Tendon Control System for Flexible Space Structures : A Hardwear Demonstration

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Tendon Control of Flexible Structures – A Hardware Demonstration

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This paper describes the hardware setup and experimental results of the active structural control experiment using a tendon actuator system. The experiment is designed to test the capability of the tendon control system for beam vibration suppression concerning the application to the active control of flexible space structures. A clamped-free thin stainless-steel beam with a length of 2.4 m and a cross section of 150 [mm] × 1 [mm] is used to simulate a flexible space structure having very low natural frequencies and a light damping. The prototype tendon actuator designed for the experiment consists of an electrodynamic force actuator with appropriate linkages placed at the beam root and a set of tension cables connecting the linkage edges to the moment arm located on the beam, and thereby it applies a control moment to the structure at the arm position. The deflection angle of the beam in the response motion is measured by a couple of electro-optical displacement sensors. The entire assembly is linked to a digital computer permitting online real-time computation of the control forces. Direct velocity feedback control is tested on the experimental hardware and shown to have desirable vibration suppression properties.

1. Introduction

Large space structures (LSS) to be placed into orbit in 1990's and the beginning of the next century will have extremely large dimensions and higher level of mechanical flexibility that have never been experienced in classical spacecraft. Hence the active control technology for vibration suppression and shape determination of the LSS will become of fundamental importance.

The use of linear feedback controllers to control flexible space structures has been intensively studied in many industries, institutes and universities and a variety of approaches have been proposed1). Hardware implementations have also been demonstrated2–5). Most of these studies are based on conventional-type actuators of the past, namely, thrusters and momentum wheels, which are external force producing devices and designed for the objective of pointing or attitude control. However they may not be the best system to meet the new class of control objecrives such as vibration suppression of flexible structures. Further, structures may be too thin and weak to allow the attachment of a massive actuator of conventional-type. Therefore an actuator of different type may be more suited to such objectives.

The authors have proposed an alternative, *i.e.*, tendon control system for flexible space structures6). This is in nature a biomechanical scheme used to control animal motion and configuration, namely, active control of muscles and tendons. This analogy can be exploited in a man-made flexible structure by the use of force actuators and tension cables. A kind of tendon control system has already been investigated in civil engineering associated with the building and bridge vibration suppression problem7).

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Figure 1 is an illustration giving the idea of a tendon control system for suppressing beam vibrations. A pair of actuators at the beam root activate the tendons, *i.e.*, tension cables, to rotate a pair of moment arms attached at a proper position of the structure. Thereby the beam motion is actively controlled by using the feedback signals from a sensor located on the beam.

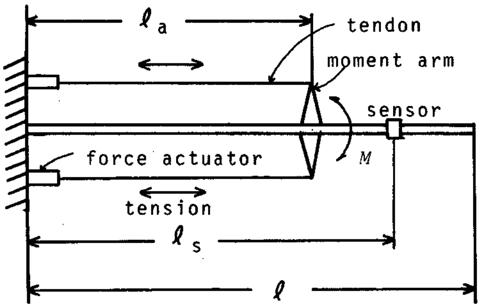


Fig. 1 Tendon control system for beam vibration suppression.

The use of tendon control provides a lot of advantages for structural control. It is suited to this control task not only because its hardware is simple to be equipped but also because a robust collocated control can be realized by using "dislocated" sensors and actuators. Typically, massive force actuator units are placed at a spacecraft-bus while the point of control action can be distributed, with a collocated sensor, at any location of a flexible appendage or a deployable mast.

However, tendon control system includes some difficulties in the practical implementation. If variation of the axial stress due to control force is not small, then it may cause nonlinearities or parametric excitations. This nonlinear tension control is known as stiffness control of structures$^{8)}$. Moreover, in the case of structures with low flexural rigidity, which is typical for LSS, the range of the tensile force must be carefully tuned in order to avoid the axial buckling of the beam and to suppress the interactions between the modes of the structure and those of the tension cables.

In this paper, the efficacy of the tendon control system is experimentally demonstrated by using a hardware model in the laboratory. The detailed hardware setup and preliminary results of the experiment are described in the following sections.

2. Experimental Hardware

2.1 Configuration

A clamped-free homogeneous flexible beam hanging in the vertical direction has been chosen as a test structure. This configuration is a simple, continuous structure with dynamic characteristics that are representative of a variety of flexible elements in many space structures, *e.g.*, booms and antennae.

A photograph of the experimental apparatus (*i.e.*, the flexible beam and its support structure) is shown in Fig. 2. The beam consists of 18-8 stainless steel with a length of 2.4 m. It weighs 2.74 Kg and has a cross section of 150 [mm] X 1 [mm]. (See Table 1.) The support structure (*i.e.*, the test stand), is constructed of steel angles and channels and weighs 700 Kg. The stiffness of the structure is large enough so that its resonant

Table 1 Beam characteristics.

Material	Stainless steel
Length	2.4 [m]
Width	150 [mm]
Thickness	1 [mm]
Flexural rigidity EI	2.39 [Nm^2]
Mass density	1.14 [Kgm^{-1}]
Weight	2.74 [Kg]

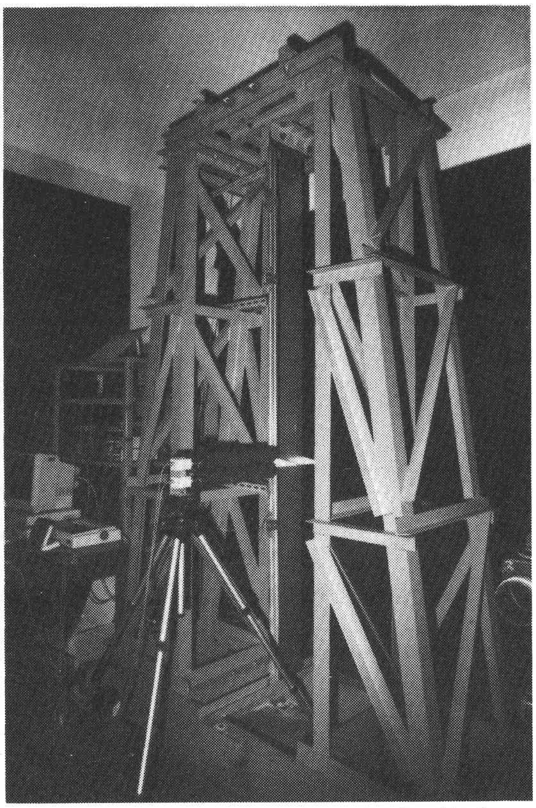


Fig. 2 Experimental apparatus – the flexible beam and its support structure.

frequencies do not interact with those of the flexible beam. A clamp is mounted at the upper girder to support the flexible beam.

The dynamics of the beam motion is modeled by Euler-Bernoulli theory including loads due to gravitational force⁹⁾. For experimental verification of the dynamic model, FFT analysis for the measured beam responses has been performed by means of impact method. Table 2 presents the theoretically and experimentally determined natural frequencies of the lowest eight modes. The theoretical natural frequencies without gravity are listed in the first column to show that the gravity effect is remarkable especially at lower frequencies. On the other hand, the gravitational force changes the corresponding mode shapes very little as shown in Fig. 3. The analysis using a finite element method based on Timoshenko theory with gravity effect has also been performed, however the results for the lowest eight modes almost coincide with those of

Table 2 Natural frequencies for beam [Hz].

Modes	Euler-Bernoulli Theory		Timoshenko	Experiment
	(without g)	(with g)	(with g)	
1 st	0.14	0.42	0.42	0.42
2 nd	0.88	1.28	1.28	1.28
3 rd	2.42	2.90	2.90	2.92
4 th	4.74	5.26	5.26	5.35
5 th	7.83	8.39	8.39	8.55
6 th	11.70	12.29	12.28	12.45
7 th	16.34	16.93	16.93	17.33
8 th	21.76	22.35	22.36	22.85

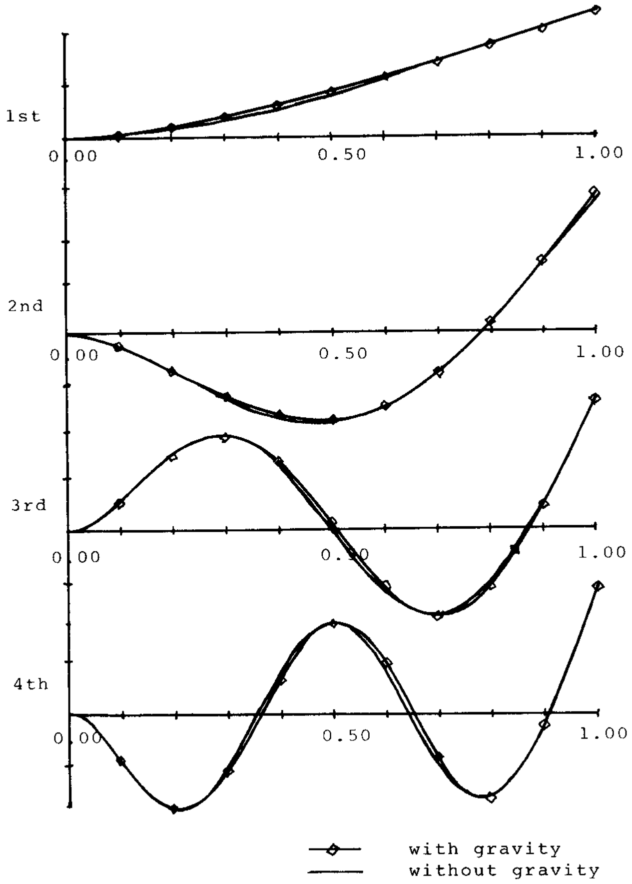


Fig. 3 Mode shapes (with and without gravitational force).

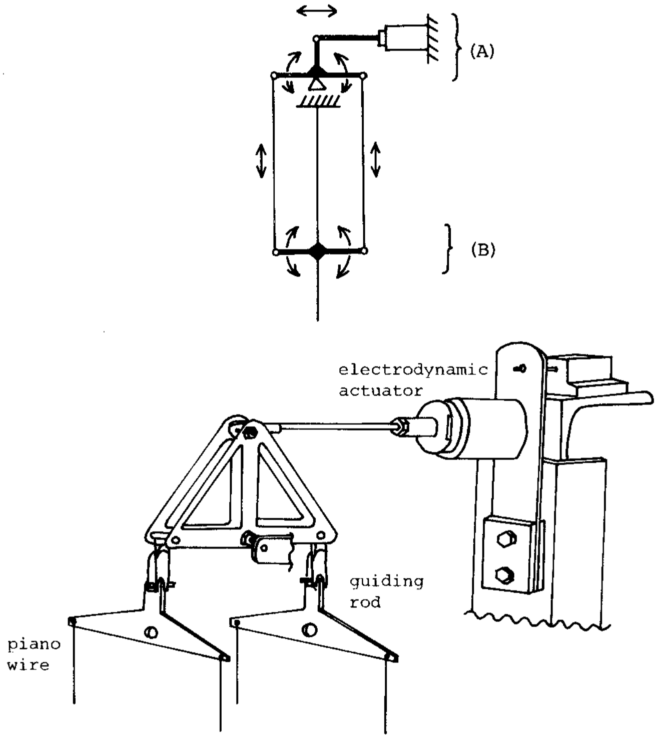
the Euler-Bernoulli theory.

2.2 Tendon actuator

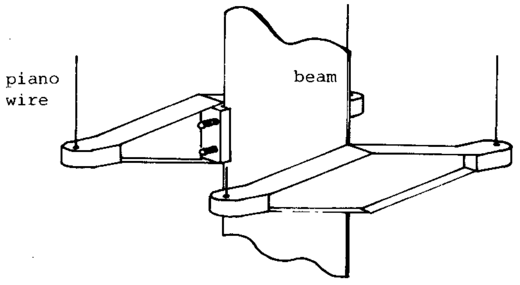
Configuration of the prototype tendon actuator is shown in Fig. 4. An electrodynamic force actuator and appropriate mechanical linkages are designed for the purpose of active tendon control. The force actuator consists of a cylindrical electromagnetic coil that is free to move in a permanent magnetic cylinder. It has the capability of applying 4N of force for a maximum 2A input with a bandwidth of 70 Hz and non-linearity of 1% for a displacement range of ±18 [mm].

With the aid of properly designed mechanical linkages, tension cables, and moment arms, the control moment generated by the force actuator can be transformed linearly to the arm position. To allow the beam response being free from the tortional vibrations, a pair of arms are attached to both side-edges of the beam. Hence four tension cables in all are used to link the moment arms to the mechanical linkages equipped at the beam root through the hinged joints and guiding rods. Piano-wires of 0.35 mm diameter are adopted as the tension cables. Other materials, such as carbon fiber twists, will be used in the advanced experiment.

The initial tensile force of an appropriate magnitude is applied equally to each



(A) Mechanical linkages



(B) Moment arms

Fig. 4 Configuration of the tendon actuator system.

cable by the adjusting screw joints. This static loading is useful to prevent the cables from being loose during the control action and keep the total axial stress of the beam in constant, and thereby to avoid the difficulties due to the time varying stiffness. Moreover, it increases the resonant frequencies of the cable vibration.

2.3 Sensors

Figure 5 shows the sensing system used in the control loop. Two sets of electro-optical two-dimensional position sensing devices (PSD) made by Hamamatsu Photonics Corporation are employed. Each PSD unit has the resolution of 0.02% over a 20 mm range with a 0.5 kHz bandwidth.

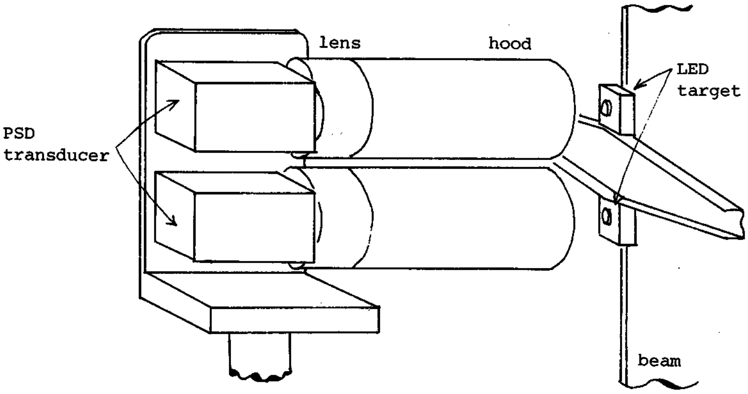


Fig. 5 Position sensing devices (PSD) and LED targets.

A pair of LED (Light Emitted Diode) targets are attached to the beam at a small distance above and below the arm position. Hence, the beam deflection angle can be obtained from the position measurements for this target pair by taking the spacial difference in the two-dimensional plane.

2.4 Controller assembly

The entire assembly of the control system is shown in Fig. 6. Two-dimensional displacements of the LED targets are transduced into voltage signals and inputted to a 12-bit analog-to-digital (A/D) converter board mounted on an NEC 9801-VM microcomputer. This microcomputer chosen for the control function is based on a V30 16-bit microprocessor operating at 8 MHz clock speed. An 8087 arithmetic processor is also mounted to accelerate the processing speed in floating point operations. A 12-bit digital-to-analog (D/A) converter is dedicated to outputting voltages proportional to the required control forces.

The employed actuator drive amplifier has a current feedback loop with compensation networks, and the input-to-output relation between the command voltage and the realized control force is found to be highly linear. Therefore the inner loop using a force sensor, which is shown in Fig. 6, is not required.

3. Experimental Results

3.1 Free vibration

The beam was equipped with the prototype tendon actuator and sensing system,

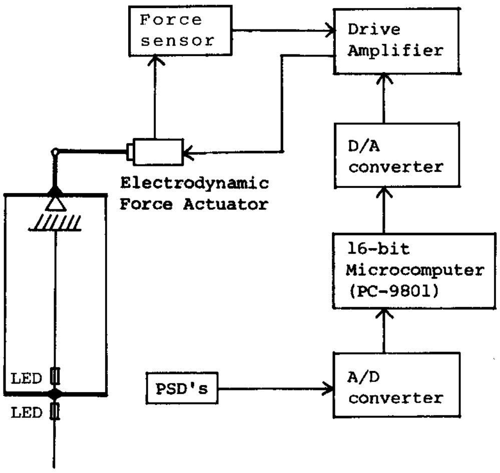


Fig. 6 Block diagram of the controller.

and a free vibration test was performed by applying an impulsive input to the actuator. The open-loop response of the test beam is plotted in Fig. 7. Transfer function, generated by an FFT analyzer, is also presented in the same figure. It can be seen that many lightly damped modes are excited by the moment impulse. The open-loop modal damping, primary due to frictions of the actuator coil and joint bearings, as well as atmospheric drag, is estimated to be 0.08 in logarithmic decrement, i.e., equivallently about 1.3% of critical damping, for the first mode.

3.2 Direct velocity feedback control

Output feedback control using the collocated rate sensor and actuator in pair is called as the direct velocity feedback (DVFB). Among various theories to carry out the control task, *i.e.*, beam vibration suppression, this approach was chosen by the following reasons. First of all, it is simple to implement and hence suited for the first step of the present control experiment. Next, it is confirmed to be energy dissipative and therefore provides a proofed stability for the closed-loop system10). Furthermore, this type of controller is quite insensitive to modeling errors since no explicit use of the model is made in the implementation of the control system.

The software has been developed to carry out the direct velocity feedback control task. The deflection angle of the beam at the arm position is computed by using the PSD outputs as described before. However, for carrying out the DVFB control task, the rate information must be derived. No state estimation is used in this controller in order to obtain the angular velocity information. Therefore, the angular displacements are numerically differentiated to provide the local rate information. A digital filter based on Simpson's rule is used for the numerical differentiation. Angular velocity thus obtained is multiplied by a constant gain to form the actuator command. The real-time control loops are coded directly in assembly language and thereby sampling time can be chosen as short as 2 ms.

The closed-loop response of the beam at the arm position is presented in Fig. 8. In this case, the arm location was chosen as a 60% beam length from the root, which is one of the best collocating position when the first four modes are considered in the controller design[6]. A good vibration suppression is achieved by this simple controller. The damping for the first mode is about 0.20 in logarithmic decrement. There is no observable spillover into the higher frequencies. Experimental open- and closed-loop transfer functions given in Figs. 7 and 8 show that the decays of the third and higher modes, as compared with those of the lowest two modes, are more remarkable. This is due to the characteristic of the moment actuator with angular velocity feedback. The

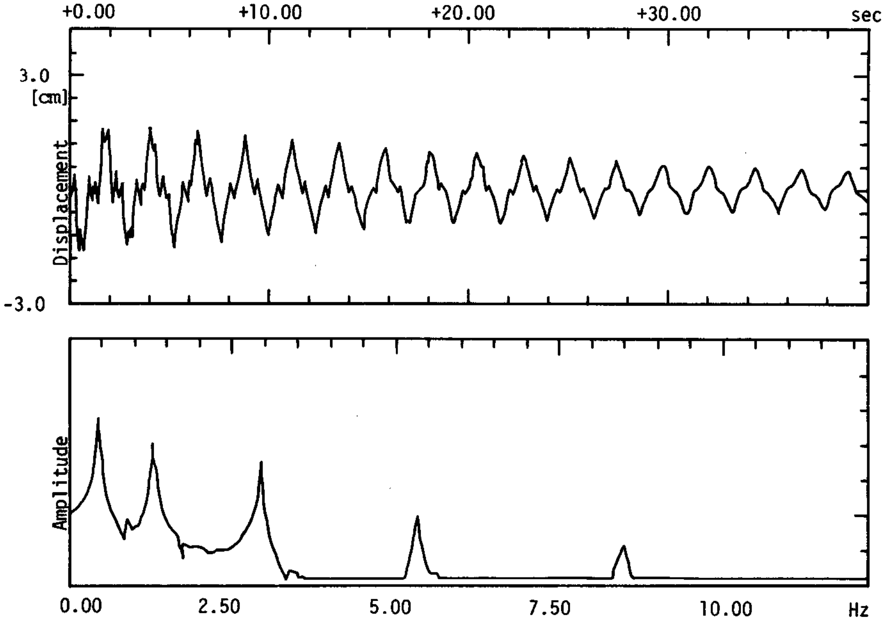


Fig. 7 Free impulse response of the beam motion at the arm position.

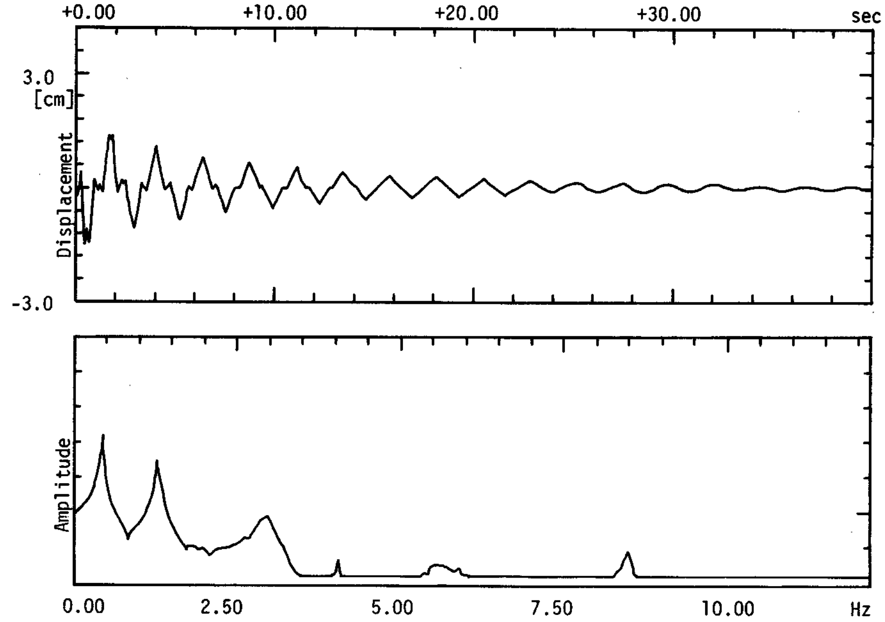


Fig. 8 Closed-loop impulse response of the beam at the arm position for DFVB control.

first and second modes would be suppressed further if a linear velocity information was included in the control law.

4. Conclusions

The flexible beam experiment showed the fundamental feasibility of the tendon control system in structural vibration suppression. Excellent results have been obtained in direct velocity feedback control although this control law is simple to implement. To test the ability of other various theories, such as modal space control using state observers or modal filters, experiments are being performed. Further studies are also in preparation involving more complex dynamics that include interactions between the rigid-body motion and flexible modes.

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References

1) G. S. Nurre, R. S. Ryan, H. N. Scofield, and J. L. Sims, J. Guid., Control and Dynamics, 7 (5), 514 (1984).
2) J. A. Breakwell and G. J. Chambers, J. Astronautical Sciences, **31** (3), 441 (1983).
3) L. Meirovitch, H. Baruh, R. C. Montgomery, and J. P. Williams, J. Guid., Control, and Dynamics, 7 (4), 437 (1984).
4) D. B. Schaechter and D. B. Eldred, J. Guid., Control, and Dynamics, 7 (5), 527 (1984).
5) B. E. Schäfer and H. Holzach, J. Guid., Control, and Dynamics, 8 (5), 597 (1985).
6) Y. Murotsu, H. Okubo, Y. Okawa, and F. Terui, Bull. of the Univ. of Osaka Pref., Ser. A, **34** (2), 137 (1985).
7) J. Roorda, Proc. of the IUTAM Symp. on Structural Control, Waterloo, 629 (1979).
8) J. L. Fansen, J. C. Chen, and T. K. Caughey, Workshop on the Application of Distributed System Theory to the Control of Large Space Structures, Jet Propulsion Lab., 351 (1982).
9) B. E. Schäfer, Ingenieur-Archiv, **55** (1), 66 (1985).
10) M. J. Balas, J. Guidance and Control, 2 (3), 252 (1979).