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EXPERIMENTAL MANUFACTURING OF A SMALL SHAKING TABLE IN UZBEKISTAN

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Abstract

Tashkent, Capital of Uzbekistan, experienced the earthquake damage in April 1966, just 50 years ago. In 1988 of The Soviet Era, devastating Armenia Spitak Earthquake occurred. Therefore, in order to research the seismic stability of structures, the reaction walls for seismic tests were constructed in Tashkent. However, soon, Soviet Union disintegrated. The reaction wall facility was left at Turin Polytechnic University in Tashkent (TTPU), Uzbekistan. TTPU tried to make a shaking table as an useful application of the facility by the small construction cost. The shaking table was made with the ready-made hydraulic equipments as the practical training for mechanical students. The shaking table moves with the hydraulic power in one horizontal direction, and has the steel table of 2.4m x 2.3m. The table, guide system and reaction frame were fabricated and assembled with welding of TTPU students. A hydraulic actuator has a single piston rod with the stroke of 30cm. The push area of piston is about 50 cm^2 and the pull area of piston is about 25cm^2 respectively. A solenoid valve uses for the oil flow control. The cylinder actuator and solenoid valve were imported from Italy. A hydraulic power supply capacity is 37Kw. The power supply was imported from China. Payload is 1.5 tones. Maximum driving force is 5tonf. Maximum velocity is 48cm/s. Mechanical responses of the shaking table were measured in open loop control, using an old analog function generator and DC power source. The actuator made drifts by differences in push-pull piston area, the piston rod made the drifts. The response movements of shaking table were unstable. In order to avoid the drift of piston rod, the baseline of input waves were adjusted with the turning of offset variable. Afterwards, the feedback control devices were prepared. The control device was designed and made in Japan. Next trials were conducted in closed loop with arbitrary inputs, by the use of PC with DA converter. The stable control of shaking table was verified. In this way, the general characteristics of shaking table have been obtained. In analysis, the simple equations of different piston areas of single rod were introduced and calculated. Calculations were conducted for the open loop and closed loop cases. As a matter of course, no drift in the actuator was confirmed in the close loop. In the paper, the outlines of TTPU seismic test facility are described. The paper is considering to construct a low-cost one horizontal direction shaking table. Cost of the shaking table manufacturing was less amounts than twenty thousand Dollars in total.

Keywords: Shaking Table; Single Rod Cylinder; Low-Cost; Hydraulic

1. Introduction

In Soviet era, Tashkent experienced the earthquake damages in 1966. According to the materials [1], magnitude of the earthquake was estimated bigger than M5.0. The epicenter was just under center of city, The depth of epicenter was very shallow less than 5km, very shallow. The earthquake intensity at Tashkent was estimated to be MSK-Ⅷ. The earthquake occurred in the morning of 5:22AM on April 26th. There were 10 - 200 Casualties, and damaged homeless peoples were about 100,000. Damaged houses were about 28,000. Most of damaged houses were one story adobe buildings. 1966 Tashkent Earthquake is considered to have given a lower bound of Magnitude of damaging earthquakes. After the earthquake, disaster prevention city planning of Tashkent city has been improved with wide streets, enough green spaces. And many Soviet style apartment buildings were constructed. In 1988, devastating Spitak Earthquake of MSK-X with Magnitude 6.8 occurred at 11:41AM on December 7th in Armenia, Soviet Union. Epicenter was north from Spitak city with depth of about 5km. Many apartment buildings [2] in Leninacan city collapsed, and peoples of about 45,000 were killed.

Considering the damages mentioned above, Soviet Union would be considered to construct the seismic test facility in Tashkent. The seismic test facility has two big reaction walls which are face to face and reduced upwards. One reaction wall has the dimension of 9.5m height and 8.8m width, floor level thickness 2.3m, and top level thickness 1.2m, approximately. The other wall has the dimension of 6.5m height and 8.8m width, floor level thickness 2.2m, and top level 1.5m, approximately, as shown in Fig.1. The reaction walls are made from reinforced concretes and steels. On the faces of reaction walls, there are slits of width 0.1m width in every 1m pitch, horizontal and vertical, for the mounting of loading test actuators, as shown in Fig. 2. Using hammer head bolts, actuators would be fixed on the reaction wall faces. The surfaces of slit ditch of 0.5m depth are covered with metal plates. The test floor of reaction wall facility locates under 2.25m from the building floor level. The test floor of reaction wall has the area of 13.5m length and 8m width. The bracket steel bolts which were used for the setting of test structures, were embedded over the floor as shown in Fig.2. By the memory of TTPU professor, the thickness of reinforced concrete test floor was 0.5m.

In the facility, there is another test floor on building floor level, in front of the reaction walls. The test floor has area of 18m x 28m with slits of 28m length with every 1m width for bracket bolt connections. The slit has same section as the slit ditch of reaction wall. The test floor is covered with steel plates. TTPU professor said that the thickness of test floor is 0.9m. On the test floor, several kind of structure element tests, as four point moment deflection, static horizontal test for horizontal deformation and loading of column and wall would be conducted.

Fig. 1 – Two reaction walls of Turin Polytechnic University in Tashkent.

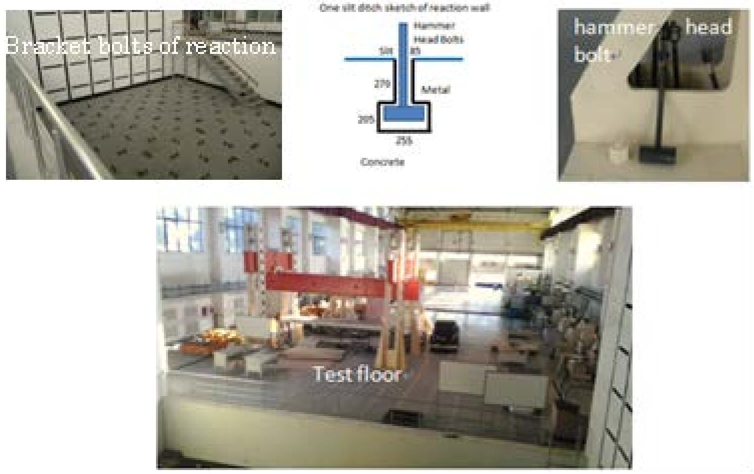


Fig. 2 – Explanations of TTPU Facility

Around 1990, social situations largely changed, and Uzbekistan went independent in 1991. The seismic test facility was left. In 2009, at the site of the seismic facility, Turin Polytechnic University in Tashkent (TTPU) was founded. TTPU made a plan to utilize the seismic test facility at TTPU site. Considering Uzbekistan situation, three dimensional shaking table has been listed as first priority test equipment. Prior to construct three dimensional shaking table, a hydraulic shaking table of one horizontal direction was made with the purpose of education for students in TTPU mechanical department.

2. TTPU Shaking Table of One Horizontal Direction

Considering the driving systems for the seismic shaking tables, there are several methods as the electromagnetic systems, the mechanical systems, and hydraulic systems. The electric servo motors are used for earthquake simulators of comparative low power system. However, the electromagnetic systems would not be good, because the seismic shaking tables require the large driving forces. For the big power shaking table with the heavy test structures, the hydraulic power would be proper. The biggest one is "e-defense" in Miki city near Kobe city, Japan. The maximum driving force of "e-defense" is 450tonf. The hydraulic power system would be proper for the dynamic strength test facility for the structures. TTPU decided to use the hydraulic system for TTPU shaking table.

TTPU which located in Uzbekistan, tried to manufacture a shaking table by themselves. The shaking table projects of TTPU were initiated about five years ago. Recently, the projects have been divided into two stages. In first stage, the shaking table of one horizontal direction is manufactured with the purpose of the education for students in TTPU mechanical department. In second stage, multi directional shaking table will be constructed after the completion of first stage shaking table. The following articles describe the records that students in TTPU mechanical department manufactured TTPU first stage shaking table of one horizontal direction.

TTPU first stage shaking table was assembled by students in TTPU mechanical department. A Reaction frame, a base frame, four guide ball bearings for one horizontal movement, and a table were cut, welded and set.

Fig. 3 – NC machines inside of Techno Park

The seismic test facility of TTPU has called Techno Park. In Techno Park, there are many kinds of numerical control machine tools for students in mechanical department, as shown in Fig. 3. Students in TTPU mechanical department handled the NC machine tools, and produced the elements of TTPU first stage shaking table.

An actuator cylinder, valve, valve driver, a power unit and hydraulic hoses, were purchased from Italy and China. The actuator cylinder had ready-made single piston rod. Piston areas in actuator cylinder were 50.24cm^2 in push side, and 25.61cm^2 in pull side. A stroke was 300mm. The actuator cylinder had a transducer of potentiometer as a piston position meter. At the top end of piston rod, a connection bolt was placed, and at the foot end of actuator cylinder, a fixed eye with the spherical bearing mounting was attached. The hydraulic power unite includes an accumulator, a relief valve and an oil filters, an electric motor, a hydraulic pump, and an oil tank. The outline of performance of power unit performance are shown in Table 1.

Table 1. – Hydraulic Power Unit Outline

Item	Performance
Electric Motor Power	37Kw
Oil Pressure	20MPa
Discharge Flow Rate	90ℓ/min
Oil tank Capacity	300ℓ
Accumulator	8ℓ(nitrogen gas)
Relief Valve,	
Two Oil Filter	

The valve was a servo proportional valve. The valve was installed to the actuator cylinder through a manifold block. The spool of valve was driven by the solenoid. The solenoid position was detected by LVDT transducer. A valve driver attached to the valve. A valve spool and LVDT transducer has constituted a closed loop control. A flow characteristics of the valve were about 90ℓ/min at Δp=70bar. A frequency characteristics were -3dB at about 40Hz to 100% spool stroke, about 100Hz to 5% spool stroke[3]. Inputs for the valve driver were analog signals. In order to control the actuator, the reference signals and the transducer signals of actuator piston rod positions should constitute a closed loop. In open loop, dynamic control of single rod actuator would be very complicated. To avoid divergences, reference signals must be deformed.

The Shaking table was fabricated at the reaction wall floor. At first, the base frame was fabricated by welding with the use of 50mm x 100mm x 4mm steel members. The outline of base frame is shown in Fig. 4. On the base frame beams, the guide boxes which confine the shaking table movement to one horizontal direction, welded at four positions. A length of guide boxes of about 45cm was longer than the actuator cylinder stroke . In each guide box, two spherical steel balls placed, which performed as bearings with the glycerin of lubricate agent. The guide boxes which were fixed on the table backside, placed downwards. The outline of guide bearing system which consisted of the guide boxes and spherical steel balls, is illustrated in Fig. 5. The payload capacity of guide bearing systems which was checked by a compression testing machine, gave the results of more than 5KN.

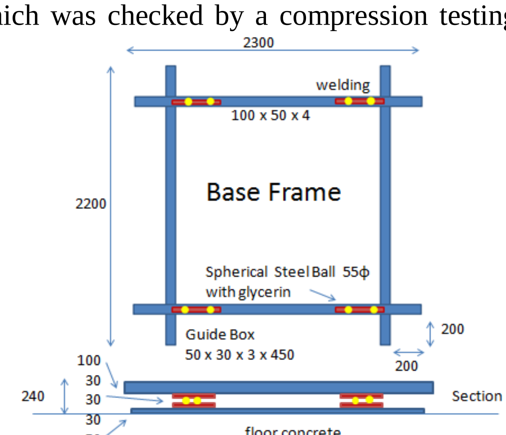


Fig.4 – Outline of base frame for shaking table

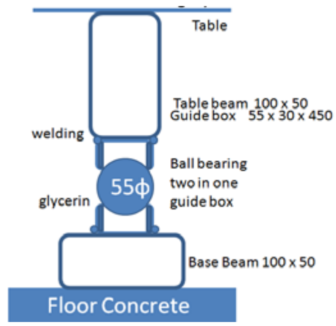


Fig.5 – Manufactured table guide bearing system

The table was made with the steel box beams of 100 x 50 x 4 and the steel plate of thickness 5mm. At first, the horizontal frame was fabricated by the welding works, and the table surface plates were welded on the horizontal frame. Over the table surface plate, there were 64 holes with diameter 20mm for bolt connections of test specimens. The table dimension was about 2400mm in X direction (driving direction) and about 2300mm in Y direction, about 105mm in the table height, as shown in Fig.6. The weight of table was estimated about 0.5ton. The actuator joint portion was strengthened, and the joint element of steel was attached. The table connected the actuator piston rod with the joint which consisted of the plates with the eye holes, and the steel bar of diameter 40mm and length 180mm, as shown in Fig.7. The reaction frame was made with the steel materials by the welding works, and fixed in the concrete floor with 6 bolt nuts of bolt diameter 27mm. The connection between the actuator cylinder and the reaction frame was carried out with a fixed eye with the spherical bearing mounting. The installation height of actuator cylinder from concrete floor was about 20cm.

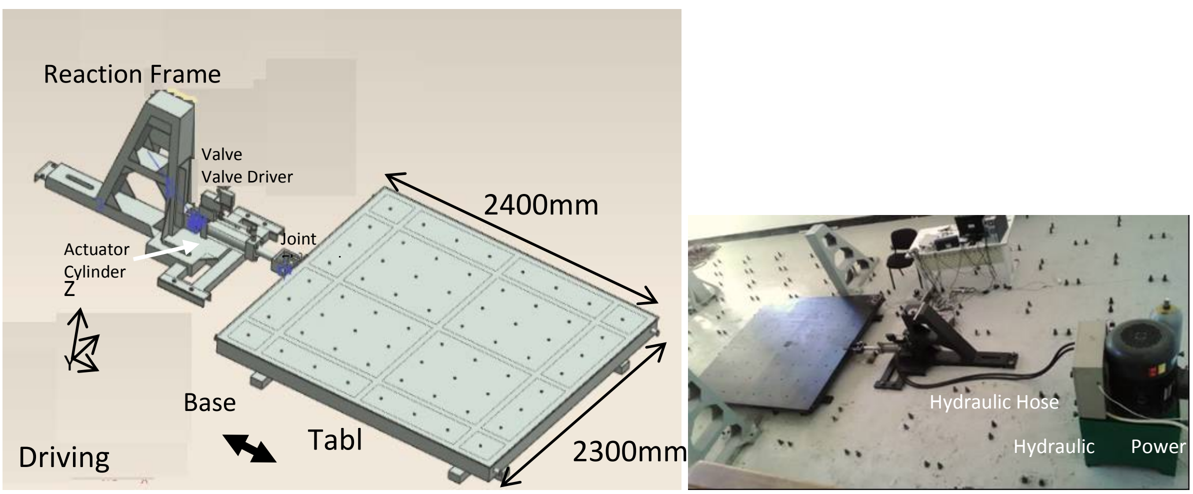


Fig.6 – Setting of shaking table, reaction frame and actuator cylinder on concrete floor

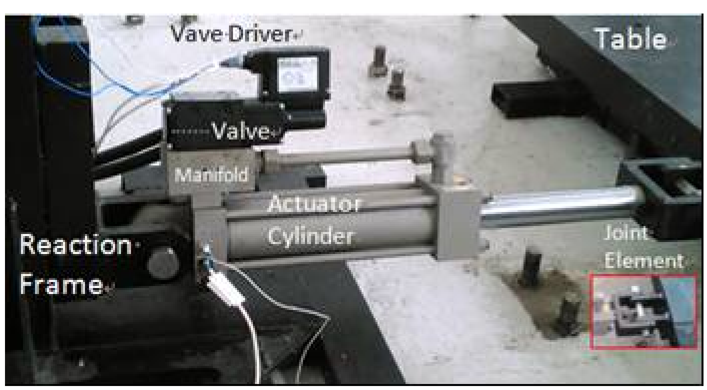


Fig. 7 – Situation around actuator cylinder

The hydraulic power unit was placed near the shaking table, as shown in Fig. 6. Electric power was supplied with three phase alternative current. No heat exchanger for oil cooling was equipped. The hydraulic hoses were connected from the hydraulic power unit to the ports of manifold block of actuator cylinder. The electric powers for the valve were supplied from an electric direct current power supply of about 140w, 35V, 4A. The solenoid of servo proportional valve was driven by the direct current 24V with a fuse of 2.5A.

At first, only an analog function generator was provided. In the situation without feedback control, shaking table responses were measured. Afterward, a PC with DA converter (±10V:16bits) for the generation of input signals was prepared. And an actuator control amplifier (analogue controller) which adjusts the piston rod position signals from a potentiometer and compares the position signals with input signals, have been provided. In this way, the closed loop system of shaking table control has been realized.

3. Trial of TTPU Shaking Table

The test runs were conducted in the open loop and closed loop controls. The outlines of driving systems in TTPU shaking table are presented in Fig.8.

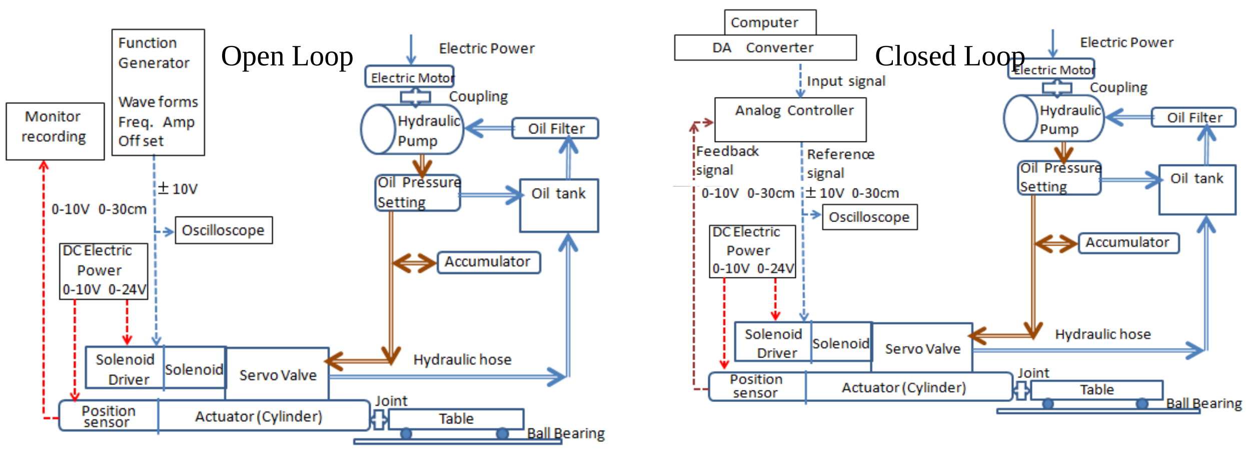


Fig. 8 – Driving system outlines of TTPU shaking table

3.1 Mechanical Responses of TTPU Shaking Table

First trial was conducted in an open loop. At first, the rectangular waves were inputted as reference signals into the valve driver. In an open loop without a servo amplifier, input signals transferred directly to the valve drive. Therefore, the position of spool in a servo proportional valve varies in accordance with input signal. Then a piston rod of actuator cylinder drew triangle waves in displacements. The accelerations of shaking table and the displacements of piston rod were measured. The pull area of piston rod in single rod cylinder is smaller than push area. Thus, the intervals of shock waves were not constant, changed alternately. Therefore, the slopes of triangle waves in displacements differed in accordance with directions. Fig.9 shows the accelerations and displacements of driving X direction. The acceleration in Fig.9 describes the response characteristics of TTPU shaking table system.

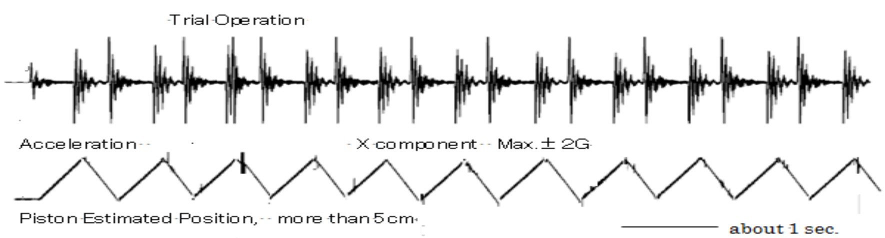


Fig. 9 – Shaking table response accelerations and actuator piston rod displacements to rectangular wave inputs

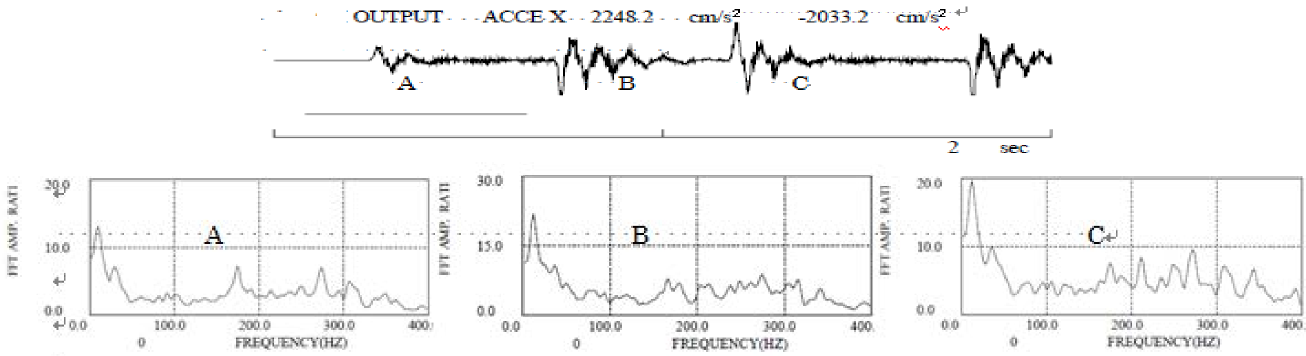


Fig.10 – Fourier spectra of TTPU shaking table acceleration responses to rectangular wave input

Fourier spectra of first three shock waves in acceleration responses are shown in Fig.10. The small amplitude response, presented 10Hz approximately, then the large amplitude response presented 12Hz. The damping characteristics of responses were estimated about 10%. The small frequency peaks of more than 100Hz were measured. In the measurements, the sampling frequency of 2KHz was selected. The natural frequencies of acceleration transducers were 400Hz approximately. The sinusoidal responses of 0.67Hz are shown in Fig.11 and Fig.12. Actuator movements associated with open loop was unstable, as shown in Fig.12. Therefore the inputs were adjusted by the turning of amplitude variable and offset variable. Sinusoidal movements of the shaking table were not accurate. The amplitude was about 1cm. Accelerations of X,Y,Z directions, included noises. The noise characteristics changed with directions. The noise frequencies were 349Hz and 173Hz. The noise level in Z direction was large. This indicated the rough setting of parts. With uses of low pass filter, the apparent response characteristics would be improved.

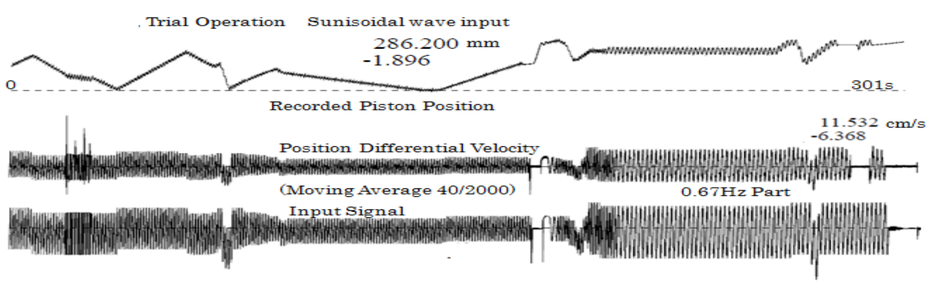


Fig 11. – Unstable movements and offset variable adjustments of input

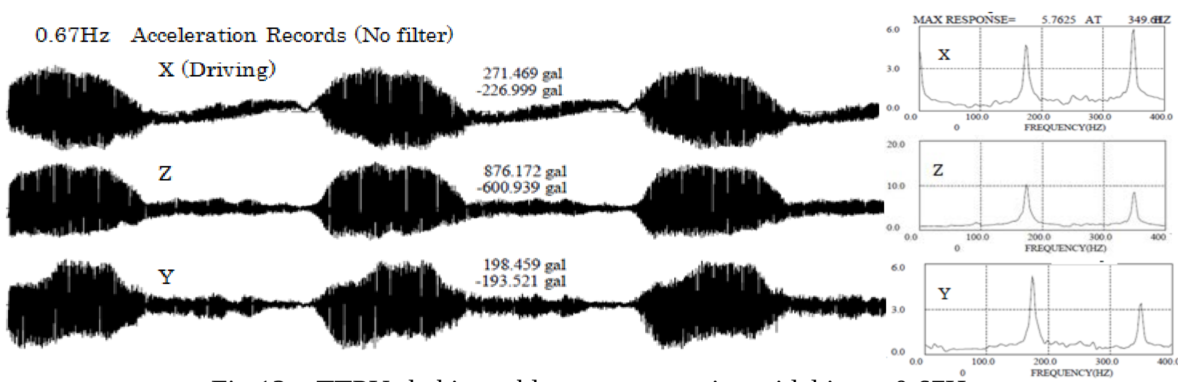


Fig.12 – TTPU shaking table response to sinusoidal input 0.67Hz

3.2 Close Loop Trial

The characteristics of a closed loop control were investigated. The input waves were prepared in PC, and transmitted to DA converter. Rectangular waves, sinusoidal waves, and earthquake records which observed at vicinity of fault in 2016 Kumamoto Earthquake on April 16 [4], were provided. The trial operations were conducted with varying loop gain and supply pressure. At first, the rectangular waves of displacement around 1cm were applied at every 2 second. The rise time characteristics with the variance of loop gain and supply pressure were measured. Fig.13 shows the rectangular wave responses of TTPU shaking table. The effects of loop gain values were understood. The sinusoidal waves of amplitude 4.5cm with period 2 seconds were applied. The loop gain effects are shown in Fig.14. With closed loop control, the more accurate sinusoidal waves were obtained in the shaking table. However, the movements of a servo valve spool were differed from the sinusoidal motions, as shown in Fig.15. The inputted earthquake wave was corrected by the elimination of tilt components in the original time history of acceleration. The integrated displacement and velocity from original acceleration without baseline correction were shown in Fig.16. The reproduced waves in loop gain 1.0 and supply pressure 15Mpa, were shown in Fig,17. The difference between original waves and reproduced waves, would be found in the short period movement of acceleration.

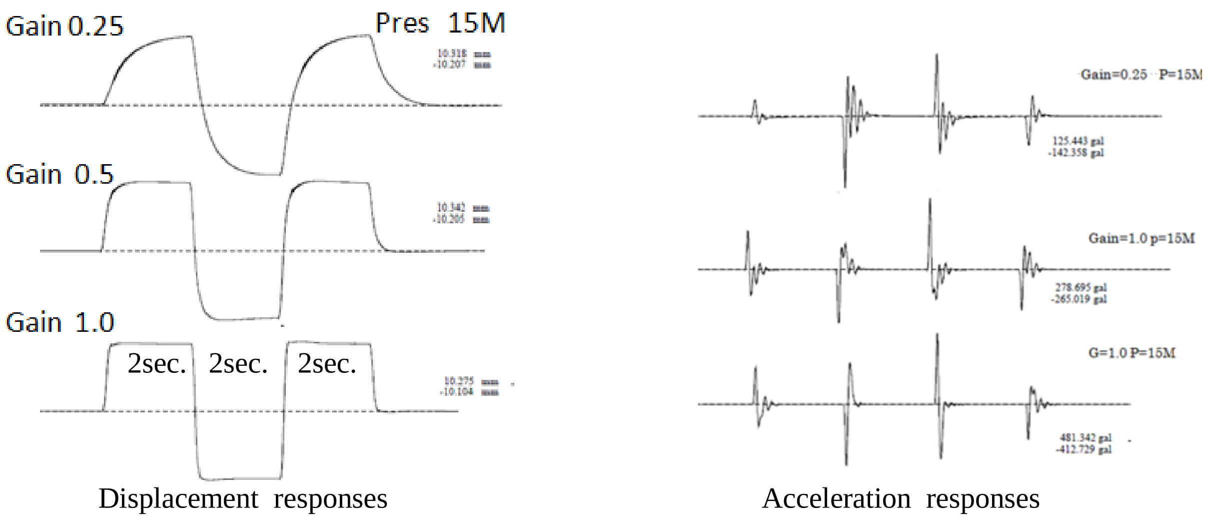


Fig.13 – Rectangular wave responses in amplitude ±10mm

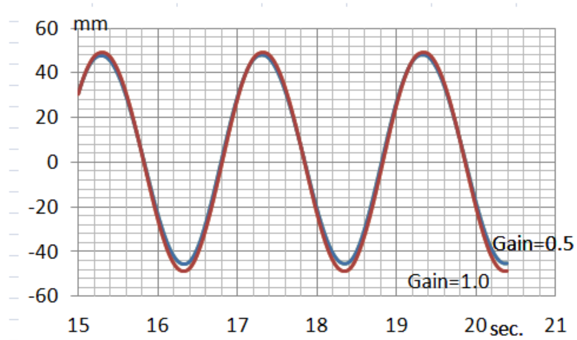


Fig.14 – Displacement response to sinusoidal wave

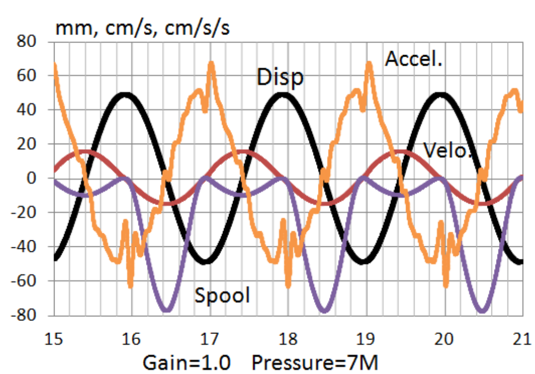


Fig.15 – Table responses to sinusoidal wave

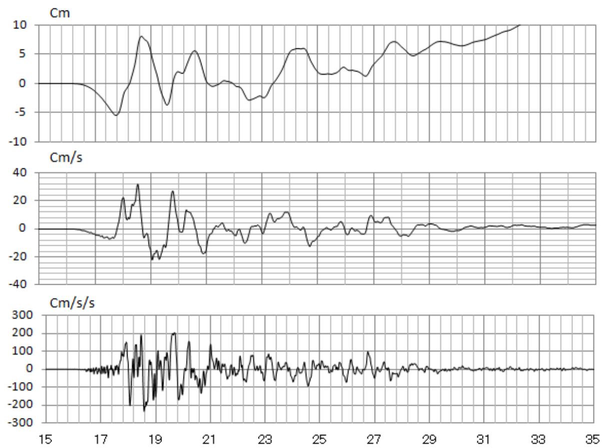


Fig.16 – Original earthquake wave (target waves).

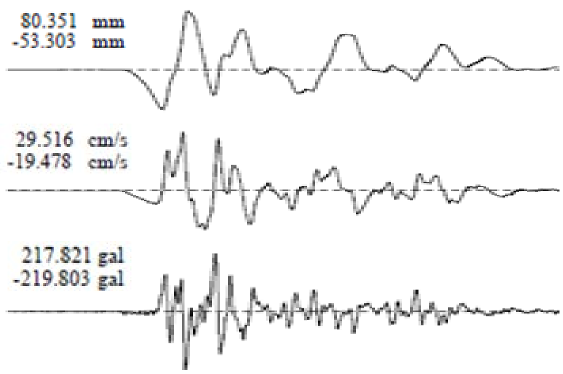


Fig.17 – Reproduced earthquake waves on shaking table.

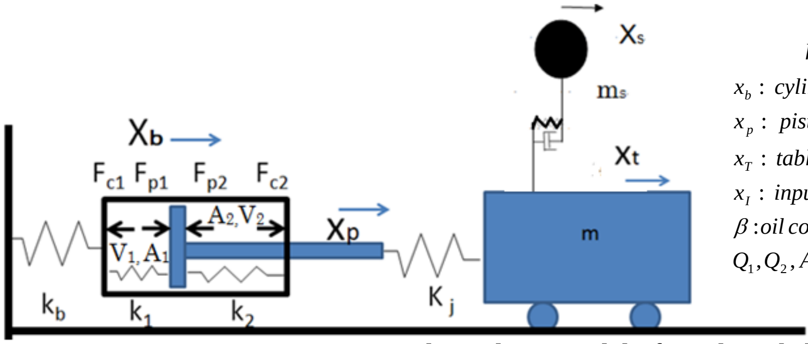
4. Discussion

Simple considerations on hydraulic flow in actuator cylinder are carried out. Using a continual equation of liquid flow and the relation between volume change and pressure, the flow equation of a single rod actuator is given as $\dot{x}_p A_1 = Q_1 - V_1 \dot{p}_1 / \beta$, $\dot{x}_p A_2 = Q_2 - V_2 \dot{p}_2 / \beta$ [5]. Considering these two relations and driving force $F = A_1 p_1 - A_2 p_2$, the actuator oil column spring is given as $k_o = \beta (V_2 A_1^2 + V_1 A_2^2)/V_1 V_2$, symbols are explained in Fig.19. A deformation of driving system x is expressed in equation (1) as follows.

$$x = x_b + (x_p - x_I) + x_T - x_p - x_b = x_T - x_I \tag{1}$$

The spring connections are serial, therefore the total spring of driving system k is given as $k = k_b k_o k_j /(k_o k_j + k_b k_j + k_b k_o)$. The driving force is expressed by $F = k(x_T - x_I)$. In following Eq. (2), x_v ; spool displacement of servo valve, ς_v, ω_v ; servo valve characteristics, y_I ; input signal to shaking table system, k_ℓ ; loop gain, F_s ; power of actuator (differ with directions), k_v ; flow rate of servo valve.

$$\begin{aligned}
& m_s(\ddot{x}_s + \ddot{x}_T) + c_s \dot{x}_s + k_s x_s = 0 \\
& m_s(\ddot{x}_s + \ddot{x}_T) + m_t \ddot{x}_T = -k(x_T - x_I) \\
& \frac{A_1 V_1 V_2}{(V_2 A_1^2 + V_1 A_2^2)\beta} k\left(\frac{\partial x_T}{\partial t} - \frac{\partial x_I}{\partial t}\right) - A_1 \dot{x}_I = x_v k_v \sqrt{1 - |k\ (x_I - x_T)/F_s|} \\
& \ddot{x}_v + 2\varsigma_v \omega_v \dot{x}_v + \omega_v^2 (x_v - k_\ell (y_I - x_T)) = 0
\end{aligned} \tag{2}$$



$k_o = k_1 + k_2$

x_b : *cylinder displacement*,

x_p : *piston rod relative displacement*,

x_T : *table displacement*,

x_I : *input displacement, given by servo valve* (Q/A)

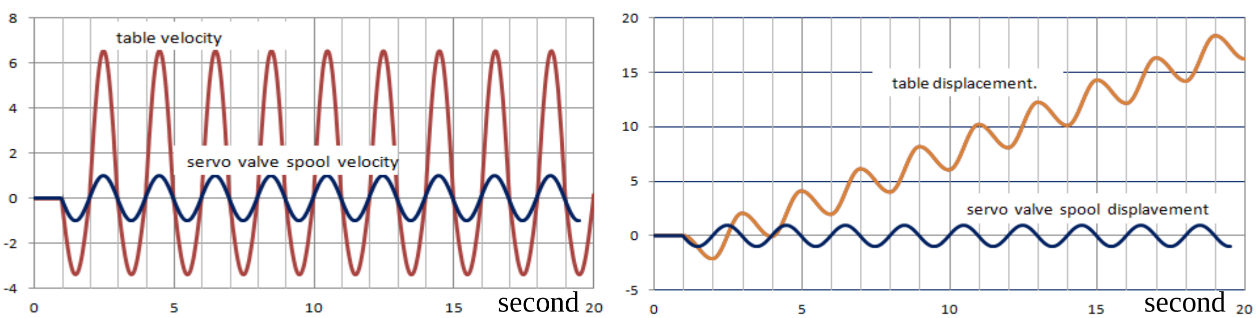
β : *oil compressibility*

$Q_1, Q_2, A_1, A_2, V_1, V_2,, p_1, p_2$ *flows, Areas, volumes, pressures of chamber* 1,2

Fig.18 – Simple analysis model of single rod shaking table

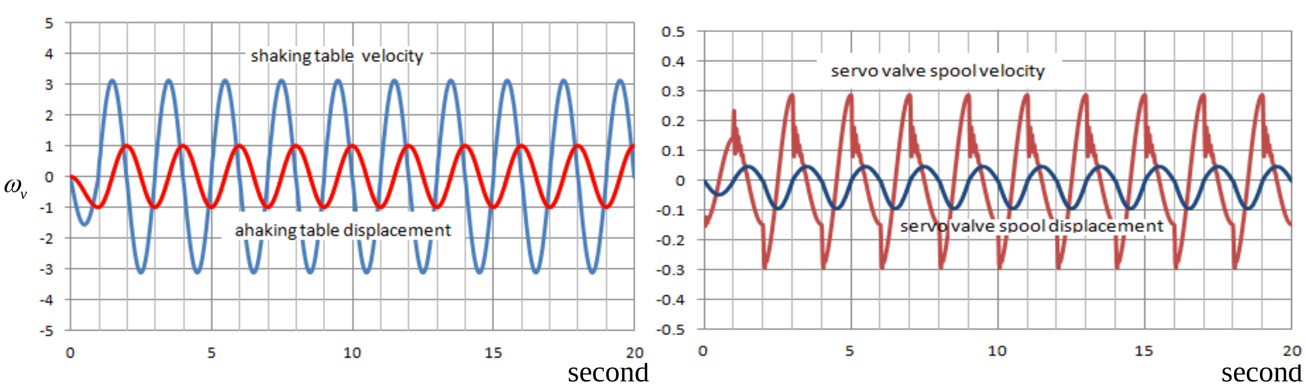
In Eq. (2), first expression is for the test structure, second one is for the shaking table, third one is for the actuator, fourth one is for servo valve. Fourth expression of Eq.(2) describes the displacement feedback control of closed loop. In open loop , fourth expression of Eq.(2) is rewritten as $\ddot{x}_v + (s_1 + s_2)\dot{x}_v + s_1 s_2 (x_v - y_I) = 0$

By applying Eq.(1,2) to TTPU shaking table, the differences of open loop and closed loop operation are discussed. It is assumed that a test structure fixed on the shaking table has a natural frequency 1Hz, a damping 5%, a weight one ton. and table mass m_t 5KN, A_1; 50.25cm^2, A_2; 25.64 cm^2, V_1; 1131cm^3, V_2; 462cm^3,ς_v: 0.5, ω_v :2π・15, Ps : 21MPs, F_s: Ps・(A_1 or A_2), k :80MN/cm, k_v :1700 cm^3/s, k_ℓ :1. The shaking table input is sinusoidal of 0.5Hz, and unit amplitude. In calculation, the step interval time is 0.00001second. In an open loop operation, the input signal is taken as velocity. Fig.15 is calculation waves for the open loop. The Servo valve spool moves in accordance with input sinusoidal. By the difference of piston areas between push and pull, the wave baseline of the shaking table velocities makes shifts. Therefore a piston position of actuator cylinder makes a drift to stroke end. In the closed loop operation, the input signal is taken as displacement. Fig.16 are the calculation waves in the closed loop. The response displacements of shaking table are same as input signals.



(a): velocity response (b):displacement response

Fig.19 – Open loop response of shaking table and servo valve spool movement



(a):shaking table responses (b): servo valve movements

Fig.20– Displacements and velocities in closed loop

The control of single rod actuator is thought to be complicate in comparison with the double rod actuator, because the piston areas of push and pull sides are different. Servo valve movements of single rod actuator are complicated. Comparing the response displacements of servo valve spool in open and closed loops (Fig.19,20), the servo valve spool movements of close loop (Fig.20 (b)) were complicated. The servo valve spool movement of an open loop are smooth. Results would be good materials to understand the single rod actuator performances.

5. Conclusions

An attempt to examine the building safety by reproduction of the movement of the earthquake that caused the damage, is of course thing Such a thing was seen in many years ago. After 1891 Nobi earthquake of Japan, there is a record that a mechanical shaking table was made[6]. In addition, after the San Francisco earthquake of 1906, the shaking table of a mechanical system was created at the Blume Center of Stanford University , and it was used in ground soil experiments and structure model experiments[7]. Afterward, hydraulic technology and electronic control technology were progressed. It made possible to conduct tests by reproduction of the earthquake records in the shaking table in 1960s[8,9]. In 1970, one directional shaking table which had a payload of 500ton, an area of 15m x 15m, a stroke of 6cm (now 48cm), was constructed in Tsukuba City (NRCDP), Japan[10,11]. In addition, in 1982, two directional shaking table which had a payload of 1000ton, an area of 15m by 15m, an stroke of 44cm, was constructed in Tadotsu City (NUPEC), Japan[12]. In 2005, three directional shaking table which has a payload 1000ton, an area of 15m by 20m, a stroke of 206cm, was constructed in Mike City (NIED), Japan[13]. Now, large-scale shaking tables have been built in various parts of the world. When considering this situation, research institutes of developing countries where there are experiences of the earthquake damages, it is understood that say want to have a shaking table to reproduce the ground motion. 50 years ago in Central Asia, Uzbekistan capital Tashkent is subjected to a catastrophic damage. Therefore, It is natural that they have the hope of having a vibration table for structural testing.

Manufacturing of a shaking table with using single rod actuators is meaningful for the help of understanding the necessity of double rod actuators. Moreover, the open loop trials of a shaking table would be also meaningful for understanding the significance of closed loop controls. A shaking table of $450million dollar is significant in its way. Also, TTPU shaking table of less than 20thousand dollar is meaningful in its way.
Despite a low price, TTPU shaking table was able to some extent of the experiment. In the future, multi-directional shaking table would like to be installed at TTPU. And reaction walls of TTPU also are desired to be used for dynamic loading tests.

6. Acknowledgements

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