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# ANALYSIS, DESIGN, AND TESTING OF A LOW COST, DIRECT FORCE COMMAND LINEAR PROOF MASS ACTUATOR FOR STRUCTURAL CONTROL

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## Abstract

In this paper, the design, analysis, and test of a low cost, linear proof mass actuator for vibration control is presented. The actuator is based on a linear induction coil from a large computer disk drive. Such disk drives are readily available and provide the linear actuator, current feedback amplifier, and power supply for a highly effective, yet inexpensive, experimental laboratory actuator. The device is implemented as a force command input system, and the performance is virtually the same as other, more sophisticated, linear proof mass systems.

## Introduction

Vibration suppression for large flexible structures in space requires some means of transferring the mechanical vibration energy into heat. A popularly proposed solution to implement this in realizable hardware is the linear proof mass actuator (or "Linear Momentum Exchange Device"). (see Refs. 1-3) The linear actuator achieves control by accelerating a mass along a linear track. The force driver is a linear motor, which applies a force to the moving mass, and hence by Newton's Laws, an equal and opposite force applied to the structure on which the actuator is mounted. If an ideal "velocity sensor" is used to apply the driving signal to a "perfect" force actuator, we have the classical force-velocity collocated control scheme, which is guaranteed to be energy dissipative, and results in a stable, damped structure.

The use of linear proof-mass actuators for control has long been recognized as a useful technique for implementing this type of control scheme. In addition to action as a control actuator, an alternate application of this device is as a force producer, where it acts essentially as a mechanical shaker. As a shaker, this device is capable of exciting the structure through a force input at the physical location of the mounting between the actuator and the structure.

The construction of linear proof mass actuators is conceptually quite simple, yet in practice, tends to be difficult to implement. They are heavy, the desired friction free linear track motion is difficult to maintain due to the precision alignment required for the linear motion, stiction in the bearings, and magnetization of the bearings and other materials. For laboratory experimentation, the construction of such actuators may be an expensive, time consuming task. The purpose of this paper is to report on an easy, low-cost implementation of a proof mass actuator which may be suitable for laboratory studies.

Proof Mass Actuator Description

The key element being proposed here to construct a proof mass actuator is to utilize the head actuation mechanism from a hard disk drive. For this application it is relatively easy to find obsolete disk drives, which are fairly large, heavy, and very reliable. The mechanism in these older drives is a sophisticated implementation of a common voice coil moving in a magnetic field. The primary advantages of these actuators are: (1) They are fairly large, hence they are easy to work with in a laboratory environment, (2) the mechanisms are very precise and reliable. The suspension system and track of the actuator are very smooth with low friction, and (3) the primary electronic component in the actuators is a high precision constant current DC amplifier. The constant current feature eliminates the back emf effect seen in a constant voltage drive system, hence there is almost no interaction of the actuator dynamics with the structure on which it is mounted.

The proof mass actuators constructed in our laboratory were constructed from old Hewlett Packard HP7925D disk drives. These are relatively old (circa 1980), fairly large drives which are obsolete for use as data storage devices. Nevertheless, the electronics and actuation are still perfectly good, and the head positioning subsystem of the disk drive makes an excellent proof mass actuator. This consists of a linear actuator, with approximately a four inch stroke, plus the power supply and regulator. For laboratory work this actuator produces several advantages. First it is reasonably inexpensive! Surplus drives of this type are commonly available for several hundred dollars. It is likely that most organizations have drives of this or other similar types, sitting around as unused, surplus equipment. Secondly, the linear actuator is fairly large, making it relatively easy to work on and modify. (Of course, it is also large and heavy making it less than desirable for a realistic space actuator. For our purposes, however, this is not viewed as a major problem.)

The mass moves within a coil of approximately three inches in diameter. Current passing through the coil produces a magnetic field, which produces a force on the mass moving within the coil. The standard mass of the actuator moving within the coil is quite small, especially in comparison to the fixed mass of the actuator. Because there is ample room on the actuator, additional mass was added to make the device more efficient in producing force without being track limited. The primary limitation on the amount of mass that can be added is the bearing which guides the actuator on its track. For our design we rather arbitrarily used a nominal 2.2 kg additional mass on the actuator to reduce the stroke required especially at low frequencies.

The current driving the coil comes from a current amplifier which produces a current proportional to the input voltage. The specifications for the power supply and amplifier can be found in the manufacturer's documentation but should be measured in situ to get the correct value for your individual system. For the HP drives used the manual specifies the amplifier gain as 1.2 amp/v. Laboratory measurements obtained a value closer to 1 amp/v, with some slight variations within the group of amplifiers tested. The actuator itself was tested by constraining the actuator mass and using a load cell to measure the force produced by the coil. For the system tested the nominal value of this gain was found to be between 1-2 lb/amp. This value can vary widely between systems and is very sensitive to the track alignment in the system. The nominal force constant in the system is close to the upper figure. Disassembly of, or damage to, the permanent magnet during construction can reduce the magnetic flux and reduce the force constant toward the lower value. Nevertheless it is easy to see from this value that the actuator can be very effective in producing a force on the attaching structure.

## Conversion to a Force Actuator

The only physical changes required to the actuator are the addition of a proof mass to the coil to decrease the stroke required to produce a given force, and the addition of an LVDT to give feedback for the position of the moving mass. The physical layout of the actuator is shown on Figure 1. For testing purposes, an accelerometer was mounted on the proof mass, to give a direct force readout. This accelerometer could also be used for feedback signals if required, but in the current implementation the acceleration feedback was not required. The LVDT used was a TransTek Model No. 244. The LVDT response is linear over about a two inch range. The LVDT requires an external power supply and has internal electronics that produce a significant phase lag in the measurement. Phase lag was measured to be 52 degrees at 100 Hz and varied approximately linearly with frequency. The linear velocity transducer (LVT) had no significant dynamics and was found to have a gain of 0.05 v/(in/sec). Using these parameters the system block diagram was modeled as shown in Figure 2. The overall transfer function (neglecting the dynamics of the LVDT) are a second order system

$$\frac{F}{V}=\frac{K_a K_f s^2}{s^2+K_a K_f K_V s+K_a K_f K_D}$$

where $K_{(.)}$ indicates an appropriate gain with

a - Amplifier
f- Force/current constant
V- LVT transducer gain
D- LVDT gain

A simple operational amplifier circuit was added to sum the LVT and LVDT signals, and to allow relative scaling of the signals to the amplifier. The general schematic of this circuit is shown in Figure 3. For our purposes the gains were set to give a low frequency cutoff of about three Hertz. Initial tests showed a lot of high frequency noise corrupting these feedback signals and causing very poor performance. Shielding all the leads from the sensors to the op-amps, and adding a number of small capacitors to the circuitry as shown on the figure, ultimately eliminated this problem and made the system respond very nicely.

Test results

Tests of the actuator show that this device performs very well as a force command proof mass actuator over a large frequency range. Figures 4 a,b show the measured transfer function from voltage input to force output (as measured by an accelerometer) for the actuator mounted in a bench test. The input used here is a one volt random input. The force output level is approximately 1.6 lb/v. As seen, the force output is extremely flat from about 2 Hz to over 200 Hz. The phase plot (not shown here) is generally quite flat but does exhibit noticeable phase shift at frequencies below about 5 Hz. In initial tests, the proof mass was not exactly centered on the axis of the moving coil. This produced noticed ripples in the response curves starting at about 50 Hz due to exciting structural dynamics of the actuator frame. Centering the mass produces the smooth response shown in the figure. Linearity of the device was tested by applying a sinusoidal voltage and plotting the voltage -force relationship. These results are shown in Figure 5. If perfectly linear, the curve should be a straight line. As seen in the figure there is slight non-linearity, and a small amount of hysteresis, but overall we judge the response to be extremely good.

Several of these actuators have been constructed and mounted on a five meter test structure in the Structural Dynamics Research Laboratory at the University of Cincinnati. The truss structure is shown in Figure 6. The bench tests previously described were repeated on the test structure to verify that the proof mass actuator continued to operate as expected when subjected to the dynamics of the truss frame. The truss is mounted vertically and suspended from the ceiling to simulate a free-free horizontal suspension. A number of large aluminum plates are used as attachment points for the actuators described here. The large masses on the truss produce a set of dynamics with significant modes at low frequency. A typical frequency response of acceleration response to force input at one of the actuator mounting points is shown in Figure 7. Numerous modes exist on the truss throughout the frequency range tested. The bench test shown in Figure 4 was repeated with the actuator mounted on the structure. These results are shown in Figure 8. There is very little difference between the two sets of curves, indicating that the actuator dynamics have negligible interaction with the truss dynamics.

## Conclusions

The intent of this paper is to present the details of the construction of a low cost proof mass actuator, suitable for research into the dynamics and control of large flexible structures. The actuators were constructed from surplus disk drive actuators for a relatively modest cost. Neglecting the cost of the drive (which we in fact obtained at no cost) the total expenditure for equipment was less than about three hundred dollars. (Normally the surplus disk drive itself may cost a comparable amount if purchased). The analysis and test results show how this relatively simple concept can be used as a highly effective linear proof mass actuator suitable for control purposes, or as a mechanical shaker. We have constructed over five of these systems and their performance is fairly reliable and repeatable. Current studies are under way to use these actuators in on-line identification schemes for structures and for vibration suppression control experiments.

## References


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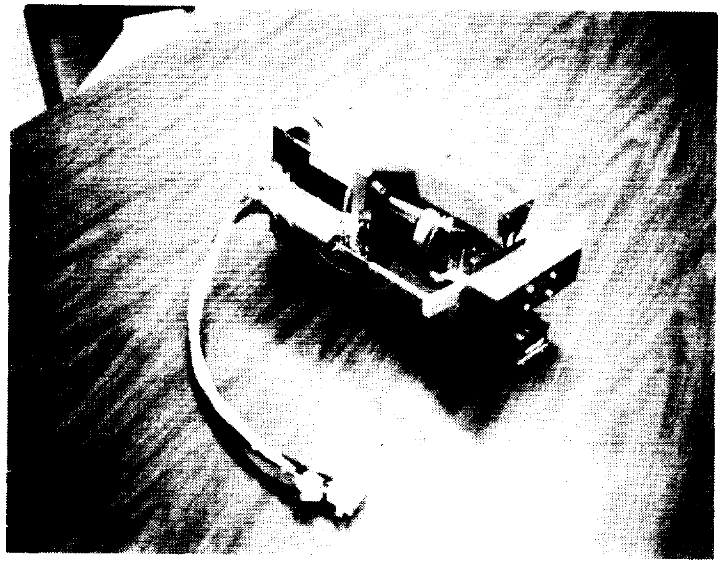

Figure 1 Proof Mass Actuator

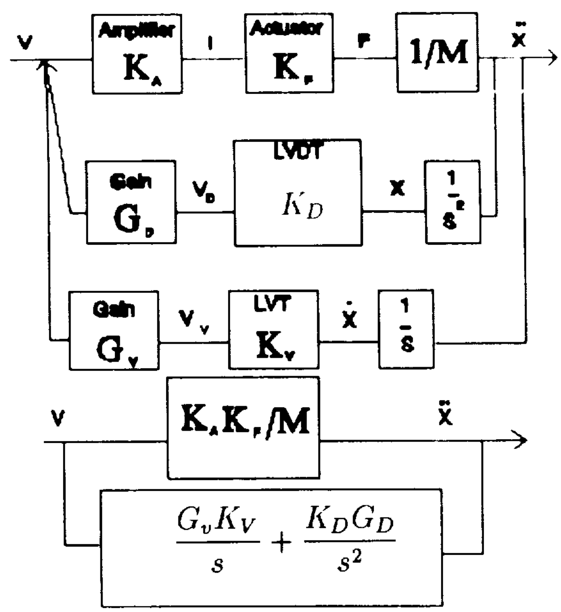


Figure 2 Block diagram of actuator feedback loop

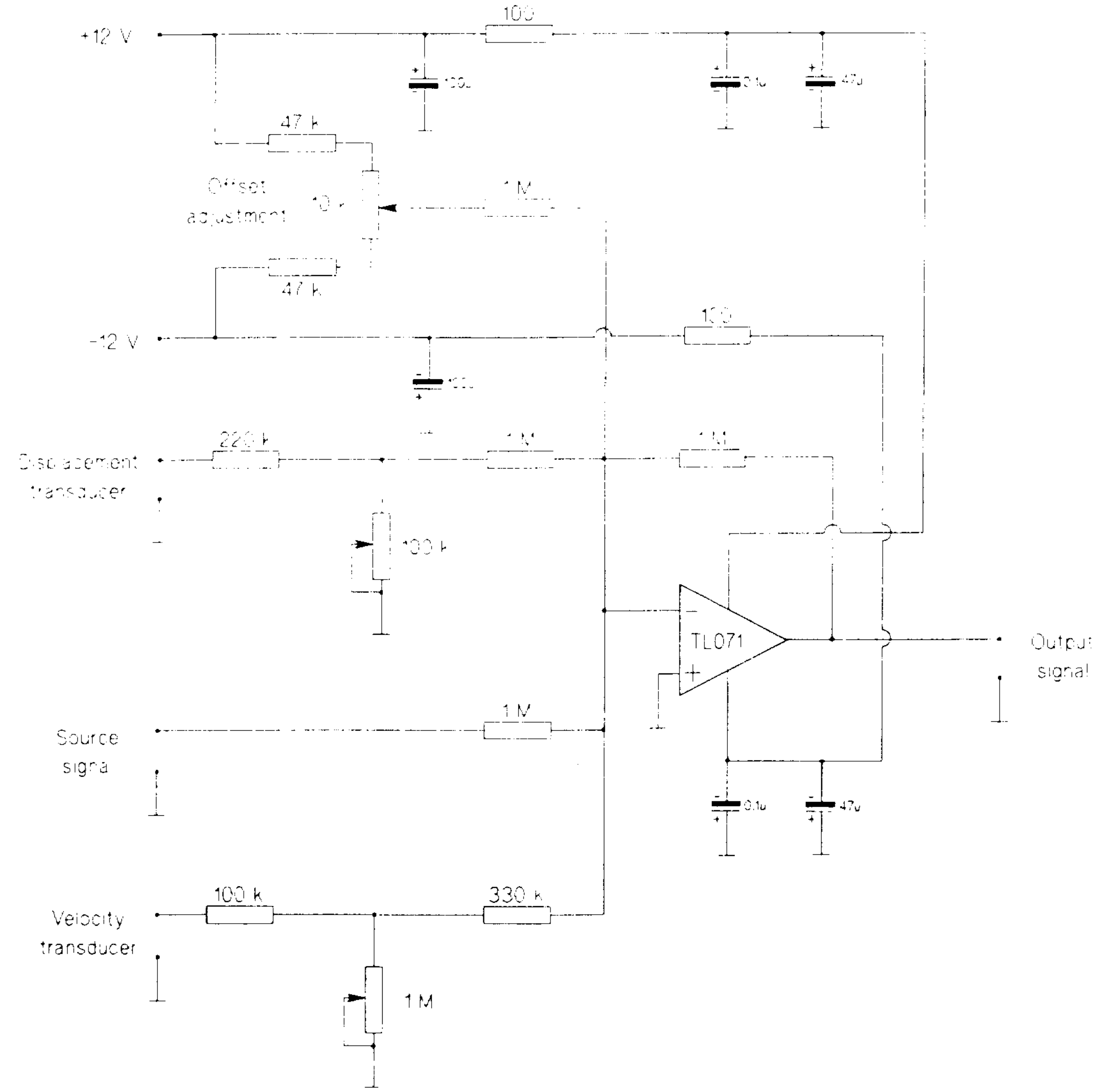


Figure 3 Op-amp circuit for conditioning of sensor signals to input amplifier

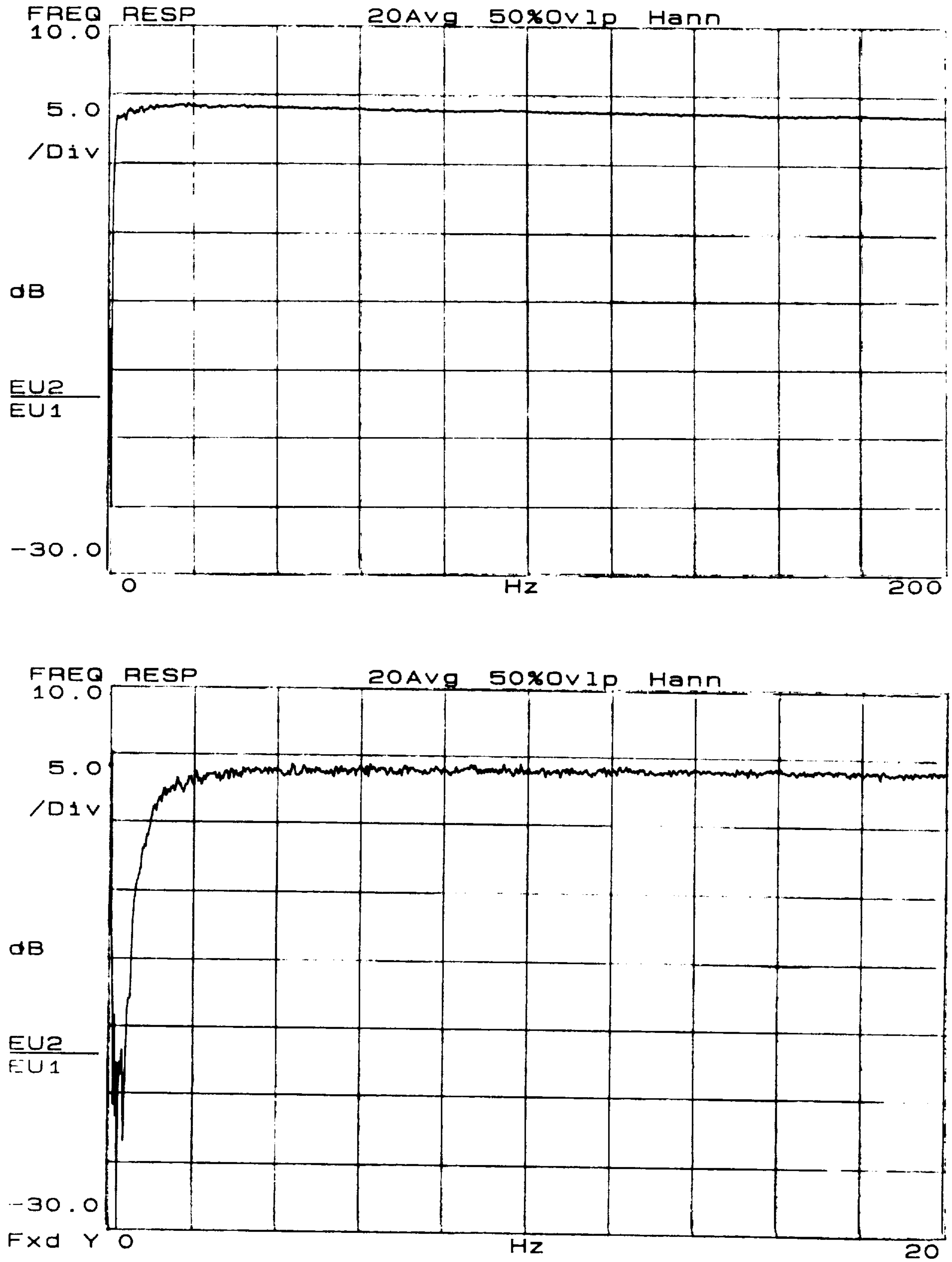


Figure 4 Transfer function magnitude for force output to voltage command (Bench Test). (a) 0-200 Hz (b) 0-20 Hz.

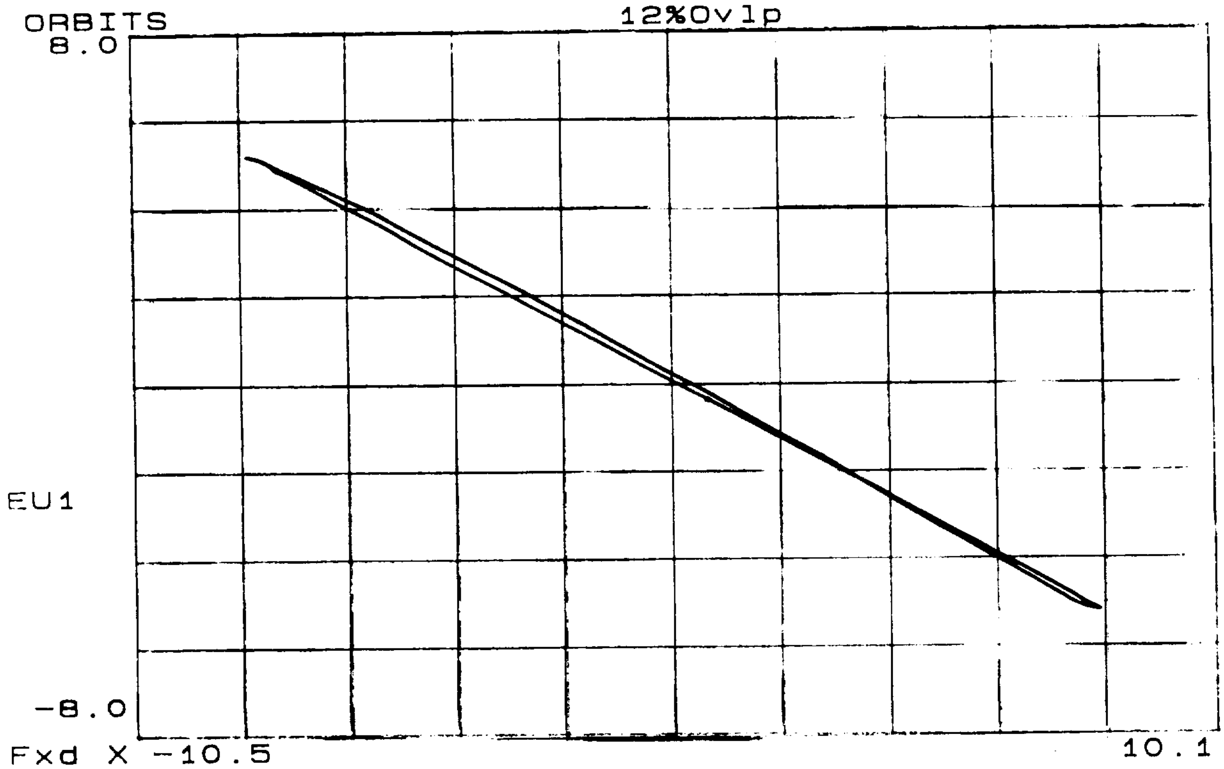


Figure 5 Force-voltage curve showing linearity of the actuator. (Reference signal is 5 v at 20 Hz.)

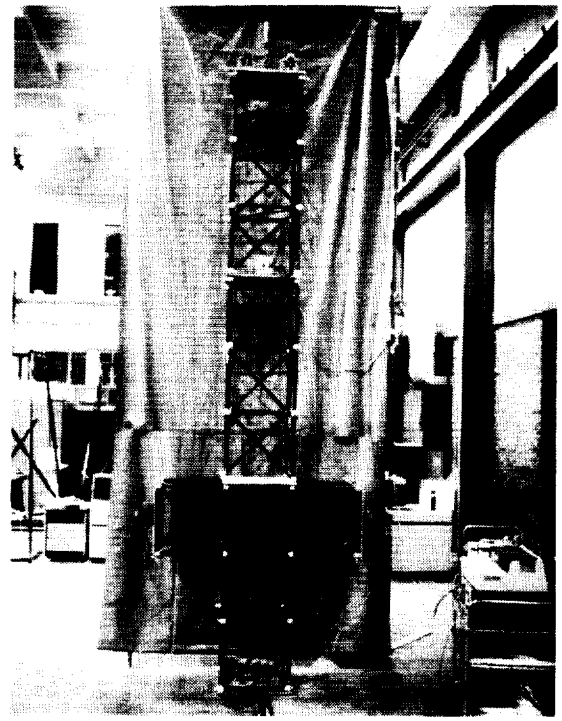

Figure 6 Laboratory truss structure used in test

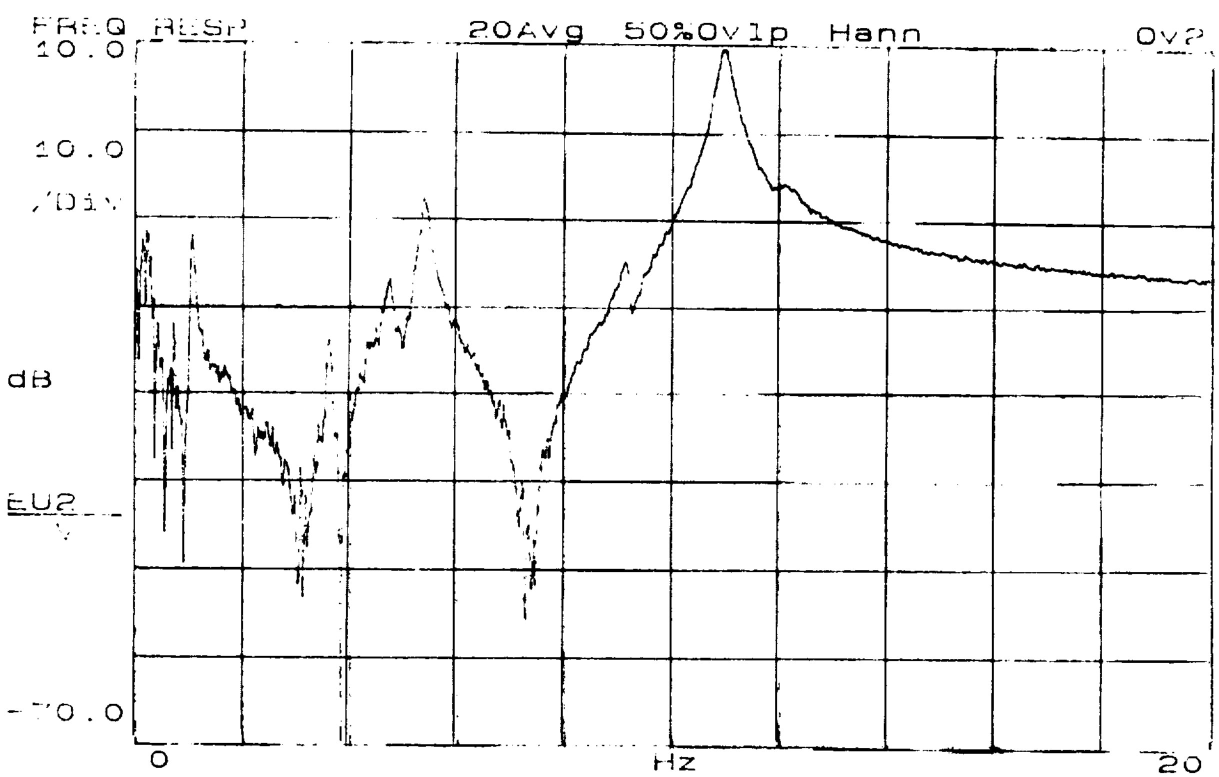


Figure 7 Frequency response of the truss structure (Acceleration/force)

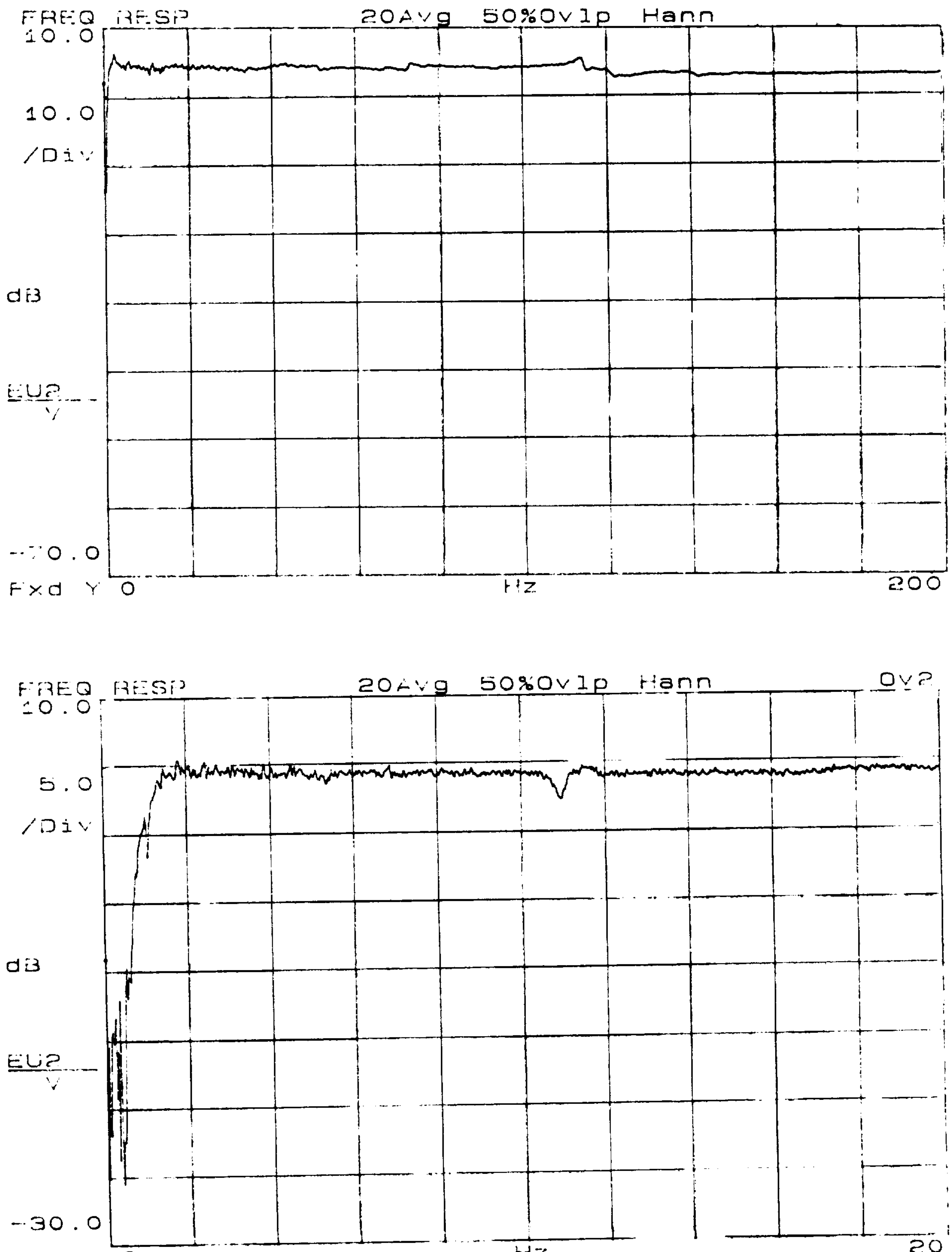


Figure 8 Transfer function magnitude for force output to voltage command (On structure). (a) 0-200 Hz (b) 0-20 Hz.