CAPACITIVE PROXIMITY SENSOR POSITION FEEDBACK IN ACTIVE VIBRATION CONTROL OF LIGHTLY DAMPED CANTILEVERS

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ABSTRACT

This paper investigates the use of capacitive proximity sensors as sources of contact-free feedback signal measurement for active vibration attenuation applications. An experimental laboratory device is introduced, which consists of a clamped cantilever beam and actuated by bonded piezoelectric actuators. A measurement model is created and experimentally verified for the assessment of beam tip deflections, using a capacitive proximity sensor and a piezoelectric sensor patch. Damping performance is analyzed both in time and frequency domains for different feedback methods, and compared to a precise reference. According to the analysis presented in this paper, real-time feedback from capacitive sensors is potentially useful in active vibration attenuation and control applications.

KEY WORDS

vibration control, feedback model, capacitive sensor, piezoelectric, cantilever beam, linear quadratic

1 Introduction

Active vibration attenuation and noise canceling is slowly departing the realm of laboratories and finds its ways into everyday mechatronic applications. While merely a decade ago active damping systems were mostly to be found in research papers, since then numerous everyday products have emerged. Good examples are promising active and semi-active automotive suspensions, military, medical and aeronautical uses of advanced materials and control algorithms [1], [2].

As it is the case with every control application, all active vibration canceling systems need feedback and some real-time measure of vibration levels. Accelerometers are the most common means of acquiring a feedback signal to controllers [3], [4], [5]; however mounting or bonding the accelerometers can be impractical or impossible in certain situations. Despite of recent advances in accelerometer miniaturization; these devices may still alter the mass and stiffness properties of mechanical systems. Other problems may arise by the bond between accelerometer and measured surface, and the presence of lead wires. Accelerometers provide an excellent measure of acceleration levels which can be integrated to gain velocity or position estimates, but they cannot sense static position changes.

Piezoelectric wafers, piezoresistive strips and other similar devices are commonly used as feedback sources in active vibration attenuation [6], [7], [8], [9]. These devices are cheap to manufacture and can be integrated into the controlled mechanical structure. This is an excellent option for a plethora of applications, however it still requires altering the original structure. Also, the presence of lead wires is not solved and piezoelectric sensors cannot provide a D.C. component of mechanical changes in the controlled structure.

1.1 Motivation

Contact-free measurement of vibration levels is an excellent alternative to the formerly mentioned feedback sources, if the modification of the controlled structure is not desired or permitted. Mass, damping and stiffness properties are naturally not affected by the sensor or its lead wires.

Laser Doppler vibrometry comes to mind at first because of its extreme accuracy. This kind of equipment is however more suited to the laboratory environment since it is bulky and extremely expensive. Industrial optical sensors based on laser triangulation are more suitable to practical use and product integration [10]. However the size of triangulation sensors is still somewhat large, and the price range of such devices is too high for a mass produced commercial item.

An array of frequency selective capacitive vibration sensors has been presented in [11] and suggested for use in vibration measurements. Although the surface - near silicon bulk microtechnology fabrication process permits low cost sensors, these devices still have to come into physical contact with the measured structure. Moreover this device is only sensitive to selected frequency lines in the range of $1-10$ kHz, thus not suitable for lightly damped structures.

Ultrasonic sensors are relatively cheap and small, however not suitable for high speed measurements. The fundamental working principle of ultrasonic sensors prevents their use in high sampling speed real time vibration measurement and control applications. The question arises: What other contact free measurement methods are appropriate for feedback control in vibration measurement?

Cheap, industrial grade capacitive sensors may be suitable for vibration damping applications. While capacitive proximity sensors are commonly used in control engineering practice, their utilization in the field of vibration control is atypical but promising possible benefits. This paper thus attempts to evaluate the possibility to utilize capacitive proximity sensors as feedback signal sources for active vibration attenuation applications.

1.2 Problem statement

A highly flexible clamped aluminum beam is equipped with piezoelectric actuators. A capacitive proximity sensor is placed near the beam to acquire a voltage reading related to the measured distance. The task is to create a state-space mathematical model of the dynamic measurement process. This model is then used for the closed-loop feedback control of the beam deflection, using a state-space control algorithm. The control goal is to minimize deflection measured and estimated at the beam tip.

Along with the practical issues regarding placement, positioning, useful range and bandwidth; this paper investigates damping performance of a given linear quadratic (LQ) controller under feedback signals coming from various sources: exact deflection reading at the beam tip using an industrial triangulation sensor, modeled deflection based on a piezoelectric strip and finally modeled deflection based on the capacitive proximity sensor. The damped, controlled beam tip vibrations are compared for the three aforementioned methods in the time and frequency domain.

1.3 Organization of this paper

This introduction is followed by the description of the experimental hardware assumed throughout the rest of this paper. The following section briefly deals with the experimental identification process of the system dynamics, along with the feedback measurement models for the capacitive and piezoelectric sensors. Section 4 summarizes the experimental validation of the feedback models, while finally section 5 analyses the effect of using position estimates instead of direct measurements on the damping performance of the controller both in time and the frequency domain. The paper is finished by a short conclusion and elaboration on possible future works.

2 Experimental hardware setup

Real time feedback measurements using a capacitive proximity sensor have been carried out on a laboratory test bench shown on Figure 1., featuring a lightly damped simple active structure. This mechatronic structure may represent a potential class of real life engineering problems, like active damping of helicopter rotor beams in flight; or stabilization of large manipulators, solar panels and antenna arrays in space. The structure is equipped with four piezoelectric strips; of which two are used as actuators, one is utilized as a feedback sensor and one is short-circuited since is not utilized in this work. Validation measurements are performed using an optical device, the controller is running in a rapid software prototyping environment.

Figure 1. Laboratory test bench.

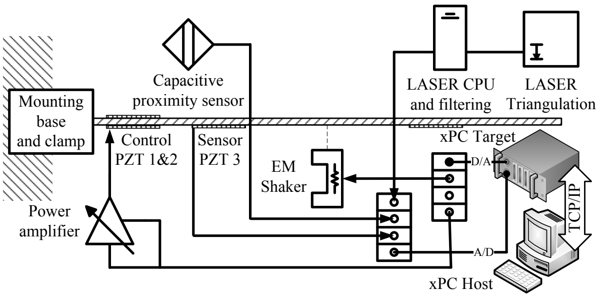


Figure 2. Simplified hardware scheme.

2.1 Hardware description

The structure in question is a beam made of commercially pure aluminum, material type EN AW 1050A and it has the dimensions of 550×40×3 mm. The cantilever beam is placed in an adjustable clamp, its length is fixed for this experiment. The beam and clamping apparatus is also fixed to a heavy base, in order to minimize mechanical interaction with the surroundings. Due to its physical dimensions and material, the beam excited in the first resonant mode is capable of relatively high deflections exceeding 10 mm, measured at the tip. If constrained model based predictive control (MPC) is considered, a wide deflection range has to be ensured which is a source of significant difficulties in MPC with guaranteed stability and constraint feasibility [12].

Two piezoelectric actuators are placed close to the clamped end, and are connected counter-phase to a high voltage electric source. All piezoelectric patches are identical, have the dimensions of 45.9×20.7×0.25mm; and are of type QuickPack QP16n manufactured by MIDÉ. The piezoelectric actuators receive an amplified high voltage control signal, with the manufacturer given 120V peak maximum voltage. A MIDÉ EL-1225 is utilized as an operational power amplifier.

Deflections at the beam tip are measured by a

Keyence LK-G82 industrial laser triangulation device; capable of providing an accuracy of $\pm 0.05\%$ with the resolution of 0.2μm in the range of 80 ± 15mm. Filtered and processed analogue outputs are provided by a Keyence LK-G3001V central processing unit to the measurement card. Measurements from this system are considered as reference and conventionally true in this work.

The controller is running real-time on the xPC Target rapid software prototyping environment. A dedicated computer implements controller software, also containing the measurement card. Development takes place on a different computer using the Matlab/Simulink suite, the controller is then loaded to the xPC Target computer using the TCP/IP protocol.

Mathematical model of the controlled structure and the measurement model are treated as separate entities in this work. Although it would be possible to create a single state-space model between actuator inputs and sensor voltage outputs, this could be impractical in numerous situations. For example if constrained model based predictive control is considered with tip deflection limits, a separate structural model is necessary to explicitly include output boundaries in the optimization process. Amongst other, the analysis presented in this work also benefits this kind of logical arrangement.

Figure 3. illustrates the simplified block scheme of the controller[1], implemented on the xPC Target machine. Analogue output from the triangulation device, voltage output from the capacitive and piezoelectric sensors is acquired through the analogue-digital input. Measured or model estimated beam tip deflection data is passed onto a Kalman filter block[2], which generates state estimates for the controller. The Kalman filter receives direct measurements in the case of laser feedback, and model based estimates in the case of capacitive and piezoelectric sensor feedback. State estimates are multiplied by the LQ row vector, and the resulting inputs are saturated. The inputs are compensated for the power amplifier and passed onto the digital-analogue output block.

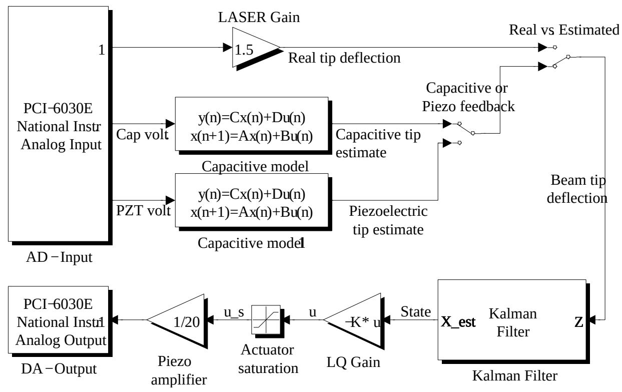


Figure 3. Simplified block scheme of the controller algorithm.

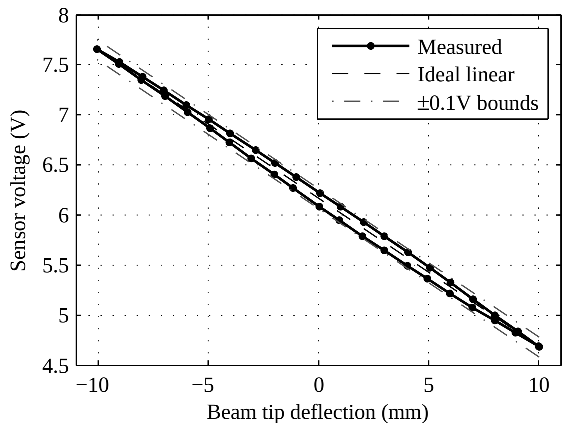


Figure 4. Static characteristics of the capacitive feedback setup, related to beam tip deflection. Dashed line denotes the ideal linear relation, while the solid line indicates actual measurements.

2.2 Capacitive proximity sensor

The industrial capacitive proximity sensor utilized in this work is a 18 mm diameter Pepperl+Fuchs 924 Series type device. Its sensing range is listed as 2-5mm and its linear voltage output is supplied from 1 to 9 Volts with a $\pm$0.25V linearity deviation. According to manufacturer specifications, its sensitivity is 2.66 V/mm and the response time 1 V/msec.

If a capacitive proximity sensor is considered as feedback source in active vibration damping applications, the main limiting factor is its response time. At full 8 V output range this device provides a 125 Hz bandwidth which is the worst case scenario. As the sensing range decreases, the bandwidth also widens. If the maximum sensing range is set to the first vibration mode at the point of measurement, higher modes may be also measured since they are less dominant thus the sensor bandwidth increases. Based on the bandwidth, capacitive sensors are suitable feedback sources for active vibration attenuation and control of lightly damped structures.

For the experimental setup in question, the expected beam tip deflections are $\pm$ 15 mm away from the equilibrium position, giving an overall 30mm deformation range. Naturally the range of the capacitive proximity sensor is much smaller, therefore it has to be placed closer to the clamped end. A sensor range of $\pm$ 1.5 mm and proportional relation to beam length and deflection gives an ideal position of 55 mm measured from the fixed end. The effective sensing range is also decreased because the beam is made of aluminum instead of steel. Taking these facts into account the sensor has been mounted 80 mm from the clamped end, its zero equilibrium position fixed at 6 V. An expected full range bandwidth of 125 Hz is well sufficient for this application, since the first three measurable vibration modes are under this limit.

The capacitive sensor is powered by 19V direct current through a stabilized laboratory supply, well within

[1] Excluding means for data logging, monitoring and electrodynamic shaker controls.

[2] A Simulink - Signal Processing Blockset product default adaptive Kalman filter block: requiring the state transition and measurement matrix, process and measurement noise covariances etc. This block does not explicitly compute the Kalman filter matrix.

the nominal range.

To assess linearity and hysteresis of the capacitive sensor in relation to deflections measured at the beam tip, the end of the cantilever has been deflected -10 mm away from equilibrium, slowly repositioned to 10 mm and finally back to its original position. Laser triangulation has been used to measure deflections, while sensor voltage output has been recorded.

Figure 5. presents static characteristics of the capacitive sensor in relation to cantilever beam tip deflections. The ideal linear relationship is denoted with a dashed thin line, while the 0.1V sensor linearity deviation bounds are also indicated for reference.

In addition to device specific built-in irregularities, linearity deviation may also be attributed to material changes. The rated sensing distance is based on a standard target, presumably steel [13]. Effective sensing distance therefore must be reduced. Moreover, the beam surface at the point of measurement is only parallel to the sensor area if the beam is resting in its equilibrium position. With increasing deflections measured at the tip, the beam and sensing surface angle elevates as well.

While there is a slight deviation from the ideal linear response, this irregularity does not prevent its efficient use as feedback source in vibration control applications. Experimentally identified mathematical feedback models could include effects caused by linearity deviations, or it is possible to correct them if necessary.

2.3 Piezoelectric patch in sensor mode

A piezoelectric patch identical to the actuators is used in sensor mode. The edge of the piezoelectric sensor is located 80 mm away from the beam clamp, coinciding with the point where the capacitive proximity sensor is mounted. The axis of symmetry of the piezoelectric patch along its length coincides with that of the beam.

Piezoelectric sensor voltage output levels exceed signal acquisition card specifications, therefore have to be attenuated. In order to do this a 100 kΩ resistor is connected in parallel with the piezoelectric sensor strip. This way voltage output is matched to the expected tip deformation range of the cantilever beam.

3 Measurement and system model

The controller and measurement models are described by linear time-invariant (LTI) second order state-space systems according to:

$$x_{k+1} = Ax_k + Bu_k \qquad y_k = Cx_k \tag{1}$$

where x is a 2×1 state vector, u is a 1×1 input, y is a 1×1 output. Matrices A,B and C are the state transition matrix, input and output matrix, and integer k denotes sampling instances.

The experimentally identified mathematical model of the structure represents the input-output relationship between voltage input to the piezoelectric actuators and beam tip deflections in millimeters. The resulting state-space model can be used both in simulations, calculating an LQ optimal controller gain or for example in the model based predictive control of tip vibrations [6], [14], [15] .

The identification procedure involved supplying an amplified chirp signal to the piezoelectric actuators, and measuring the resulting beam tip movements. The chirp signal time span has been set to 200 seconds, while it covered the $0.1 - 20$ Hz frequency range. Time domain data has been converted into frequency domain using Fast Fourier Transform (FFT), then filtered and detrended. System model sampling time has been set to $T = 0.01$ s, as this sufficiently exceeds the 8.1 Hz first resonant frequency of the beam.

A subspace iteration method described in [16] has been utilized to create the final system model, in (2). This type of approach proved to be effective previously and has been utilized for the MPC of this laboratory device, assuming direct beam tip measurements in the feedback loop. This second order cantilever model sufficiently covers the first eigenfrequency, hence the overly dominant vibration mode, while it might provide damping effect even when excited in the higher frequency modes.

$$A = \begin{bmatrix} 0.867 & 1.119 \\ -0.214 & 0.870 \end{bmatrix} \quad B = \begin{bmatrix} 9.336E^{-4} \\ 5.309E^{-4} \end{bmatrix} \tag{2}$$

$$C = [-0.553 \quad -0.705]$$

3.1 Capacitive sensor feedback model

The sensor feedback models featured in this paper are also second order linear time-invariant systems, explicitly including only the first mode of vibration. Sampling time for both the capacitive and piezoelectric sensor feedback model are $T = 0.01$s.

The capacitive sensor model takes the proximity sensor voltage as input, and outputs the estimated beam tip position in millimeters for the controller. The sensor feedback model has been identified experimentally, using a time domain data set. The beam has been subjected to manual excitation, while the voltages coming from the capacitive sensor were acquired along with the laser measured beam tip positions.

This data set was then filtered, detrended and a suitable portion used for identification. The state-space model of the capacitive feedback measurement process has been identified using an iterative prediction-error minimization method introduced in [16].

Akaike Final Prediction Error (FPE) criterion for this model has been calculated to be 0.0432 (-). After numerous trials the model in (3) has been selected as best for the purposes of this paper. The model validation process proved to yield a satisfactory match, while the transient and frequency response of the model was also adequate.

$$A = \begin{bmatrix} 1.229 & -0.216 \\ 2.048 & 0.190 \end{bmatrix} \quad B = \begin{bmatrix} -2.086E^{-2} \\ -7.674E^{-2} \end{bmatrix} \tag{3}$$

$$C = [97.28 \quad -1.159]$$

3.2 Piezoelectric sensor feedback model

The measurement model based on the output voltage of the piezoelectric strip is a single input, single output state-space model as well and has been created according to [17]. It takes voltages as its input and outputs the beam tip deflection position estimates for the controller. This feedback model has also been identified using a time domain data set, while subjected to pseudo-random manual excitation. Beam tip deflections have been recorded along with sensor voltage output.

The data set was then filtered, detrended, mean values removed and divided into parts for system identification and model validation. The mathematical model of the feedback based on piezoelectric wafer signals has been identified using a subspace iteration method [16].

FPE criterion for this model has been calculated to be 0.0091 (-). Comparing the measured and estimated model output for different portions of the data set, and by judging the quality of the transient response, frequency response and model residuals; the model in (4) has been chosen for further use in this work.

$$A = \begin{bmatrix} 0.987 & 0.144 \\ -0.274 & 0.009 \end{bmatrix} \quad B = \begin{bmatrix} 3.959E^{-2} \\ 1.851E^{-1} \end{bmatrix} \tag{4}$$

$$C = [34.72 \quad -1.3595]$$

4 Experimental feedback model validation

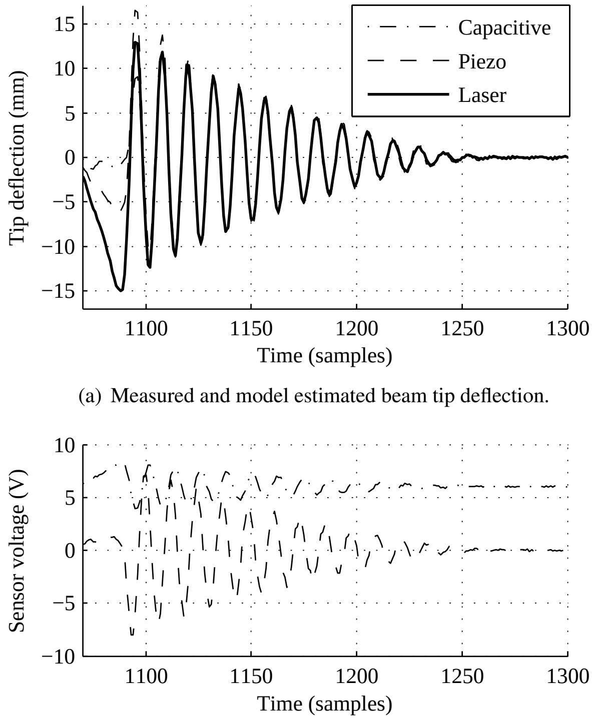
The feedback model has been validated experimentally both in time and frequency domain. Experiments introduced in this paper assume the system model described by (2), capacitive proximity sensor feedback measurement model according to (3) and piezoelectric sensor feedback measurement model (4). Although model estimate sampling remained at periods of $T = 0.01$s, output measurements have been adjusted in the case of the frequency domain measurement to a rate of $T = 0.0002$s in order to capture higher frequency effects.

4.1 Time domain position estimates

The measured and estimated beam tip deflections were compared in a test involving an initial deflection 10 mm away from equilibrium. The beam has been displaced and released to vibrate under saturated LQ control[3] without further outside force interaction. The results of this test are indicated on Figure 5.

As it is evident from Fig. 5(a), both model estimates have a difficulty to correctly asses slow displacement changes. In addition to that the piezoelectric patch is only usable in dynamic mode, slow frequency changes cannot be readily detected. However as the beam is released just before the 1100 sample time mark, the estimates become more accurate - in fact indistinguishable

[3]LQ controller identical to the description presented in Section 5.



(a) Measured and model estimated beam tip deflection.

(b) Capacitive and piezoelectric sensor voltages.

Figure 5. Comparison of measured and estimated beam tip deflection is shown on (a), while output voltages for the piezoelectric patch and capacitive proximity sensor for the same experiment are featured on (b).

form the laser triangulation measurement taken as reference. Fig. 5(a) shows the unprocessed voltage output from the capacitive and piezoelectric sensors[4].

4.2 Frequency domain position estimates

Tip displacement estimates have been compared with the true laser based reference under a wide-band mechanical excitation. For this purpose, a Bruel&Kjær Type 4810 electrodynamic shaker has been connected to the beam surface. The shaker is located approximately 170 mm from the clamped beam base and the mechanical connection was present only in frequency domain tests. The shaker received a chirp excitation signal through a Bruel&Kjær Type 2718 amplifier in the frequency range of 0-500Hz, time span of 200 seconds.

Figure 6. indicates the single-sided amplitude spectra of laser measured and piezoelectric sensor and capacitive proximity sensor based tip displacement estimates. Laser reference indicated with the solid black line on the figure shows the measured response the numbered resonant nodes[5]. As it is expected from a second-order tip deflection estimate model, deformations are assessed correctly only in the vicinity of the first resonant mode.

Frequencies above approximately 15Hz are not cov-

[4]Laser reference output is directly proportional to the measured value, in this case there is a 1.5 mm/V gain.

[5]Modes (3) and (5) are twisting modes and cannot be measured nor controlled with the current sensor/actuator configuration.

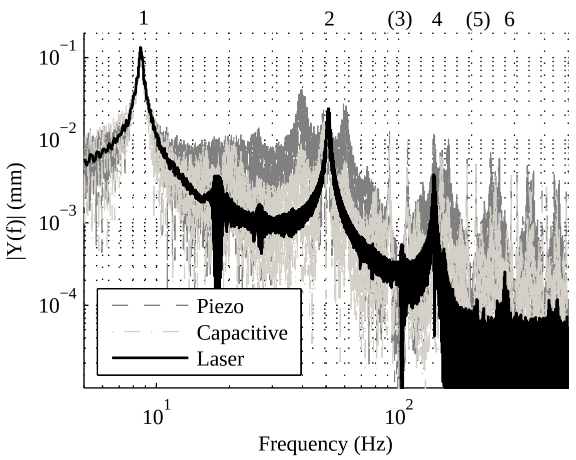


Figure 6. Single-sided amplitude spectrum of measured and estimated beam tip deflections. Numbers denote laser measured amplitude peaks due to corresponding structural vibration modes.

ered by the tip position estimate models, as their order and sampling period does not allow this. The repeating and re-occurring peaks in the capacitive and piezoelectric feedback data are merely artifacts of the FFT process on a data set lacking high frequency components, often referred to asa spectral leakage.

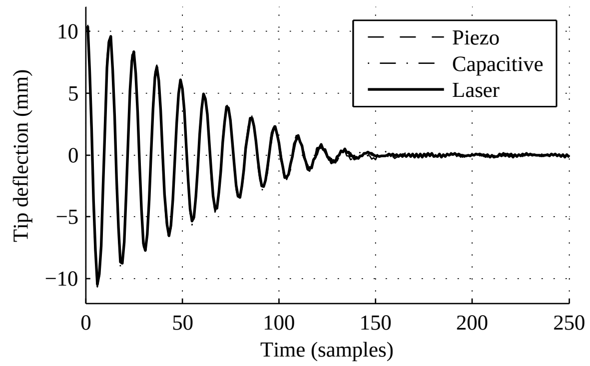
Higher order position estimate models could explicitly include higher resonant modes, but would also require faster sampling which is a serious issue in model based optimal control [12]. Additionally, simpler models can perform very well even at higher frequencies as it is demonstrated in 5.2.

The capacitive sensor has bandwidth limitations, although it is hard to asses this from the given experiment as the vibration ranges decrease with increasing frequency. Furthermore slow or near D.C. vibrations cannot be detected through the piezoelectric sensor feedback, due the physical nature of the hardware.

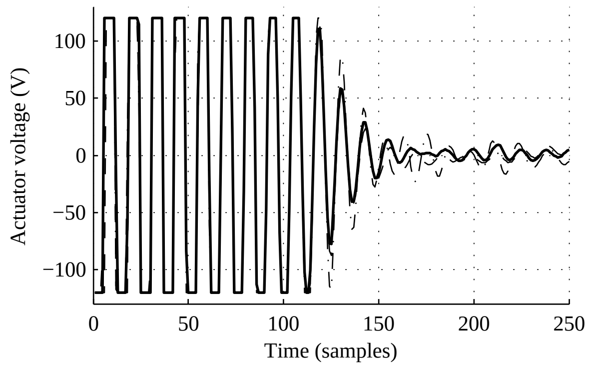
5 Effect on damping performance

This section introduces experiments performed in order to determine the effect of different feedback schemes on damping performance. System and sensor models used throughout the tests are according to (2), (3) and (4). Control sampling is $T = 0.01$s

The control scheme used throughout the experiments was a simple saturated linear quadratic controller. Saturation levels were set to ± 120V according to manufacturer specified safety limits, preventing the depolarization of piezoelectric material. The LQ controller has been calculated using a state penalty matrix $Q = C^T C$ and an input penalty $R = 10^{-4}$. Previous experiments and simulations indicate that this seemingly small input penalty is ideal for the given physical system [10], [15]. The state controller gain K is then according to relation (5).



(a) Laser measured beam tip deflections



(b) Controller voltage signal to actuators

Figure 7. Comparison of direct position feedback based control with piezoelectric and capacitive sensor estimates in an initial deflection test is shown on (a), while corresponding controller voltage outputs are presented on (b).

$$K = [12.97 \qquad -125.50] \tag{5}$$

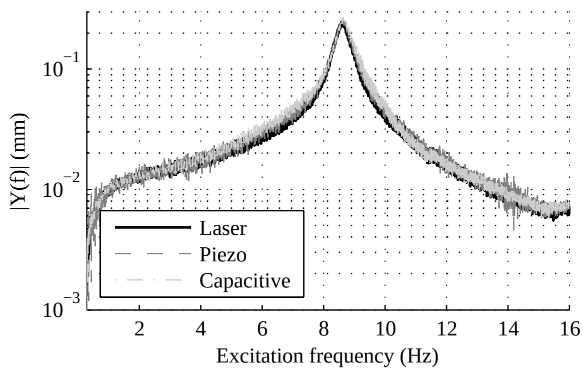
Free response without control is not indicated in these validation experiments in order to keep diagrams readable. However we have to note that saturated LQ control with direct feedback provides a very effective damping performance, comparable to constrained MPC control where settling times are reduced by an order of magnitude [10], [12], [15].

5.1 Initial deflection test

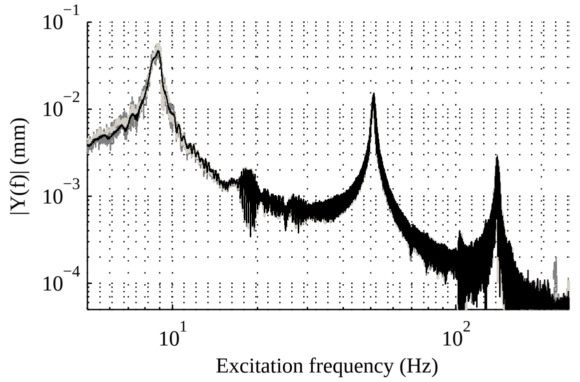
The beam tip has been set to an initial position of 10 mm away from equilibrium, then controlled responses have been recorded without further structural interaction. Beam tip deflections in all scenarios have been measured using the laser triangulation.

Figure 7.(a). shows the evolution of beam tip vibrations to this type of excitation while control voltage supplied to the actuators is indicated on 7.(b). Both position feedback estimating methods are considered here, with direct laser measurement acting as reference.

As it is clear from the results, there is no substantial difference in the damping performance, when estimates are used as feedback. Measured beam tip deflections un-



(a) Laser measured amplitude spectra



(b) Response to wide band excitation

Figure 8. Laser measured single-sided amplitude spectra of beam tip deflections in the region of the first vibration mode are indicated on (a), while (b) shows damping behavior in the first three dominant structural modes.

der LQ control with piezoelectric sensor feedback or capacitive proximity sensor feedback are practically identical to directly measured laser feedback.

The evolution of controller voltages on Figure 7.(b) demonstrates no considerable deviation from the reference; response is virtually identical up to time sample 120. Slight deviations after this mark are attributed to the fact that these are three separate measurements with the beam subjected to outside sources of error at each time. These errors are compensated by the controller, therefore only to be noted in the voltage output but not on the beam deflections.

5.2 Damping performance in the frequency domain

All three different control schemes have been evaluated in a frequency domain experiment. The beam has been excited using the electromagnetic exciter introduced in 4.2, utilizing and identical setup.

Figure 8. indicates the directly measured single-sided amplitude spectra of beam tip vibrations, showing all considered feedback control schemes. As it is expected, Figure 8.(a) demonstrates that the estimated position based feedback schemes provide a nearly indistinguishable damping performance to direct feedback in the region of the first structural vibration frequency.

It has been demonstrated in 4.2 that capacitive proximity sensor and piezoelectric sensor based second order feedback models are limited to give a correct deflection estimate only in the vicinity of the first resonant frequency. Despite of this fact, all three control schemes provide a good damping performance even when excited by higher frequency mechanical disturbances. The measurement illustrated by Figure 8.(b) utilized second order system and measurement estimate models; however it has been excited to frequencies exceeding 300Hz. As the results clearly indicate, using low order tip deflection estimate models, the damping performance is practically indistinguishable from that using direct tip position measurements.

6 Conclusion

Modeling, experimental validation and control performance evaluation of a capacitive proximity sensor based feedback applied to a lightly damped active structure has been presented in this paper. Comparison to directly measured feedback and piezoelectric sensor patch based control systems has been also introduced.

A good match has been observed between model output estimates and measurements in the feedback verification experiments. Free and LQ controlled vibrations of the beam tip are governed predominantly by the first vibration mode, therefore the considered second order models provide a satisfactory tip position estimate. However limitations of low order measurement models were evident from the frequency domain test.

Capacitive and piezoelectric sensor based feedback has been utilized in experiments investigating the overall damping effect change due to different control schemes. Initial deflection tests demonstrated, that under equivalent controllers both capacitive and piezoelectric sensor based feedback control provide identical performance to that having access to direct measurements. Moreover, the damping performance of both estimate based controllers is on par with direct laser feedback in the frequency domain even if higher order structural vibration modes are being excited.

It may be concluded, that according to the analysis presented in this paper industrial grade capacitive proximity sensors are suitable as position feedback sources for structural vibration control of lightly damped mechanical structures. These devices present an edge over laser triangulation and laser Doppler vibrometry equipment based feedback because of their price, availability and compactness. Since precision is not necessarily an issue in practical applications, capacitive sensors provide an adequate signal to the controller. Furthermore, capacitive proximity sensor feedback possesses the advantage of providing contact-free deformation estimates, in cases where structural integration of piezoelectric strips is not possible.

6.1 Future works

Future works shall investigate qualitative increase of beam deflection position precision estimates using higher order models, and whether the inclusion of higher resonant modes in the feedback model has any practical advantages in the model based optimal control of lightly damped structures.

Increased sensing range possible with other types of capacitive proximity sensors could be beneficial for this application, but the extent of improvements needs further analysis. Also the exact useful bandwidth of capacitive sensors in vibration attenuation remains questionable and shall be the subject of future inquiry.

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