Active Control of Structures Subject to Large Temperature Variations Using Piezoceramic Actuators*

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The effect that temperature dependant piezoceramic properties have on the active vibration control of a light flexible structure can be of considerable importance in real-life systems. Piezoelectric properties can vary significantly with moderate changes in temperature, hence affecting their control authority. By varying the operating temperature of a flexible structure (cantilever beam) fitted with piezoceramic actuators, this investigation explores the influence of temperature on the damping and natural frequency of the system using velocity feedback control. Experimental results show the dynamic properties of the system are not only dependent on the piezoceramics variation with temperature, but additionally on the type of adhesive used to bond the ceramics to the structure. This can cause significant nonlinear behaviour in system damping. These results indicate that for systems operating over a large temperature range, unless adequate pre-thought is employed, unanticipated damping and control characteristics may arise.

Key Words: Nonlinear Control, Piezoelectric Actuator, Active Control, Flexible Structure, Thermal Effects, Damping

1. Introduction

Controlling vibration via the use of piezoelectric devices has received considerable attention for a number of years. Research into many aspects of active control has resulted in numerous control strategies in addition to placement and sizing criterion for optimal control of beams, plates, tubes and even aircraft wings using piezoelectric devices. Early studies^{(1),(2)} (along with many others) help provide suitable design methodologies for the sizing and placement of actuators and sensors based on various optimal control techniques. These studies assumed that material properties do not change with time and the analysis was performed on simple uniform beams.

More Recent Studies^{(3),(4)} have adapted and designed their own procedures for placement of piezoceramics to the more complicated 'real-life' structure of an aircraft wing to actively control its aer-

oelastic properties. Many other applications have been analysed with various authors developing control systems for both discrete and distributed control of spacecraft structures, active beams, slewing beams and antenna⁽⁵⁾.

Although the above studies provided valuable insight into the mechanisms of actuator placement and sizing for control, they appear to have neglected the effect that temperature changes can have on structural and actuator/sensor material properties which in itself may affect control. Typical ambient temperature variations for aircraft can be from -49 to 40°C , with satellites in a space environment experiencing temperature variations from -73 to 77°C ⁽⁶⁾. At these temperature extremes, material and piezoelectric properties can vary significantly.

Spirnak and Vinson⁽⁷⁾ evaluated the effect of temperature on the free vibration of composite beams showing that the structural damping can vary by as much as 59% over a 150°C temperature range. Piezoelectric properties are also shown to vary considerably with temperature. Lee and Saravanos⁽⁸⁾ display a number of charts showing the nonlinear dependency of piezoceramic and composite properties with

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temperature to assist their nonlinear analysis of plate response. Variations of up to 50% over a 150°C temperature range were evident.

Recognising that temperature can influence both static and dynamic control of flexible structures, a number of authors have examined and developed numerical models for nonlinear piezoelectric devices. Tzou and Ye⁽⁹⁾ used finite element methods to develop nonlinear models to investigate the influence of piezothermoelasticity in sensing and control of a cantilever beam. They demonstrated that by considering the strain and pyroelectric effects of the actuator/sensor, a static deflection in the beam resulted which would need to be taken into account in static control. Bao et al.⁽¹⁰⁾ also performed a numerical study on nonlinear piezothermoelastic beams. They investigated the change in stiffness properties with temperature and the resulting change in natural frequency and control voltages needed to compensate for these changes. Tzou and Zhou^{(11),(12)} extended the theory by performing a numerical analysis on circular plates and concluded that with appropriate control voltages, the nonlinear oscillations can be controlled to manageable linear oscillations. They also summarised from their numerical studies that nonlinear deflection and natural frequencies are all influenced by temperature and the controlling voltages. They also acknowledged that these previous studies have not included temperature dependent material properties and hysteresis as this would complicate the analysis considerably.

Song and Li⁽¹³⁾ studied the nonlinear properties of piezoceramics and showed that the hysteresis properties can vary considerably with frequency. They proposed a neural network controller to learn the characteristics of the individual elements using experimental results as these may vary from manufacturer to manufacturer. This neural network can then be incorporated into the main control strategy.

A more recent paper⁽¹⁴⁾ applied thermal effects to the control of a simply supported beam and investigated the performance of different control laws. This numerical study again ignored many temperature dependent system properties, although they demonstrated that the pyroelectric effect of the piezoceramic is significant and the control system should accommodate this to effectively control thermally induced vibrations.

The large number of numerical studies have all concluded that temperature effects are important and need to be considered for effective control. Although, for various reasons, they have all neglected some aspects of the system which may vary with temperature. This study sets out to present the results of an experimental investigation into the combined effect of

Fig. 1 Outline of experimental setup

nonlinear piezoceramic and material properties on the active control of a simple flexible cantilever beam. This is performed by controlling the vibration of a sample of piezoelectrically actuated beams using simple velocity control techniques. The results show that not only do the piezoceramic and the beam material properties affect the dynamic performance of the system, but also the type of adhesive used to bond the ceramics to the beam.

2. Experimental Setup

The flexible structure under investigation is a thin aluminium cantilever with piezoceramic actuators adhered to the clamped end of the beam. The beam and test bed are contained within an environmental chamber to maintain a desired operating temperature as shown in Fig. 1.

The temperature inside the chamber could be maintained to within ± 1 degree Celsius of the desired value during a test run. The construction of the environmental chamber resulted in an operational temperature range of -35 to 90°C , although temperatures below room temperature are more difficult to obtain as external cooling is required.

A non-contact proximity probe (inductance type) is used to monitor the beams transverse displacement towards the clamped end of the beam. A computer containing a custom data acquisition and control algorithm monitors the displacement and determines the appropriate control signal.

The control signal is passed via a voltage amplifier to the piezoceramic actuators to suppress vibration. The Amplifier is capable of a maximum driving voltage of $\pm 100\text{ V}$.

The test bed is capable of constraining a large array of shapes and sizes of cantilevers and allowed adjustment of the probe position along the beam. The

Table 1 Test article parameters

	Beam (1)	Beam (2)	Beam (3)	Al Beam
Length (mm)	303	303	304	303
Width (mm)	26.6	27.1	27.8	25.1
Thickness (mm)	1.0	1.0	1.2	1.0
# Piezoceramics	2	1	2	N/A
Adhesive	Epoxy	Epoxy	Super-glue	N/A

beams were remotely given an initial displacement and released to initiate vibration. This ensured that the individual tests were not compromised by opening the chamber to reset the experiment.

The beam temperature was monitored by a platinum Resistance Temperature Device (RTD) located on the beam-clamp interface.

3. Test Articles

Three test articles using different bonding agents to adhere the actuators to the beam were examined. Additionally, a representative aluminium beam with no actuators was investigated. Each beam had a small piece of steel shim adhered to their free end to allow the hold and release mechanism to provide the initial tip displacement. The main specimen parameters are listed in Table 1.

Beams (1) and (3) both had two piezoceramic elements attached (on the upper and lower surfaces) towards the clamped end. However, only one actuator was used during these experimental tests for control. The other was installed for future use as a feedback sensor, which will form part of upcoming research activities.

Beam (1) also has a small RTD temperature sensor adhered to it for measuring beam temperature away from the clamped end.

Beams (1) and (2) had the actuators bonded to the beam with a two part epoxy adhesive, whereas on Beam (3) the actuators were attached using a fast drying 'Super-Glue' type adhesive.

These specimens were prepared for previous research activities and therefore the curing temperature and time of the adhesives used to bond the ceramics to the beam are unknown. Additionally, Beam (3) is slightly thicker than the other beams. It is believed that this only resulted in an increase in natural frequency of this beam compared to the other beams as it is only the elasticity of aluminium that is affected by temperature.

Beam (1) was studied in-depth due to its peculiar nonlinearities, and as such was taken below room temperature to -20°C to determine its behaviour at low temperatures. As little change in properties appears to occur at lower temperatures, Beams (2)

Fig. 2 Percentage deviation in resonant frequency and capacitance with temperature of piezoceramics using the IEEE Resonance Method

and (3) were only investigated at temperatures at or above that in the laboratory (laboratory temperature was typically 26°C and this was used as the reference temperature in the following analysis).

The piezoceramic specimens used were piezoelectric acoustic generator elements. These elements are approximately 20 mm in diameter with a brass backing plate. They are of low power and have relatively low control authority compared to more recent advanced piezoceramics. They do however demonstrate a nonlinear behaviour of these devices.

4. Results

The Resonance method described by ANSI/IEEE Std 176-1987 Standard on Piezoelectricity was used to characterise the piezoceramic element properties. The resonant frequency and capacitance were measured at various temperatures and the piezoelectric constant and elasticity calculated. Figure 2 shows the percentage deviation in resonant frequency and capacitance of the test piezoceramics with temperature. The results obtained from the characterisation closely match the manufactures specifications of these acoustic devices. The manufacturer determined a change of 10% and 31% in resonant frequency and capacitance respectively over the temperature range of -20 to 60°C (These results obtained from the AVX Kyocera Piezoelectric Acoustic Generators data catalogue). The results show a change of 12% and 34% change in resonant frequency and capacitance respectively and show how properties vary significantly with temperature.

Open and closed loop vibration tests were performed on the beam specimens. The beams were placed in the environmental chamber and the temperature adjusted to the desired value. Initial tip displacement was obtained from the hold-release mechanism, then

Fig. 3 Percentage deviation in first natural frequency with temperature (Reference=26°C)

released and the time history recorded.

Initial tip displacements during the tests were relatively large compared to other studies, being in the order of 1 - 2% of the beam length from the static position.

Velocity (rate) feedback supplied by the proximity probe located along the beam was used for control of beam vibration. The probe was used as a sensor instead of a piezoceramic in order to eliminate any influence that temperature may have on the sensing properties of the piezoceramics.

The feedback gain was set at its maximum value within the voltage limitations of the amplifiers at room temperature, and before spillover instabilities occurred for the individual beams. This gain was then held constant for the remaining tests.

The open loop test results of all beams were examined to determine the variation of the natural frequency with temperature. Figure 3 shows the percentage deviation of the first natural frequency of the beams with temperature relative to laboratory temperature (26°C).

The general trend is that the systems natural frequency decreases as the temperature increases due to changes in material stiffnesses. Similar trends were observed with the second and third natural frequencies.

The change in the natural frequency results from a combination of factors. The aluminium beams natural frequency drops relatively linearly with increasing temperature. This can be explained from the change in elasticity of aluminium which varies roughly linearly with temperature for the temperature range considered here. Beams (1) and (2) show a marked decrease in natural frequency at 35 and 50°C respectively. This appears most likely due to the adhesive passing through its glass transition temperature, hence reducing the total stiffness of the system.

Fig. 4 Percentage deviation in open loop damping ratio with temperature (Reference=26°C)

Beam (3) shows a relatively linear decrease in natural frequency with temperature indicating that the elasticity properties of the entire system vary roughly linearly including the adhesive, in comparison to Beams (1) and (2).

The natural frequency did not noticeably change between the open and closed loop tests for all the beams.

The damping ratio was calculated from the time histories using logarithmic decrement. Figure 4 shows the percentage deviation of calculated open loop damping ratio of each individual beam with temperature. The reference for the percentage is the individual beams room temperature damping ratio. The damping of the aluminium reference beam is shown for comparison.

A number of interesting results were observed. Firstly, Beams (1) and (2) showed a sharp increase in open loop damping ratio around 42°C and 68°C respectively. After an investigation into the cause of these peaks in damping ratio, it appears most likely that it is due to the epoxy adhesive passing through its glass transition temperature. The transition temperature is usually around 60 - 70°C for these types of adhesives under controlled curing temperatures and times. This corresponds well to the results of Beam (2), although this temperature may vary under other circumstances. The curing temperature and times for Beams (1) and (2), as well as the brands of the adhesive, are unknown. Therefore, it can only be assumed that the increase in open loop damping ratio is a result of the glass transition temperature of the epoxy. Beam (3) using a 'super-glue' type adhesive does not exhibit this marked increase in damping ratio. A general decrease in damping ratio with temperature is evident with much less variation over the temperature range compared to Beams (1) and (2).

Figures 5(a) and 5(b) show the settling time to

Fig. 5(a) Open loop settling time to 10% of peak amplitude with temperature

Fig. 5(b) Closed loop settling time to 10% of peak amplitude with temperature

10% of peak amplitude for the three beams against temperature in open and closed loop situations respectively. The trend reflects the damping ratio variation shown in Fig. 4.

Although the magnitude of the decrease in settling time is relatively small around the glass transition temperatures of Beams (1) and (2), the results indicate that away from this temperature the relative proportion of time reduced between open and closed loop is roughly constant. Beam (3) shows a slight decrease in the change in settling time between the open and closed loop tests as temperature increases. However, the figures show that the total time for controlling vibrations to 10% of peak amplitude varies significantly. The reduction of time between the open and closed loop tests is in the order of 0.4 to 20 seconds to 10% of peak amplitude across all the beams.

5. Simulation Model

A reduced-order lumped parameter model of the distributed system was developed. The beam was discretised into a number of different elements and a set of system equations obtained using the finite ele-

Fig. 6(a) Experimental response of Beam (1) at 26°C

Fig. 6(b) Simulation response of Beam (1) at 26°C

ment method as described by Thomson⁽¹⁵⁾. These equations were used to create a simulation model using the Matlab® and Simulink® software packages.

The mass and stiffness properties of the beam and piezoceramic elements were incorporated into the model. Damping was assumed to be directly proportional to the stiffness matrix.

$$[C] = \beta[K] \quad (1)$$

with atmospheric damping ignored in this model. Control was implemented via velocity feedback of a point midway along the beam as was performed in the test.

Measured and published temperature dependant stiffness and piezoelectric properties were incorporated into the model via look-up tables. The damping proportionality factor (β) was adjusted until the open loop settling time to 10% of peak amplitude matched that of the test data for various system temperatures. The velocity feedback gain was then set to give the same room temperature closed loop response. This

Fig. 7(a) Experimental response of Beam (1) at 42°C

Fig. 8(a) Experimental response of Beam (1) at 60°C

Fig. 7(b) Simulation response of Beam (1) 42°C

Fig. 8(b) Simulation response of Beam (1) at 60°C

feedback gain was then held constant for all other closed loop simulations at varying temperatures as per the experiments.

Figures 6(a) and (b), 7(a) and (b), and 8(a) and (b) show comparisons of the simulated and experimental open and closed loop time histories at 26, 42 and 60°C respectively. The initial tip displacement was set to that used in the experimental results.

Figures 6, 7 and 8 reflect that around 42°C, Beam (1) exhibited maximum structural damping as indicated in Fig. 4 and hence the minimum settling time.

The maximum control voltages required for the simulation were found to be consistent with those experienced during the experiment. Additionally, the settling times and damping ratios were of the same trend as the tests. Figure 9 shows a set of simulated and measured settling times to 10% of peak amplitude for Beam (1).

The results show good generalisation of settling time and damping behaviour of the beam. Addition-

Fig. 9 Simulated and experimental settling time to 10% of peak amplitude for Beam (1)

ally, the reduction in settling time between open and closed loop simulations is to within a maximum of 26% of those experienced in the tests, with the best accuracy occurring at the lower temperatures and the

largest error occurring at the higher temperatures.

6. Discussion

The material and piezoelectric properties of real systems will generally vary with temperature. Figure 2 shows that the piezoceramic properties vary significantly with temperature. This variation can be even more nonlinear depending on the type of material forming the ceramic. Various manufacturers show that some ceramics are very stable with moderate temperature changes, although some high-power actuators can vary significantly with temperature.

Figure 3 shows that the material stiffness of the beams also varies with temperature. This reduction in stiffness caused a decrease in natural frequency by up to 8% in Beam (1) for these experiments. The change the aluminium beam natural frequency reflected the change in Young's Modulus experienced over this temperature range and was verified using the simulation model. This change in natural frequency may cause problems for control strategies or for systems that have an excitation frequency close to the beam natural frequency.

The damping ratio of Beams (1) and (2) showed the most dramatic change with temperature, with a suspected glass transition temperature of the adhesive being experienced above room temperature. This caused a significant increase in the damping ratio and decrease in settling time. This may be beneficial in vibration control through increased passive damping, although real structures may not have these temperatures as set points, and may pass through these regions of high and low damping during normal operating cycles.

Although there were a number of limitations in this investigation, such as the maximum amplifier voltage, low power piezoceramics, spillover and using relatively large initial tip displacement, it has been shown that temperature can have a marked affect on the active control of a cantilever beam. Due to the low moment produced by the actuators in controlling the large vibrations the total settling time seems dominated by the trend in open loop damping with temperature. Ideally, thicker actuators with higher control authority would be employed with higher control voltages to provide more dramatic decreases in settling time. This may also highlight the changes in piezoceramic properties more with temperature, which may not be apparent in this study.

The reduced-order lumped parameter simulation model was developed with look-up tables to account for the nonlinear temperature dependant properties of the structure and piezoceramic materials. These tables were necessary to model the entire system and

enabled the model to be validated against the test data. The simulation model did not however include the effects of atmospheric damping, which could account for the discrepancy between the experimental and simulation results.

7. Conclusions

The effect that temperature has on the active control of a fixed-free beam has been investigated using piezoceramic actuators and velocity feedback control. The beam specimens were constructed from aluminium and the actuators located towards the fixed end of the beams.

The results confirm our expectation that the natural frequency, damping ratio and controlled settling time all vary with temperature. Additionally, the tests reveal a dependency on the type of agent used to bond the ceramics to the beam, all of which could influence the active control of the structure.

The simulation model employing nonlinear look-up tables proved consistent with the test results and will be a valuable tool in evaluating the performance of different control strategies in controlling vibration over large temperature ranges.

Future research will focus on the control of light flexible structures investigating the behaviour of different control strategies with varying temperatures. The use of more powerful actuators at higher voltages will be utilised and the effect of temperature on collocated piezoceramics used as sensors will be investigated.

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