Space Robotic Force Moment Sensing: Boundary Condition Influences

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ABSTRACT

A non-linear concept for a space robotic force moment sensor (FMS) which reduces the problems of boundary conditions and thermal strains, is presented.. A 3 degree of freedom (dof) version has been built and partially tested to investigate the feasibility of several novel mechanical approaches to eliminate the more conventional force moment sensor issues which have plagued space robotic applications to date.

The testing to date has shown that the concept has promise, but there have been problems encountered which are yet to be resolved experimentally. The work of this study is an analytical characterization of some of the experimental observations that presented themselves during testing.

The sensor concept is based on a non-linear system which allows for transduction based on frequency shift rather than amplitude measurement. The non-linearity is one which stiffens under increasing load level. All space robotic operations are generally fairly slow, so that the sensor must be drift free in the low frequency range - something which is generally difficult to achieve.

INTRODUCTION

There have been a number of force moment sensors built for space which have not achieved all of their design goals, Ma and Martin [1] allude to the difficulties of space robotic FMS. JPL (Jet Propulsion Laboratory) built one which flew as part of an SRMS (shuttle remote manipulator) space shuttle mission on STS-62 [2]. CSA (Canadian Space Agency) has a pair of FMS sensors on SSRMS. The Japanese Space Agency flew one on their mission ETS-7 [3,4,5]. In all of these cases, the sensors were limited by their thermal sensitivities. In the case of the SSRMS (space station remote manipulator system) sensor, sufficient thermal measurements were taken to largely compensate for the temperature issue, but the sensor design was stiff enough that the local flexing of the interface flanges caused errors. Apparently that influence has now been successfully calibrated out of the system as well, with extensive on-orbit testing.

It is certainly preferable that a way be found to avoid such extreme efforts. We have been working on a force moment sensing concept for a number of years, based on frequency shift as a transduction approach. This approach has allowed us to utilize piezoceramic's, even in low frequency space robotic applications (0-20 Hz). The drift problems which result from using time domain, amplitude measurements in low frequency applications are well considered. The models and physical manifestations associated with '1/f Noise' have been extensively reviewed [6].

One of the additional benefits to switching away from time domain strain or displacement measurement, to modal domain, frequency measurement, is the availability of a variety of normal modes to track for load levels. The higher modes of a structure are not totally isolated from boundary condition effects, but they are less sensitive to them.

This paper is to present our initial limited test work on boundary condition influences and thermal gradients. Analytical work on the problem, based on finite element evaluation of the problem of local flexing of interface flanges is also presented. Some of these influences were observed during the testing, but were not quantified.

The space robotic force moment sensing problem is significantly different from the terrestrial problem, due to the combined problems of thermal gradient and mission operations such as capturing ‘free-flyer’ payloads, which generate large moment loads, but also require accuracy in manipulating small linear forces, such as occur for force/moment accommodation operations.

SENSOR CONFIGURATION

The 3 dof force and moment sensor breadboard, is pictured in Figure 1, along with the cut-away drawing.   The sensor diameter is 15.25", with a height of 2".   The presence of the pin-ended struts in the load path create the stiffening non-linearity. An applied load results in a change in mechanical system frequency. The segmentally poled ceramic cylinder (Sensor Technology BM 400 cylinder - 2 “ diameter, 1.0" height, wall thickness 1/8") in the centre is directly in the sensor load path. The ceramic cylinder is electrically driven to excite the mechanical system frequency, the electronics then identifies the frequency. This combination of simple modal analysis with piezoceramic characteristic provides a novel method of determining static to 20 Hz applied forces, for multiple dofs.

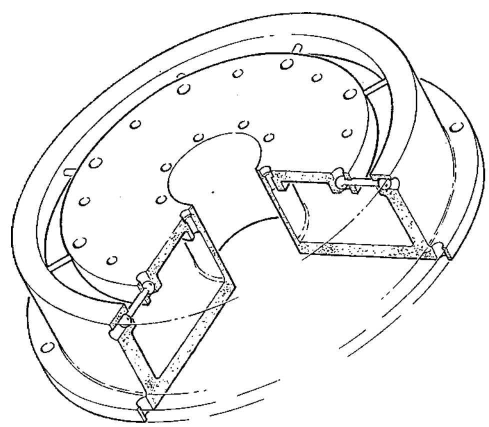

Figure 1 FMS Configuration

The method of transduction is based on segmentially poled piezoceramic elements of Draisey et al [7]. The approach, tested to date, is limited to 3 dof sensing. The work reported in [4] has clearly shown that there are modes which can be used to track varying force levels and that there is very little measurement drift. The extension to a 6 dof sensor will need a more complicated poling arrangement to ensure shear strains can be measured and excited. Both the 3 and 6 dof results would likely be improved by eliminating the axi-symmetric nature of the upper loading plate modes.

Figure 2 presents the calibration curve derived for the axial load degree of freedom. It is based on tracking the highest mode we measured, at about 1900 Hz (anti-aliasing filters limited results to 2000 Hz)

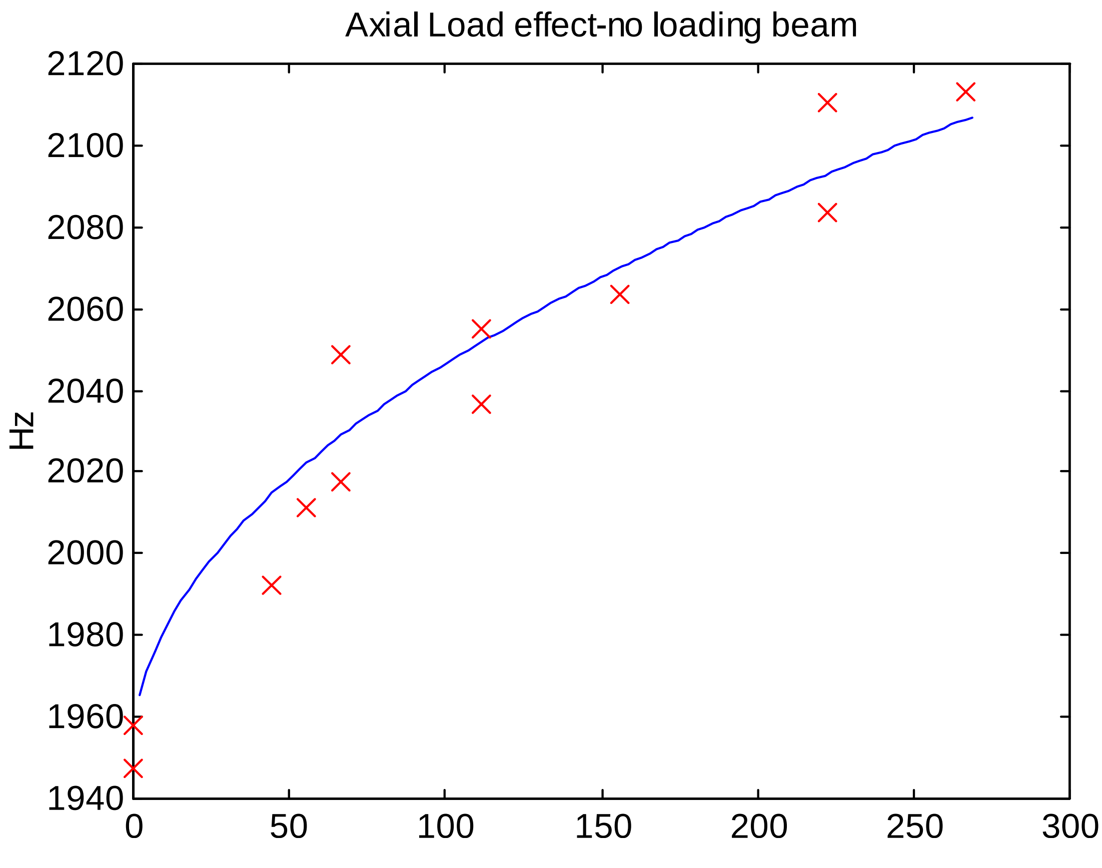

Figure 2
Frequency vs Axial Load Calibration Curve

FINITE ELEMENT MODEL

The finite element modelling has been done in UAI NASTRAN. The predictions for this project are based on linear static, temperature and normal modes analysis, though earlier non-linear investigations have been made.

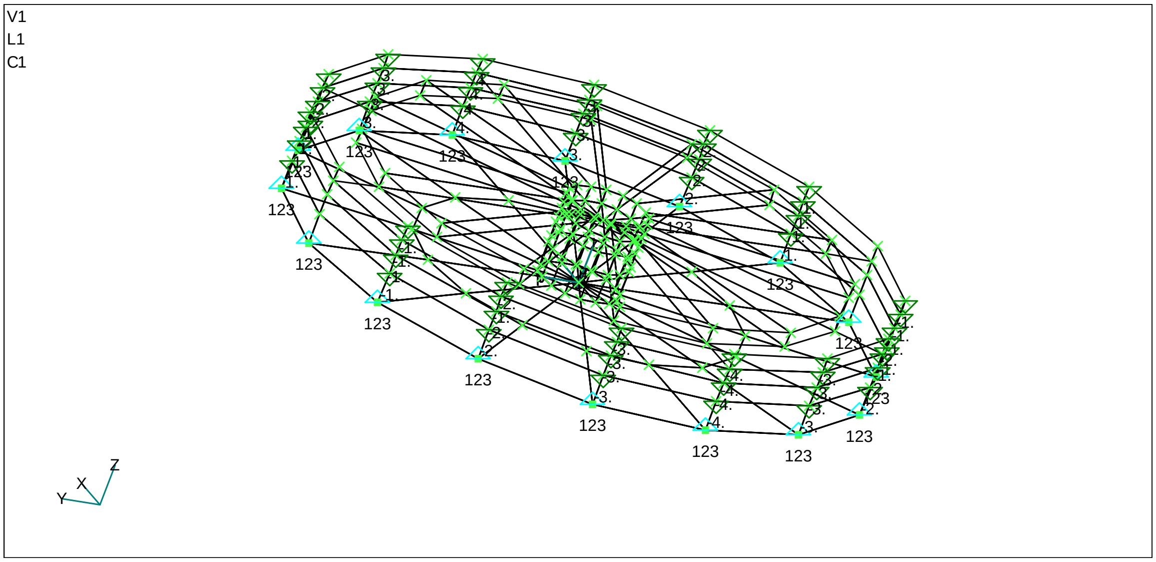

Figure 3, Finite Element Model

The model consists of: housing (112 plate elements); piezoceramic sensor (64 plate elements); loading plate (16 solid elements + 17 plates); struts (8 beam elements). There are a total of 210 grids. The model is shown in Figure 3.

The initial model had 8 three dof single point restraints (SPC), representing the 8 bolts mounting the structure to the test rig. This initial analysis uncovered a pair of unimportant housing modes in an already heavily clustered set of significant modes. The FE analysis was used to eliminate this pair of unimportant modes (1725 Hz) with the addition of 8 more three dof SPC's. This modification was then successfully implemented in hardware (with the addition of 8 bolts).

The model has been updated to match the test modes, but only to try and bring the test and analysis modes to within 10% of each other, because the testing method is not considered to be accurate for some types of modes. The testing method was limited to the resonance frequency identification we could make, using the piezoceramic element as a driver.

The model was run for a thermal case of +/- 4 °C gradient across the sensor diameter. The equivalent stiffening effect was then applied and run for a normal modes analysis to predict the frequency shift. The model was also run with two sets of interface boundary conditions - the pinned conditions shown in Figure 3 and then with similar fixed conditions. These runs were done as normal modes runs to check the types of frequency shifts that occur from modified boundary conditions. During testing, it was clear that the lowest modes shifted too much to be reliable enough for frequency transduction, but the higher modes we were tracking were stable. The interface boundary condition study was done to quantify the effect.

THERMAL GRADIENT: PREDICTIONS and MEASUREMENTS

Figure 4 presents the deflected shape of the thermal gradient case, overlaid with the original model.

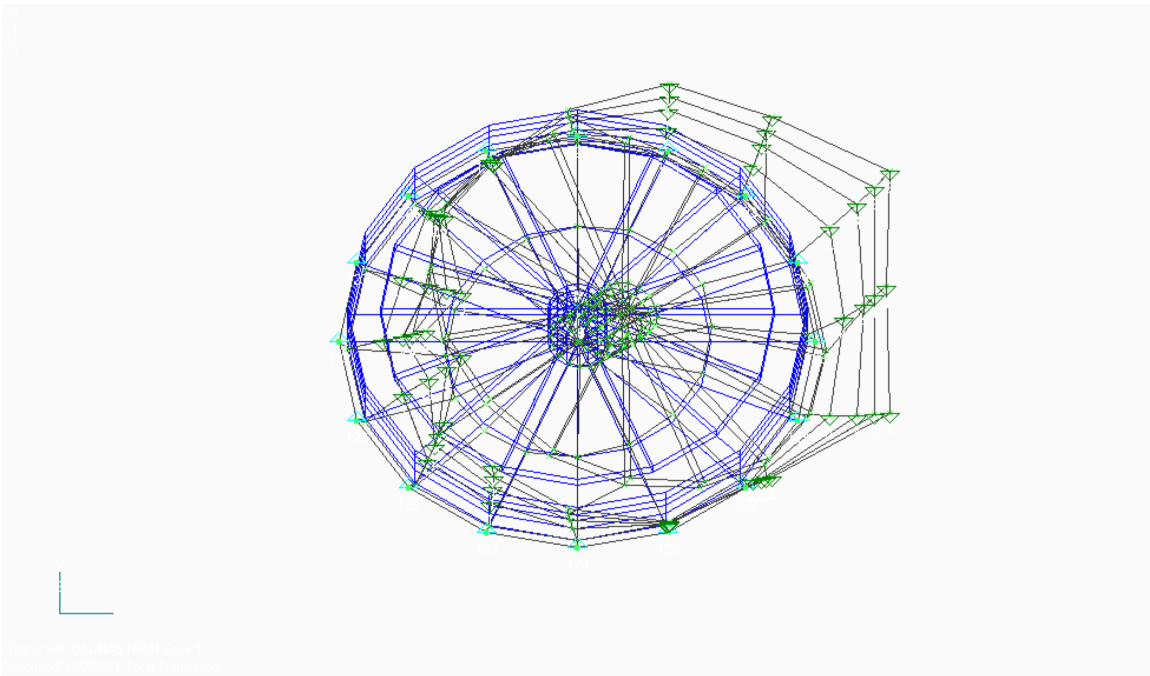

Figure 4
FE Predicted Thermal Deflected Shape for +\- 4 °C Gradient

MODAL ANALYSIS RESULTS

Table 1 presents the measured and FE predicted modal frequencies for three configurations, 2 of boundary conditions - two interface fixations and one attempting to model the thermal gradient interface.. The model had been matched to within 10% of the test frequencies, for the pinned boundary condition case.

Table 1 - Modal Frequencies

Mode	Test Frequency	FE Frequency, pinned boundary	FE Frequency, pinned boundary, thermal gradient	FE Frequency, fixed boundary
1	250.	261.133	267.875	279.618
2	302	333.942	339.751	336.213
3		334.086	349.000	336.356
4	440*	401.089	410.081	401.090
5	600	694.466	696.589	706.013
6	950*	922.296	925.844	922.394
7		923.979	927.665	924.076
8	1377	1269.946	1270.811	1295.048
9		1270.012	1272.142	1295.122
10	1547	1570.130	1570.137	1696.042
11		1759.525	1759.625	2122.772
12		1759.544	1759.775	2122.782
13	1900*	1977.265	1978.980	1977.385
14		1979.657	1981.246	1979.776

The test frequencies, marked with an asterisk are the modes which were used in tracking frequency shift, for the transduction between frequency and load. The symmetry of the structure made it impossible to distinguish axi–symmetric modes, such as occurred for the modes pairs 2-3; 6-7;11-12 and 13-14.

The modes which were used for load prediction are almost unaffected by the changed boundary conditions, while some of the others - most notably those involving the housing show some very heavy boundary condition influences. The higher mode numbers show generally less sensitivity to either boundary condition or thermal gradient than the lower modes.

We had originally hoped to use the first mode of the structure for transduction purposes, but even in our preliminary testing we could see that it was too sensitive to boundary condition influences. The modes we used for transduction involved deflections of the upper loading plate and were largely independent of the housing modes. The pin-ended strut configuration has the effect of isolating the loading plate from the housing for some modes.

TRANSDUCTION FROM FREQUENCY RESPONSE FUNCTIONS

The frequency response, shown in Figure 5, generated by driving the piezoceramic element with 2 poled segments and measuring response from the 2 corresponding cross axis segments shows a rather disappointing set of peaks. But when some minor corrections are applied to the phase shift portion, as shown in Figure 6, the peaks become much more promising as a means of tracking for frequency shift.

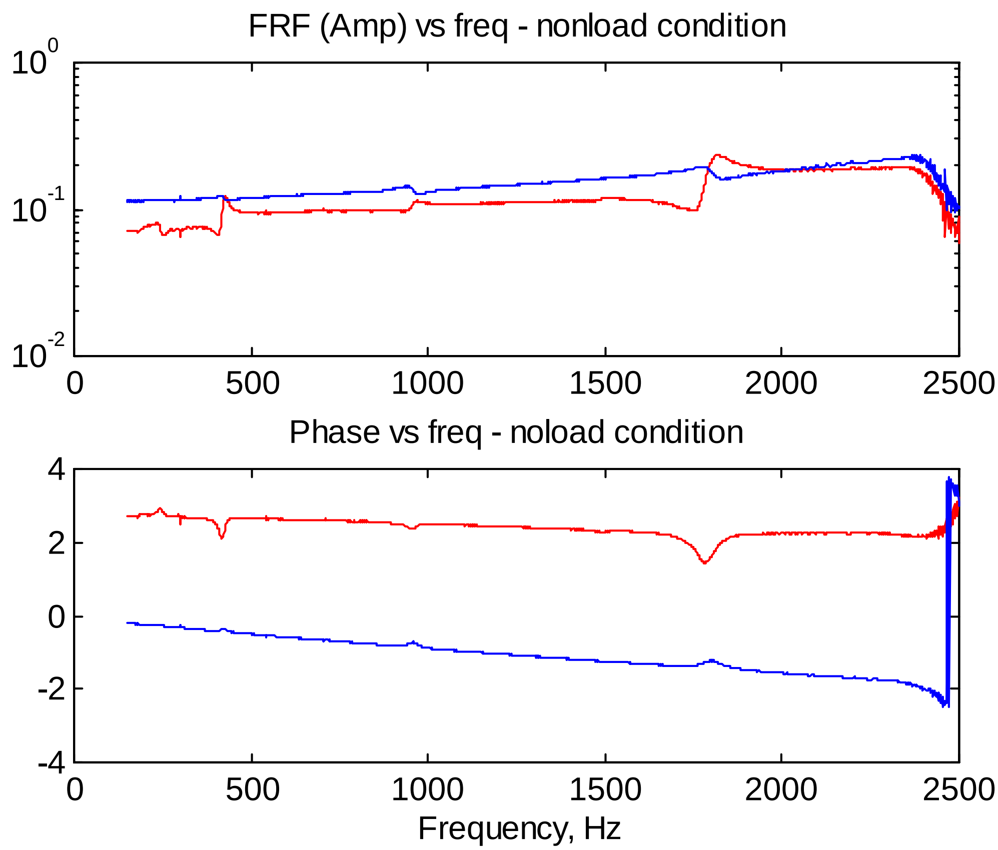

Figure 5
Frequency Response Function

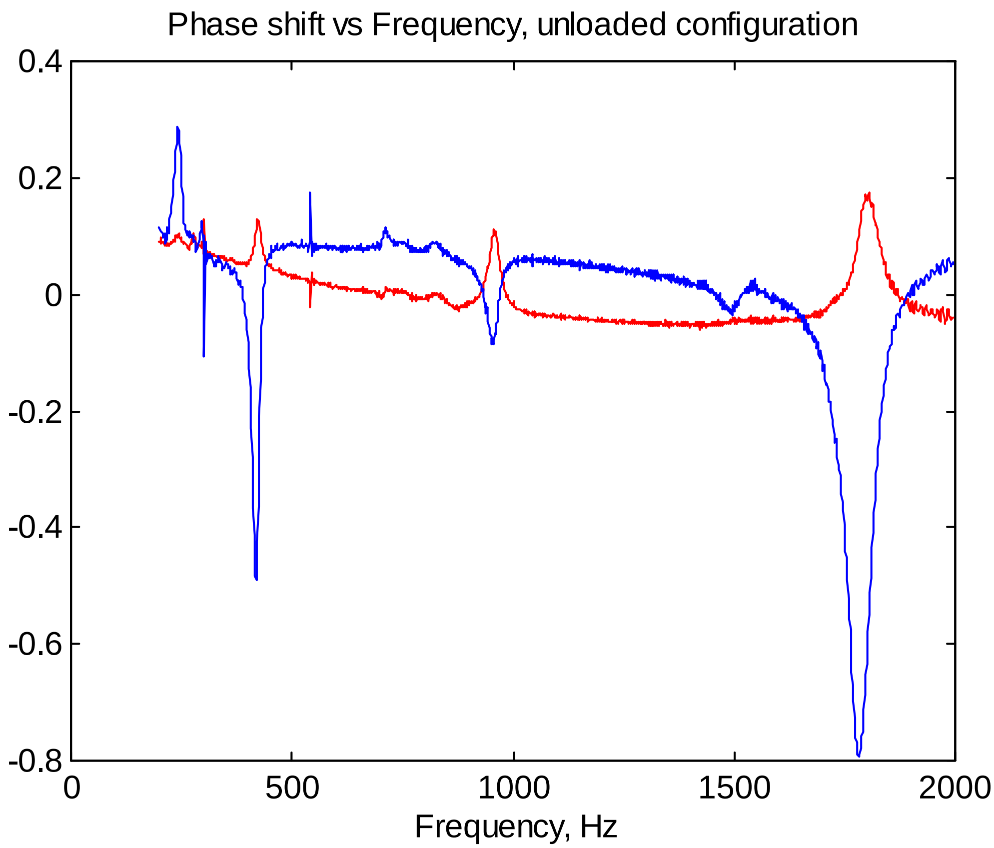

Figure 6 Phase Shift (corrected) vs Frequency

THERMAL TESTING EFFECTS

The two types of thermal testing done on the structure showed limited sensitivity on modal frequencies. There was no environmental control system in the building, and thus room temperature varied from 18 °C to 28 °C with no appreciable effect on modal frequencies. There was a thermal gradient test applied to the structure.

A thermal gradient was created across the sensor by heating the ambient air with a heater placed 0.3 metres from the sensor. The warm air flow was blocked (as much as possible) from travelling past the mid line of the sensor. Thermometers were used to measure temperature across the sensor. After 15 to 20 minutes, the air on the warm side was 2 degrees C warmer than the other side. Table 3-1 presents the errors resulting from the thermal gradient.

Table 2
Frequency Shift for a 2 º C Thermal Gradient

Load	Axial Channel 1 (base frequency 1848 Hz)	Axial 2 (base frequency 1848 Hz)
no load 49 N 68 Nm	6 Hz 3 Hz 6 Hz	4 Hz 0 Hz 0 Hz

There is some indication of thermal distortion, but examination of experimental deviations in calibration curve of figure 2 make the distortions difficult to determine above experimental error, for such preliminary results. The influence which these generate on load predictions are maximum of 2.2 Newtons.

FUTURE PLANS

A number of problems and surprises occurred during the testing work done for this project. The most difficult one was not discovered till after the work was completed and the structure partially dismantled. One of the loading struts was bent. This must have occurred because of a loss or preload in the strut - it began carrying moment load, which eventually caused permanent deformation.

Obviously one of our most near term plans has to be to modify the method of tightening the struts, so the minor preload ensures the struts remain as struts, not beams. The subsequent plans include:

- upgrading the FE/test results to match more accurately, probably by performing a modal test.
- modifying the structure to eliminate axi-symmetry, to split the coincident modes and increase measurement degrees of freedom
- obtain more specially poled element to allow for excitation of shear modes

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