Development of a 3-Axis Planer Force/Torque Sensor for Very Small Force/Torque Measurement*

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In the present paper, we propose an H-slit beam which can be effectively utilized to achieve a highly unidirectional deformable structure. The outlines and characteristics of a 3-axis force/torque sensor based on the above proposal is also reported. This sensor can measure very small reaction forces and torques generated by the motions of a robotic manipulator having its degrees of freedom in only one plane. For such an application, a sensor structure which accepts no effect of gravitational force on the manipulator is needed. The important point to consider is that the sensor should be sensitive only in the direction of measurement of force/torque, and very stiff in all other directions. To achieve this goal, we propose the H-slit structure as an extension of the parallel beam structure. The idea behind is the formation of a 4-link closed structure, the joints between the links are deformable, hence the strain gauges can be fixed at these positions. By changing the dimensions of links, a variation in sensitivity and directional stiffness is possible, and by changing the dimensions of H-slit, a mechanical over-load protection is also achieved.

Key Words: Mechatronics and Robotics, Sensor, Stress Concentration, Planer Force/Torque Sensor, Unidirectional Force/Torque Measurement, Over-Load Protection, Parallel Plate Structure

1. Introduction

It is very important for safety and design optimization of mechanical systems and large structures, for example bridges, dams etc., to measure the loads and stresses at their design stages and in operation.

A loadcell is the most widely and commonly used stress measuring instrument in industry. An octagonal elastic ring has been used for a long period to sense the 3-axis forces and torque in the machine cutting tools⁽¹⁾. Recently, many types of force/torque sensors are being used in the field of robotics as

fundamental load measuring means⁽²⁾⁻⁽⁴⁾.

In developing a force/torque sensor, it is the most important point to design a proper sensing mechanism which should convert the forces and torques into the elastic strains.

The accuracy of the developed elastic strains corresponding to the applied forces/torques, stiffness of the sensor structure itself, and the sensor dimensions are the important features to be considered during designing such sensors. Among these, the sensing accuracy is the most important feature to be thought about at the design stages.

In this paper, we report the development of a highly unidirectional force/torque sensor to measure the forces and moments in only one direction.

Many different types of sensors have been developed and commercialized, but they measure the forces and torques in all directions. Consequently, they have no proper stiffness even in the directions which are not of interest. Specially in designing such devices to measure very small forces, unnecessary strains are developed in the other directions too. This situation

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Fig. 1 Experimental model of a flexible-base space manipulator system

can be improved by employing a parallel beam structure⁽⁵⁾. However for measuring very small forces, very thin and long beams are to be used which become very weak against the twisting forces and also the natural frequency of vibration drops.

The force/torque sensor reported in this paper is to be used to measure the reaction forces from a space manipulator and to simulate its behavior, in a comparatively easier way⁽⁶⁾. This special space manipulator has freedom in only one plane, and the developed reaction forces are only of the order of ~ 5 N. In simulating the manipulator's behavior, we need to avoid any effects due to other forces, e.g. gravity etc. The mass of the manipulator is 2.4 kg, comparatively much larger than the reaction forces, and it acts directly on the sensor, hence a moment is also produced along with a planar motion due to influence of gravity. It is needed for the force/torque sensor to accept no influence of such undesired forces on the manipulator. The outline of this experimental manipulator system is shown in Fig. 1.

To fulfill the above mentioned needs, commercially available sensors can not be used, but a sensor which can sense forces in only one direction, while it should be insensitive in all other directions, is needed to be developed.

Considering this desired highly unidirectional feature, in this paper, the design and outline of a small force/torque sensor are reported.

2. Specifications for Designing of a Force/Torque Sensor

2.1 Load detecting element

Strain gauge converts the material deformation (expansion/elongation, contraction) into the electric resistance to give sense of the working force, and has been widely used for this purpose.

It is the normal practice to put the strain gauges on an easily deformable portion of a mechanical structure to sense the amount of external forces acting on it. Using the above method, the developed force/torque sensors have following properties.

- (1) High precision and good linearity.

- (2) Little influences to the varying temperatures.
- (3) Measurement of forces in dynamic phenomenon is possible, as displacement is very small.
- (4) It is Possible to make small and light load-cells, and
- (5) There is a possibility of remote measurement.

Considering the above features, we have been using strain gauges for force sensing in various different systems, and have also used them in the force/torque sensor being reported here.

2.2 Elastically deformable structure

A cantilever beam, torsional rod or an elastic ring are the common types of elastically deformable structures where the strain gauges can be used to sense the effects of external forces. The dimensions of these structures are changed depending on the amount of forces to be measured.

Moreover, it is also important for this portion of the sensorstructure to be helpful in fixing the strain gauges on it, and to produce minimum temperature dependent strains, once the gauges have been fixed. Because of these reasons, it is generally good for this deformable portion to be part of a plane surface instead of a curvature, and all other parts of the structure should be sufficiently rigid.

The effective force acting on this portion is not essentially very simple, but a combination of various different forces. However, it is demanded for this portion to deform only due to the forces in desired directions while it should be insensitive to all other forces. In case of a torsional rod, making the deformable portion very simple, strain gauges are fixed at various different places.

However, even then, sensitivity is not very good and decomposition of forces from the gauge signals is very difficult. To increase the sensitivity and to make the force decomposition simpler, a crossed beam mechanism is considered. However, in this case also, to measure small forces, the thickness of the beams is to be reduced or their lengths to be increased, again resulting in a weak structure.

On the other side, it is good from the point of view of force decomposition to use a parallel beam structure or radial plate structure⁽⁷⁾. However, here to, thinner and longer beams are desired to sense small forces. In case of thin beams, the main problem arising is the weakness of the structure and difficulty in building such a difficult and sophisticated structure by available machine tools. While using longer beams will increase the dimensions of the sensor. Both of the above changes will make the structure sensitive to undesired forces and hence corrupting the desired signals. Moreover, the natural frequency of the structure will also decrease, making the sensor unable to

respond to faster changes.

To increase the sensitivity in a simpler way, an elastic ring has been widely used, but again the structural stiffness is very small and natural frequency is quite low. That's way, it is mostly used to measure small static forces. To increase the stiffness, the portions other than the deformable area are made thicker which also adds to the directional sensitivity of the sensor to measure and decompose the forces acting on the cutting tools, for example. As the sensor base and the point of application of forces remain opposite to each other, hence even though the structure looks like a modified parallel beam structure, basically it works on the principle of a torsional ring sensor. To measure the forces in multiple directions, these structures are to be cascaded which consequently increases the total dimensions of the sensor and also reduces the natural frequency. To solve this problem of octagonal elastic ring, a sensor with two sets of parallel beams has also been proposed⁽⁸⁾. Moreover, as another solution to the mentioned problem, we can find examples of an ultra small force/torque sensor using a parallel beam structure, and one used in a robot hand^{(9),(10)}.

The necessary conditions for the ultimate sensor being reported in this paper are,

- (1) The sensor should be sensitive to only forces and moments in a plane, and it must be insensitive to all other forces and moments.
- (2) It should be quite sensitive to measure the small reaction forces ~ 5 N generated due to manipulator motions.
- (3) It should be stiff against the gravity.

3. An H-Slit Beam Structure

In this section, we will develop the design concept of the elastically deformable part of the sensor which should obey the necessary conditions outlined above.

3.1 The cantilever beam model

As the force to be detected is very small, we need

Fig. 2 Beam model of sensor

to think about a structure which should deform easily. Thinking about this factor, a cantilever beam model given in Fig. 2 can be considered.

Departing from the model [A] of a simple cantilever beam in Fig. 2, we will proceed to fulfill the above requirements. In all the models given in this figure, the forces acting on the beam tip are detected by the strain gauges fixed at the root of the beam.

First of all we will think about condition (1) given above. F_z , M_x and M_y are the force and moments of no interest in [A] and hence we need to modify the structure not to deform due to these parameters. For F_z and M_x , increasing the width of beam b will stiff it to this force and moment, increasing the thickness of beam will make it stiff to M_y . However, increasing both width and thickness will make the beam insensitive to F_x also, which is one force of our interest. To avoid this, a parallel beam cantilever structure of [B] can be thought, where ($b' > b$). There is no effect of the space between the beams, h , on its sensitivity to F_x , and hence it can be made stiffer to M_y .

Now, considering about the condition (2), due to limitations of strain gauge sensitivity and amplifier gains, it is desired to modify the structure so that it may show larger deflection even to vary small force F_x . To make the beams easily deflectable, it is a normal practice to increase their lengths l . Doing so will increase the amount of deflection even with the same small force F_x . Another choice is to decrease the thickness of the beams t , and this will also make the beams easily deformable with small forces. Shortly, condition (2) will be met by modifying the beams as shown in [C] ($l' > l$, $t' < t$).

However, doing the above modification will make it difficult to fulfill the condition (3). In other words, making the beams weaker to increase the sensitivity will decrease the stiffness generally. Therefore, it is important not to reduce the stiffness below a desired value. To detect the amount of deflection, it is sufficient to only fix the strain gauges where deflections are the largest, while there is no need of putting gauges in the other parts. Considering this, it is sufficient to reduce the thickness of beams only where the deflection is the largest, and gauges are fixed, as shown in [D]. However, in this way, reducing only the thickness of places where gauges are fixed and keeping the rest of beams thicker, will make it difficult for them to even deflect at the thinner parts, due to structural resistances. Therefore, the points closer to the tips are also made equally thin to make it possible for the structure to deflect as a parallelogram distance between thinner portions l'' will increase the sensitivity, while an increment in the

Fig. 3 Deformation mechanism of parallel plate and H-slit beam

Fig. 4 Experimental model of H-slit beam

beam width b' and distance between them h will increase the stiffness, without affecting the sensitivity. s is the width of the slit to make the beams easily deformable and it has no effect on the sensitivity. We will name this structure as an H-slit beam.

The main advantage of the H-slit beam over the parallel beam structure is that all the stresses develop strains only in the parts where strain gauges are fixed. While in the parallel beam structure, as forces distribute over the span of the beams, it is desired to increase the beams' lengths to increase the sensitivity. Doing this will make parallel beams sensitive to other undesired stresses too.

The difference between the deflections of the two structures is shown in Fig. 3.

3.2 Experimental verification

Here, we will verify the above-mentioned conditions using the experimental H-slit beam shown in Fig. 4.

Two rectangular Aluminum pipe sections, working as the two ends of the beam, are connected with each other through two flexible beam elements (brass plate: $t=0.5$ mm). To make the unnecessary parts of these flexible beams stiffer, as desired for H-slit, solid aluminum cubes are fixed with bond and screws. To

	(A)	(B)	(C)	(D)	(E)	(F)
	$0F_x$	$1F_x$	$0F_z$	$0M_y$	$1M_y$	$1F_y$
Load	$1M_z$	$0M_z$	$0M_x$	$0F_z$	$0F_z$	
[N]				$0M_x$	$0M_x$	
0	0	0	0	0	0	0
0.49	-25	30	0	0	0	0
0.98	-58	59	0	1	0	0
1.47	-82	88	1	2	1	0
1.96	-114	118	1	3	1	0
2.45	-140	147	2	3	1	1
2.94	-167	176	2	4	1	1

Fig. 5 Relationship between load and strain

this experimental H-slit beam structure, a combination of 6-directional load is applied, as shown in Fig. 4, and the characteristics are examined using the strain gauges data. The results are shown in Fig. 5. 0 and 1 indicate the minus and plus directions of an axis.

From this experiment, it is very clear that the H-slit beam structure is sensitive only to F_x and M_z while it is almost insensitive to F_y , F_z , M_x and M_y . From this, we can conclude that the proposed H-slit beam structure is fulfilling all the three conditions, and it is safe to use it in the sensor development.

3.3 Over-load protection (mechanical stopper)

In case, when the modulus of elasticity of the deflecting portions of the beams is very small, care is to be taken not to deflect the beams beyond the elastic limits. It means that the elastic beams are to be protected against a permanent deformation and the strain gauges against their workable limits.

The H-slit beam proposed in this paper has a property of being highly directional. The four thinner and easily deflectable portions and the solid portions make this structure the same as a 4-bar mechanism, and changing the dimensions of four bars allows variations in directivity and sensitivity. Using this property of 4-bar mechanism, an overload protection, like one shown in Fig. 6, can be realized. This overload protection does not allow the H-slit structure to deform beyond a limit.

Considering the deforming portion of H-slit beam

Fig. 6 Mechanism of mechanical over-load protection

Fig. 7 Overview of the 3-axis force/torque sensor

structure the same as a rectangular cantilever beam, as illustrated in Fig. 6, we can calculate the maximum deformation as given below. Taking the thickness of the cantilever beam as t , breadth as b , maximum loading as $F_{\max}$, distance between the point of application of force and the fixed end of the beam as l , and the number of parallel cantilever beams as n (here $n=2$), the maximum deformation $\delta_{\max}$ can be,

$$\delta_{\max} = \frac{F_{\max} l^3}{3nEI} \quad (1)$$

where, E is the longitudinal modulus of elasticity and I is the moment of inertia of the cross-sectional area, in this case $I = bt^3/12$. The change in the slit length s is almost negligible, and hence the deformation angle θ can be taken simply equal to θ' i.e. $\theta = \theta'$. Then the length of the mechanical stopper d can be calculated as,

$$\tan \theta' = \frac{\delta_{\max}}{s} = \frac{s}{d} \quad (2)$$

$$d = \frac{s}{\tan \theta'} \quad (3)$$

WEDM (Wire-cut Electrical Discharge Machine) can easily cut a slit of width 0.05 mm and hence by changing s and d , a good mechanical stopper can be made.

Fig. 8 Part of H-slit 3-axis force/torque sensor

4. Planer 3-Axis Force/Torque Sensor

4.1 Sensor structure

An overview of the prototype planer 3-axis force/torque sensor is given in Fig. 7. The material with high modulus of elasticity, like spring-steel, Cu-Be alloy and high-strength aluminum alloy etc., can be used to manufacture the sensor. As the main theme behind the development of this prototype sensor was to sense very small forces, and since a light structure is necessary, we used high-strength aluminum alloy (JIS: A2017).

During machining the internal parts of the H-slit, to maintain a high quality and precision, a specially-made jig was used for the WEDM (wire diameter is 0.3 mm).

For the sensor structure, two separately prepared H-slit beam structures, one for x -direction and one for y -direction, are cascaded one above the other. In Fig. 7, the lower part is for x -axis force sensing and the upper one is for y -axis.

Both of these parts are the same in structure, but they are placed at right angle one upon the other in the external case, after fixing the strain gauges at proper places, and tightly fixed in the case with screws. A strain gauge on a face and the one placed at the opposite face make a set and consequently opposite limbs of the wheat stone bridge. To fix the sensor compactly in the manipulator, a hole for the sensor motor shaft is also drilled in the sensor structure. Therefore, H-slit is little drifted to remain well away from this servo attachment. However, there is no change in characteristics of the sensor due to this drift. The modified pattern of the H-slit beam is shown in Fig. 8.

4.2 Estimation of prototype sensor ability

In the present prototype sensor, four strain gauges are fixed in both x and y directions to double

the sensitivity, and a 2-gauge method is used to pick up the deformation data. There are a total of eight deformable sections in each direction and using eight strain gauges, a 4-gauge method can be used to increase the sensitivity up to four times. With these two sets of H-slit sensors, forces in x and y directions and a moment around z -axis can be sensed.

It is desired to calculate the force and moments ($\mathbf{F}$) using the small deformations in the strain gauges (ϵ). Considering the deformation in the sensor structure as completely elastic, the linear relationship between ϵ and $\mathbf{F}$ will become

$$\epsilon = \mathbf{C}\mathbf{F}. \quad (4)$$

Here $\mathbf{C}$ is an $n \times m$ compliance matrix of strain gauges, n is the number of elements in the strain vector, m is the number of desired forces and moments. Knowing the elements of $\mathbf{C}$ in a preliminary experimentation/calibration, $\mathbf{F}$ can be calculated by the above simple equation. There are various methods of calibration. In this paper, we used the complex loading method proposed by Uchiyama⁽⁴⁾. This method has advantages of demanding simple equipment and there is no problem of friction.

In this calibration method, different forces under the action of gravity are applied at randomly different points, away from the center of gravity, by changing the orientation of the sensor. From the data obtained, the compliance matrix of strain gauges is calculated. Sensor is fixed with a simple mechanical arrangement, and a calibrated weight is freely hanged through a point in the sensor body. For the moment, a cantilever beam is fixed with sensor and a calibrated load is applied on it at a known distance. This procedure is repeated for each axis.

For the proposed prototype sensor, the compliance matrix $\mathbf{C}$ is known to be

$$\mathbf{C} = \begin{bmatrix} -1.2987154 & -62.126375 & 358.91188 \\ 64.584132 & -1.3464009 & -437.60554 \\ 0.11082143 & 66.864708 & 373.09010 \\ -59.483303 & 0.966183368 & -385.34039 \end{bmatrix}. \quad (5)$$

The unit for the elements of column 1 and column 2 is [$\mu\text{St}/\text{N}$], and that for column 3 elements is [$\mu\text{St}/\text{Nm}$]. The different data acquired in this calibration are shown in the plots of Fig. 9.

Figures 9 (a), (b) and (c) show the deflections ϵ_1 through ϵ_4 when the sensor is loaded along x -axis, y -axis and z -axis respectively. For x -axis loading, only ϵ_3 and ϵ_4 are sensitive. ϵ_3 and ϵ_4 are fixed exactly opposite to each other, and hence, when one stretches, the other one is compressed, and therefore the signals obtained are also complementing each other. In this way, it is possible to know the direction of application of force also. Similarly, in the y -direction too, only ϵ_1

Fig. 9 Relationship between output and the load

and ϵ_2 are generating outputs, and there is no sensitivity in the z -axis direction.

Figures 9 (d) and (e) show the moments around x -axis and y -axis, and there is no sensitivity at all. From these results, it can be concluded that there is high sensitivity for the forces and moment in a plane while there is a high degree of stiffness to all other forces and moments in the perpendicular directions.

Figures 9 (f) and (g) give the moment around z -axis, the data obtained is the addition of forces purely in x and y directions and the moment due to them around z -axis.

The x -axis variables in the plots (d) through (g) are the forces F_z , F_y and F_x plus the moments developed due to these forces, $1M_x$ and $1M_y$, $0M_z$, and $1M_z$, respectively.

An inspection of this plots revealed that, the maximum offset around the fitted linear curves was $\pm 0.7\%$. Therefore it can be concluded that the

response is adequately linear. Moreover, the ratio between the desired data in a plane (F_x, F_y, M_z) and the undesired ones (F_z, M_x, M_y) was a maximum of 2%, which is quite small to consider.

5. Conclusions

In designing a force/torque sensor, it is demonstrated that an H-slit beam is very useful when it is desired to increase the sensitivity retaining the stiffness of the sensor. Moreover, it is also reported that this structure has also an embedded overload protection capability.

Using this H-slit beam structure, development of a sensor for very small forces is demonstrated and its characteristics are investigated.

This idea is useful for sensing small forces with a high natural frequency in the probe of an AFM (Atomic Force Microscope), an accelerometer, etc.

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