'91 KACC 1991. 10. 22~24

# The Design of Six Degrees of Freedom Stewart Motion Platform Using High Power Electro-hydraulic Servo Control

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A high power stewart platform is designed and manufactured to simulate the 6 degrees of freedom motion of moving vehicle. This paper describes the design of such a motion system including kinematic and kinetic analysis, real time servo control techniques, mechanical and hydraulic system configuration, and techniques of regeneration of test records. Discussions are also presented for an algorithm called remote parameter control, which has been developed to compensate the dynamic delay of the electro-hydraulic servo actuators and the nonlinearities of stewart platform.

## 1. Introduction

The six degrees of freedom stewart motion platform[3] developed by ADD will be used for the evaluation of sighting system of moving vehicle. This large, and high performance motion system has such features[1] as follows:

o Static performance
  - large linear and angular excursions
  - high nominal payload
o Dynamic performance
  - very smooth movements
  - high bandwidth and acceleration
o Safety and maintenance
  - mechanical and electrical safety
  - Simple maintenance

The motion system comprises the following sub-systems
o The actuator assemblies with 3-stage servo valve
o The hydraulic power supplies
o The accumulator/distribution system
o Motion table for specimen attachment
o The high angle pivots
o Base frame for structure attachment
o Microprocessor based controller

The motion table is a rigid steel structure, designed to accept the nominal payload, and is powered by six identical double-acting cylinders with 3rd-stage servo valves which have high rated flow.

The twelve pivots have high rotating angle relative to the mounting bases, that is, motion table and base frame.

Base frame comprises three base sections, joined by three steel beams. It accepts the lower pivots, provides the attachment structure to the concrete base, and houses accumulators and distribution manifolds.

Figure 1 shows the 6 DOF motion platform drawn by CAD system prior to installation of the system.

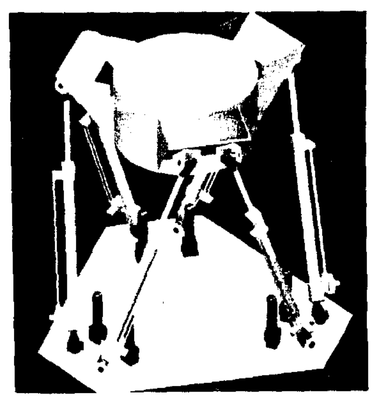


Fig. 1. 6DOF motion platform

The hydraulic power supply delivers hydraulic oil to the actuators through pipes and hoses.

The motion system is controlled and monitored by the microprocessor based motion controller[2]. It is mounted in a cabinet along with the servo electronics, manual control knobs, data acquisition units and power supplies.

This paper describes the design features of such a system including kinematic analysis, kinetic analysis, hydraulic system design[5], and real time electro-hydraulic servo control techniques[6],[7]. An algorithm called remote parameter control (RPC)[4] is also discussed.

## 2. Design Features

### 2.1 Performance Requirements

Maximum nominal payload is required over 50 tons, and the range of motion is;

- X,Y,&Z motions should be over +1.0m/-1.0m
- Angular rotation in any direction should be over +30/-30degrees
- With any single translation of +0.5/-0.5m an angular rotation in any single axis should be over +15/-15 degrees.

Specimen mass of 30ton should have acceleration of over 4.5g in vertical direction, and angular acceleration of 650deg/sec2

The analog controls should be capable of displacement control of each actuator, and the motion be smooth. Real time 6 DOF kinematic computation and system control are required. The safety of motion operation should be provided by:

- the design of the mechanical guard hydraulic units,
- the presence of a number of electrical monitoring circuits.

### 2.2. Kinematic and Kinetic Analysis

The displacements of the actuators can be determined by a geometric model. Kinematic analysis is made by the definition of Euler's angle and coordinates translation matrix.

The actuator stroke that is capable of achieving required ranges is 1.9m. The cylinder length in the fully retracted position is to be 3.3m.

The calculations that we made in sizing the system were based on a total specimen and motion total mass of 30 metric tons with a rotational inertia about the horizontal axis of 12,000Kg.m and a rotational inertia about the vertical axis of 25,000Kg.m

Static and dynamic load which is applied to cylinder determines the cylinder size. Selected standard cylinder size, considering buckling force, has bore diameter of 152mm and rod diameter of 114mm.

Motion range maxima shown in the table 1 are those provided in each degree of freedom defined individually with respect to a fixed coordinates system centered at the centroid of the platform in its neutral position.

table 1. Motion Range of platform

| parameter | Maximum Excursion | Maximum velocity | Maximum Acceleration |
|---|---|---|---|
| Pitch | +35/-25deg | 60deg/sec | 650deg/sec2 |
| Roll | +30/-30deg | 70deg/sec | 680deg/sec2 |
| Yaw | +65.-65deg | 35deg/sec | 640deg/sec2 |
| Heave | +1.0/-1.0m | 1.6m/sec | 4.5g |
| Sway | +1.9/-1.9m | 2.4m/sec | 2.5g |
| Surge | +1.9/-2.2m | 2.4m/sec | 2.6g |

Platform excursions can be reached to the instable region at which the motion table cannot return to its initial position or can result in system failure. Therefore, it is necessary to limit the motion range of platform. All of the possible cases in motion range within cylinder length were analyzed by means of kinetic and kinematic analysis program, and one of the results is shown as in figure 2. Fig.2 shows maximum range of motion table center in vertical(z-axis) and horizontal(x,y axis) directions in case of parallel movement without angular motion.

It is found from fig 2 that instability zone is, for an example, a point(-300, 270, -320).

Limitation of motion range is made by means of the motion software which generates the motion, monitors the range of motion, and stops the system at emergency state.

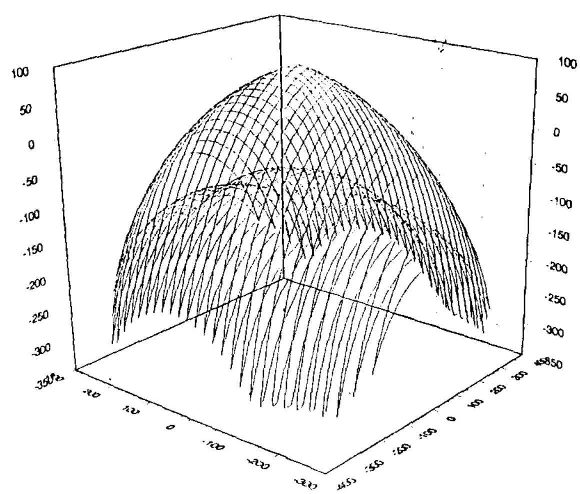
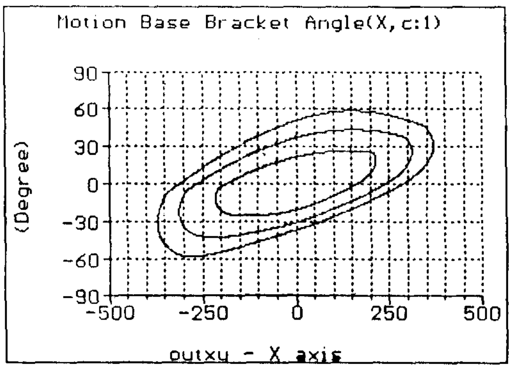



Fig 2. Motion range of platform center

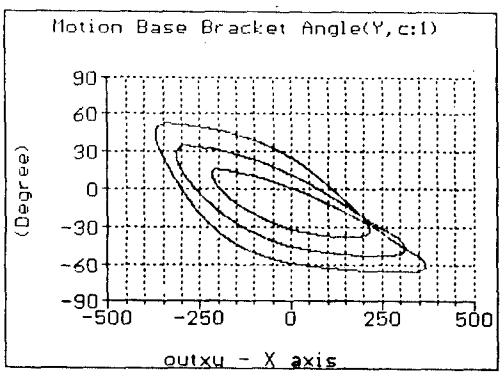
Pivots should have large angular ranges in order to cover the overall motion range without failure of motion table and base frame. Clevis end of a pivot rotates relative to its mounting base, and the relative rotating angles have two directions.

Computation of relative angles of 12 pivots is executed by translation of moving coordinates, and one of the results analyzed for pivot relative angles is shown in figure 3.

Fig. 3 shows the angular range of a base pivot which is mounted on base frame during the motion table center position is moving along with x-axis direction within the motion excursion limit. Mounting position and possible rotating angle of the pivot can be determined from these results.




(a) Rotating axis : Pivot shaft(x)




(b) Rotating axis : Perpendicular to x(Y)

Fig 3. Angular Range of a pivot

## 2.3. Electro-hydraulic System

The highest actuator velocity is required when the table is in the mid-stroke position in a long stroke excursion and the table is being rotated in a roll motion. This peak actuator velocity is 2.13m/sec. The servovalves are capable of a loadless actuator velocity of 3.15 m/sec. This configuration allows the actuators to be loaded with the mass of the motion table and specimen, and moves them at the required velocity. The peak flow that is calculated in any mode of motion is 4086 liters/min.

Hydraulic power supply system comprises six hydraulic supply units, each of them comprises four variable displacement piston pumps, connected in parallel, and delivers nominally 3406 liters/min at 210 bar working pressure.

Hydraulic distribution system has accumulators capable of delivering the peak flows required by the system.

Accumulation system has 680 liters of pressure accumulators distributed around the actuators to provide intermittent flows to the actuators at peak demand excursions. Typically, the return side of the system would have 30% of the volume that is supplied on the pressure side of the system. Therefore, return accumulation capacity is about 200 liters of volume.

It requires a switched gain controller and large capacity of hydraulic supplies so that the four-port hydraulic system,which is used in general,should drive heavy and unidirectional load in gravitational field. Especially for the hydraulic system using single-ended piston, it is very difficult to design the controller because of the differences between accelerations according to their directions. Therefore, it is necessary to consider the 3-port hydraulic system which is usually used for mechanical servo and flight servo system.

Comparison 3-port system with 4-port is made to obtain optimal design for the above system. Figure 4 shows the maximum accelerations of two systems according to frequency variation. It is found from fig 4 that 3-port system is more adequate than 4-port for the heavy load system which is usually operated at lower frequencies.

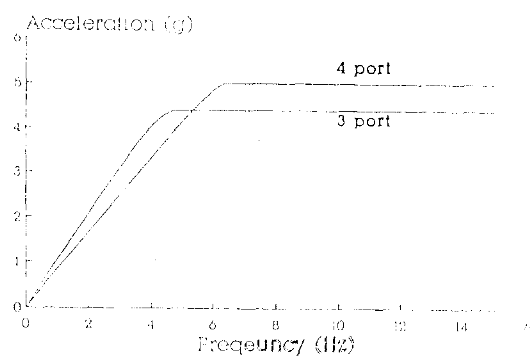



Fig4. Power Analysis-accelerations

A high performance electro-hydraulic analog servo controller is designed using 3-port servo valve. It includes dynamic pressure feedback as a inner loop and position feedback as a outer loop. Figure 5 shows the diagram of linearized hydraulic model and its servo controller.

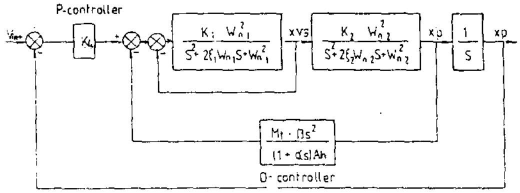



Fig 5. Servo Controller for Linearized Model

2.4. Real Time Motion Control

Motion commands from host computer, data file, or manual controller are six values of degrees such as pitch, roll, yaw, heave, sway and surge. A micro-computer executes a real time computation for six cylinder lengths using given values of 6 DOF, and sends the length values to the servo controller which controls the position of cylinders.

The emergency state is checked automatically by the cylinder length limit or excessive range of motion. When it happens, the motion system is shutdown, which removes power from the hydraulic power supply, de-energizes the settle valves causing actuators to retract, and de-energizes the pressure dump valve allowing pressure to bleed from the accumulators. Figure 6 shows the flow chart of motion control software.

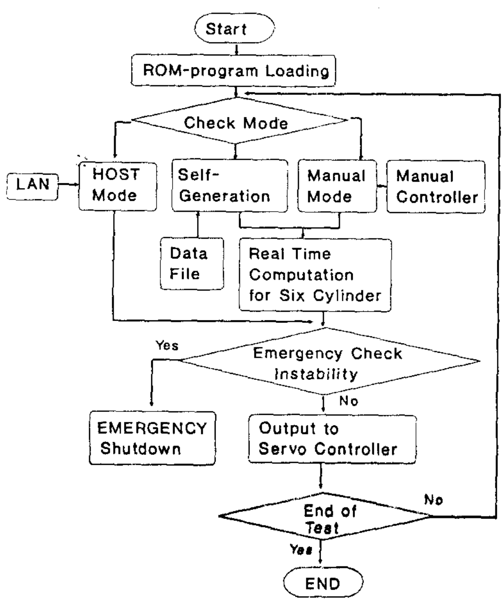



Fig 6. Flow Chart of Motion Control Software

Computation of cylinder length is made by motion analysis program within required execution time. In order to minimize execution time, repeatedly used values are pre-calculated and saved to the memory. And DSP boards are used for the improvement of processing speed. These techniques make it possible to execute the control algorithm programmed by C language within 8 mili-seconds per one cycle using 16 bit IBM PC compatible.

3. Remote Parameter Control

The stewart motion platform with electro-hydraulic actuators is a kinematically heavy non-linear system, and has a certain amount of motion delay due to hydraulic response for a input signal. Without any compensation of input command, actual system response is different from the desired output. Hence, alteration of the input signal should be made to compensate the nonlinearities of stewart platform and the dynamic delay of electro-hydraulic system. Such an algorithm is called as remote parameter control(RPC).

RPC executes several signal processing to generate the proper input time history from the desired output time signal. These processes are divided into two steps. The first step is system identification process determining the transfer function of the motion system at a given position. Independent 6 random input signals are used to obtain the independent 6 transfer functions. The second process is the iteration process upgrading the input command time history to minimize the error between the desired output and test output. The iteration processing composed both of initial trial time history generation process multiplying the inverse transferfunction into desired output and interactive test processes for minimizing the errors. Figure 7 shows the determination process of initial transfer function and exciting signal.

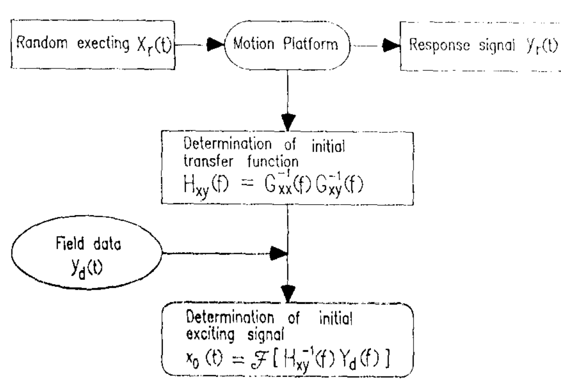



Fig 7. Determination of Initial Transfer Function and Exciting Signal

The Stewart motion platform is excited by a random signal and an output signal is received from the sensor attached to the platform. Frequency response function of the system can be obtained from this procedure. If input signal vector and output signal vector are $x(t)$ and $y(t)$ respectively, auto spectrum $G_{xx}(f)$, correlation spectrum $G_{xy}(f)$, and frequency response function $H_{xy}(f)$ are determined by

$$H_{xy}(f) = G_{xy}(f) / G_{xx}(f)$$

where

Initial exciting signal is determined from $H_{xy}(f)$ and field record data $y_d(t)$ as follows:

$$Y_d(f) = F[y_d(t)]$$

$$X(f) = H_{xy}^{-1}(f)\, Y_d(f)$$

$$x_0(t) = F^{-1}[\, X_0(f)\, ]$$

where

F : Fourier transformation
-1 : matrix inverse

For the ideal linear system , $x_0(t)$ can be used as input time history to generate the test output which is desired output $y_d(t)$. The existence of hydraulic lag and kinematic nonlinearity requires special iteration process to compensate errors. Figure 8 shows the algorithm for revision of input signal.

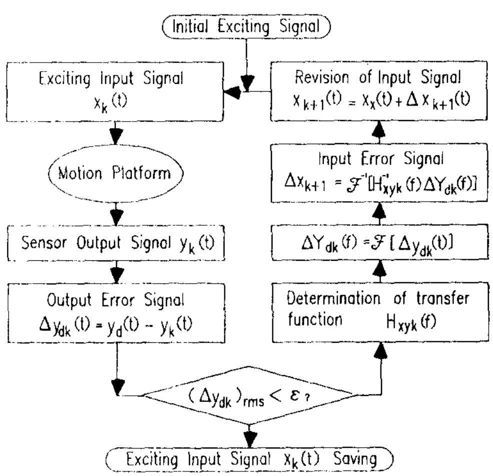



Fig 8. Algorithm for revision of input signal

Initial exciting signal determined from figure 7 is sent into the motion platform as an input signal $x_k(t)$, and an output signal from sensor $y_k(t)$ is received. Comparison between $y_k(t)$ and desired output signal $y_d(t)$ is made, and if error signal is bigger than the tolerance, then the next iteration is performed as follows;

$$\Delta y_{dk}(t) = y_d(t) - y_k(t)$$

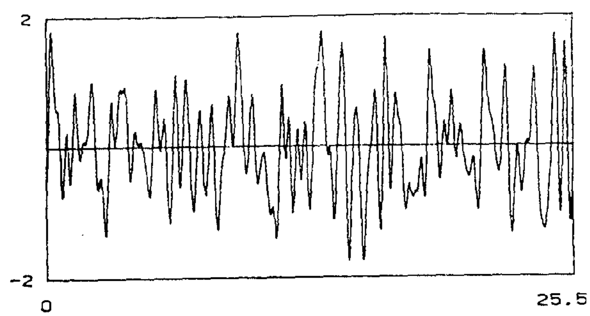
$$\Delta Y_{dk}(f) = F[\Delta y_{dk}(t)]$$

$$\Delta X_{k+1}(f) = H^{-1}{}_{xyk}(f)\Delta Y_{dk}(f)$$

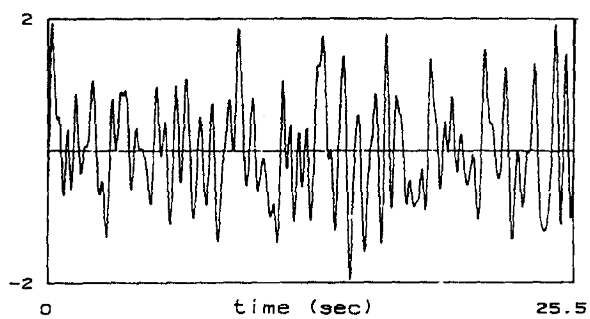
$$\Delta x_{k+1}(t) = F^{-1}[\Delta X_{k+1}(f)]$$

$$x_{k+1}(t) = x_k(t) + \Delta x_{k+1}(t) \qquad k = 0,1,2,3,...$$

Instead of rigorous verification of convergence and the stability of this algorithm, a simple experiment are made using simplified stewart platform using electric D.C motor drive type actuator. Fig 9(a) represents the desired field data, and fig 9(b) the test result after 12 iteration. It is found that two signals are almost the same.




(a) Field Data




(b) Test result

Fig 9. Experimental result of RPC

## 4. Conclusions

A high power six degrees of freedom stewart platform was designed to simulate the motion of moving vehicle, and the design features were described in this paper.

Mechanical and electro-hydraulic systems could achieve the required motion range, and the real time control techniques made it possible to excute the simulation within 8 mili-seconds per one cycle.

Using the algorithm called RPC, the required field movement of vehicle could be simulated successfully.

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