DESIGN AND SIMULATION OF HYDRAULIC SHAKING TABLE

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To my beloved family,

The lover in you who brings my dreams comes true,

To my child Luqmanul Hakim and Fatin Nur Atikah, who have brought

a new level of love, patience and understanding

into our lives.

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ABSTRACT

Recent industrial progress and computational technology made it possible to construct more complex structures. Vibration of these structures due to seismic strength must be measured and proved to prevent them from damage when they are subjected to earthquake. However, the accuracy of estimating the effect of vibrating structures is limited by the mathematical models, which are normally simplified from the actual complex structures. Due to this problem, a study on the development of shaking table is proposed. The main purpose of this study is to obtain the design specifications for a 1-axis (horizontal) hydraulic shaking table with medium loading, which can function primarily as an earthquake simulator and a dynamic structural testing apparatus. The project employs a three stage electrohydraulic servovalve, actuator system complete with hydraulic system as the power and drive unit. Mathematical model for closed loop control experimentation was presented and used to investigate the influence of various parameters on the overall system. The investigation includes the study on the effect of controller gain setting (for PD and AFC), disturbances and system stability. Time domain analysis using computer simulation was conducted to explain and predict the system's response. Comparison between PD and PD-AFC controllers was done and it was found that latter PD-AFC fulfills the performance and robustness specifications for this project. Other design outcome that limits the change of disturbances on the system was also identified and taken as the framework for real world. This suggests that the next stage in implementation of the designed system can be made for the purpose of an earthquake simulator, since it works very well especially at low frequency level of shaking (0 to 5 Hz).

ABSTRAK

Perkembangan dan kemajuan teknologi terkini dalam bidang industri dan perkomputeran membolehkan struktur bangunan yang lebih kompleks dibina. Getaran struktur bangunan ini terhadap gegaran sismik perlu diukur dan dibuktikan untuk mencegah daripada kerosakan teruk apabila gempa bumi sebenar berlaku. Walaubagaimanapun, untuk struktur yang kompleks, penganggaran kesan getarannya menggunakan model matematik adalah terhad disebabkan beberapa anggapan dalam analisa dinamiknya. Disebabkan masalah ini, telah membawa kepada perkembangan alat lantai gegaran hidraulik. Tujuan utama kajian ini adalah untuk merekabentuk spesifikasi alat lantai gegaran hidraulik 1 paksi (mendatar) pada skala beban yang sederhana. Ianya digunakan untuk tujuan simulator gempa bumi dan untuk menguji pelakuan dinamik sesuatu model atau prototaip struktur. Projek ini menggunakan peringkat ketiga injap servo elektrohidraulik, sistem penggerak lelurus dan sistem hidraulik sebagai unit kuasa dan penggerak. Model matematik untuk ujian kawalan gelung tertutup telah dibincangkan dan digunakan untuk mengkaji kesan beberapa parameter terhadap keseluruhan sistem. Kesan yang dikaji termasuk penetapan pemalar pengawal, kesan pengawal PD dan AFC, kesan gangguan dan kestabilan sistem. Analisa dalam domain masa menggunakan simulasi komputer telah dijalankan untuk mengenalpasti kelakuan sistem. Perbandingan antara pengawal PD dan PD-AFC dikaji dan didapati pengawal PD-AFC memenuhi keperluan spesifikasi sambutan masa dan kelasakannya untuk kajian ini. Parameter lain hasil daripada simulasi yang menghadkan kelakuan sistem daripada kelakuan asalnya juga telah dikenalpasti dan dijadikan asas dalam aplikasi sebenar. Secara keseluruhannya, fasa untuk membangunkan sistem yang telah direkabentuk ini boleh dilakukan untuk tujuan simulasi gempa bumi kerana ianya berfungsi dengan baik terutamanya pada lingkungan frekuensi 0 hingga 5 Hz.

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β	-	Bulk modulus
V	-	Volume
dP	-	Change in pressure
dV	-	Change in volume
F	-	Force
μ	-	Coefficient of friction
N	-	Normal force
Q_E	-	Input flow rate into the cylinder’s blank end side
v	-	Extending velocity of the cylinder rod.
q_E	-	Output flow rate from the cylinder’s rod end side
a'	-	Cross sectional area of the piston on the rod end side
A	-	Cross sectional area of the piston on the blank end side
D	-	Diameter of piston on the blank end side
d	-	Diameter of piston on the rod end side
$p1$	-	Pressure on the blank end side
$p2$	-	Pressure on the rod end side
Q_R	-	Output flow rate from the cylinder’s blank end side
u	-	Extending velocity of the cylinder rod
q_R	-	Input flow rate into the cylinder’s rod end side
P	-	Pressure
Q	-	Flow rate
$v_{average}$	-	Average extending velocity
BP	-	Burst pressure

t	-	Thickness
D_0	-	Outside diameter
D_i	-	Inside diameter
WP	-	Working pressure
FS	-	Factor of safety
S	-	Tensile strength
η_V	-	Volumetric efficiency
η_m	-	Mechanical efficiency
η_0	-	Overall efficiency
Q_T	-	Theoretical flow rate
T	-	Torque
ω	-	Angular velocity
W_{theory}	-	Theoretical flow rate
W_{actual}	-	Actual power developed by the pump
W	-	Viscous friction factor
B	-	Dry friction
m	-	Total mass
a	-	Acceleration
L	-	Piston rod length
I	-	Second moment of area
E	-	Young Modulus
K	-	Bending coefficient
f	-	Frequency
λ	-	Wavelength
x	-	Stroke length
t	-	Time
V_D	-	Fluid displacement
N	-	Speed rating

C_q, C_d	-	Discharge coefficient
P_S	-	Supply pressure
P_T	-	Load pressure
ρ	-	Density
δy	-	Additional displacement
x_V	-	Pilot spool displacement
x_m	-	Main spool displacement
r, c, e	-	Geometric coefficient
w	-	Valve spool perimeter
K_V, K_{VP}	-	Valve flow gain
T	-	Time constant
V_i	-	Voltage error signal
Q_P	-	Pilot stage flow rate
A_m	-	Effective area of main spool valve
K_d	-	Derivative gain
K_P	-	Proportional gain
K_i	-	Integral gain
EM	-	Estimated mass
F_a	-	Measured force from sensor
F_{active}	-	Active force
K_a	-	Servovalve controller gain
K_f	-	LVDT 1 gain
K_p	-	LVDT 2 gain
V_{in}	-	Input voltage command signal
Q_{bal}	-	Compression flow rate
Q_{piston}	-	Volume oil flow because of piston movement

Q_{total}	-	Total flow rate into actuator
f_r	-	Natural frequency (Hz.)
F_V	-	Viscous friction force
L	-	Leakage factor
Q_{leak}	-	Leakage flow rate
G_C	-	Overall reduced transfer function
G_a	-	Sensor transfer function
ω_n	-	Natural frequency (rad/sec)
t_s	-	Settling time
t_r	-	Rise time
g	-	Gravity = 9.81 m/s^2

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CHAPTER 1

INTRODUCTION TO SHAKING TABLES

1.0 Project Introduction

Shaking table is a machine that can perform realistic simulation of earthquakes or any other dynamic loading imposed to the test model or structures. There are many types of shaking table but it can be classify to its method of vibration actuation by electrically driven, hydraulically driven and manually driven shaking table. Shaking table is related to earthquake since much of its parameter is custom designed to the earthquake's parameter such as acceleration, displacement, frequency and stroke.

However hydraulically driven shaking table have more advantages from other method of actuation. Table 1.1 lists some of the advantages of using hydraulic shaking table.

Table 1.1: Comparison of hydraulic and electric shaking table

Hydraulic shaking table	Electric shaking table
1. Can be used for any size of load	1. Limited to small and medium size load.
2. Some of the parameter such as stroke, velocity, frequency can be changed easily depend on application.	2. Most of the time , the parameter have been set cannot be changed.

1.1 Objectives of Study

The main objectives of this study are:

1. To design a medium hydraulically driven shaking table to be used as an earthquake simulator.
2. To perform simulation of the designed hydraulic shaking table using techniques of dynamic system analysis especially in time domain method to investigate the linearity characteristics between input signal and the desired output.

1.2 Scope of Study

The scope of this study are:

1. Investigate the nature and properties of earthquake and its relation to the parameter to be used in the design of hydraulic shaking table.
2. Design a complete hydraulic circuit of a medium scale simple hydraulic shaking table based on selected parameter.
3. Derive the dynamic equation of the hydraulic shaking system and develop a mathematical model for the overall system.
4. Select a proper practical value for each parameter assigned in the mathematical model.
5. Perform computer simulation using MATLAB Simulink on the time domain analysis, feedback system design and to check the stability of the overall system.
6. All simulations are performed within the limitation of the selected parameter such as maximum load range, frequency range, shaking axis and maximum acceleration range.

In this project, the works are bounded in the frequency range of 20 Hz, maximum acceleration of 1.5g and maximum load of 4330 kg. Main component of hydraulic circuit and the hydraulic circuit diagrams have been designed and discussed.

Mathematical modeling of this project is being done on the servovalve and hydraulic servomechanism using Laplace Transform. Separate modeling will be done that is modeling of servovalve and modeling of actuator mechanism. Not only that due to nonlinearities in the servovalve, it is better to do a separate modeling of servovalve so that proper steps can be applied in order to take care of the nonlinearities. Then the modeling will be combined using block diagram and can be programmed in the Simulink.

Simulation part will be done in Semester II and the program that will be used is MATLAB Simulink. In this program the overall block diagram will be programmed in it and input signal will be imposed on the block diagram. Types of input signal to be tested are Step, Sinusoidal and Random input signals. Simulation also being done separately that is simulation of servovalve and combined simulation of servovalve and actuator to investigate the individual response. A proposed controller will be added. Then it will be compared and tested against disturbance effect on the system. Finally, the controller that fulfills the performance and robustness specifications will be selected. In the simulation, some design limitation and outcomes will be investigated in order to compensate for any practical changes that might occur during the actual condition.

This project is important to get the preliminary design of hydraulic shaking table of medium scale that have many benefit to the future work and development of this machine. Future research in this field is interesting since it can develop more realistic design of hydraulic shaking table.

1.3 Operation of Shaking Tables

Shaking table is a mechanical device that is used to test any structures under seismic or other types of dynamic loading such as step load, sinusoidal varying force, or random load. If the shaking table is designed primarily to test civil structure under seismic loading, then it is also called earthquake simulator. Normally test model are developed to understand the effects of different parameters and process that leads to failure of prototype at a real time. If the test model are performed under gravitational field of earth, then it is subjected to the shaking table test, whereas if the model tests are performed under higher gravitational field then it is subjected to centrifugal test. Therefore shaking table test is an experimental approach in order to assure the validity of the theoretical estimation of the response of the structure with the exact dynamic characteristics thus to develop the safety margin of design for the structure.

In the shaking table test, test specimens are placed on the table and it is fixed by mechanical fastener or artificial soil compacted on the table. Then the structure will experience a shaking process at a certain frequency values until a certain time limit set by the operator. The earthquake simulator or shaking table has a wide range of applications such as:

- Models of buildings or structure in a given scale, subjected to actual earthquake.
- Models of power supply or industrial buildings under specific dynamic loading conditions.
- Mechanical equipment and transportation facilities test
- Mechanical testing and development of dampers for power transmission lines.

Shaking table device operates in various means. Some of them use all-electric servo motor driven type as in Figure 1.1, servo hydraulic means of actuation for high mass payloads such as in Figure 1.2 and manually operated shaking table as in Figure 1.3 that use external applied force to shake the table.

Figure 1.1: Electric shaking table [1]

Figure 1.2: Servo hydraulic table [1]

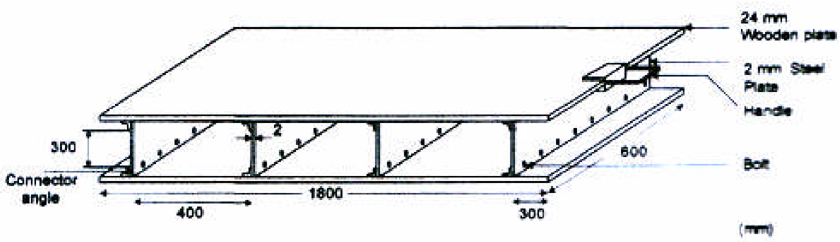

Figure 1.3: Manual shaking table [2]

1.4 Types of hydraulic shaking table

Since most of the shaking table is used as an earthquake simulator purposes, there is some of them been used as an apparatus to test the response or frequency of a structure or a test model. This permits the versatility and wide range of shaking table model. Shaking table is grouped based on its actuator power, frequency range and the maximum load it can handle. Normally it is classified either in small scale, medium scale or a large scale load. Small scale load hydraulic shaking table ranging from 0 to 1000 kg load whereas for medium scale can range from 1000 to 5000 kg and large scale range is greater than 5000 kg load. Section 1.4.1, 1.4.2 and 1.4.3 shows some manufacturer of hydraulic shaking table in the market.

1.4.1 INOVA – Servo hydraulic Testing System

INOVA is one of the leaders in seismic simulations for earthquake and structural research. Their seismic simulator called “Seismic Shaking Table” is used for seismic qualification and seismic simulation in civil engineering and academic research into earthquake. INOVA’s seismic shaking tables are designed for earthquake testing of a wide range of test applications. INOVA systems can be used to simulate a variety of seismic tests as well as evaluating many different types of components in vibration and shaking environments. The DOF refers to the number of shaking axis the machine can apply to the test model. Typical configurations are one, two, three and six degrees of freedom (DOF) as in Figure 1.4, 1.5 and 1.6.

Figure 1.4: 6 DOF shaking system [3]

Figure 1.5: 3 DOF shaking system [3]

Figure 1.6: 1 DOF shaking system [3]

The six degrees of freedom hydraulic shaking table machine is intended for general-purpose vibration tests. It is classified as a large-scale machine .In this machine, test model can be loaded in one axis or simultaneous axes. Test can be run in constant amplitude, block program or full simulation with combination of more than one wave profiles to be simulated simultaneously.

1.4.2 ANCO-Model R150.142 shaking table

This servo-hydraulic type-shaking table was used by Columbia University. It is a medium scale shaking table facility to conduct experimentation in structural dynamics and particularly to monitor and actively control structures subjected to earthquake ground motion or other force excitations. The table which was custom designed by ANCO Engineers for the Civil and Structural Research Engineering capable of carrying maximum three ton payload on the 5ft x 5 ft table size. The table is able to shake two ton payload with 3g acceleration (three times the acceleration of gravity in horizontal direction). Thus the table is ideally suited to seismic application. The hydraulic actuator can produce a stroke of maximum 10 inch (± 5 inch). The actuator has a three-stage servo-valve controlled by an analog inner-loop control system and a digital outer loop control system (acceleration feedback based).

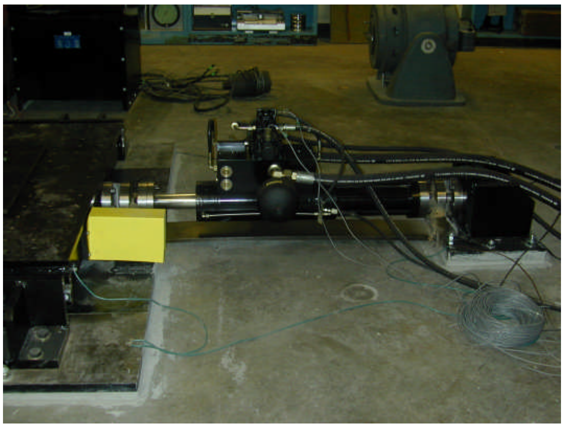

Figure 1.7: Close up of the 22 kip actuator with 3 stage servo valve [1]

Specifications of ANCO-Model R150.142;

1. Shaking direction : Uni-axial horizontal motion
2. Table size : 5 ft x 5 ft.
3. Peak to peak displacement : 10 inches of double amplitude
4. Peak velocity : 60 inch / sec.
5. Peak acceleration : 3.0g
6. Maximum test specimen weight : 2 tonne
7. Frequency range : 0 – 100 Hz.
8. Servo valve : 3-stage electrohydraulic servovalve.

1.4.3 NIED-E Defense Facility in Japan

Recently due to a number of major damage caused by earthquakes and structural buildings failure cases in Japan have led to the start of NIED-E Defense project. National Research Institute for Earth Science and Disaster Prevention (NIED) have three main objectives that are to conduct research and experimentation on the structural building failure test, developing three dimensional motion of the simulated real earthquake from past record earthquake data and build full scale model to predict the real behavior of the damage. NIED use a big scale shaking table facility as in Figure 1.8 to test their ready-made full-scale model. Some of the specifications of the shaking table facilities are;

Shaking table type	:	3D Full scale earthquake testing facility
Payload	:	1200 ton
Shaking table size	:	20m x 15m

Driving type	:	Accumulator charge, Electro-hydraulic Servo control
Shaking direction	:	X and Y Horizontal, Z – Vertical
Maximum acceleration at maximum loading.	:	X, Y Horizontal is > 900 cm/s^2 Z-Vertical is >1500 cm/s^2
Maximum displacement	:	X, Y Horizontal is ±100 cm Z-Vertical is ±50 cm

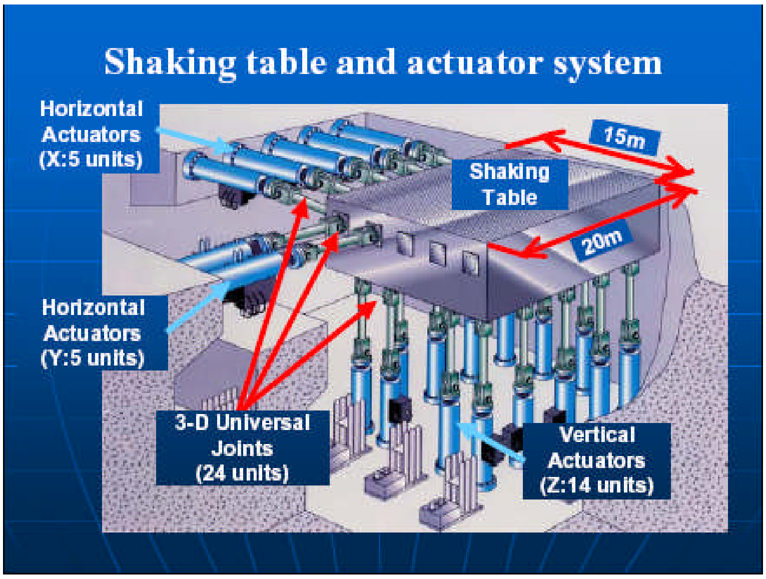

Figure 1.8: NIED earthquake simulator from Japan [4]

1.4 Project Scheduling

This project will be done within two semesters. Thus, breakdown of work structures must be implemented to make sure all the work being done within its allocated time. In the first Semester, initial literature research work will be done. This is to get a better picture on how to implement the scope of study number one until three. In Semester two, scope of study number four until six was performed. The breakdown of work structures for Semester one and two are attached in the Appendix A.