTEP,YAMAX,YA,FG,SKA,CA,QSR,DT,SM,SK,C)
      CALL ALGORI(YA,FG,DT,NSTEP,YAMAX,SM,C,SK)
C
      STOP
      END
C
C*****************************************************************
C
C
      SUBROUTINE EQWAVE(NSTEP,YAMAX,YA,FG,SKA,CA,QSR,DT,SM,SK,C)
C
C     ***********************************************************
C     *                                                         *
C     *      EARTHQUAKE TIME HISTORY INPUT AND NORMALIZATION    *
C     *                                                         *
C     *      reads in earthquake acceleration data and          *
C     *      normalizes it according to YAMAX                   *
C     *      computes ground velocity and ground displacement   *
C     *      and returns the applied earthquake force, FG       *
C     *                                                         *
C     *                                                         *
C     ***********************************************************
C
      DIMENSION YA(1),FG(1),YV(1),YD(1)
C
      REAL AFACT,EQMAX,YAMAX,DEL,YANEW,YAOLD,
     *     YVNEW,YVOLD,YDNEW,YDOLD,SKA,CA,QSR,SM,SK,C,DT,D10(1,2)
      INTEGER I,NSTEP
C
      COMMON DUM(15),D10
C
C                 read in earthquake time history data
C
      READ (5,*) (YA(I), I=1,NSTEP)
C
C                 determine maximum value of acceleration
C                 in original time history
C
      EQMAX=0.0
      DO 40 I=1,NSTEP
C
          IF (ABS(YA(I)).GT.ABS(EQMAX)) EQMAX=YA(I)
C
40    CONTINUE
C
C                 compute ground velocity and ground
C                 displacement coefficients, SKA and CA
C                 compute ratio of YAMAX/EQMAX to use in
C                 normalizing the time history to the
C                 desired maximum level
C
C
```

```
      SKA = D10(1,1)
      CA = D10(1,2)
C
C
      AFACT=YAMAX/EQMAX
C
C                 normalize the time history (YA)
C                 compute the ground velocity (YV) and
C                 the ground displacement (YD) from YA,
C                 assuming linear acceleration between
C                 time steps
C
C                 compute the applied earthquake force,
C                 FG, from the coefficients and YA,YV,YD
C
      YANEW=0.
      YVNEW=0.
      YDNEW=0.
C
      DO 50 I=1,NSTEP
C
      YAOLD=YANEW
      YVOLD=YVNEW
      YDOLD=YDNEW
C
      YA(I)=AFACT*YA(I)
      YANEW=YA(I)
      DEL=YANEW-YAOLD
      YVNEW=YVOLD+(DT/2)*(2*YAOLD+DEL)
      YDNEW=YDOLD+DT*YVOLD+(DT*DT/6)*(3*YAOLD+DEL)
      YV(I)=YVNEW
      YD(I)=YDNEW
      FG(I)=-(SM*YA(I)+CA*YV(I)+SKA*YD(I))
C
50    CONTINUE
C
      RETURN
      END
C
C
C*****************************************************************
C
C
```

```
      SUBROUTINE ALGORI(YA,FG,DT,NSTEP,YAMAX,SM,C,SK)
C
C     *****************************************************
C     *                                                   *
C     *          OPTIMAL FEEDBACK CONTROL ALGORITHM       *
C     *          FOR SDOF SYSTEM                          *
C     *                                                   *
C     *          earthquake time-history is passed in and *
C     *          used as input in the open-closed loop    *
C     *          control algorithm                        *
C     *          system response and control force are computed *
C     *          and are written to output file           *
C     *                                                   *
C     *****************************************************
C
      REAL A1ZOLD(2,1),D(2,1),ZG(2,1),G(2,1),ZNEW(2,1),ZOLD(2,1)
C
      DIMENSION X(5000),V(5000),A(5000),ABSA(5000),U(5000),
     *          FG(1),T(5000),YA(1)
C
      REAL*4 FGOLD,FGNEW,UNEW,UOLD,ANEW,AOLD,DA,AMAX,VMAX,
     *       XMAX,ABSMAX,UMAX,FGMAX,SK,SM,C,DT,C2,C3,C4,TAU,YAMAX
C
      INTEGER I,J,NSTEP
C
      COMMON C2,C3,C4,A1(2,2),A2(2,1),A3(2,1),D9(2,2),D10(1,2)
C
C
C                set all variables in time step loop
C                to zero before starting loop
C
      ZNEW(1,1)=0.
      ZNEW(2,1)=0.
      FGNEW=0.
      ANEW=0.
      UNEW=0.
      XMAX=0.
      VMAX=0.
      AMAX=0.
      ABSMAX=0.
      UMAX=0.
      FGMAX=0.
C
C
C                start time step loop, 1 to NSTEP
C
      DO 1000 J=1, NSTEP
C
C                increment variables from the
C                previous time step
C
           FGOLD=FGNEW
           ZOLD(1,1)=ZNEW(1,1)
           ZOLD(2,1)=ZNEW(2,1)
           UOLD=UNEW
           AOLD=ANEW
           FGNEW=FG(J)
C
```

```
C                 compute coefficients needed to
C                 calculate ZNEW and UNEW
C
               CALL MATMUL(A1,2,2,ZOLD,2,1,A1ZOLD)
C
               DO 222 I=1,2
                  D(I,1)=A1ZOLD(I,1)+A2(I,1)*UOLD+A2(I,1)*FGOLD
                  G(I,1)=D(I,1)+A3(I,1)*FGNEW
C
222            CONTINUE
C
C                 compute ZNEW as a function of ZOLD,
C                 UOLD,FGOLD,and FGNEW compute UNEW
C                 as a function of ZNEW
C
C
         CALL MATMUL(D9,2,2,G,2,1,ZNEW)
         CALL MATADD(ZNEW,2,1,G,ZG)
         CALL MATMUL(D10,1,2,ZG,2,1,UNEW)
C
C
C                 put the components of ZNEW into
C                 displacement and velocity arrays
C                 compute the relative acceleration
C                 from ZNEW, FGNEW, and UNEW
C                 determine absolute acceleration and
C                 put A, ABSA, and UNEW into arrays
C
               X(J)=ZNEW(1,1)
               V(J)=ZNEW(2,1)
C
               DA=(-C2*AOLD-C3*ZOLD(2,1)-SK*ZOLD(1,1)+UNEW+FGNEW)*C4
C
               ANEW=AOLD+DA
               A(J)=ANEW
               ABSA(J)=YA(J)+A(J)
               U(J)=UNEW
C
C                 check for maximum values
C
C
               IF  (ABS(X(J)).GT.ABS(XMAX))  XMAX=X(J)
               IF  (ABS(V(J)).GT.ABS(VMAX))  VMAX=V(J)
               IF  (ABS(U(J)).GT.ABS(UMAX))  UMAX=U(J)
               IF  (ABS(FG(J)).GT.ABS(FGMAX))  FGMAX=FG(J)
               IF  (ABS(ABSA(J)).GT.ABS(ABSMAX))  ABSMAX=ABSA(J)
C

1000  CONTINUE
C
C                 compute time-history of time values
C
      TAU=0.
      DO 1500 I=1,NSTEP
         T(I)=TAU
         TAU=TAU+DT
1500  CONTINUE
C
```

```
C                 write output to a file for use
C                 in plotting (T,X,V,ABSA,U,FG,YA)
C
C
      WRITE(6,1100) XMAX,VMAX,ABSMAX,UMAX,FGMAX,YAMAX
      WRITE(6,2010)
1100  FORMAT(6(1PE20.6))
C
C
      DO 5000 I=1,NSTEP
         WRITE(6,4090) T(I),X(I),V(I),ABSA(I),U(I),FG(I),YA(I)
4090     FORMAT (6(1PE10.3,1H,),1PE10.3)
5000  CONTINUE
C
C
      RETURN
      END
C
C
C*****************************************************************
C
      SUBROUTINE INVERS (A,B)
C
C     ***********************************************************
C     *                                                         *
C     *     SUBROUTINE FOR USE IN INVERTING 2X2 MATRICES        *
C     *                                                         *
C     *     inverts square 2x2 matrix A and returns it as B     *
C     *                                                         *
C     ***********************************************************
C
      REAL*4 DET
      REAL A(2,2),B(2,2)
      DET=A(1,1)*A(2,2)-A(1,2)*A(2,1)
      B(1,1)=A(2,2)/DET
      B(1,2)=-A(1,2)/DET
      B(2,1)=-A(2,1)/DET
      B(2,2)=A(2,2)/DET
C
      RETURN
      END
C
C
C*****************************************************************
C
      SUBROUTINE MATADD (A,M,N,B,C)
C
C     ***********************************************************
C     *                                                         *
C     *     SUBROUTINE FOR USE IN ADDING MATRICES               *
C     *                                                         *
C     *     adds together two matricies (A & B) having the      *
C     *     same dimensions (M x N) and returns the sum as C    *
C     *                                                         *
C     ***********************************************************
C
      REAL A(M,N),B(M,N),C(M,N)
      INTEGER M,N,I,J
```

```
C
      DO 30 I=1,M
          DO 20 J=1,N
            C(I,J)=A(I,J)+B(I,J)
20        CONTINUE
30    CONTINUE
C
      RETURN
      END
C
C*******************************************************************
C
      SUBROUTINE MATMUL (A,M,N,B,K,L,AB)
C
C     *************************************************************
C     *                                                           *
C     *     SUBROUTINE FOR USE IN MULTIPLYING MATRICES            *
C     *                                                           *
C     *     multiplys two matricies (A & B) having dimensions     *
C     *     (M x N) and (K x L),respectively, where N = K         *
C     *     returns the product as AB                             *
C     *                                                           *
C     *************************************************************
C
      REAL*4 PART
      INTEGER M,N,MM,NN,K,L,LL,I,J
      REAL A(M,N),B(K,L),AB(M,L)
C
      DO 30 I=1,M
          DO 20 J=1,L
              AB(I,J)=0.0
20        CONTINUE
30    CONTINUE
C
      DO 60 MM=1,M
          DO 50 LL=1,L
              DO 40 NN=1,N
                  PART=A(MM,NN)*B(NN,LL)
                  AB(MM,LL)=AB(MM,LL)+PART
40            CONTINUE
50        CONTINUE
60    CONTINUE
C
      RETURN
      END
C
C
C*******************************************************************
```

```
C
      SUBROUTINE TRANS (A,M,N,B)
C
C     ************************************************************
C     *                                                          *
C     *     SUBROUTINE FOR USE IN TRANSPOSING MATRICES           *
C     *                                                          *
C     *     transposes matrix A with dimensions (M x N) and      *
C     *     returns the transposed matrix B, dimensions (N x M)  *
C     *                                                          *
C     ************************************************************
C
      REAL A(M,N),B(N,M)
      INTEGER N,M,I,J
C
      DO 30 I=1,M
          DO 20 J=1,N
              B(J,I)=A(I,J)
20        CONTINUE
30    CONTINUE
C
      RETURN
      END
```

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NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

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