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Engineering Notes

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Deadbeat Predictive Control on a Space Truss Structure

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I. Introduction

FUTURE space missions are expected to place into orbit large systems having long truss-type structures supporting many modules and appendages for logistics, habitation, power and propulsion [1]. The combination of large and lightweight design results in trusses being highly flexible and having many lightly damped low-frequency modes. A large space truss is likely to require an active control system to effectively suppress the vibration induced during slewing, pointing and docking maneuvers.

The laboratory truss experiment for space structure (TESS) is a 54-bay truss specifically designed to validate different active control techniques [2]. The dynamics of TESS are such that many closely spaced modes fall into the bandwidth of significant disturbances and attitude control crossover region. This makes TESS an excellent candidate for testing new control techniques for vibration suppression [3,4]. TESS is equipped with cold air jet thruster actuators, which are very effective to damp out large low-frequency oscillations but consume nonrenewable fuel. Effective controllers are thus required to optimize control energy.

One type of controller tested on TESS was a deadbeat predictive controller. Deadbeat predictive control (DPC) is a linear controller with many appealing properties with regard to feedback stabilization of large flexible structures [5]. DPC is robust with respect to modeling errors and can control time-varying systems, because the control gains can be computed onto an experimentally identified input-output model which can be performed once on orbit and updated when needed. The controller can assume a compact dynamic output feedback form of appropriate order to take into account real plant dynamics and constraints. Finally, DPC design is basically characterized by two integer parameters that can be easily tuned to achieve a wide range of solutions from minimum-time to minimum-energy control. Derivation of DPC and numerical testing on a truss structure were presented in [5]. A preliminary evaluation of DPC design simplicity and performance for low-frequency vibration suppression of TESS is presented in this note.

II. Experimental Setup

TESS is a modular beamlike truss of total length of approximately 19 m, with a basic cubic bay of 0.35 m with one diagonal on each side. A photograph of TESS is shown in Fig. 1. The truss is suspended from the ceiling with horizontal axis by three pairs of soft springs. The structural members are plastic tubes, terminated in steel bolt assemblies that connect to plastic octahedral nodes. The characteristics of the first six modes in the horizontal plane are listed in Table 1. TESS is equipped with six control inputs; each one consists of a pair of on/off air jet thrusters. They are located at bay 1, 23, 24, 30, 31, and 54 along the truss and provide a thrust of 2.1 N in the horizontal plane. Actuator locations were selected in a previous work as a compromise between system controllability and static deformation. In this study, only thruster pairs positioned at the tips of the truss were used and a first-order multi-pulse-width-modulation (MPWM) technique [6,7] was adopted to drive each on/off jet as a pulse amplitude modulated (PAM) device. Two Analog Devices accelerometers having bandwidth limited to 100 Hz were used as the primary sensors for feedback control. They were positioned one at each tip of the truss, i.e., at bay 1 and 54, to measure transversal vibrations in the horizontal plane. Based on manufacturer's specifications, the design-stage uncertainty of the accelerometer measurement is assumed to be 0.16 g at 95% probability. The approach to the experimental testing was to reduce as much as possible hardware components. Antialiasing filters were avoided by oversampling the accelerometer signals at 10 kHz. Once sampled, acceleration values were first low-pass filtered to reduce observation spillover and then high-pass filtered integrated to eliminate accelerometer dc bias and produce velocity values for the feedback controller [7]. Instead of using a dedicated timer board to manage MPWM timing, jet electrovalves were opened and closed, at the appropriate time instants, by driving via software a relay board. The digital input/output conditioning and controller operations were implemented on a Pentium III 700 MHz computer running a real-time multitasking operating system. The data acquisition system was a 12-bit National Instruments 6071E board.

III. DPC Algorithm and Design

The basic approach of DPC is to bring the output response to rest after a few finite time steps. This can be obtained by forcing the state vector to zero at time step h, i.e., $x(t+h)=0$. h is called prediction horizon. A solution is given by the standard state-feedback control law $u(t)=-Gx(t)$, where $G=[A^{h-1}B, A^{h-2}B, \ldots, AB, B]^{+}A^{h}$. Here, $[\,]^{+}$ denotes the pseudoinverse of the matrix in the bracket, and A and B are the matrices of the discrete-time state-space model of the system. Instead of explicitly implementing a state estimator as required by the preceding formulation, DPC can be accomplished through an input-output model. In this way the deadbeat predictive controller is converted into a dynamic output feedback form. The input-output model used in this study was an autoregressive with exogenous input (ARX) model [8], which has the following form:

$$y(t)=\sum_{i=1}^{n_\alpha}\alpha_i y(t-i)+\sum_{i=1}^{n_\beta}\beta_i u(t-i) \tag{1}$$

where $y(t)$ is the n_y-vector of system outputs. Here, the order of the autoregressive part was set equal to the order of the exogenous term, i.e., $n_\alpha=n_\beta=n$. The model of Eq. (1) can be put in an observable canonical state-space form (A_n, B_n, C_n) by introducing auxiliary variables $z_i(t)$, defined by the following recursive relationship:

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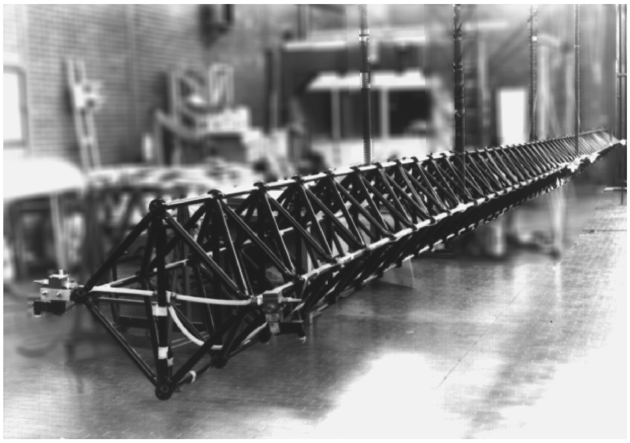


Fig. 1 A photograph of TESS.

$$z_i(t+1) = \alpha_{i+1} y(t) + \beta_{i+1} u(t) + z_{i+1}(t)$$
$$i = 1, 2, \ldots, n-2$$
$$z_{n-1}(t+1) = \alpha_n y(t) + \beta_n u(t) \tag{2}$$

The corresponding state vector is given by $\hat{x}(t) = [y(t) z_1(t) z_2(t) \ldots z_{n-1}(t)]^T$. The state-feedback deadbeat controller becomes $u(t) = -G_{(n,h)}\hat{x}(t)$, where the matrix $G_{(n,h)}$ was taken to be the first n_u-row partition of $[A_n^{h-1}B_n, A_n^{h-2}B_n, \ldots, A_nB_n, B_n]^+ A_n^h$, i.e., a receding horizon approach was adopted. The deadbeat predictive controller can be written as

$$u(t) = -g_1 y(t) - \sum_{i=2}^{n} g_i z_{i-1}(t) \tag{3}$$

where $G_{(n,h)} = [g_1, g_2, \ldots, g_n]$. Substituting Eq. (2) into Eq. (3), the current control input is calculated as a linear combination of past input and output measurements:

$$u(t) = \sum_{i=1}^{n} \alpha_i^c y(t-i) + \sum_{i=1}^{n} \beta_i^c u(t-i) \tag{4}$$

where the controller gains matrices are given by

$$\alpha_{i+1}^c = -\sum_{j=1}^{n-i} g_j \alpha_{i+j} \qquad i = 0, 1, \ldots, n-1$$
$$\beta_{i+1}^c = -\sum_{j=1}^{n-i} g_j \beta_{i+j} \qquad i = 0, 1, \ldots, n-1 \tag{5}$$

As outlined, DPC design mainly relies onto two integer parameters, i.e., the order n of the ARX model used to build the implicit observer, and the prediction horizon h. No systematic procedure exists to determine the values of these parameters. However, because the meanings of n and h are clearly defined, workable designs can be easily produced [5]. As discussed in the next section, the value of n was chosen to correctly model plant dynamics and optimize system identification results with respect to measurement noise. The value of h was tuned to regulate control effort and performances. A realistic DPC simulation was first performed to determine the nominal ranges of the control parameters to be used on TESS.

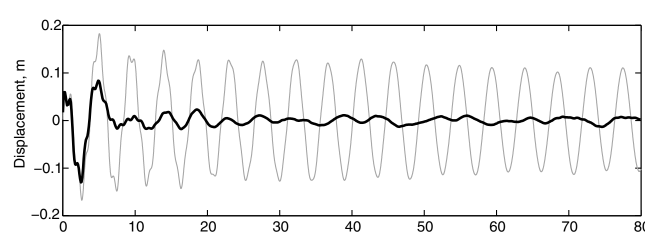
Table 1 First six modes of TESS in the horizontal plane

Mode	Description	Frequency, Hz	Damping factor, %
1	Pendulum rotation	0.207	0.32
2	Pendulum translation	0.209	0.85
3	First bending	1.085	0.99
4	Second bending	3.057	1.00
5	Third bending	5.539	1.10
6	Fourth bending	8.956	1.10

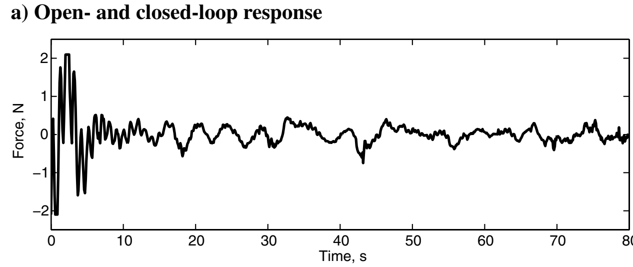
IV. Experimental Results

DPC was first tested on TESS in a collocated single-input-single-output (SISO) case, i.e., by using control and sensing devices at bay 1. A set of input-output data for system identification was generated by driving the jet thruster pair with a pseudorandom signal and collecting the tip acceleration response [8]. From this set of data a deadbeat predictive controller was designed with $n = 24$ and $h = 40$. The sensor output was filtered with a discrete-time fourth-order Bessel filter having a cutoff frequency of 5 Hz. System response was dominated by a few low-frequency modes due to the limited bandwidth of jet actuators. The controller order was appropriately selected to capture this dominant structural behavior and to take into account noise level and signal distortion introduced by antispillover sensor output filtering. Figures 2a and 2b show the result obtained by this SISO controller. The truss was excited for 20 s with a combined-mode disturbance including the first four modes in Table 1, and then the controller was turned on to suppress the vibration. The controller sampling rate was 10 Hz. Figure 2a shows the decay time histories of the displacement output at bay 1. The gray curve is the uncontrolled tip response, whereas the black curve is the response after control. Figure 2b shows the time history of the control force in N as a result of the PAM-MPWM equivalence. The controller is able to effectively dampen TESS tip vibration to some acceptable magnitude within approximately 10 s. The value of $h = 40$, selected after some trail and error, produced a system response well balanced between the desired closed-loop performance and command input saturation. As can be seen, the damping time is quite satisfactory and the saturation of the jet actuator is limited to a few steps during the first phase of the control activity. After that, rather large steady state level of the control force was observed, probably due to a small alignment error of the jet thrusters with respect to the horizontal plane. This misalignment caused a slightly-coupled motion between the vertical and horizontal plane producing a forcing effect on the TESS pendulum rotation which the controller tries to struggle with.

Testing of DPC on TESS in a multi-input-multi-output (MIMO) case is shown in Figs. 3a–3d. Both control and sensor devices located at the tips of TESS were used, i.e., collocated configuration. Even if good stable control is easier to achieve with collocated sensors and actuators than with noncollocated configurations, the open-loop plant is not guaranteed to be strictly passive due to the very limited bandwidth of the jet thrusters which has a strong destabilizing influence on the frequency modes in the control bandwidth. A

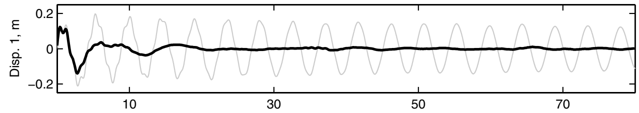


a) Open- and closed-loop response

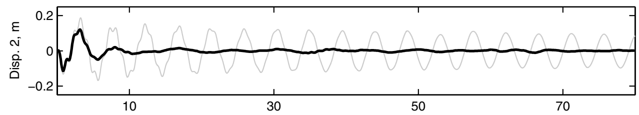


b) Control input time history

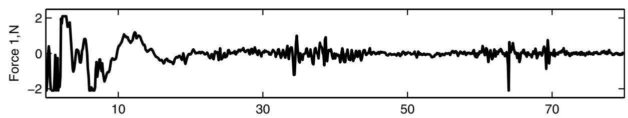
Fig. 2 SISO deadbeat predictive control of TESS.



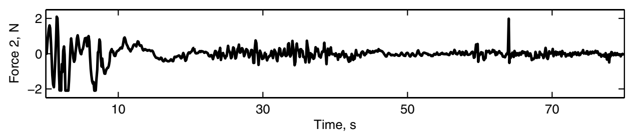
a) Open- and closed-loop tip response (bay 1)



b) Open- and closed-loop tip response (bay 54)



c) Control input time history (bay 1)



d) Control input time history (bay 54)

Fig. 3 MIMO deadbeat predictive control of TESS.

deadbeat predictive controller was designed with $n = 12$ and $h = 25$. The coefficients of the ARX model were determined from a set of input-output data generated by simultaneously driving jet thruster pairs with two independent pseudorandom signals and collecting tip accelerations. Using two outputs, the controller order can now be halved [8]. The same sampling rate and digital filtering settings of the SISO case were adopted. As before, the truss was excited with a combined-mode disturbance and then the controller was turned on to suppress the vibration. Figures 3a and 3b show uncontrolled (gray curves) and closed-loop (black curves) tip displacements. Figures 3c and 3d show the related control activity. Again, satisfactory closed-loop performance and reasonable control effort were obtained using a simple design and an efficient implementation. As before, spikes in the control forces well after the system response has damped out were due to the coupling between horizontal and vertical motion of the truss. Even though a Pentium III was used during the tests, the MIMO control algorithm only required about 5% of the CPU.

V. Conclusion

A preliminary study of a deadbeat predictive controller on a space truss structure using on/off jet thrusters has been presented. Through experimental work, we could observe that the proposed controller, even if not optimal, was able to effectively suppress large low-frequency vibration with reasonable control effort and minimal computational requirements. It would be interesting to evaluate the efficacy of the controller with noncollocated sensors and actuators. Further application on TESS of a recursive version of the algorithm with adaptive tuning of the design parameters may also prove interesting. In this way, the controller will have the opportunity to control the system changes and achieve optimal performance.

Acknowledgments

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