# RESEARCH AND DEVELOPMENT OF THREE-DIMENSIONAL SHAKING TABLE

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## SUMMARY

The progress of mechanical and control engineering is making possible to precisely manufacture and control a shaking table capable of simulating a three-dimensional motion, and we can foresee the completion of such table in near future. Since 1978, we have consistently studied to develop a three-dimensional shaking table for clarifying seismic behavior through three independent motions activating on X, Y and Z axes, which are completely free from mutual interference. We have also manufactured full-scale hydrostatic joint, large-flow servo valves and actuater as prototypes and completed performance tests on them to clarify the control of three-dimensional motions. This report summarizes the basic design standard of three-dimensional vibration testing facility, manufacturing techniques of the joint and servo valves, and the results of performance tests made on them.

## INTRODUCTION

Many researchers and engineers were demanded to develop the three-dimensional shaking table which is possible to reappearance the actual motion of earthquake by reason that the actual earthquake motion is the cubic motion ( three-dimensional motion ). However, the manufactured shaking table were almost one-dimensional or two-dimensional one up this point by the technical problem.

The progress of mechanical and control engineering is making possible to precisely manufacture and control a shaking table capable of simulating a three- dimensional motion, and we can foresee the completion of such table in near future. Since 1978, the National Research Center for Disaster Prevention ( NRCDP ) have consistently studied to develop the high-accuracy medium-size three-dimensional shaking table which has a sufficient accuracy of acceleration wave form and symphathize motion and high responsibility.

### PROGRESS OF DEVELOPMENT

The progress of the research and development for a three-dimensional

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shaking table is as follows;

| | |
|---|---|
| 1978 fiscal year | operation of the basic design, |
| 1979 | operation of the secondary basic design, |
| 1980 | manufacture of the hydrostatic joint, |
| 1981 | manufacture of the large-flow servo valve, |
| 1982 - 1983 | manufacture of the actuater and operation of the performance tests for them. |

## TECHNICAL PROBLEMS AND TARGETS OF DEVELOPMENT

### DESIGN SPECIFICATION

The basic design specification of three-dimensional shaking table is shown in Table 1 and the vibration performance is shown in Fig. 1. Fig. 2 shows the bird-eye view of the designed facility.

### PROBLEMS AND TARGETS

The technical problems and the targets of development are as follows;

1) To develop the mechanism of three-dimensional motions ( joint ).
Development of the mechanism to completely free from mutural interference at three independent motions activating on X, Y and Z axes and to stabilized set the floor at the time of except for the operation.

2) To maintain the high accuracy of the limit performance.
Development of the system to maintain high characteristics of the performance for the large-flow servo valve.

3) To maintain the accuracy of the wave form.
Improvement the total accuracy to add the accuracy of mechanical elements such as actuater, joint, servo valve and etc., to control technique.

4) To improve the symphathize motion control of the multiple actuaters.
Adoption of the acceleration control ( acceleration fiedback ) system in which directly controlled the acceleration of the table to mixed with the parallel symphathize control by using the signals of amplitude, velocity and acceleration of the table.

5) To betterment the response characteristics in the region of medium and small amplitude.
Improvement the servo valve characteristics in the region near by zero.

6) To secure the safety supporting system of dead lord, the protection system for the safety and the maintenancebility.

7) To rapid measure and treat the enomous data.

By the arrangement of these many technical problems, we have manufactured the full-scale hydrostatic joint, large-flow servo valves and actuater as prototypes and completed the performance tests on them to clalify the control of three-dimensional motions. And, we were confirmed a degree of accomplishment of the targets of development by the performance test of actuating system ( system constructed by actuater, joint and servo valves ).

## MANUFACTURE OF HYDROSTATIC JOINT

### STRUCTURE AND SPECIFICATION

The joint united with actuater and table mechanically, its job is the mechanism to communicate effectively the activating force to the table, and to free the orthogonal in-plane motions for the activating motion, and to prevent the mechanical gap to the utmost. The typical mechanism of joint are shown in Fig. 3. (a) and (b) in Fig. 3 are called the linked spherical bearing joint, and (c) is the hydrostatic bearing joint. In this project, we were adopted to (c) which is not generated the geometrical interference ( cross-talk ).

The general view of the hydraulic actuater with hydrostatic joint is shown in Fig. 4, and the section of joint is shown in Fig. 5. This hydrostatic joint is the mechanism to communicate the activating force by the oil films among up and down sides of slide bar and spherical bearing, to smoothly slide by almost ignore of friction between this oil films to the orthogonal in-plane motions. According to the specification as shown in Table 1, the specification of designed hydrostatic joint is shown in Table 2 and section of joint is shown in Fig. 6.

### MANUFACTURE OF JOINT

The most impotant process technique at the manufacture of joint is the adjustment of the gap between slide bar and spherical bearing, and between the salient surface and the concave one of the spherical bearing. The gap adjustment has been done to adjust and process by measuring with gap senser, and the process error is set up to ±0.01 mm for the gap amount of designed value 0.2 mm. And, this gap amount is desirable to uniformity cover the all surface of gap. By the manufactured results, the slide surface between slide bar and spherical bearing is able to slide almost no-friction at the oil pressuredfloat, and is possible to move all region of amplitude by the little finger. The natural frequency of joint is 101.3 Hz, we were considered that the manufacture of joint is satisfy to the design value.

## MANUFACTURE OF LARGE-FLOW SERVO VALVE

### TYPE OF SERVO VALVE

To control the large output force by the small input force, we use the electro-hydro servo valve. It is impotant to select the system in which to benefit for the purpose, because the many types of servo valve are made in the world. The types of servo valve are classified as follows;

- servo valve
  - nozzle flapper type
    - force fiedback type
    - follow onself type
  - torque moter type

└ force moter typr ─┤
└ moving coil type

In these types, we were selected to the force moter and moving coil type by the following reason;

1) To have the high responsibility.
   The available frequency of pilot valve is higher than 500 Hz.
2) To have the high accuracy.
   The histeresis between input current and rated flow, and between input current and rated pressure are small value.
3) To have the high reliability.
   In order to have the high stability, the damping coefficient of servo valve is changeable.
4) To easy the adjustment of the control system.
   The steps of the valve are less than other types.
5) To have the characteristic to strengthen to external noise.
   It is easy to make measures to very small micro noise.

## SPECIFICATION AND MANUFACTURE OF SERVO VALVE

The specification of designed servo valve is shown in Table 3, the roughly dimension and section of servo valve is shown in Fig. 7. If we assume that the dynamic force of actuater is 120 ton and pressure fall is 70 $kgf/cm^2$, the pressured area of the actuater become

$$\frac{120{,}000\ kgf}{(210-70)\ kgf/cm^2} = 855\ cm^2$$

The velocity is assumed to 100 cm/s, the necessary rated flow becomes to 5,130 l/min. It is unreasonable to supply the one servo valve for the rated flow 5,130 l/min, we were designed to supply two servo valves.

The manufactured servo valve is shown in Photo. 1, and the characteristics of servo valve are shown in Figs. 8 and 9. Fig. 8 shows the frequency characteristics of pilot valve, the frequency at phase delay -90° is higher than 500 Hz. Fig. 9 shows the frequency characteristics of servo valve, the frequency at phase delay -90° is higher than 150 Hz. We were considered that the manufacture of servo valve is satisfy to the design value.

## CONCLUSION

Photo. 2 shows the manufactured actuating system ( actuater, servo valve and joint ). In this report, we describe the out line of the development of three-dimensional shaking table, especially the manufacturing result of the hydrostatic joint and the servo valve. Through these research and development, we consider to obtain the prospect of realization of the useful three-dimensional shaking table.

## ACKNOLEDGEMENT

To prompt this project, the NRCDP has been established the investigation committee of three-dimensional vibration testing facility ( Chairman; Dr. S.

Okamoto, Proffesor emeritus of University of Tokyo ). This present work would not have been possible without the advice and the guidance, the authors would like to thanks the all of committee members.

Table 1 Specification of three-dimensional shaking table

| Item | Specification |
|---|---|
| Direction of vibration | Horizontal X, Y and Vertical Z (Simultaneously) |
| Vibration method | Electro-Hydraulic servo control method |
| Max. loading capacity | 75 tons |
| Max. displacement | X, Y ±200 mm |
| | Z ±100 mm |
| Max. velocity | X, Y ±100 cm/s |
| | Z ±75 cm/s |
| Max. acceleration | X, Y, Z ±1.2 g |
| | (at max. load) |
| Max. overturning moment | Pitching and rowing 100t-m |
| | Yowing 50t-m |
| Frequency range | 0 to 50Hz (wave form control) |
| | 50 to 100Hz (actuating only) |
| Input wave form | Regular wave form and random wave form |
| Control signal | Acceleration and Displacement |
| Joint | Flat plane hydro-static bearing |
| Oil power | Q=8,100 l/min P=210 kg/cm$^2$ |
| Electric power | About 5,500 kVA |
| Digital controller | Real Time Disk Operation Computer System |
| Data acquisition | 300 channel with sample and hold |
| | Sampling speed 130Hz/300 channel |

Table 2 Specification of Hydrostatic Joint

| | |
|---|---|
| Stroke | ±200 mm |
| Oil film | 0.1 to 0.15 mm |
| Supply pressure | 140 kgf/cm$^2$ |
| Max. loading capacity | 160 tons |
| Friction | < 20 kgf |
| Resonance frequency | > 100 Hz |

Table 3 Specification of Servo Valve

| Pilot valve | Main valve |
|---|---|
| Force motor type | Hysteresis |
| Input current 4A | of pressure < 3% FS |
| Hysteresis 2% FS | Hysteresis |
| Frequency > 500 Hz | of flow < 1% FS |
| Rated flow 10 ℓ/min | Frequency > 150 Hz |
| Rated pressure 210kgf/cm² | Rated flow 2500 ℓ/min |
| ξ (damping) 0.1 to 0.5 | Rated pressure 210 kg/cm² |

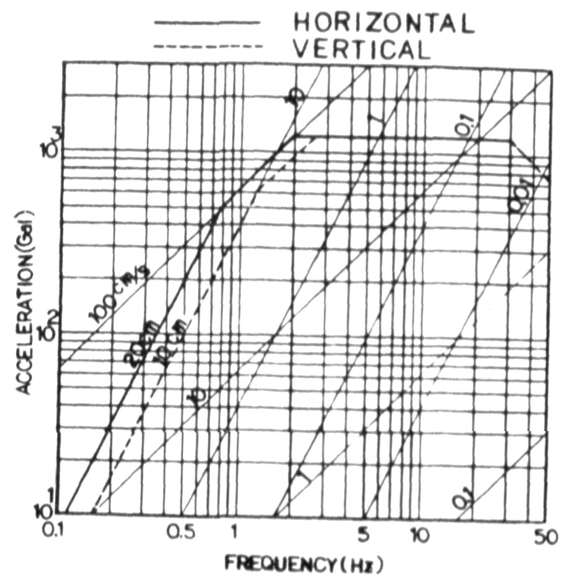


Fig. 1. Vibration performance

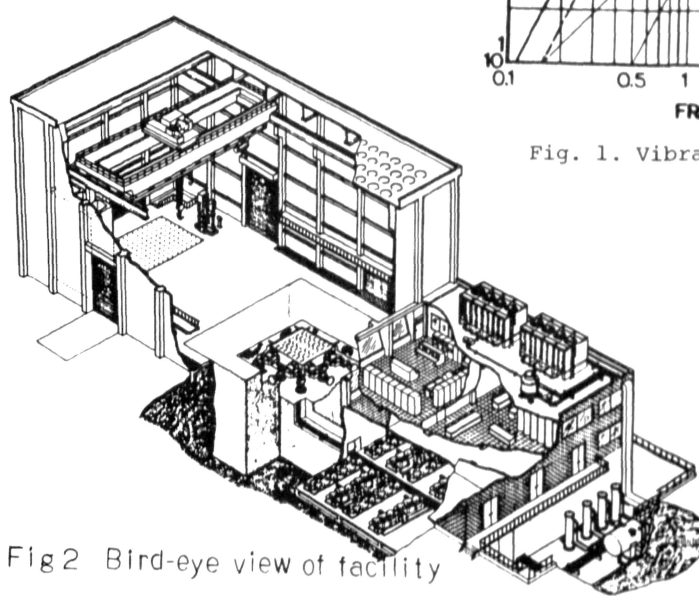

Fig 2 Bird-eye view of facility

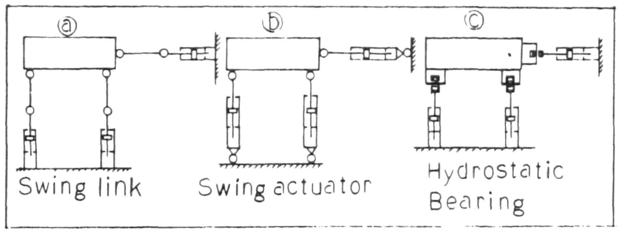


Fig. 3. Joint system

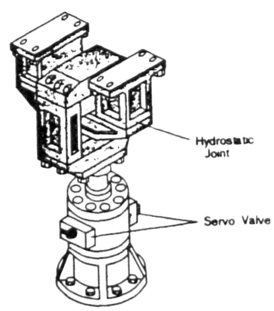


Fig. 4. Hydraulic Actuator
with joint

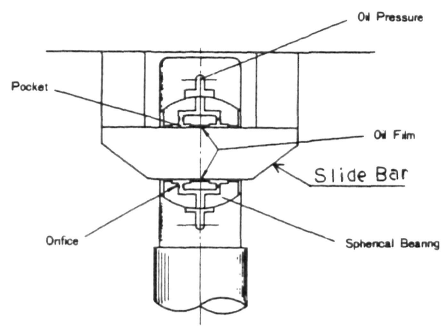


Fig. 5. Hydrostatic Bearing Joint

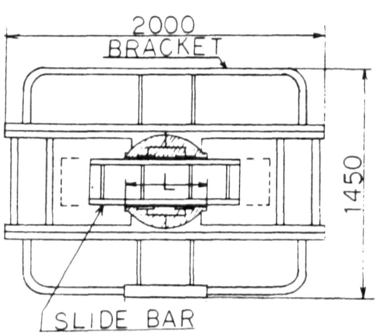


Fig. 6. Hydrrostatic Joint

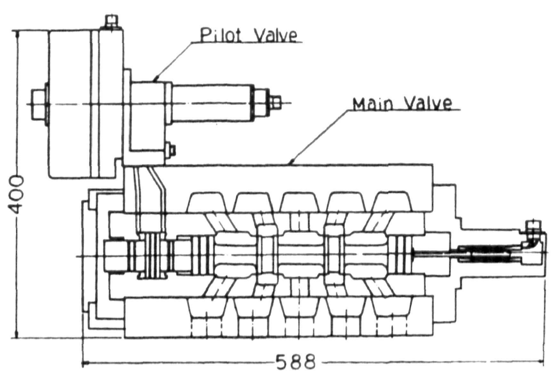


Fig. 7. Section of Servo Valve

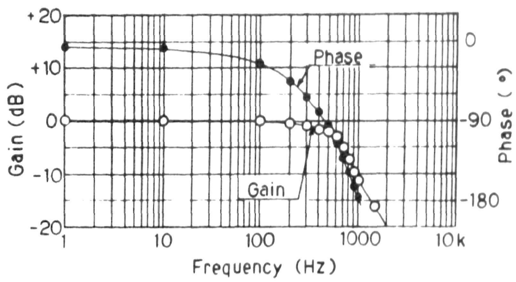


Fig. 8. Frequency Characteristics of Pilot Valve

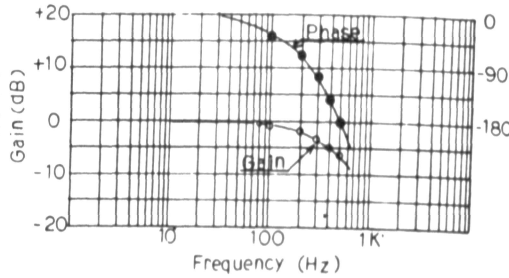


Fig. 9. Frequency Characteristics of Servo Valve

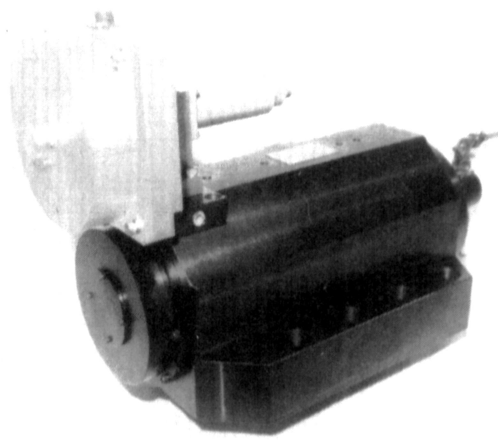

Photo. 1 Manufactured servo valve

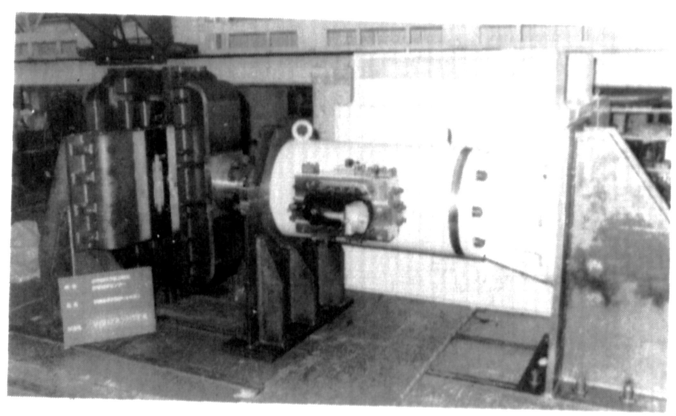

Photo. 2 Manufactured actuating system