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Building up of Pseudo-Dynamic Structural Testing Systems

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Application of Digital Controlled Actuator in Pseudo-Dynamic Structural Testing

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ABSTRACT

The pseudo-dynamic structural testing method is a newly developed experimental techniques to simulate the earthquake response of structures without using the conventional shake table. This report describes a study program in cooperation with Lehigh University to build a pseudo-dynamic structural testing system. The reliability of the pseudo-dynamic structural testing system depends greatly on the equipment used. In the past, D/A, A/D and servo controller are the essential equipment for the pseudo-dynamic testing, and lots of experimental error arose from these devices. In this report, the digital controlled servo valve is utilized in the pseudo-dynamic structural testing for the first time. The performance of this digital system is examined and suggestions are made.

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1. INTRODUCTION

1.1 General

In the seismic resistant design of structures, safety and economy are two aspects needed to be compromised with each other. Due to the economy consideration, most current design specifications allow structures to behave inelastically during moderate to strong earthquake. However, the catastrophic collapse is always prohibited even under strong earthquake. Many researchers have engaged in the investigation of the behavior of structures under strong earthquake ground motion. In general, their research techniques can be classified into two groups: namely, the analytical research and experimental research. Since seismic behavior of structure is so complicated that it is very difficult, if not impossible, to find a closed form solution, numerical procedures (such as finite element method) are always utilized in the analytical study. A hysteretic model of structural elements need to be presumed in order to carry out the analysis. However, the hysteresis behavior of the structure depends greatly on material types, structural types and loading history. Although many researchers have investigated the hysteretic behavior of structural elements and several different models have been suggested, yet, there is no general accepted model available.

Since the analytical research for the seismic behavior of structure has some drawbacks and limitations, another promising way to study this problem is the experimental research. Depending on the loading rate, the experimental research work can be classified as static type and dynamic type. In the static type, the loading are either monotonic increasing or predetermined cyclic load. It is easier and inexpensive to carry out a static type experiment. However, this may not be able to capture the complicated behavior of structural elements or structures under strong earthquake ground excitation. From this point of view, one would agree that the dynamic type loading by using shake table is the most convincing way to study the structural behavior under seismic load. Unfortunately, building a large shake table which is able to carry the full scale structure is extremely costly and impractical. In fact, the majority of shake tables used are about 3 to 6 meters in plane dimensions and with capacities of about 20 tons to 50 tons only. Obviously, this kind of shake table is suitable for small scale structures only and may introduce another uncertainty between small scale and real scale structures.

From above, it can be concluded that both static type and dynamic type experimental method are not adequate for the study of the seismic behavior of structures. Besides these classical methods, the newly developed pseudo-dynamic structural testing method (or so called as computer on line testing) may serve as a promising alternative.

1.2 Pseudo-Dynamic Structural Testing

In 1969, Professor Hakuno of Tokyo University used a digital computer to control the actuator in the study of a single degree of freedom cantilever beam under seismic loading [1]. This is the first experiment by using pseudo-dynamic technique. Although Professor Hakuno's testing was not successful due to the limitation of the capacity of the computer and the accuracy of the experimental devices, his concept of combining the analytical and experimental work is the origin of the pseudo-dynamic structural testing method. Professor Takanishi applied this technique in the study of a one story steel frame and good results was reported [2]. Since then the pseudo-dynamic structural testing method has become one of the major techniques in earthquake engineering research and many institutions have built this kind of systems.

The basic concept of pseudo-dynamic structural testing method can be viewed as a hybrid method which combines both analytical and experimental work. The behavior of structures under seismic loading can be modeled mathematically by using the equation of motion. There is no difficulty in solving this mathematical equation except that the restoring force needed to be predetermined, which is not a easy task especially when the structure has been loaded into inelastic range. In pseudo-dynamic testing method, this restoring force is measured from the load cell or strain gages during structural testing and its value is sent back to the computer through an A/D (analog to digital) converter. Then the magnitude of the displacement of next step is calculated inside the computer and this displacement signal is again sent to the actuator from the computer through a D/A (digital to analog) converter and servo controller. By repeating this closed loop, the behavior of the testing structure under earthquake ground excitation can be simulated.

The pseudo-dynamic structural testing method can be explained by using a flow chart (Fig. 1). The equation of motion can be written in the following form:

$$\underset{\sim}{m}\,\ddot{\underset{\sim}{x}}_n + \underset{\sim}{c}\,\dot{\underset{\sim}{x}}_n + \underset{\sim}{F}_n = -\underset{\sim}{m}\{1\}\ddot{X}_{on}$$

in which $\underset{\sim}{m}$ is the mass of the tested structure, $\underset{\sim}{c}$ is the damping coefficient, $\underset{\sim}{Fn}$ is the structural restoring force, $\ddot{X}_{on}$ is the ground excitation, $\underset{\sim}{Xn}$ is the displacement of the structure.

If the central difference method (CDM) is utilized as the integration scheme for the equation of motion, then

$$\dot{\tilde{x}}_n = \frac{1}{2\Delta t}\left(\tilde{x}_{n+1} - \tilde{x}_{n-1}\right)$$

$$\ddot{\tilde{x}}_n = \frac{1}{\Delta t}\left(\tilde{x}_{n+1} - 2\tilde{x}_n + \tilde{x}_{n-1}\right)$$

Substitute the above two equations into equation of motion, then the displacement of next time step can be stated as:

$$\tilde{x}_{n+1} = \frac{2\tilde{m}\,\tilde{x}_n + (0.5\Delta t * \tilde{c} - \tilde{m})(\tilde{x}_{n-1}) - \Delta t^2\left(\tilde{F}_t + \tilde{m}\,\ddot{X}_{on}\right)}{\tilde{m} + 0.5\,\Delta t * \tilde{c}}$$

It should be noted that at time step n the right hand side of the above equation are already known, in which the value $\tilde{F}t$ is the reacting force at time t measured from the load cell of the actuator and is fed back to the computer via a A/D converter. From the above equation, the displacement at next time step (n+1) can be calculated without difficulty. The displacement X(n+1) is then transmitted to the actuator via a D/A converter. By repeating this procedure it is possible to study the structural behavior under ground excitation.

2. TEST SET-UP

2.1 General

The theory involved in the pseudo-dynamic structural testing method is quite simple. However, the reliability of pseudo-dynamic testing method highly depends on the hardware used. In fact, due to hardware limitation, Professor Hakuno was not able to carry out his testing successfully -- although he had the original idea of pseudo-dynamic testing. With the advance of modern technology on computer and testing equipment, the pseudo-dynamic testing method has become much easier and more reliable then before. For example, with the introduction of magnetic type displacement transducer (digital type), the feedback accuracy can be as high as 0.0001 mm and this has been used almost as a standard equipment for pseudo-dynamic testing. However, there is not much progress on the control technique for actuator. Professor Takanashi used a NC servo motor instead of hydraulic actuator in order to achieve better reliability of the control of the movement of actuators [3]. Good results has been reported from his study, yet, his testing is performed on a small scale machine.

Recently, the digital servo valve has been developed [4]. With this new type of servo valve, one is able to communicate with the actuator easily and the accuracy can be improved.

Besides, all the information during the control action can be recorded into the floppy disk or hard disk easily. Surprisingly, the digital controlled actuator system is much less expensive then the conventional machine. However, there is no application example has been carried out in the pseudo-dynamic structural testing by using digital controlled actuators. It is for this reason that a simple test is carried out in order to study the applicability of this new type of actuator in the pseudo-dynamic testing. Fig. 2 shows the overall test set-ups for the purpose of calibrating the new system.

2.2 Specimen and Material Properties

A cantilever column is selected as the testing structure for the calibration of the pseudo-dynamic structural testing system. This is due to the cantilever column is easier in the fabrication, erection, and also provide enough flexibility during test. A W8X40 steel column with a total length of 8 feet was used as the testing specimen. The material used is A36 steel. The actuator acts at a height of 7 feet which would result a maximum load on the specimen of about 20 kips. This load is about one tenth of the capacity of the actuator (Fig. 2).

Six tension coupons were tested according to ASTM specification (Fig. 3). Fig.3 also shows a typical stress strain curve from the coupon test. The average yielding stress is 38.88

ksi which is about 8 percent higher then the book value.

2.3 Testing Equipment

The equipment used for the pseudo-dynamic testing can be classified as two major parts, namely: displacement (or load) control and data acquisition. The items of the hardware used are as following:

a. Actuator:

Ten inches bore jack made by Airline Hydraulic, with a Digital Closed Loop servo valve made by Vicker. The maximum capacity is 230 kips.

b. Feed Back Displacement Transducer:

Ten inches Temposonic LVDT made by MTS with a resolution of 0.0001 inch.

c. Loading Measurement:

Full bridged strain gages on the steel column and displayed by a B&F strain indicator.

d. Rotation Gage:

Tilt rotational gage with resolution of 0.01 degree.

e. Control and Calculation:

PC AT for control of actuator.

PC XT for integration of equation of motion.

2.4 Calibration of Loading Measurement Device

Two full bridged strain gage groups were used for the measurement of loading (Fig.4). The strain gage readings are calibrated against a load cell. (The load cell has been calibrated.) The calibration result is shown in Fig. 5. The average calibration factor is 0.014583 for channel 0 and 4.7893×10^{-3} for channel 1. Channel 0 is selected for loading measurement during the pseudo-dynamic testing to avoid any premature yielding due to residual stress from the manufacture of the specimen.

3. PSEUDO-DYNAMIC STRUCTURAL TESTING OF A SINGLE DEGREE OF FREEDOM SYSTEM

3.1 Initial Stiffness Test

The initial stiffness test is performed first with the testing results as follows:

Load: 10.08 Kips

Displacement: 0.3528 inches

Initial Stiffness: 10.08/0.3528 = 30.94 kip/inch

The initial stiffness from theory of strength of material can be calculated as following:

Length : 72 inches

Young's Modulus: 29000 ksi

Moment of Inertia: 146 inch

Displacement due to Bending and Shear = 3.193×10^{-2} inch/kip

Initial Stiffness = 31.32 kip/inch

The comparison of measured stiffness and calculated stiffness is

30.94 / 31.32 = 0.988

which is less than 2 percent difference.

3.2 Pseudo-Dynamic Structural Testing

The control algorithm of the pseudo-dynamic structural testing is shown is Fig. 1. A computer program by using Basic language is developed for this purpose. In the calculation of displacement, the central difference method (CDM) is used for the integration of equation of motion. A 2 percent of viscous damping is assumed for the testing specimen and a lumped mass of 0.31 kip-sec-sec/inch is assumed at the location of 72 inches from the base plate. Part of the ground acceleration record from Taft Earthquake, California, 1952 is selected for ground excitation input (Fig.6). The time increment for each step is 0.02 second. Due to time restrain, only 1.30 second are tested. Fig.7 shows part of the testing record. Fig.8 and Fig. 9 show the displacement response and the force-displacement relationship, respectively. From these figures, it can be found that during elastic response (t=0.0 to 0.38) the testing results agree very well with the analytical results. From the previous experience of pseudo-dynamic structural testing, it has been found that the testing results in the inelastic range is always better than elastic range. This is simply because the displacement control is easier in the inelastic range. Since the results in the elastic cycles are in good agreement with theory, it can be assumed that the results in the inelastic range should be as good.

4. SUMMARY AND SUGGESTIONS

a. The results from experimental study agrees very well with the analytical study. The difference is less than 5 percent.

b. The actuator system with digital servo valve is very handy for the control in the pseudo-dynamic structural testing.

c. The success of any pseudo-dynamic structural testing system relies highly on the performance of the feedback system. The magnetic type displacement transducer should be used for the feed back system.

d. Due to possible movement on the actuator itself, the feed back measurement device should be directly mount on the testing structure instead of on the head of the jack.

e. The control software depends greatly on the hardware used. Since the research work are almost one of the kind, it is suggested to develop ones own software program. The black-box type software program provided by the vendor may not suitable for the research institution.

f. It is suggested to use a master computer and several slave computers for a pseudo-dynamic structural testing system. The master computer controls the slave computers and is the key control unit for the whole system. The slave computers are used for control of the actuators, data acquisition, monitoring and checking the key portions during testing. The personal computer should be good enough for the purpose of both master and slave computers.

f. The pseudo-dynamic structural testing method is quite simple on the concept, yet, it depends highly on the hardware used. It is suggested to build a small to medium scale laboratory in Taiwan as soon as possible. This laboratory can be served as a place to train the necessary technicians and researchers who are interested in this technique and this can also be a pilot program for the proposed National Earthquake Center.

5. References

[1] Takanashi,K. and Nakashima, M., Japanese Activities on On-Line Testing, Journal of Engineering Mechanics, Vol. 113, No. 7, 1987

[2] Takanashi,K. et al. Nonlinear Earthquake Response Analysis of Structures by a Computer Actuator On-Line System, Trans. Architectural Inst. of Japan, No. 229, 1975

[3] Takanashi, K. et al., High Performance Testing System for Earthquake Response Simulation Using NC servo-motor Drive, Institute of Industrial Science, Tokyo University, 1987

[4] Sperbeck, A.J., Totally Digital Valves Fully Utilize Hydraulic Servos, Hydraulics and Pneumatics, December, 1987

[5] Takanashi, K., Application of the On-Line Control Method to Earthquake Response Analyses, Theoretical and Applied Mechanics, vol. 36, 1988

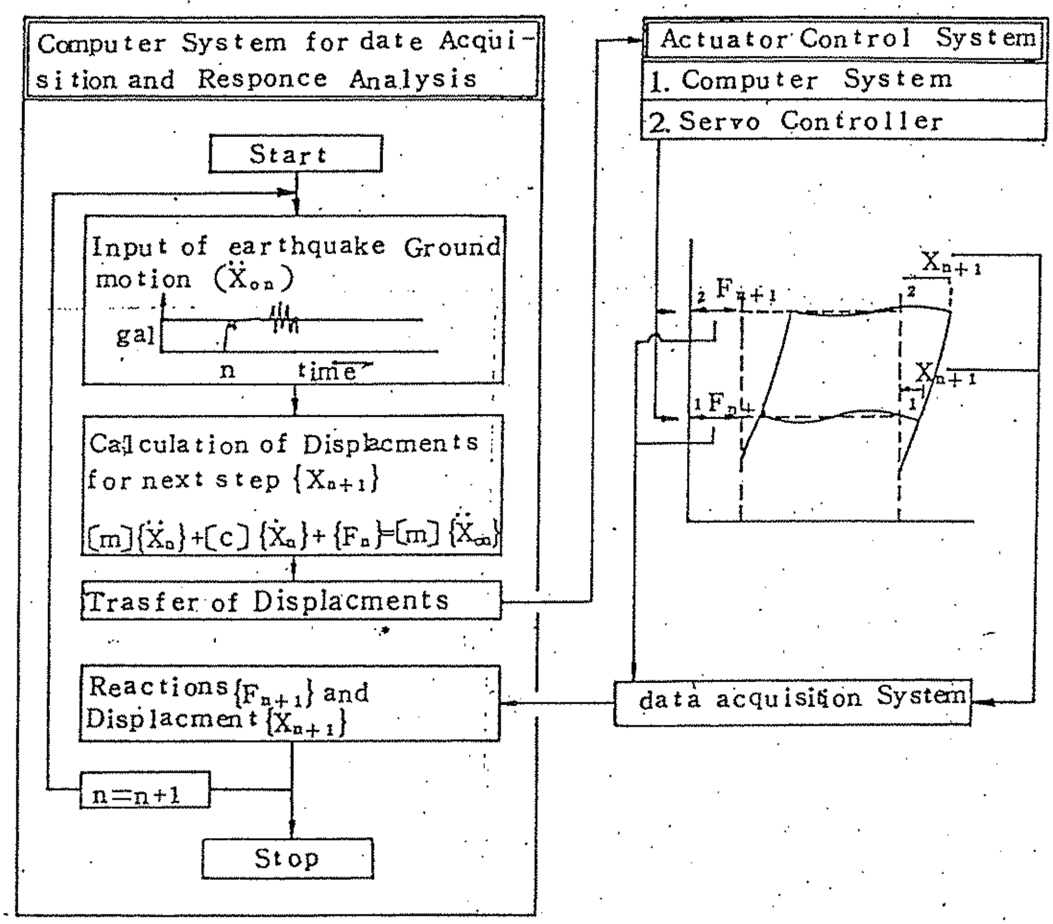

Fig. 1 Flow Chart for Pseudo-Dynamic Structural Testing

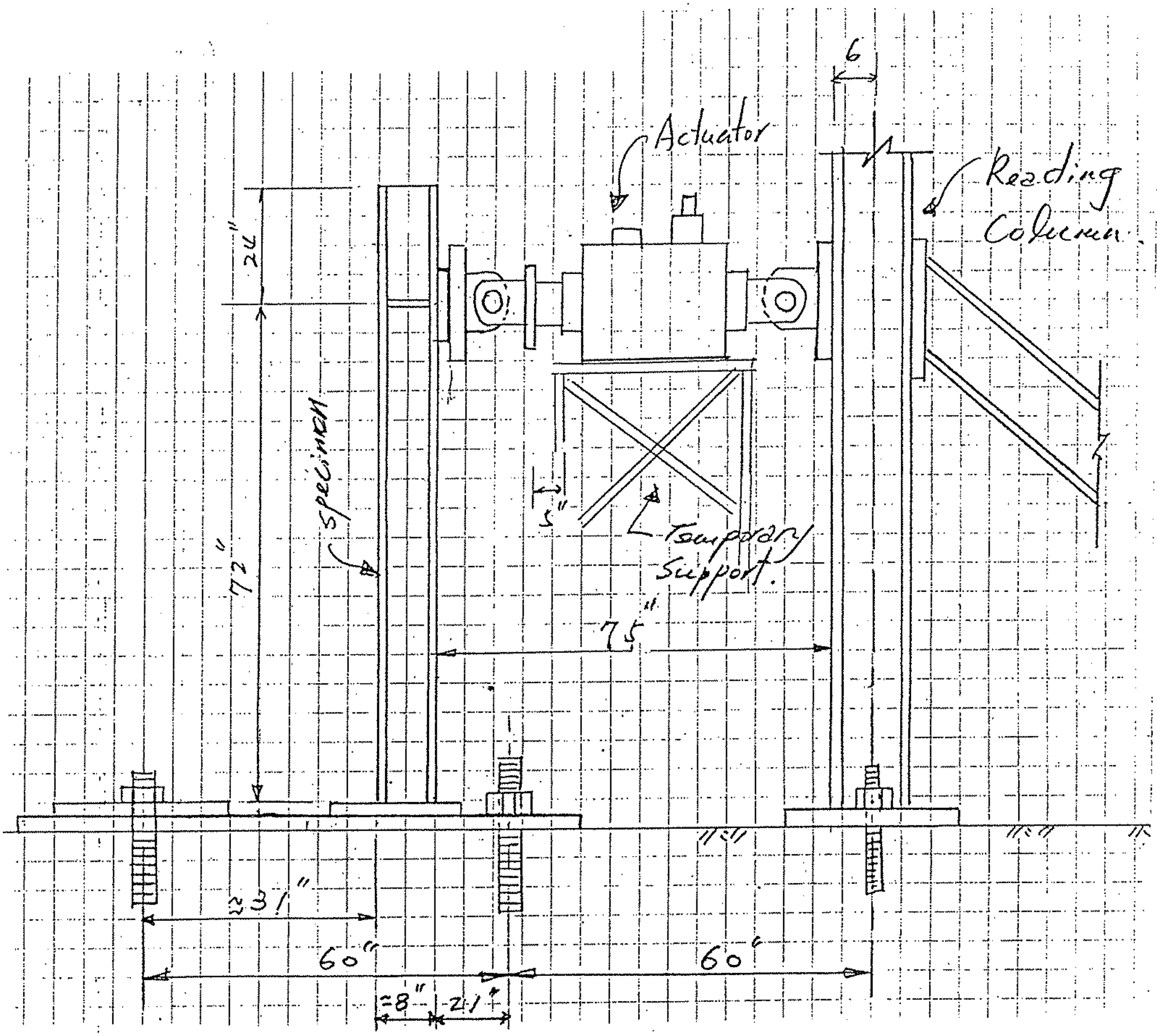

Fig. 2 Test Set Up

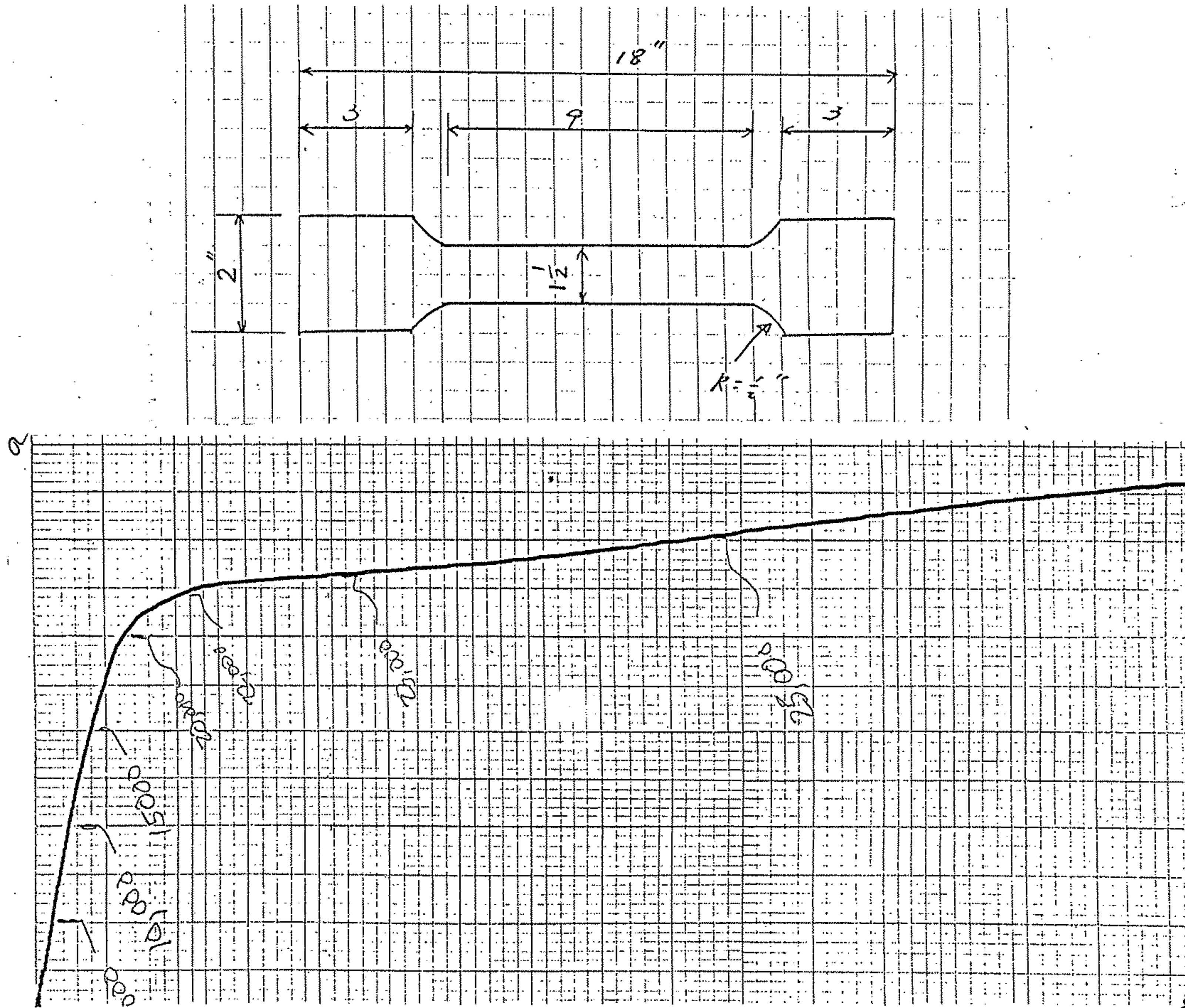

Fig. 3 Tension Coupon and Typical Stress-Strain Curve

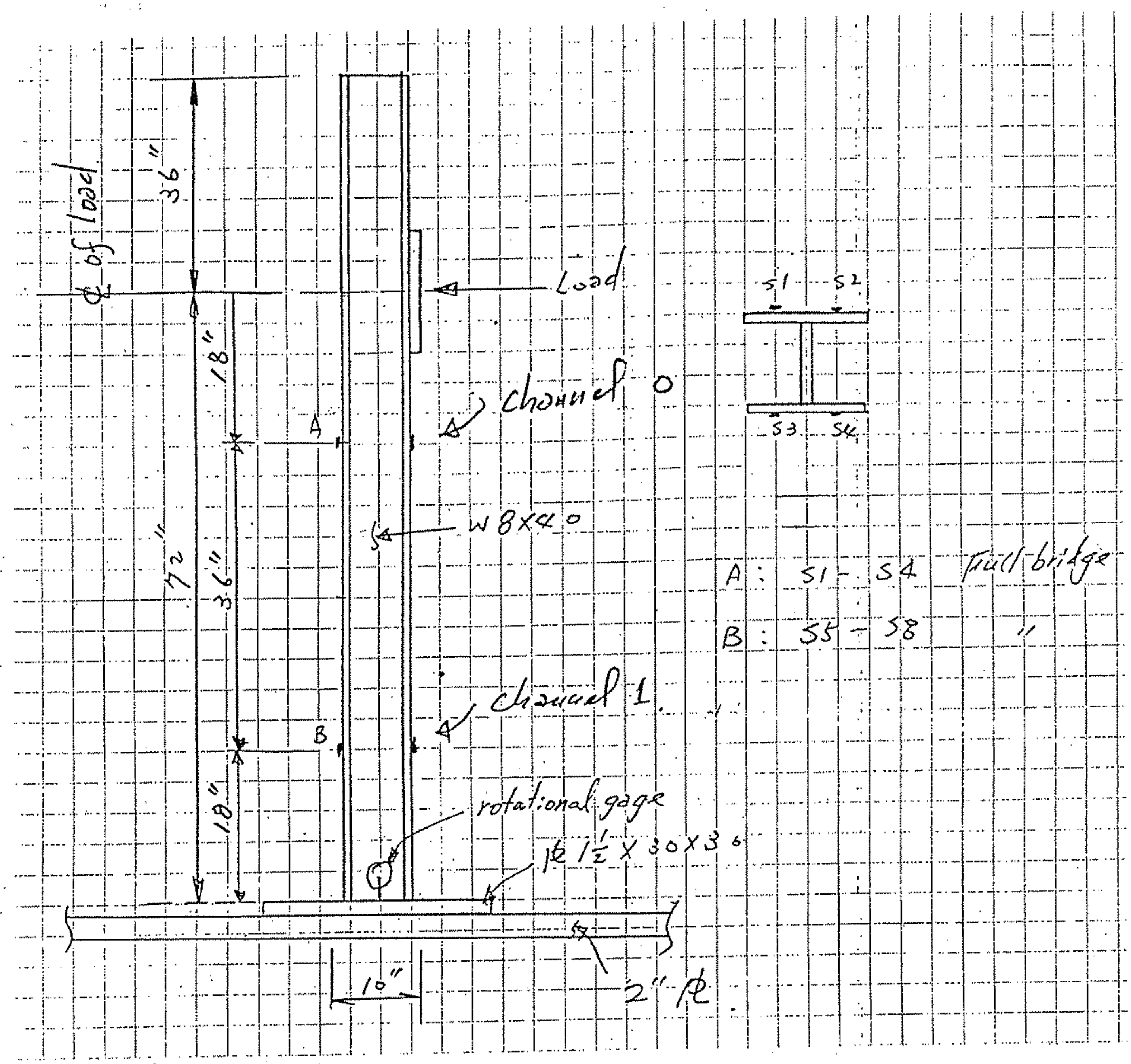

Fig. 4 Instrumentation Arrangements

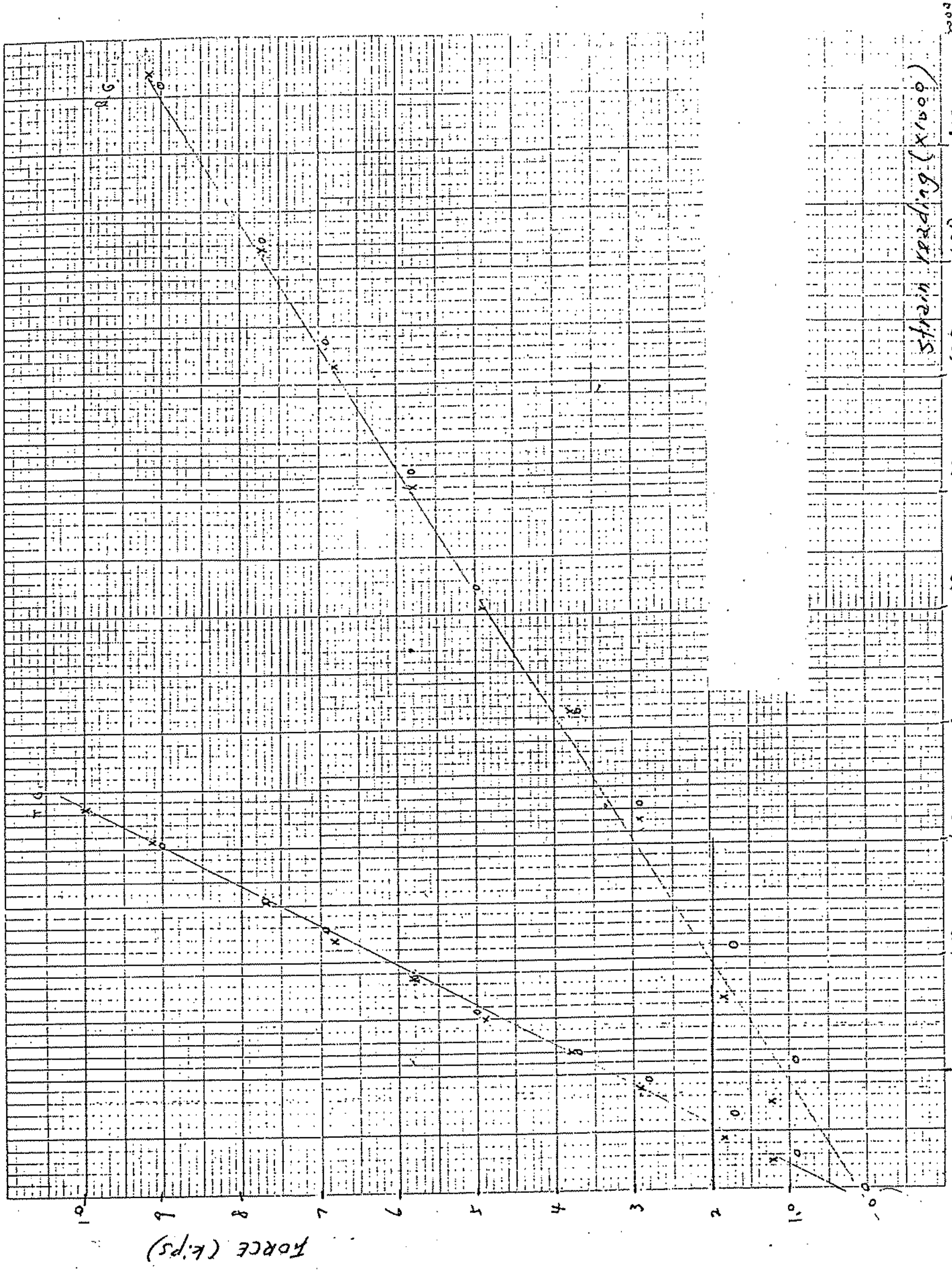

Fig. 5 Calibration Curves for Loading Measurements

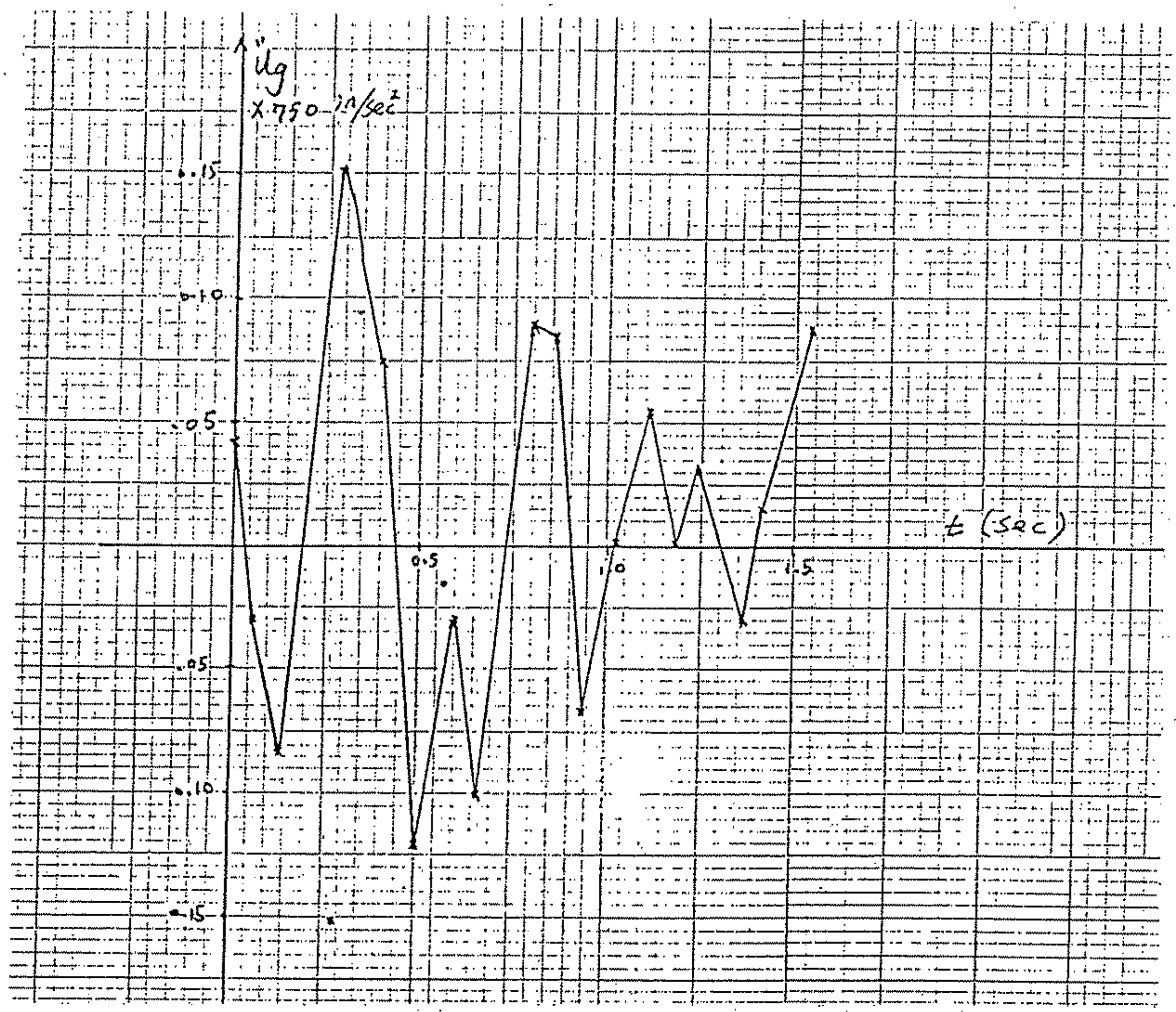

Fig. 6 Ground Acceleration.

```
RUN
ESTIMATED NUMBER OF DATA POINTS? 99
MASS=? 0.31
DAMPING RATIO=? 0.02
TIME INCREMENT=? 0.02
STIFFNESS= 30.94
TIME=  .02 DISP=-6.400349E-03

LOAD THE SPECIMEN TO THE DISPLACEMENT X(2), (AFTER COMPENSATION)
THEN FEED BACK REACTING FORCE= ? -0.15
TIME= .02 DISP=-6.400349E-03                    FORCE=          -.15

TIME= .04 DISP=-1.816835E-02
LOAD THE SPECIMEN TO THE DISPLACEMENT X(N+1), (AFTER COMPENSATION)
THEN FEED BACK REACTING FORCE = ? -0.44

TIME= .04 DISP=-1.816835E-02 FORCE=-.44
DO YOU WANT TO SEE GRAPHIC OUTPUT? Y OR N?? -1.0

DO YOU WANT TO CONTINUE? Y OR N?   ?

TIME= .06 DISP=-2.775019E-02
LOAD THE SPECIMEN TO THE DISPLACEMENT X(N+1), (AFTER COMPENSATION)
THEN FEED BACK REACTING FORCE = ? -1.0

TIME= .06 DISP=-2.775019E-02 FORCE=-1
DO YOU WANT TO SEE GRAPHIC OUTPUT? Y OR N?? -1.0

DO YOU WANT TO CONTINUE? Y OR N?   ?

TIME= .08 DISP=-.0273052
LOAD THE SPECIMEN TO THE DISPLACEMENT X(N+1), (AFTER COMPENSATION)
THEN FEED BACK REACTING FORCE = ? -1.0
```

Fig. 7 Part of the record of computer control

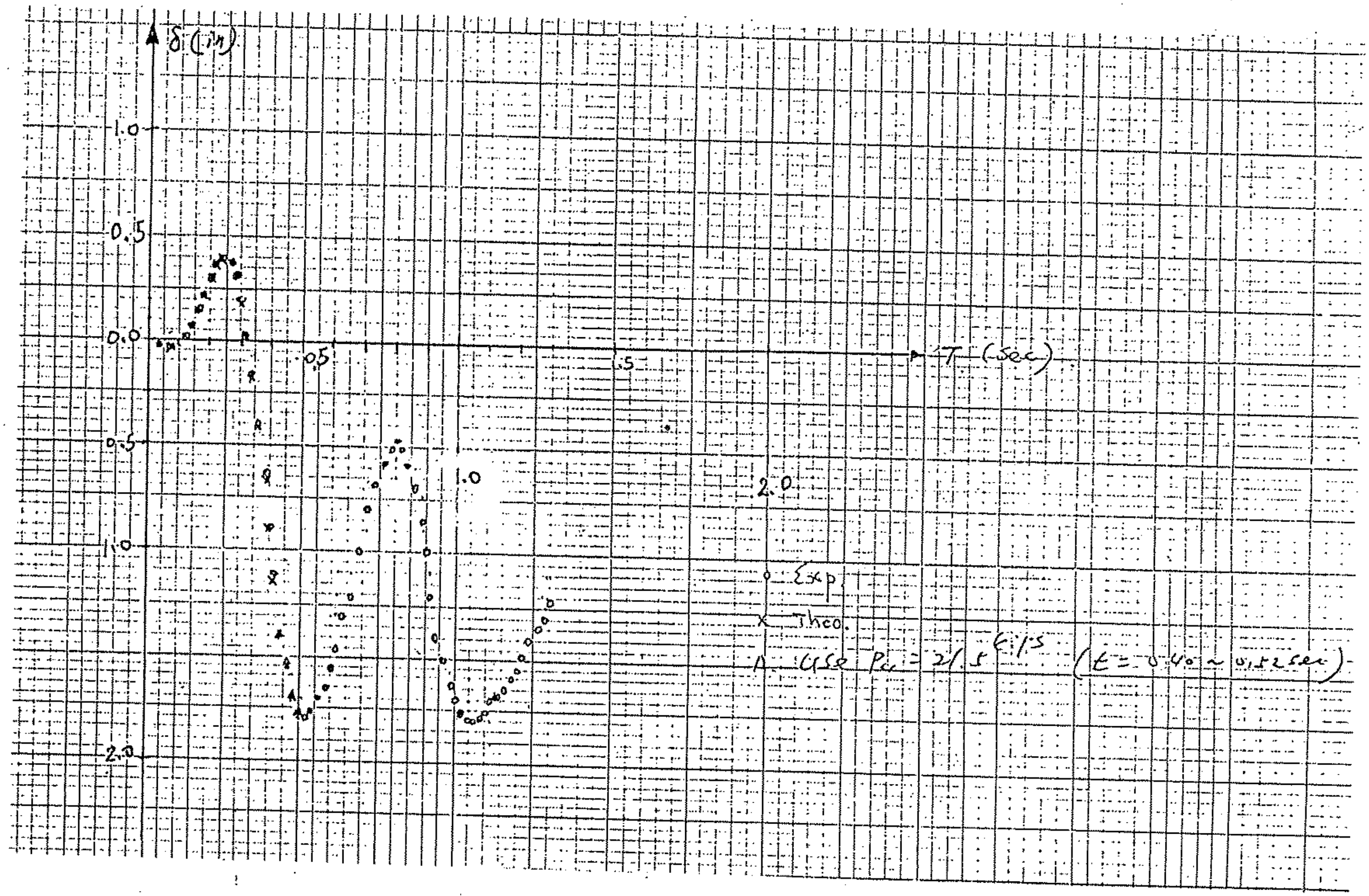

Fig. 8 Displacement Response

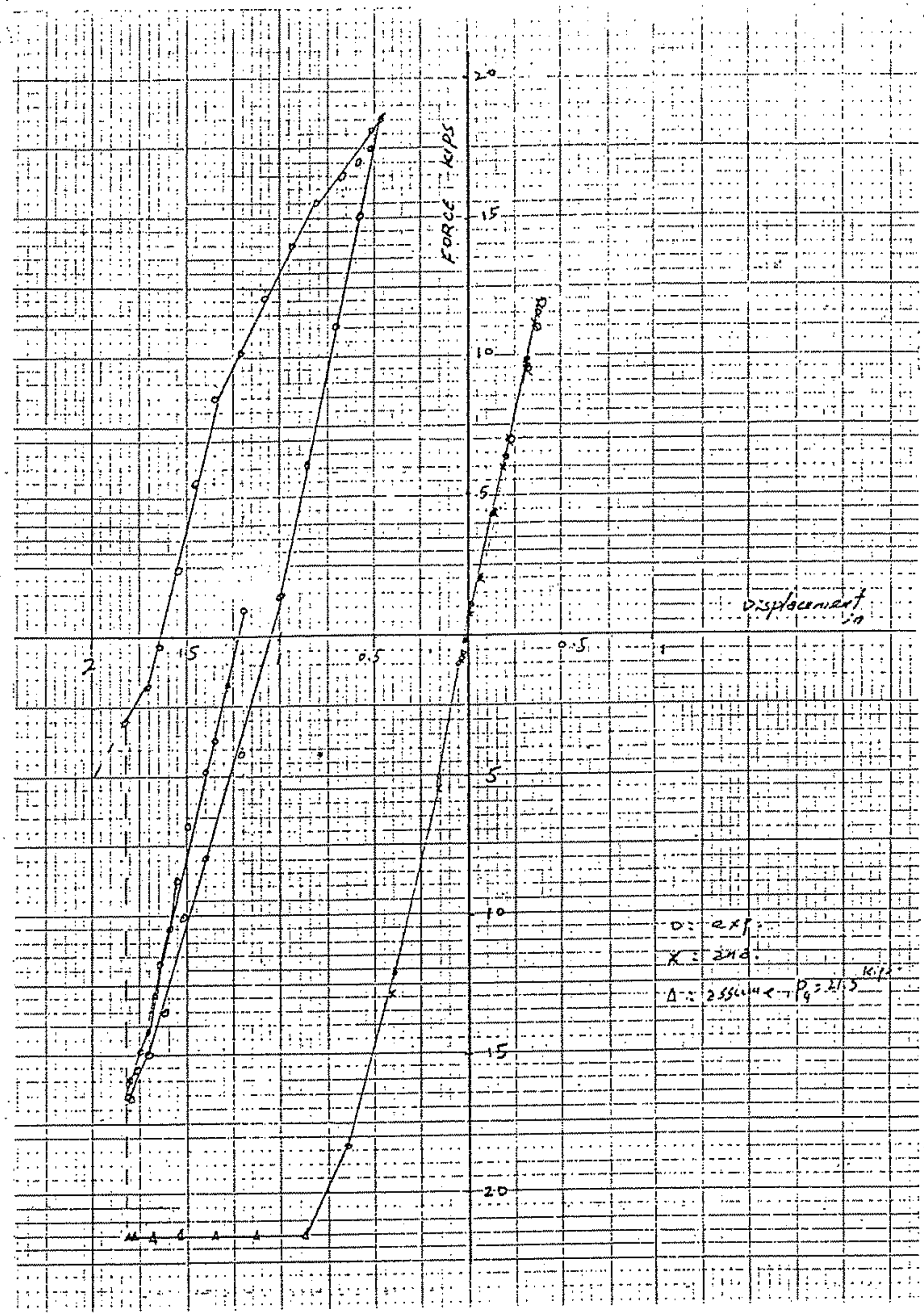

Fig. 9 Force and Displacement Relationship