Participation Factors for Poled Piezo Ceramic under Dynamic Loading

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Abstract

A segmentially poled ceramic element dynamically driven along its longitudinal axis is being used to monitor 6 force degrees of freedom in a non-linear structure. To that end, the dynamic influence of the ceramic element has been measured. The results reported here are for the tangential response characteristics of the cylinder. The force sensor torsion degree of freedom relies on the tangential response. It is driven indirectly, via Poisson's Ratio effect from 2 opposing ceramic element segments. The peak cross-axis accelerations (tangential) are in the range of 30% of the drive axis (Z). This paper describes the results of phase shift between those segments to maximize the torsion response. The peak responses are examined to extract damping and then to generate a form of participation factor. This provides some insight into interaction between poled segments. The damping of the torsion mode is much higher than the other structural modes.

Keywords—poled piezo ceramic element, non-linear structure, Poisson's Ratio, damping, force sensor

I. Introduction

There are 3 significant design challenges in developing a force moment sensor for space: insensitivity to external boundary condition influences; a stiff structure to adequately maintain controllability; large dynamic range, extending down to D.C. The boundary condition influences include extreme thermal variations, as well as changes resulting from rigid body motion of either supporting structure or payload being handled.

To date, such sensors have been passive systems, functioning in the time domain. The active nature of piezo-ceramic elements provides the opportunity to avoid the conventional problem of sensor drift for low frequency operations, by monitoring higher frequency (>100 Hz) structural resonances which change with load level.

The ability to segmentially pole and then excite individual or combinations of each ceramic element segment offers the ability to excite a multitude of structural modes (eigenvectors). The direct excitation of element segments has been used to excite axial and moment degrees of freedom [1], axes shown in Fig. 1 and 3. The torsion degree of freedom is more difficult to excite, because it relies on cross-axes influence. It can be excited using a variety of combinations of opposing segments. This study looks into segmentially poled combinations that can be adequately employed to note resonant frequency changes of the torsion mode.

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The non-linearity and the 6 dof sensing capability of our prototype are made possible through the sensor configuration [2]. The mechanical design analysis, is based on a finite element (FE) model. There are at least 3 types of non-linearities in the structure and they have been analytically modelled with matlab simulations and still need experimental validation. The viability of driving the torsion mode, with cross-axis influence can only be done experimentally.

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II. Force Sensor

A. Mechanical Configuration

Fig. 1 shows prototype sensor cross section. Dynamic testing of poled ceramic element is done within the configuration.

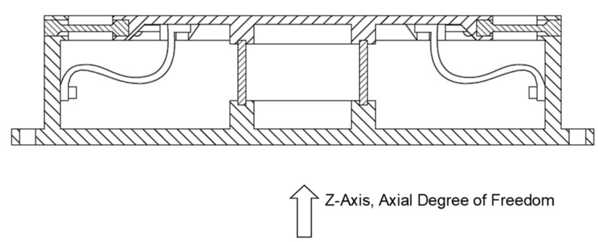

Fig. 1 Force Sensor Cross Section

Loading plate – a 5.875" diameter, 0.125" thick aluminum plate with 8 strut/cable attachments equally spaced along circumference.
Housing – an 8" diameter, 2" high, hollow cylinder, one end closed. The other end has strut/cable attachments, spaced along open end circumference. The closed end of the cylinder has a 9" diameter flange.
Struts/cable – the current design is actually based on slightly tensioned cables, rather than pin-ended struts. There are 8 0.1" diameter cables, which act to join the loading plate with the housing. The finished cable + end fitting length is 1.4375". The cable ends are swaged into end fittings which are counter threaded to allow for changes in the nominal preload
Delrin inserts – there are 2 hollow delrin cylinders to position the piezoceramic element between the housing based and loading plate. The ceramic element will be glued into grooves. The delrin is to ensure electrical isolation and reduce wear on the ceramic element pole.
Piezoceramic element – a hollow cylinder, 2" diameter, 1" high is segmentially poled into 4 quadrants. The element is driven to small amplitudes (~0.08g's) at a multitude of loading plate

resonances. The sequence of element drive is varied to ensure modes of significance are excited.

Thermal straps - 8 thermal straps connect the loading plate to the housing walls. They reduce the thermal gradient.

The struts generate the non-linearity. There are 3 regions of non-linearity, which we have identified from correlation between experimental and analytical results with our 2nd prototype. Testing reported here for 3rd prototype is linear only, ie unloaded.

Fig. 2 shows the segmentially poled ceramic element, also shown in Fig. 1, joining the upper loading plate to housing base.

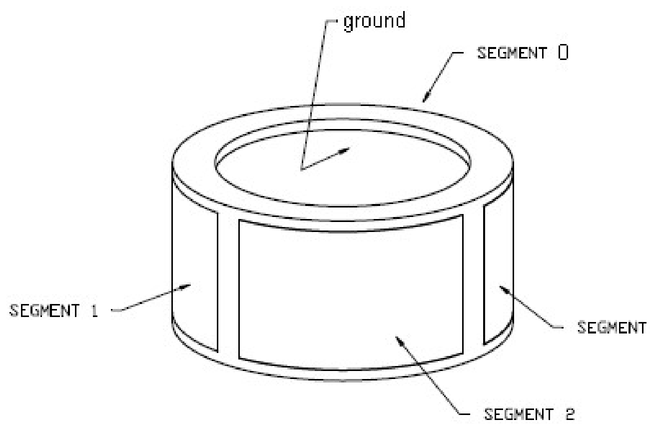

Fig. 2: Segmentially Poled Ceramic Element

B. Experimental Power Subsystem

Power is provided for 3 subsystems:

accelerometers: 5V

AC/DC 5V adaptor for BeagleBone microprocessor

3.3V generated to run drive electronics.

Data transferred from microprocessor to a PC running either Matlab or Excel.

C. Instrumentation

Five 3 axes LSM6DS33 accelerometers, capacitance set to allow maximum frequency of 2500 Hz. Though they don't meet the maximum frequency requirement, they are adequate to validate at least one mode for all 6 force degrees of freedom. The higher frequency modes were validated, for breadboard work, using 2 existing in-house Dytran accelerometers

Fig. 3 shows the axis system and drive segment orientation and accelerometer placement on under side of loading plate. Accelerometers are marked in red as AxC, Ax0 to Ax3.

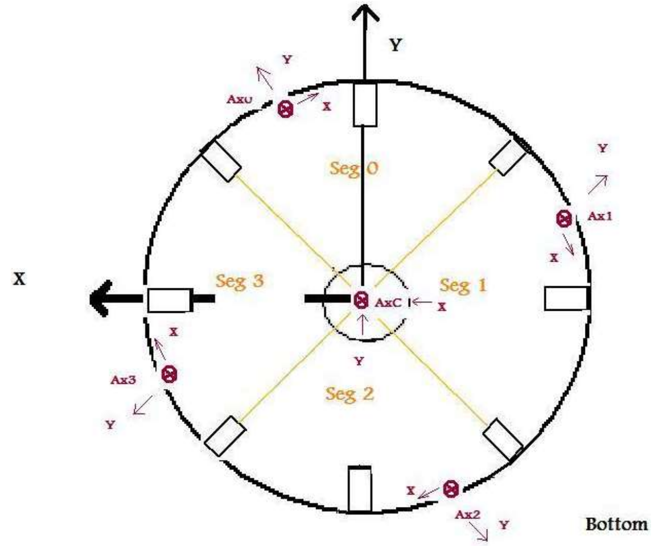

Fig 3 Instrumentation on Loading Plate

III MODAL DOMAIN APPLICATION

The excitation of the sensor in a higher frequency regime than that of operation has the effect of avoiding the drift problem. It also offers the advantage of increased accuracy by allowing for additional measurements. Each resonant peak, n, is proportional to equation (1) or (2); from pages A-15,A-16 of reference [5], depending on the excitation.

For well separated modes, the response to input acceleration:

$$\frac{\ddot{Y}_j}{\ddot{A}} = \frac{s^2 \mathcal{L}_n \psi_{nj}}{m_n(\, s^2 + 2\,\xi_n \omega_n s + \,\omega_n^2)} \dots\dots(1)$$

where: n is the mode or resonance number,

k is the driving point and

j is the response point

ψ is mode shape coefficent

$\mathscr{L}$ is participation factor, a representation of applied force

At resonant peak n, i $\omega_n = s$

And the equation reduces to

$$\frac{\ddot{Y}_j}{\ddot{A}} = \frac{\mathcal{L}_n \psi_{nj}}{m_n(\, 2\,\xi_n)} \dots\dots(2)$$

If we extract damping factor

ξ_n , based on half-power bandwidth method, and consider

$$\frac{\mathcal{L}_n \psi_{nj}}{m_n}$$

as forcing function or participation factor for mode n.

The accelerometer amplitude is proportional to the shape coefficient at which the measurement is taken, and the shape coefficient at which the structure is driven. The m_n term is constant for a particular mode – the modal mass. For some eigenvector scaling conventions this term is unity. For the 1st torsion mode of interested, all the tangential eigenvectors are considered equal.

From our testing conditions, we can easily extract acceleration input and peak acceleration for each mode. For well separated modes, this is a frequency response function, based on acceleration data, with rigid body input eliminated.

IV. TESTING CONFIGURATION

The instrumentation is built into the structure, locations shown in Fig. 3. The excitation is provided by the segmented piezo ceramic element is shown in Fig. 2. Each of the 4 segments can be excited independently along Z axis direction, though there will be some overlap and cross axes influences.

This testing phase was done using sine sweeps from 500 to 1500 Hz, because the mode we're tracking is between 900-1000 Hz. The sweep rate used is 9.5 Octaves per minute. The bulk of testing for other modes has been 20 Octaves per minute to cover a larger range (330-3300 Hz). Some early testing was done using pseudo random.

TABLE I. DRIVE SEGMENT PATTERNS

Excitation Descriptor	Drive Segment Configuration
Axial	All in phase
Rocking 1	+0,-2
Rocking 2	+1,-3
Saddle	0,2 +; 1,3 -
Half Saddle 1	+1,+3
Half Saddle 2	+0,+2
Segment Zero	Segment 0 only
Segment One	Segment 1 only
Segment Two	Segment 2 only
Segment Three	Segment 3 only

Testing to optimize torsion mode response has been a transition from Rocking 2 to Half Saddle 1 in 10 degree phase shift between segments 1 and 3. Some investigation at 5 degree segments was done, but not reported here.

Data Acquisition

Data acquisition was done with an inhouse system to acquire the data through BeagleBone processor for the low cost, light weight low frequency accelerometers. Part of that processor s/w is in C, part of it is in assembly language. The low frequency accelerometers have high frequency filters that have been removed to enable frequency high frequency content.

After the data is transferred from BeagleBone processor to PC, there is LIST code to do some initial FFT work, but data is eventually processed within matlab .

The matlab extraction and presentation is controlled through main program, lbsweep which reads data, extracts the peaks, plots and outputs peak data.

V. TEST RESULTS

Figure 4 and 5 show acceleration frequency response functions for accelerometer 3, driven in direction with 180 degree phase shift between segments 1 and 3 – ie half saddle excitation. Figure 4 shows acceleration response for all 3 degrees of freedom and is dominated by out of plane response (red). The torsion mode is largely obscured, but Figure 5 shows the same data, for tangential acceleration only (torsion mode).

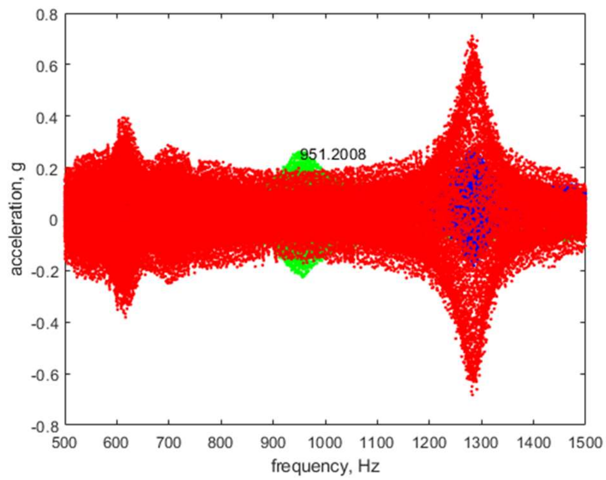

Figure 4 Sine Sweep, Accelerometer 3

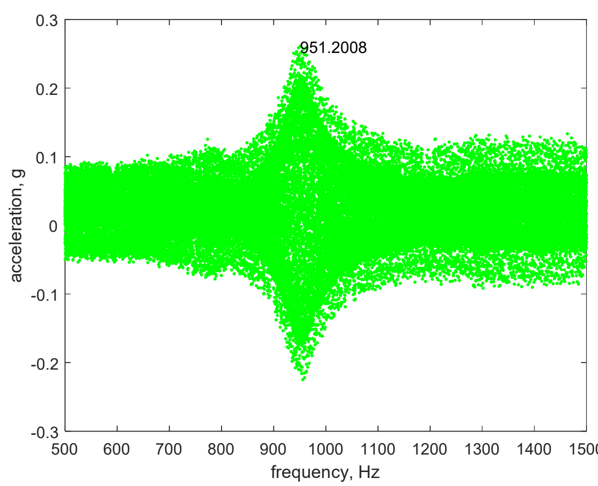

Figure 5 Sine Sweep, Accelerometer 3

VI. EXPERIMENTAL EVALUATION

The goal of this test series was to define a poled ceramic element drive configuration to excite our force torsion degree of freedom.

Figure 6 shows the resonance peak of torsion mode near 950 Hz, for 10 degree increments of phase shift between drive at segments 1 and 3. The is a general tendency of amplitude increase from the pure rocking mode to the half saddle excitation.

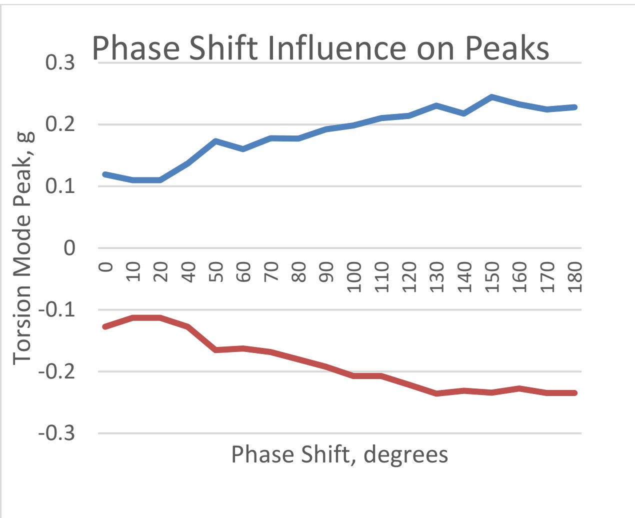

Figure 6 Accelerometer 3 Peak vs Phase Shift between Segments 1 and 3

Figure 7 shows the damping values and participation factors we calculated for the various test configuration. The damping values are based on the half-power bandwidth method of Clough & Penzien with data extracted from measured accelerations (frequencies at peaks and associated ½ power levels). The damping values vary from 3.5% to 8%, for the torsion mode, which is predominantly the twisting of the piezo-ceramic element. The other structural modes are in the range of 1-2%.

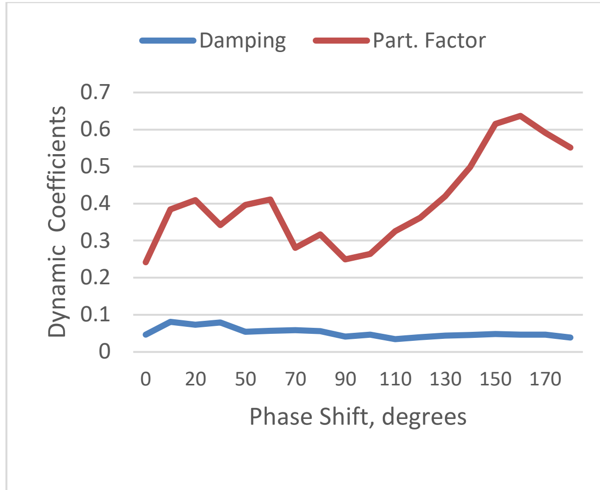

Figure 7 Dynamic Factors vs Phase Shift between Segments 1 and 3

The participation factor, as defined in section III

$$\mathscr{L}_n * \psi_{nj} / m_n$$

shows the most significant variation. It is provides a means of assessing which form of excitation is most effective. The highest participation factor occurs at 160 degree phase shift.

VII. DISCUSSION

The mode to be used to monitor torsion, within our force moment sensor (because it is a non-linear system where resonant frequency changes with applied load) can be excited using segmentially poled ceramic element. The resonant frequency predicted for the torsion mode, by finite element model after some updating is 1052 Hz. There is mass loading from cables that has not been well quantified, and needs to be corrected with improved instrumentation. It is feasible that the mass loading influence causes the difference.

The higher frequency regime has been examined, and there are additional modes which will provide additional force resolution, but the higher mode shapes are not well enough defined to determine which of them can be categorized as influencing particular force dof's.

Table II Unloaded Modal Test Results

Force dof	description	Frequency (Hz)
Axial	outer	640-650
	center	1254-1276
	saddle	1457-1467
Rock about X	1st rocking	522-535
	2nd rocking	708-733
	3rd rocking	2688
Rock about Y	1st rocking	550-587
	2nd rocking	777-804
	3rd rocking	2700
Torsion	1st	960-1035
Shear X	1st	1500-1560
	2nd	3300
Shear Y	1st	1600-1630
	2nd	3330

VIII. CONCLUSION

Opposing segments, with 160 degree phase shift between them provide an adequate means of exciting our torsion degree of freedom. The damping value for that mode is approximately 5%, which will is higher for other structural modes, and will require more effort in picking peaks for force transduction, but it is fairly well separated from other modes, which simplifies things.

References

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