Stack structured hybrid load cell for a high-stroke system

Namryul KIM* and Bumjoo LEE*
* Department of Electrical Engineering, Myongji University
San 38-2 Namdong, Yongin, Gyeonggi-do, 449-728, South Korea
E-mail: bjlee@mju.ac.kr

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Abstract
The load cell is an essential sensor for the force measurement systems. The sensitivity of a typical load cell for general force measurement is constant over the full operating range. For high stroke systems such as hydraulic systems, this property is not suitable because of insufficient resolution at the small loading force. High stroke systems require higher sensitivity in the small loading force compared with in the large loading force. In other words, for the high control performance, the smaller loading force is applied, the higher sensitivity is necessary to the systems. The optimal relationship between strain and force can be expressed as a logarithmic function. Based on this relationships, we developed a hybrid load cell which has a piece-wised linear model based on a stack structure. In addition, equipment for loading test was invented to examine and compensate the load cell quantitatively. By using this equipment, compressive force, tensile force and torque can be applied from a small force to a large force in accordance with the seesaw principle. The performance of the proposed system was verified by experiments.

Keywords: Load cell, Strain, Logarithm, Piecewise model, Hybrid structure

1. Introduction

A load cell is a transducer that converts mechanical forces and/or torques to electrical signals quantitatively (Muller et al., 2009). When a load is applied to the sensor system, the elastic parts of the mechanical structure are deformed at the micro-scale. Subsequently, mechanical strains are converted to electrical signals by using strain gauges which have resistances proportional to the strain. After that, these are translated into digital information by using ADC (Analog to Digital Converter) circuits. A load cell is widely employed in a lots of applications which require quantitative measurement of the applied force. In robotics especially, the load cell enables high precision force control by providing accurate information of actuator output forces and/or contact reaction forces (Adami et al., 2009; Choi et al., 2001; Demetropoulos et al., 2009; Gilbertson et al., 1999; Gobbi et al., 2011; Mastinu et al., 2011; Oh et al., 2009).

It is necessary to measure large forces in several applications such that operate with high contact forces with an environment. In these applications, it is difficult to acquire force values with sufficient sensitivity at a small loading force because typical load cells are designed to operate as a linear scale for the whole operating range. In addition, this gets worse due to the limited ADC resolution. When a physical quantity is changed to the other information (e.g., conversion from force to strain), it is necessary to assign the sensitivity properly based on the input scale. A biological system can capture the small difference in a low stimulus, while it cannot distinguish between identical differences in a high stimulus. This illustrates that the system possesses high sensitivity at a low input value and low sensitivity at a high input value. Similarly to the biological system, it is effective for a load cell to follow the nonlinear behavior which enables to cover a wide measurement range with sufficient performance. That is, high sensitivity is required at a low applied force value and vice versa. In this paper, a mathematical model is formulated and a subsequent approximation model is introduced to examine the fore-mentioned characteristics.
In Section 2, a strain model with respect to the applied force is formulated to cover a wide measurement range effectively. In Section 3, a stack structured hybrid mechanism is proposed and a prototyped system is also explained. Section 4 presents and analyzes experimental results involving vertical loading. Finally, the study conclusions are discussed in Section 5.

2. Problem definition and formulation

Mechanical deformation occurs when the external load is applied to the frame of a load cell. Subsequently, this causes a strain corresponding to the force. By measuring the strain value, the applied force can be estimated indirectly. A strain gage is commonly utilized to measure the strain. The resistance of a strain gage is proportional to its strain, and Wheatstone bridge circuit is utilized to convert the resistance to an electrical signal (Takezawa et al., 2010). After amplification, it is possible to measure the electrical signal to estimate the applied force.

In lots of applications, a load cell is often utilized to control the task of the manipulator robot by measuring the forces of actuators and/or the external forces. The higher the precision and the wider the operating range, the better the performance. Since there is a trade-off between the precision and the operating range, an optimal model is required. In this section, mathematical model of force and strain is formulated and piece-wised model is introduced.

2.1 Nonlinear strain model

The sensitivity of a load cell can be defined as the differential motion of the strain and the applied force as follows:

Definition 1: The sensitivity of a load cell is expressed as the derivative of strain with respect to force.

\[ \rho = \frac{ds}{df} \]

where \( f \) and \( s \) represent applied external force and consequent strain of a load cell, respectively. The elastic part of a conventional load cell is modeled and designed to generate linear deformation along the applied force (Lee et al., 2014). Consequently, the sensitivity of the load cell is constant over the entire operating range. The sensitivity in a small loading force should be larger than the sensitivity in a large loading force for the precise control. Conversely, to enlarge the measurement range, accuracy in a large loading force becomes low. That is, the measurement range is more important than the accuracy in a large loading force (Mason et al., 1991). To apply this relationship, a new nonlinear property is proposed in which the sensitivity is inversely proportional to the applied force as follows:

\[ \rho = \alpha \frac{1}{f + \beta^*} \]  \( \text{(1)} \)

where \( \alpha(>0) \) and \( \beta^*(>0) \) denote a proportional coefficient and offset constant to limit the initial sensitivity as a finite value at the origin, respectively. The nonlinear relationship between the force and the strain is derived by applying Eq. (1) to the sensitivity definition as follows:

\[ ds = \alpha \frac{df}{f + \beta^*} \]  \( \text{(2)} \)

Integrating Eq. (2) gives the logarithmic function:

\[ s = \alpha \ln |f + \beta^*| + c \]  \( \text{(3)} \)
where \( c \) denotes the integral constant. Strain does not arise when the force is not applied. This initial condition is applied to Eq. (3) and \( \beta^* \) is substituted with a new parameter \( \beta = 1/\beta^* \) to derive the strain function with respect to the applied force as follows:

\[
s = \alpha \ln|1 + \beta f|
\]  

(4)

Figure 1 Nonlinear strain model.

Figure 1 represents the nonlinear strain model expressed as a logarithmic deformation with respect to the applied force. As shown in the figure, the slope (=sensitivity) is high in the low force region and vice versa. That is, the variation rate of the sensor output with respect to the applied force changes based on the logarithmic graph in a manner similar to a biological system’s manner. Consequently, this enables a sensitive reaction at a low input value and can accommodate a wide range of input signals by desensitizing an input at a high input value.

2.2 Piecewise linear model

Although the logarithmic strain model is optimal, it has some difficulties of implementation. Instead, a piecewise linearization technique is adopted to approximate this model. Deformation parts are divided into two linear segments as shown in Fig. 2, where \( f_0 \) denotes the origin and \( f_1 \) and \( f_2 \) denotes the upper boundary of the operation range for the micro and the macro sensors, respectively. The first segment approximates a nonlinear strain model with high steepness for the low input value. In contrast, the second segment deforms with a low slope. As a result, it can accept a large range of the applied force. For the purposes of simplicity, each segment is named as micro sensor \( (f \in [f_0, f_1]) \) and macro sensor \( (f \in (f_1, f_2]) \), respectively.

As shown in the figure, the micro sensor deforms from \( f_0 \) to \( f_1 \) while the macro sensor deforms from \( f_0 \) to \( f_2 \). The deformation part in the micro sensor was designed to operate under \( f_2 \), and thus, it should be limited when an overload is applied. Therefore, a protection mechanism is installed to prevent plastic deformation, which any further deformation with respect to the loading.
3. Hybrid structure

3.1 Stack structured mechanism design

The proposed load cell is composed of a micro sensor and a macro sensor that are connected in the form of a stack structure as shown in Fig. 3. Thus, these two sensors are simultaneously deformed when an external force is excited. Each sensor continues deformation until it reaches a saturation point ($s_m \leq s_m^1$ and $s_M \leq s_M^1$), i.e., stopper.

![Fig. 3 Hybrid load cell structure (clearance and design of the parts).](image)

In the figure, “a” and “e” denote the top and bottom plates, respectively, to transmit the external load to the deformation parts. Additionally, “b” and “d” denote core sensor frames for the micro sensor and the macro sensor, respectively, and “c” and “e” denote the mechanical stoppers for “b” and “d” to prevent the plastic deformation over the maximum loading, respectively.

3.2 Electric circuit design

Strain gauges are utilized to measure the strain of the deformed frames. In order to maximize the output signal with respect to the applied force, the strain gauges are attached at the optimum point at which the maximum strain occurs. The proposed load cell is designed to only measure the vertical load. Therefore, it is designed such that the other directional forces and the torsional force are canceled. In a manner similar to the conventional scheme, the signal outputs due to the other directional forces except the vertical load are cancelled by a symmetric arrangement of the strain gauges as shown Fig. 4. Four strain gauges are attached at the top and the bottom plates as a single pair. In the developed system, two pairs of strain gauges are used for both x- and y-axis directions as shown in the figure. Wheatstone bridge circuits are also utilized to effectively generate an output voltage signal, which is proportional to the strain.

![Fig. 4 Strain gauge attachment in the developed prototype.](image)
Since the electric signal of the Wheatstone bridge circuit is too low for the microprocessor, the signal was amplified through the OP amp circuit. The resistance value of each strain gauge is slightly different from the other gauges inherently. Also, misaligned bonding of the strain gauge increases the imbalance. To compensate and calibrate the signal, voltage divider circuit was added at the non-inverting input of OP amp circuit as illustrated in Fig. 5.

![Fig. 5 Signal measurement circuit with a compensator.](image)

The compensation circuit distorts the original input signal, and thus it is necessary to analyze associated side effects. By a computer simulation, it was ensured that the difference does not exceed an error corresponding to 0.03%. The signal can be effectively amplified as well as compensated by using the measurement circuit.

4. Experiments

To apply the load only into the vertical direction of the prototyped load cell, loading equipment was also developed as shown in Fig. 6. Gravitational force is utilized to generate the vertical force by loading premeasured weights with a high precision scale. To remove the influence of the other directional forces, a small metal sphere was employed to transmit the loading force except the horizontal force from the misaligned loading, which is shown in the red box in the figure.

![Fig. 6 Equipment for loading test (test jig and employed small metal sphere).](image)

Loading test was accomplished several times by increasing the weights until the maximum value which is computed with FEM simulation. Experimental results is shown in Fig. 7. Since there are two pairs of Wheatstone bridges for each micro sensor and macro sensor, four graphs were displayed. The upper two graphs and the lower two graphs are corresponding to the micro sensor and the macro sensor, respectively. As intended, the steepness of the micro sensor is higher than that of the macro sensor. Both of the strain curves of the two micro sensors were similarly saturated near 150 N. The strain curve for the x-axis was saturated near 300 N, which is twice as designed; however, the strain curve for the
y-axis of the macro sensor was not saturated until 400 N. This discordance was observed because the actual clearance was larger than the designed clearance in stopper at micromachining and assembling.

![Strain curve](image)

**Fig. 7** Strain curves of each sensor.

Although the load cell is intended to measure only the vertical force, i.e. z-axis force, the horizontal and/or the torsional forces can be applied to the sensor in actual applications. This possibly can cause undesirable distortion to the strain of the sensor frame and degenerates the accuracy by correlation effect. To reduce this, the developed system was designed to reject the undesirable force mechanically and electrically by symmetrical frame design and strain gauge attachments. To analyze the influence, the equipment should be able to apply the horizontal force quantitatively. Figure 8 illustrates the device, which generates the force in tangential direction as well as the normal force. Experiments of the horizontal force will be carried out in a future work.

![Inclined load measurement unit](image)

**Fig. 8** Inclined load measurement unit.

### 5. Conclusion

This paper proposed the nonlinear logarithmic model as a strain function with respect to an applied loading force. Subsequently, piece-wised linear approximation was adopted to simplify the model, and the stack structured hybrid load cell was developed. The load cell was composed of two linear sensors: a micro sensor and a macro sensor. The micro sensor takes charge of low loading force range and gives more sensitive output than the macro sensor. This enables high precision task. Conversely, the macro sensor focuses on a wide range of sensing rather than the sensitive information, which enables to cover the wide measurement range. The proposed method was verified by quantitative experiments with loading test equipment. In future work, sensor stiffness will be taken up to increase the measurement range. In addition, the interference of the force correlation and the impulse response will be analyzed.
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References

Adami, A. M., Pavel, M., Hayes, T. L. and Singer, C. M., Detection of Movement in Bed Using Unobtrusive Load Cell Sensors, IEEE Transactions on Information Technology in Biomedicine, Vol.14, No.2, (2009), pp.1089-7771.
Choi, K.-H., Kim, G.-C. and Lee, D.-G., Analysis of Walking Loads Measured by Using Loads Cells, Architectural Institute of Korea Conference Proceedings, Vol.21, No.1 (2001), pp.219-222.
Demetropoulos, C. K., Morgan, C. R., Sengupta, D. K. and Herkowitz, H. N., Development of a 4-axis load cell used for lumbar interbody load measurements, Medical Engineering & Physics, Vol.31, No.7, (2009), pp.846-851.
Gilbertson, L. G., Doehring, T. C., Livesay, G. A., Rudy, T. W., Kang, J. D. and Woo, S. L., Improvement of Accuracy in a High-Capacity, Six Degree-of-freedom Load Cell: Application to Robotic Testing of Musculoskeletal Joint, Annals of Biomedical Engineering, Vol. 27, No.6, (1999), pp.839-843.
Gobbi, M., Previati, G., Guarneri, P. and Mastinu, G, A New Six-axis Load Cell. Part II: Error Analysis, Construction and Experimental Assessment of Performances, Experimental Mechanics, Vol.51, No.3, (2011), pp.389-399.
Lee, D. W., Park, M. H., Lee, G. G., Kim, I. H. and Lee, S. S., Development of the Pin Type Load-cell Using Strain Gauge, Journal of the Korean Society of Manufacturing Process Engineers, Vol.13, No.4, (2014), pp.75-82.
Mason, W., Johnson, P. F. and Varner, J. R., Importance of load cell sensitivity in determination of the load dependence of hardness in recording microhardness tests, Journal of Materials Science, Vol.26, No.24, (1991), pp.6576-6580.
Mastinu, G., Gobbi, M. and Previati, G., A New Six-axis Load Cell. Part I: Design, Experimental Mechanics, Vol.51, No.3, (2011), pp.373-388.
Muller, I., de Brito, R. M., Pereira, C. E. and Brusamarello, V., Load Cells in Force Sensing Analysis-Theory and a Novel Application, IEEE Instrumentation & Measurement Magazine, Vol.13, No.1, (2009), pp.1094-6969.
Oh, S.-N., Lee, G.-S. and Kim, G.-I., Design of ZMP Sensor System for Biped Robots, KIEE Conference on information and control systems, (2009) pp.170-171.
Takezawa, A., Nishiwaki, S., Kitamura, M. and Silva, E. C., Topology optimization for designing strain-gauge load cells, Structural and Multidisciplinary Optimization, Vol. 42, No.3, (2010), pp.387-402.