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Information Package for the Simplified Six-Axis Load Cell

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Introduction

Sandia National Laboratory has developed a new type of force-torque sensor (or six-axis load cell) that is surprisingly simple. U.S. Patent 5,850,044 has been granted on the design and concept of the load cell. As a national laboratory, Sandia does not intend to produce the load cell but rather to license the technology to industry for production. Because of this, a commercial product has not been developed. Instead a series of prototype load cells have been produced to demonstrate the technology. The prototypes are available for loan to interested parties for testing and evaluation.

Load cell concept

Sandia's six-axis load cell is an analog device designed to measure the three vector components each of force and torque that can be applied to the cell. The design and construction of the load cell is very straightforward. It consists of a single machined part of simple geometry with strain gauges placed on the surface. The only constraint on the design geometry of the load cell is that the area where the strain gauges are attached must have a uniform cross-section and that the cross-section have two orthogonal axes of symmetry. This means that a six-axis load cell could be constructed by properly placing strain gauges on the surfaces of a pipe, square tube, hexagonal bar or I-beam. This simplified design means that an exceptionally rugged and complete force-torque sensor can be built at very low-cost.

The current prototype uses an annular cross section with six sets of 4 semiconductor strain gages. Each set is in a full bridge configuration placed around the circumference at the center of the cell. The ability to construct a complete force-torque sensor from any prismatic section means that the load cell can be built into a device rather than added later. Examples of this might include incorporating a load cell into a structural support, robot arm, or vehicle suspension.

By properly positioning the strain gauges, six strain gauge bridges can be constructed so that each bridge is sensitive to only one of the six possible applied vector components and is insensitive to the other five. This inherent load separation means that the analog voltages from the strain gauge bridges can be used to directly measure the six components of force and torque without complicated data reduction or onboard electronics. The load separation is achieved by a combination of three separate effects: 1) the closed form elasticity solution to an end loaded prismatic section, 2) gage angle selections to separate shear strain from axial strain, and 3) classical gauge combinations of full bridge configurations.

Other configurations which do not inherently separate the six applied loads but still provide sufficient information to determine the six applied loads are also possible. As little as six strain gauges can be used to determine all six load components. In such a system a single calibration matrix is used to convert the six output voltages into the six applied loads.

Prototype details

The dimensions of the prototype load cells are shown in figure 1. The prototypes are cylindrical with a length of 2.5" and end flanges having a diameter of 2". Each flange has a 1-9/16" bolt circle consisting of four ¼-20 x 3/8" holes. The bolt circle holes are aligned along the *x* and *y* axes. The holes corresponding to the positive *x* and positive *y* axes are labeled on the load cell flange. The *z* axis lies along the axis of the cell, completing a right handed coordinate system. The *x* and *y* moments measured by the cell are relative to the center of the cell.

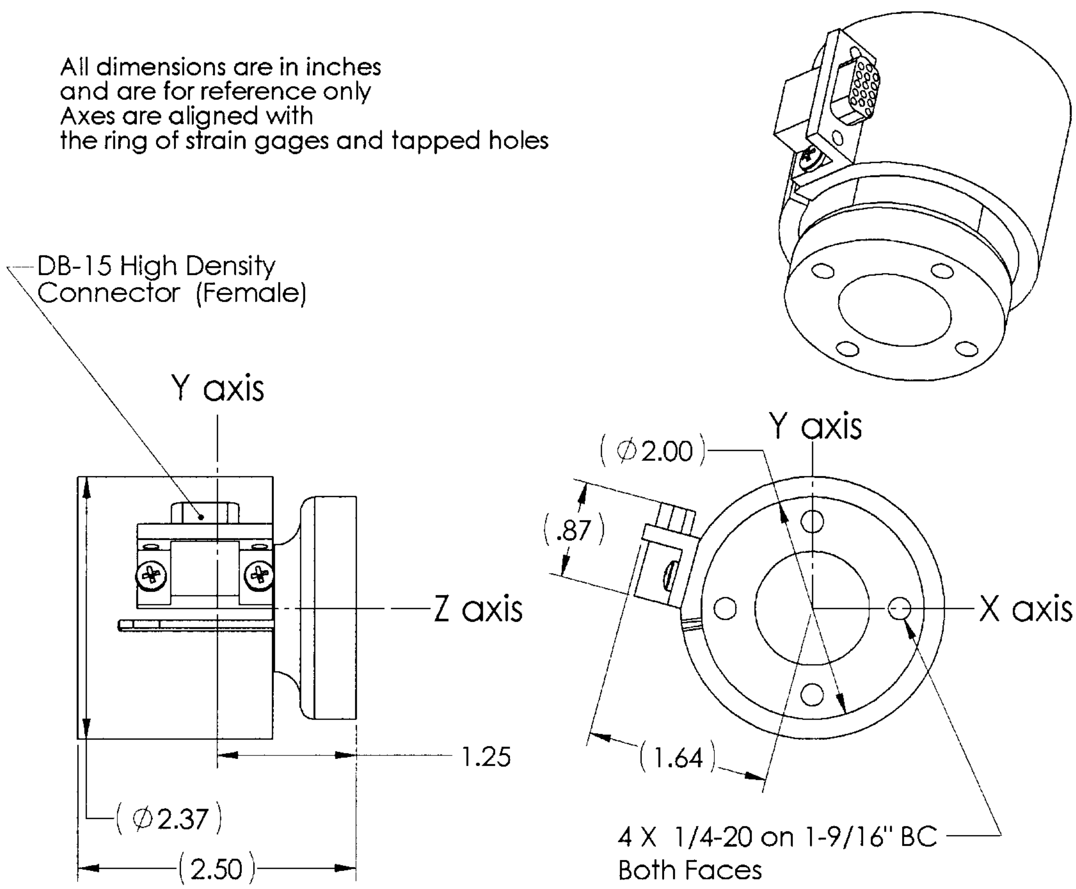

Figure 1: Prototype load cell dimensions

The cell is powered by a single DC excitation voltage (typically 10 volts) and provides six differential voltage outputs. Each of the six voltages is proportional to one of the vector components of load and to the excitation voltage. Positive voltages indicate a load in the positive axis direction or a positive moment according to the right-hand rule.

The load cell has a 15 pin female D-connector like those used with VGA video monitors. The load cell requires 14 pins of the connector. Pin 9 is left unconnected. Table 1 below provides a complete description of the connections including the standard wire colors for a VGA monitor cable.

Operation details

The most basic application of the load cell is to use the six differential voltage outputs to independently represent each of the 6 applied loads. Calibration factors are supplied with the cell to convert each output voltage into an applied load. These values are determined by solving for a best fit sensitivity based on calibration data. An analytic form of the sensitivity relationships also exists and can be found in the associated patent. Because of tolerance problems in load cell manufacture, direct application of the six analog voltages does not produce the most accurate results. These imperfections lead to some cross sensitivity between the six channels. The most severe cross sensitivity is for the *z*-axis force (Pz) channel. New load cell designs are being pursued to reduce this sensitivity. This difficulty can be corrected by multiplying the six differential voltages by a 6x6 calibration matrix. The calibration matrix is determined by a calibration procedure for each individual load cell. With the use of a calibration matrix, excellent load cell accuracy can be expected.

Standard VGA Cable Wire Color	Pin	Signal	Description	
Inputs				
Black	1	$+V_{cc}$	Excitation voltage supplied to gages	
Brown	2	GND	Excitation and sensor ground	
Outputs				
Red	3	Px +	*x*-axis force output (+)	Horizontal (*x*-direction) shear force differential voltage
Orange	4	Px -	*x*-axis force output (-)	
Yellow	5	Py +	*y*-axis force output (+)	Vertical (*y*-direction) shear force differential voltage
Green	6	Py -	*y*-axis force output (-)	
Blue	7	Pz +	*z*-axis force output (+)	Axial (*z*-direction) force differential voltage
Purple	8	Pz -	*z*-axis force output (-)	
Open	9	Open	No Connection	
Grey	10	Mx +	*x*-axis moment output (+)	Transverse (*x*-axis) bending moment differential voltage
White	11	Mx -	*x*-axis moment output (-)	
Pink	12	My +	*y*-axis moment output (+)	Vertical (*y*-axis) bending moment differential voltage
Mint	13	My -	*y*-axis moment output (-)	
Black/White	14	Mz +	*z*-axis moment output (+)	Torsion (*z*-axis) differential voltage
Brown/White	15	Mz -	*z*-axis moment output (-)	

Table 1: Six axis load cell electrical connections

Representative calibration results

The calibration results of a typical prototype load cell are provided here. This is designed to give a quantitative idea of the level of cross sensitivity and the expected correlation of the load cell response to the applied load. Figures 2 through 7 show the results of testing a prototype load cell under individual load components. A perfect load cell would yield a linear response for the output voltage of the one bridge sensitive to the applied load component and zero voltage for the other five outputs. The six figures included show the response to various load values for each of

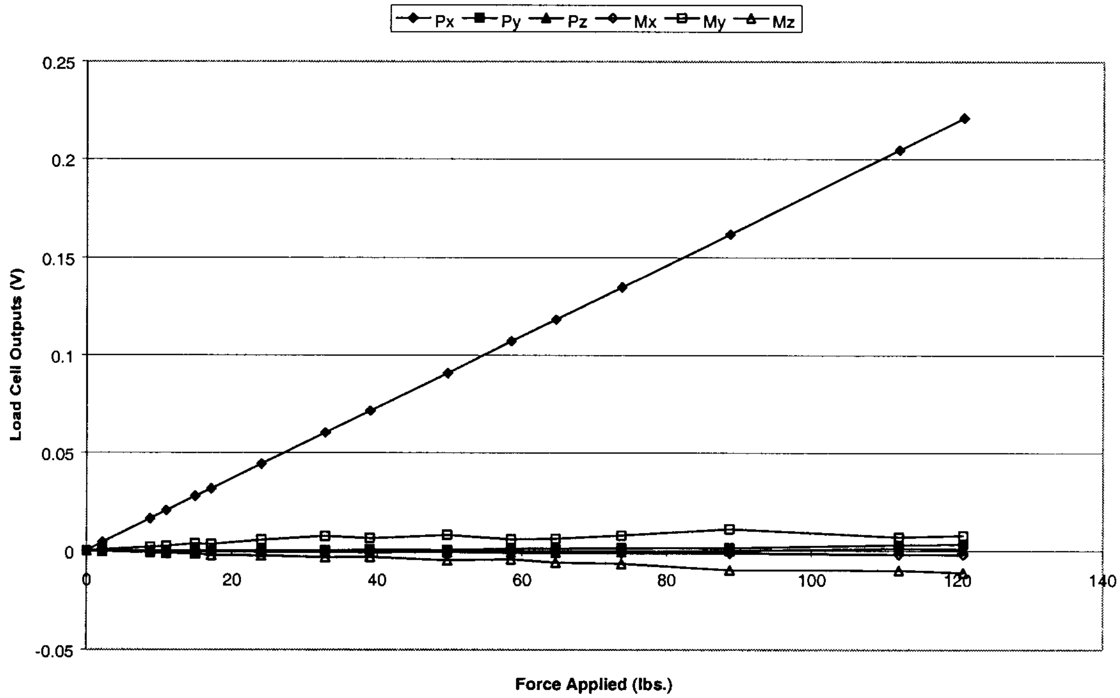

Figure 2: Load cell prototype response to $+x$ directed shear load

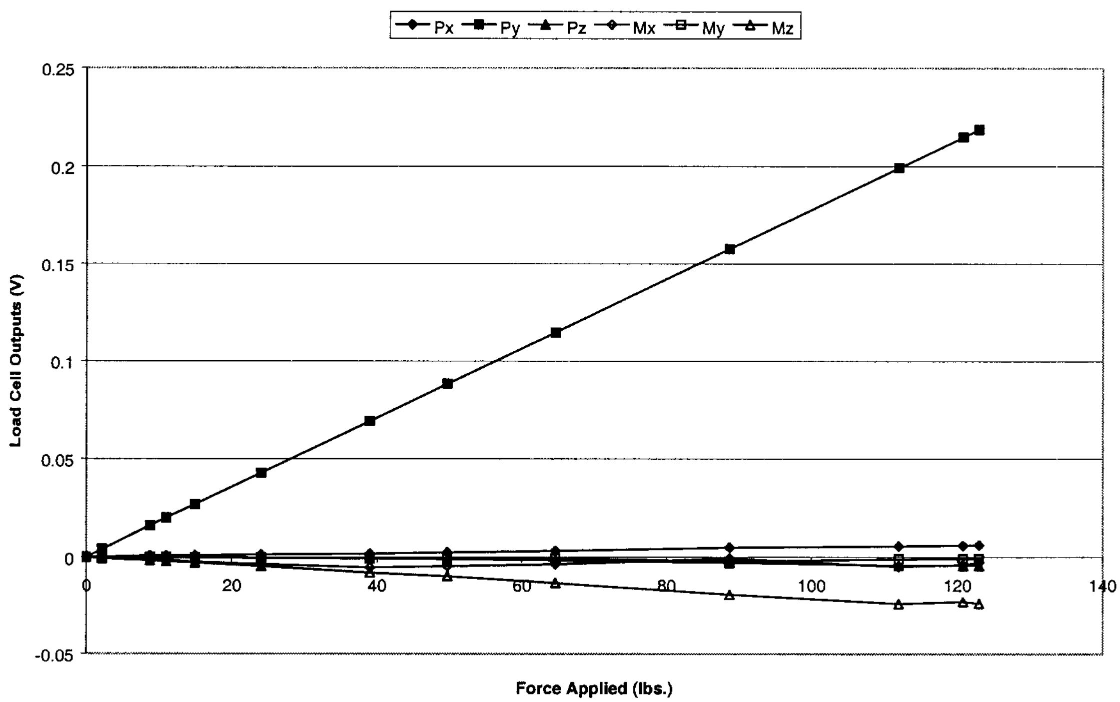

Figure 3: Load cell prototype response to $+y$ directed shear load

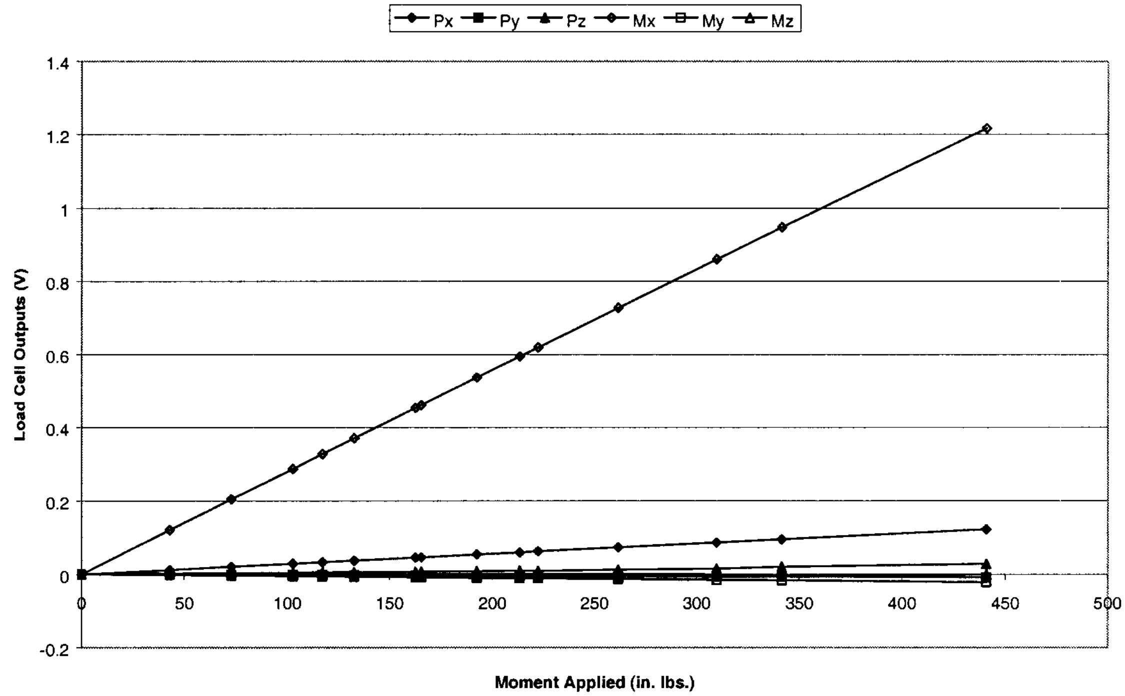

Figure 4: Load cell prototype response to bending about the *x*-axis

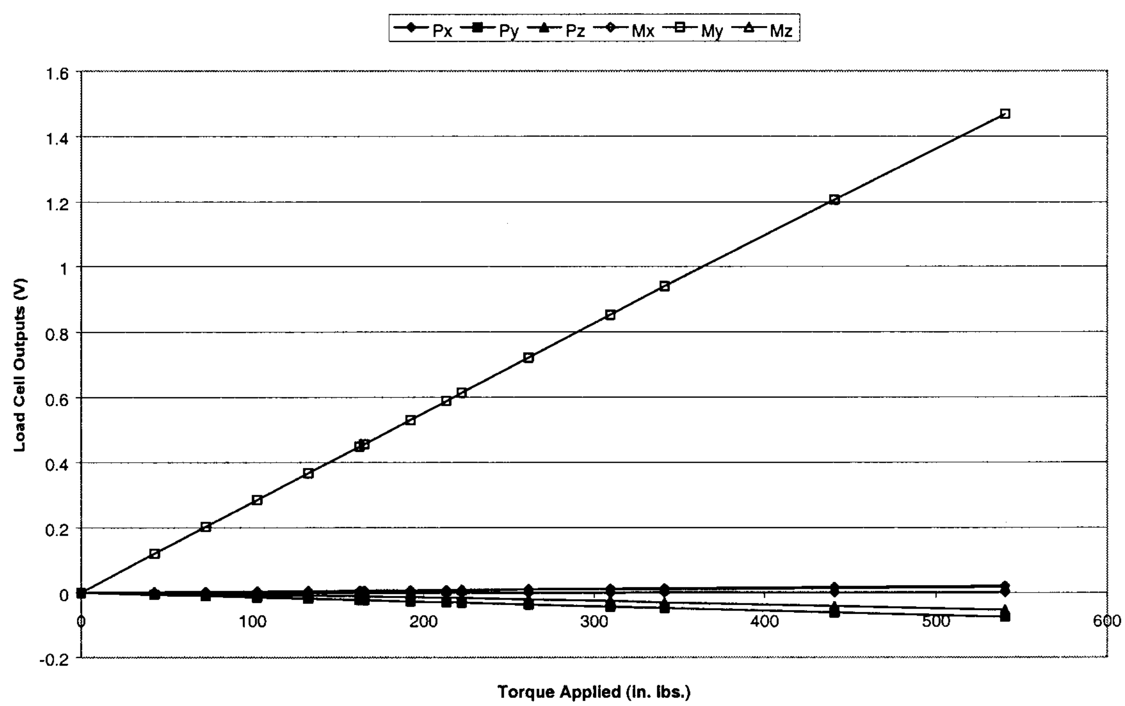

Figure 5: Load cell prototype response to bending about the *y*-axis

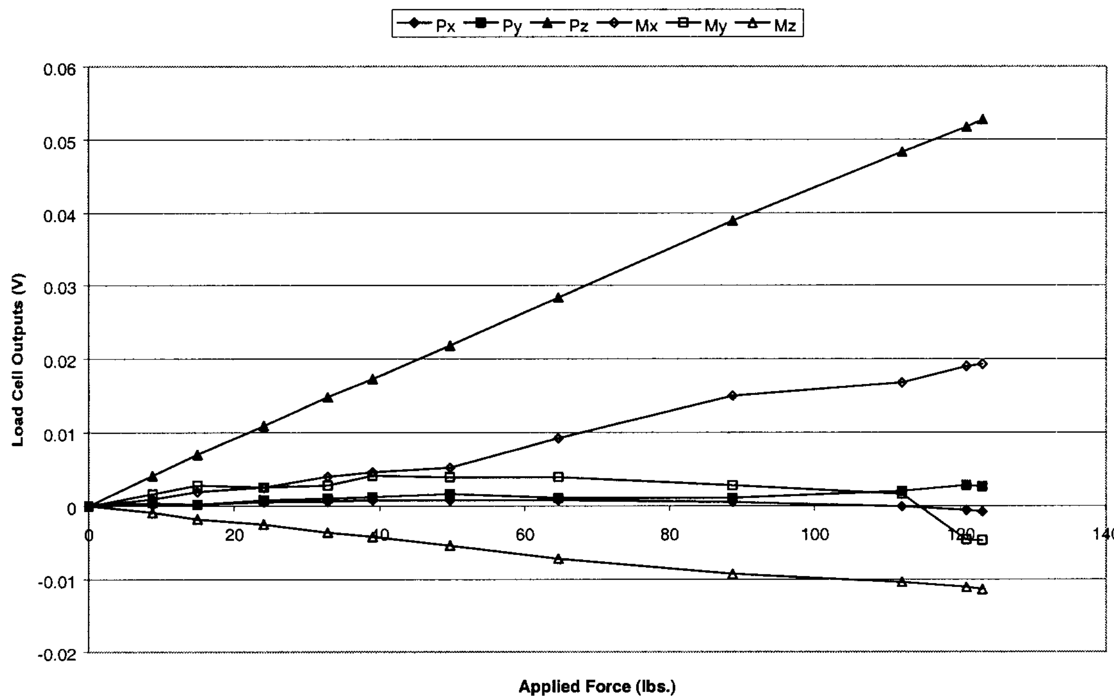

Figure 6:Load cell response to axial (z-axis) loading

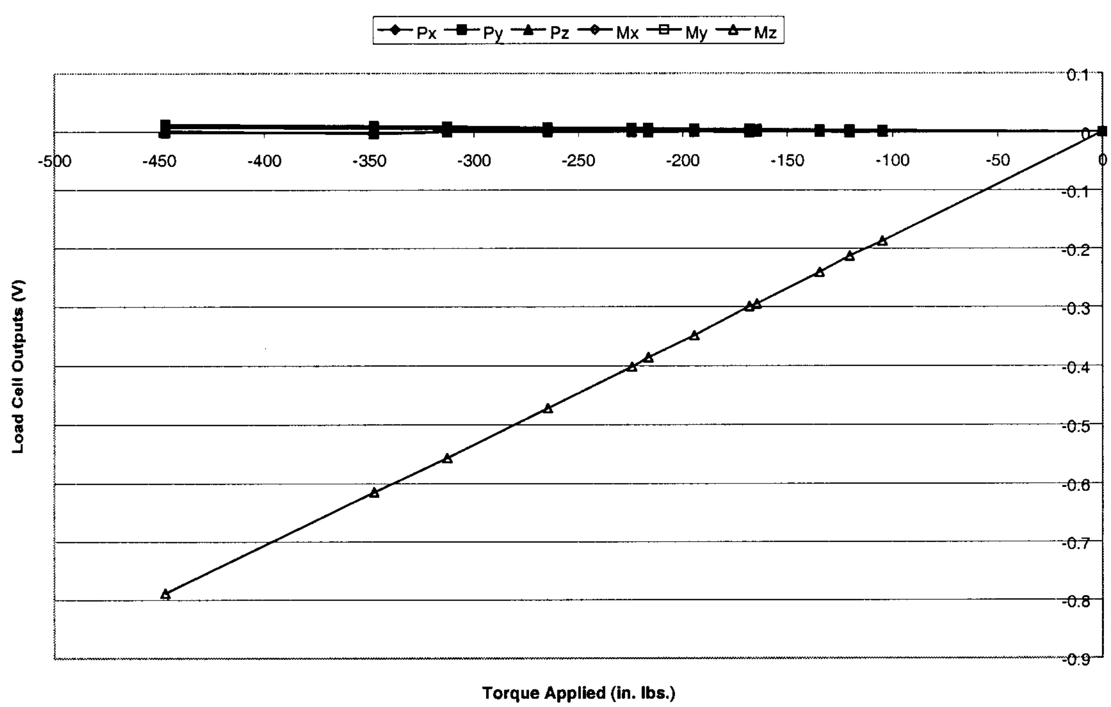

Figure 7: Load cell response to torsional loading

the six single load components. In general the load cell response is quite good. In Figures 2 through 5, a linear response and a relatively small cross sensitivity (<10%) are exhibited. Figure 6 shows the response to axial (z-axis) force applied to load cell. Here the cross sensitivity is significant, especially for x-axis bending and shear. As mentioned before, this is caused by tolerance issues in the load cell manufacture and design changes are being pursued to correct this. Figure 7 showing torsional response displays the least cross sensitivity.

As shown by the previous plots some errors will result in full six axes load measurement if the loads are assumed to be completely decoupled. These errors can be largely eliminated by using a calibration matrix rather than six independent sensitivity values for the load cell. For the above data, the best fit calibration matrix is:

$$\mathbf{C} = \begin{bmatrix} 54.7.1 & -14.9 & 21.5 & -56.5 & 1.0 & 6.1 \\ -7.0 & 563.6 & -27.2 & 6.4 & 28.1 & 8.2 \\ -2.5 & 45.2 & 2322.6 & -39.4 & 76.9 & -3.6 \\ 3.7 & 5.5 & -126.5 & 362.6 & -9.3 & 3.9 \\ -18.6 & 2.9 & -5.0 & 8.7 & 366.1 & -1.7 \\ 27.0 & 64.9 & 124.1 & 0.044 & -1.57 & 567.5 \end{bmatrix}$$

The above matrix can be used to directly convert the output voltages (in mV of output per volt of excitation input) to the applied load in lbs. or in.-lbs. by the matrix multiplication:

$$\mathbf{P} = \mathbf{CV}$$

In an ideal compliance matrix, the off axis values are all zero. Here the diagonal values are large and the off axis values are generally quite small but nonzero. The performance of the load cell can be quantified by determining the correlation coefficient between actual applied loads and the loading indicated by the voltage output. Table 2 lists these correlation coefficients. A correlation coefficient of 1.0 indicates a perfect match between actual and applied load. Numbers below 1.0 indicate less correlation. The table displays correlation coefficients both for a simple diagonal matrix and for the full calibration matrix discussed previously.

Load Component	**Correlation coefficient (R^2)**	
	Diagonal matrix	**Full calibration matrix**
PX	0.7444	1.0000
PY	0.9263	1.0000
PZ	0.5461	0.9814
MX	0.9994	1.0000
MY	0.9996	1.0000
MZ	0.9978	0.9999

Table 2: Correlation coefficients for load cell calibration

The table shows that for the diagonal matrix excellent correlation exists for moment loading but significant deviations from ideal behavior occur under sheer and axial force loading. The full calibration matrix yields excellent correlation and therefore excellent accuracy for all loading conditions.

Sandia's simplified six-axis load cell concept is not intended to be a commercial product yet but rather a technology available for licensing. This technology has the potential to produce a full six-axis load cell at much lower cost than many current technologies. Further, the lack of constraint imposed by the rules governing possible load cell geometry allows the cell to be produced in a very wide range of sizes and shapes and potentially incorporated into structural components at minimal cost.

Contact

For further information on Sandia's simplified six-axis load cell including details for arranging a prototype loan or licensing information contact:

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