

Vibration Control of Cantilever Smart Beam by using Piezoelectric Actuators and Sensors

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Abstract- Vibration of a smart beam is being controlled. This smart beam setup is comprised of actuators and sensors placed at the root of a cantilever beam. Vibrations can be caused by various sources including human activity and nearby motorized equipment. In this case, disturbance is produced using a white noise signal to the actuator. The piezoelectric sensors are used to detect the vibration. Simultaneously, feedback controller sends correction information to the actuator that minimizes the vibration. To optimize results, controllers were designed using Linear Quadratic Gaussian (LQG) theory. This theory generally results in high-order controllers. Additionally, optimal control theory is being used to directly optimize low-order controllers.

Keywords: - Vibration Control, Actuators, Sensors, LQG Theory

I. INTRODUCTION

The motivation for this work stems from the possibility of using induced strain actuation for vibration suppression, stability augmentation, and noise reduction in beam-like aerodynamic surfaces. These beams are used in such applications as helicopter and airplane wings, turbo-machine blades, missiles, space structures and civil structures. Several theories apply to the control of vibration. The best way to optimize a single mode, as being proposed in this research, is to optimize the performance metric corresponding to the mode of interest. This methodology is ideal for the design of low-order controllers.

A smart structure involves distributed actuators and sensors along the structure and some type of processor that can analyze the response from the sensor and use control theory to output commands to the actuator. The actuator applies local stresses/strains to alter the behavior of the system. Therefore, a smart structure has four major components: the structure, sensor, actuator, and controller. Actuators and sensors are widely used in various applications and are generally integrated with main structures via surface bonding or embedding.

When building the beam, it is taken into consideration that piezoelectric materials must be bonded to the beam in a uniform fashion along with the fact that both materials must have electrical contact on each side of the material. These

facts bring about the controversy between surface bonding and embedding. Surface bonding for piezoelectric actuators is advantageous in that there is better access for fabrication, easier access for inspection, and less maintenance cost. However, since these materials are exposed, they are more vulnerable and more prone to be damaged. In this experiment, it is necessary for the piezoelectric components to be on the surface because it was the only way it could be easily manufactured.

II. SENSORS AND ACTUATORS

Piezoelectric sensors operate using the direct effect, i.e., electric charge is generated when a piezoelectric material is stressed causing deformation. These sensors are extremely sensitive, have superior signal-to-noise ratio, and high-frequency noise rejection. Piezofilm is approximately ten times as sensitive as semi-conducting gauges and over 300 times as sensitive as resistance gauges. Sensors can be bonded to another material, which causes the sensor to deform with the base structure. The deformation of the sensor can be measured by measuring the voltage across its electrodes. In this case, the sensor is bonded to the bottom surface of the beam using a small strip of two-sided adhesive tape that is approximately equal in thickness to that of the PVDF film.

Typical piezoelectric actuators operate using the converse effect of piezoelectric materials. This effect states that when a piezoelectric material is placed into an electric field i.e., a voltage is applied across its electrodes; a strain is induced in the material. PZT, a piezoceramic, is commonly used for actuation because it has a maximum actuation strain is 1000 microstrain. This is a respectable maximum actuation strain for the purposes of the experiment. Other, more exceptional actuation materials such as terfenol can create twice the maximum actuation strain as PZT, while nitinol, available in wire forms can deliver a maximum actuation strain of 20,000 to 60,000 microstrain. However, these materials are extremely costly. PZT is ideal because of its respectable maximum actuation strain, reasonable cost, and high accessibility.

III. SYSTEM SETUP

To identify the dynamics of the beam, the beam needs to be stimulated via the actuator. White noise signal is appropriate for system identification. The white noise signal is generated in MATLAB/Simulink and passed on to the dSPACE controller board - ACE1104. The dSPACE controller board has 8 Analog-to-Digital (ADC) and 8 Digital-to-Analogue (DAC) channels and is able to handle 8 input and 8 output signals. Since the analogue white noise signal generated by the dSPACE board is from a digital signal from the computer it has discrete jumps leading to high frequency noise. Thus the signal is passed through a Krohn-Hite Model 3364 4-channel filter, which removes the high-frequency noise and helps the researcher to restrict the frequency range of operation. Finally the signal is sent to the actuator using a Krohn-Hite Model 7602M wideband power amplifier. The amplifier was used, rather than the computer, to increase the power sent to the actuator. The sensor detected the response. The sensor voltage was filtered and amplified before it was displayed on the oscilloscope and was read into the computer using one of the ADC channels on the dSPACE controller board. Figure 1 shows the line diagram of beam setup with all instruments.

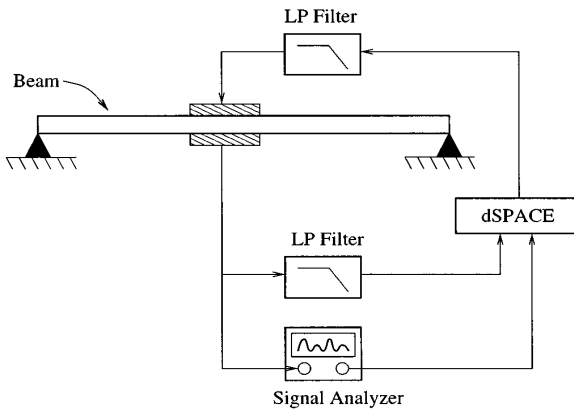


FIG. 1 BEAM SETUP

Figure 2 shows the basic block diagram of the system before the controller is implemented.

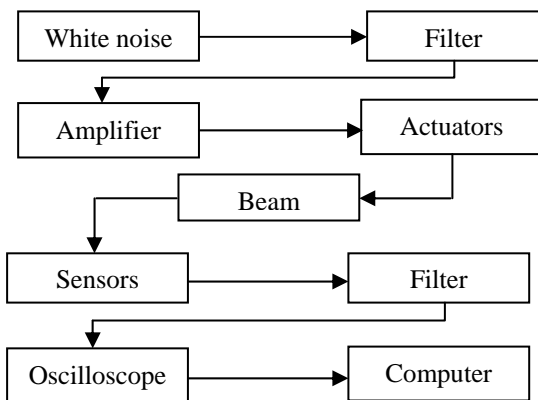


FIG. - 2 SYSTEM SETUP

Using the identification toolbox in MATLAB, it is possible to find a system model that best fits the sensor response to the white noise actuation. These models were used to create controllers based on Linear Quadratic Gaussian (LQG) theory. The controllers were first implemented on the identified model to find successful results by varying Control and power values. Figure 3 shows the basic block diagram of the system as the controller is implemented.

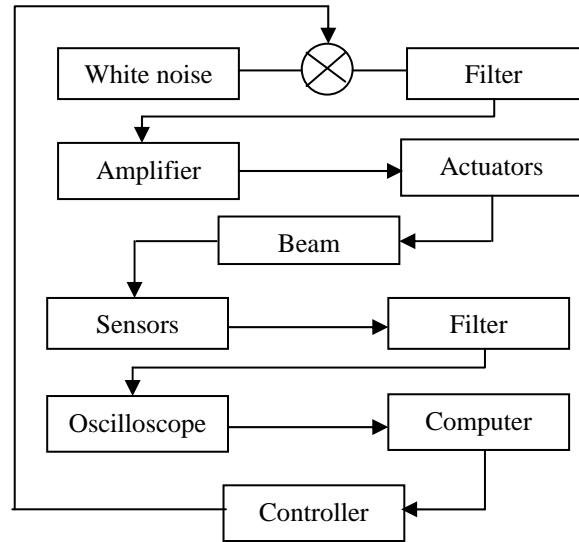


FIG. - 3 SYSTEM SETUP WITH CONTROLLER

The controllers were then implemented on the beam system by using the same system settings as used for system identification. Results were found by running the system first without the controller and then with the controller. Bode plots were used to see the change in frequency response of the first mode of the beam between the uncontrolled and the controlled trials.

IV. THEORY AND CONTROLLER DESIGN

The theory used in the construction and optimization of controllers built in this experiment is rooted in Linear Quadratic Gaussian theory. This theory allows for the design of optimal dynamic regulators through transformation of a state-space model. The theory takes into account the control and state costs in the design of controllers.

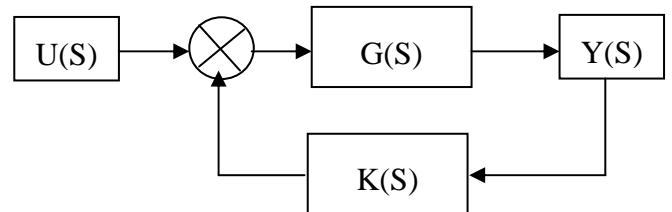


FIG. - 4 SYSTEM BLOCK DIAGRAM

Figure 4 shows a simplified block diagram of the system. In the system, $u(s)$ and $y(s)$ are the actuator/disturbance input

and sensor output, respectively, $G(s)$ is the identified system, and $K(s)$ is the unknown controller system.

A discrete time model of the system dynamics is computed using the identification toolbox in MATLAB. The model is in the form:

$$x^{n+1} = Ax^n + Bu^n \quad (1)$$

$$y^n = Cx^n + Du^n \quad (2)$$

The major conundrum that accompanies this research is the construction of a controller that will optimize state and control cost. The unknown for this system is $K(s)$, the controller system itself, which can be represented as:

$$x_c^{n+1} = A_c x_c^n + B_c y^n \quad (3)$$

$$u^n = -Kx_c^n \quad (4)$$

Now the construction of the controller can begin. After running the experiment, only data for one state of the beam is known. This is due to the fact that there is only one sensor in the system. To determine the rest of these states, some type of estimator must be used.

Design of the linear-quadratic state-feedback regulator is conducted using the function `dlqr` in MATLAB. This regulator calculates the optimal gain matrix K such that the state-feedback law, (from above), minimizes the quadratic cost function:

$$J = \sum_{n=1}^{\infty} (\pi[n]^T Q \pi[n] u[n]^T R_u[n]) \quad (5)$$

Where, R , the variable in the control cost function must be positive, and, Q , the variable in the state cost function, must be non-negative.³ To solve for the feedback gain, $K(s)$, `dlqr` solves the modified Riccati equation given below:

$$A^T S A - S - (A^T S B)(B^T S B + R)^{-1}(B^T S A) + Q = 0 \quad (6)$$

Once the Riccati equation is solved to obtain S , K is derived from the expression:

$$K = (B^T S B + R)^{-1}(B^T S A) \quad (7)$$

For this regulator to operate, the system matrices A and B must be stabilizable.

This theory is only the start to finding what is really needed for the creation of efficient controllers. Further, the procedure to obtain this solution must be known for true understanding of this research and its results.

To design the controller, the data obtained from the sensor, after actuation without the controller, is passed to dSPACE controller. In the present research, a sample time of 0.002 seconds was used. This data is read and saved in a time sample that was thought to be ample. Next the data was loaded into MATLAB and input and output signals were identified as read by dSPACE controller board. A range was then selected such that a part of the signal was considered for identification while a part was left for validation. The model of the data was created using a state-space parametric model of order ten. The model output shows the percent fit

of the newly made model compared to the validation data. The frequency response was another factor in whether or not a model was used in experimentation.

If this model was close enough to the original data, it was forwarded to MATLAB to be the basis for controller construction. From the command window, the data is further observed to make sure that the system is stable and there are no imaginary roots.

Finally, the model is used as the basis for the prospective controller. A program written in MATLAB uses this model to design linear-quadratic state-feedback regulator, Kalman estimator (used to calculate unknown states of the system) for variations of the values for the cost function variable, R . The final constraint a model must surpass to become a controller is the theoretical reduction in vibration amplitude. This is seen from the decline in frequency response on the y-axis of a Bode plot.

V. RESULTS

Using the procedure described above, the controller was implemented on the system. This implementation was a process unto itself. First, signal was sent to the beam without the controller and data was taken and saved in dSPACE controller. Then, with the controller added in the system, the signal was sent to the beam, the actuator implemented the response from the controller due to displacement detected by the sensor, and the data was taken and saved in dSPACE controller.

Both of these data sets were loaded into MATLAB and imported to MATLAB's identification toolbox. The same procedure from above was used to obtain a model closest to the original data set and these were sent to the command window where a Bode plot showed the reduction in vibration amplitude after the controller was implemented.

This procedure was followed and adjusted for about four months until there was finally success. Slowly insignificant results in vibration amplitude turned into a high of about 30% reduction in vibration amplitude.

From the beginnings of this experimental research, it was known that the vibration first mode of the beam was going to be the focus. The results reflect this statement in that the reduction in vibration amplitude in the first mode as compared to the second mode is substantial.

Figure 5 shows the frequency response (For white noise input) of the beam with and without activcontrol. It is seen that there is approximately a 30% reduction from an initial peak of 1.2335 to a controllepeak of 0.8445 for the first mode. In the second mode, the initial peak 0.7773 reduces to a final, controlled peak at 0.757. This is approximately a three percent reduction in frequency response for the second mode.

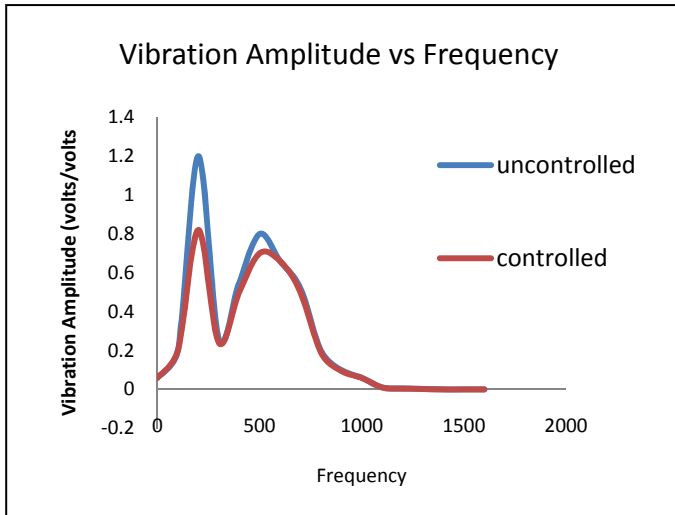


FIG. – 5 RESULTS (VIBRATION AMPLITUDE VS FREQUENCY)

VI. CONCLUSION

A smart beam was constructed using a Lucite beam, PZT actuator, and PVDF sensor. A dSPACE controller card was installed and integrated with related electronics to create an active control setup. Experiments were conducted to control the Vibration response to broadband disturbance. A 30% reduction in 1st-mode vibration response was achieved. Results in this experiment can be further improved. Additional focus onto the first mode is one way to improve results. Further focus on the first mode will allow the creation of better controllers through more accurate models of best fit. This research has touched just the tip of the iceberg in vibration control. As this experiment has come to an end, various opportunities for expansion have been identified. This experiment leads well into many applications of aerospace and structural engineering. Whether used in airplane wings, helicopter propellers, or any type of slender beam where vibration is an obstacle that has to be overcome active vibration control using smart material is everywhere.

VII. REFERENCES

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