Design and Development of Impact Load Sensor for Dynamic Testing Purposes

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Abstract. The purpose of this research is to produce an impact load sensor - a laboratory dynamic testing equipment that fulfills good criteria for education purposes and real time impact load measurement in actual conditions. For this purpose, a force transducer with 4-gauge system was used. A performance of the sensor was evaluated by considering static characteristics of the sensor exhibited upon applying static load and dynamic load of maximum 10 kN. Experimental tests were performed on a blank of aluminum Al601-T6 and strain gauges configured with Full-Wheatstone bridge system and held in the Dynamic Laboratory, Indonesia University of Education (UPI) Bandung. The experimental tests showed that the static characteristics of the sensor indicating its promising performance. The accuracy, linearity, and repeatability in static and dynamic load measurements showed error values bellows ± 3 % f.s. (full-scale reading). Those meet with specifications expected in the research design.

1. Introduction

An electrical resistance strain gauge force transducer is the most common sensing instrument to measure loads used in various field including, machinery, automobile, electrics, civil engineering construction, chemical, medical treatment and laboratory experiments. It typically consists of metal as transducer body and strain gauges as sensing elements to detect strain in the transducer body.

Use of strain gauge enables detection of minute elongation or contraction occurring on a structure. The detected elongation or contraction enables us to know stress generated in the structure. Strain gauges are manufactured for various purposes ranging from static strain measurement to dynamic and impact strain measurement at several hundred kHz. The wide application range makes them conveniently usable for structures of various materials and shapes.

Strain gauges are also used as sensor elements for measurement of loads, pressure acceleration, displacement, and torque. Thus, they are widely used not only for experiment and research but also industrial measurement and control.

Industrial force transducers are usually made from one of three materials, namely aged-hardened aluminum, alloy tool steel, and stainless steel. Those materials can be selected upon requirement of loads to be measured, and static characteristics of the instrument required.

For laboratory experiments, strain gauge force transducers made from aluminum are of most common to measure loads in small range usually up to 10 kN [1]. The laboratory measurement using strain gauge transducers is usually taken to estimate maximum loads that can be applied to structures or machineries. For instant, the transducer is used to estimate unbalance force in crankshafts, and measure dynamic load in bearing cases.

At the moment, the availability of force transducer and its instrumentation in dynamic laboratory DPTM UPI Bandung is very limited. It makes barrier for students from doing experiments and research to measure forces occurring in structures and machines. They need to deeply understand the effect of dynamic loads to the machines and structures in order to make proper engineering designs. Thus, some experimental works need to be done. Unfortunately, this can't be accomplished due to the limited facilities in the laboratory. In order to solve the problem, this research focused in creating a dynamic force transducer is proposed.

1.1 Scope of the research
This research mainly focused in creating a force transducer to measure static and dynamic loads which can be used for laboratory purposes. It is expected to have bellow specifications:

- Input range = 0 to 10 kN
- Type of load: static and dynamic.
- Maximum overall error = ± 3% f.s. (full-scale deflection).

1.2 Research aims
The main goal of this research is to create a force transducer to measure static and dynamic loads for education purposes, especially for Engineering dynamics course. It should meet with the specifications, easy to operate, and low cost.

2. Theory

2.1 Principle of strain gages and strain measurement
Each metal has its specific resistance. If external tensile force (compressive force) increases (decreases) the resistance by elongating (contracting) it. Suppose the original resistance is R and the strain-initiated change in resistance is ΔR. Then, the following relation is concluded:

$$\frac{\Delta R}{R} = Ks.\frac{\Delta L}{L} \qquad (1)$$

Where, Ks is a gage factor, expressing the coefficient of strain gage sensitivity. General purpose strain gages use copper-nickel or nickel-chrome alloy for the resistive element, and the gage factor provided by these alloys is approximately 2 [2].

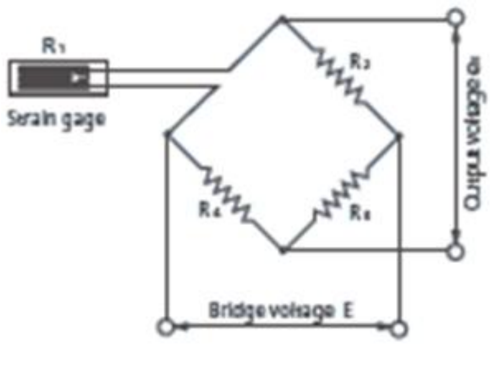

Figure 1. Strain gage connection

Strain initiated resistance change is extremely small. Thus, for strain measurement a Wheatstone bridge is formed to convert the resistance change to a voltage change. Suppose in Fig. 1 resistances (Ω) are R_1, R_2, R_3 and R_4 and the bridge voltage (V) is E. Then, the output voltage e_o (V) is obtained by the following equation [3]:

$$e_0 = \frac{R_1R_3 - R_2R_4}{(R_1+R_2)(R_3+R_4)}.E \qquad (2)$$

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2.2 Strain gage wiring system

Bridge circuits are used very commonly as a variable conversion element in strain gauge wiring system and produce an output in the form of a voltage level which changes as the measured physical quantity changes in value. A null-type bridge with d.c. excitation, commonly known as a Wheatstone bridge is widely used.

A strain gage Wheatstone bridge is configured with a quarter, half, or full bridge according to the measuring purpose. With the 1-gage system, a strain gage is connected to one side of the bridge and a fixed resistor is connected to each of the other 3 sides. This system can easily be configured, and thus it is widely used for general stress or strain measurement [1]. The output voltage is derived from equation (2).

With the 2-gage system, 2 strain gages are connected to the bridge, one each to adjacent or opposite sides with fixed resistor inserted in the other sides. The output voltage for the active-active system is expressed as follow:

$$e_0 = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} + \frac{\Delta R_2}{R_2}\right)E \quad (3)$$

The 4-gage system (Fig.2) has 4 strain gages connected one each to all 4 sides of the bridge. This circuit ensures large output of strain gage transducers and improves temperature compensation as well as eliminates strain components other than the target strain. The output voltage is determined as follow:

$$e_0 = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)E \quad (4)$$

If the gages at the four sides are equals in specifications including the gage factor, Ks, and receive strains, ε_1, ε_2, ε_3 and ε_4, respectively, the equation above will be:

$$e_0 = \frac{1}{4}.Ks.(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)E \quad 5)$$

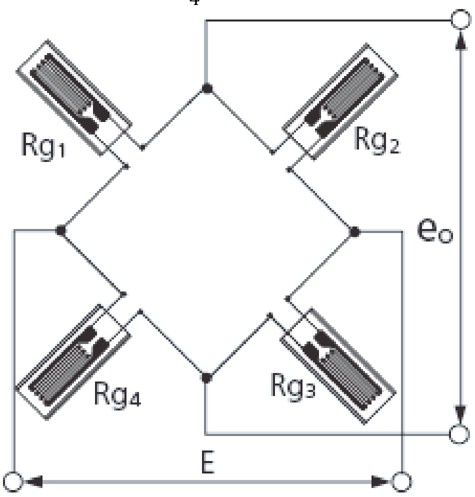

Figure 2. 4-gage system

2.3 Previous studies of strain gage application

Many researchers describe the applications of strain gage in all purposes have met with their requirements; however, not of them relates to application in education purpose. The basic idea presented in theses references is that strain gage is very powerful to be used as strain measuring instruments as well as force transducers.

Strain gage sensor used to measure deflection of an electric turbine base shows stable output without any effect of temperature and electric field [4]. A linier output of strain gage sensor with + 4.4% margin error can be established when it is used to measure load in a cantilever beam [5].

Mikkelsen [6] found that application strain gage to measure strain in soft materials exhibits small hysteresis error with under 5.5%. Measurement results of stress concentration in medium carbon steel using strain gage show the same values with those obtained by finite element method [7].

From those research results, it is obvious and clear that strain gage is a type of sensor that can be used in many engineering measurements.

3. Experimental work

3.1 Design

The accuracy of a force transducer is widely affected by the specific design. As a result of the electrical resistance strain gage measuring principle, any change of strain caused by loading effects will show directly in the output signal.

In this research, the design of strain gage transducer follows the specifications required for laboratory applications (education purpose). The transducer is expected to carry load up to 10 kN with maximum overall error ± 3 % f.s. For this requirement aluminum alloy Al-601T6 which is easy obtained in Indonesia market was prepared.

3.1.1. Tensile testing. A tensile testing to obtain actual mechanical properties such as maximum tensile strength, yield stress, and maximum elongation was carried out in a Universal Testing machine with loading rate 5 kg per second. Three specimens according to ASTM standard for tensile testing of aluminum were prepared (Fig. 3).

Figure 3. Specimen for tensile testing

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The tensile testing results are presented in Table 1 bellow.

Table 1. Tensile testing results of aluminum Al601-T6

Specimen Number	1	2	3	Average Values
Area (mm^2)	130.70	118.82	124.69	124.74
Maximum force (kgf)	3,354	3,132	3,310	3,265
Elastic force (kgf)	2,825	2,927	2,703	2,818
Elongation at fracture (%)	14.53	14.38	16.25	15.05
Maximum Stress (MPa)	251.74	258.58	260.41	256.91
Yield stress (MPa)	212.04	241.66	212.66	222.12

It can be seen from the table-1 that actual maximum tensile stress is 256.91 MPa and actual yield stress is 222.12 MPa. The yield stress value of 222.12 MPa is a maximum stress that will be considered as the reference strength of the material.

3.1.2. Design of transducer body. A transducer body was expected to withstand dynamic load of maximum 10 kN. This load should be kept under the yield stress of the material as to make sure that the material undergoes strain in elastic region. The allowable stress of typical transducer should not exceed 20 percent of the yield stress [2], hence the allowable stress is 44.4 MPa.

The form of the transducer body was chosen to be round in order to simplified machining processes and to ease strain gage installation as well.

If the allowable stress, σa, is 44.4 MPa, the maximum load, F, is 10 kN then the minimum cross section area of the transducer is:

$$A = \frac{F_{max}}{\bar{\sigma}} = \frac{10{,}000}{44.4\ x\ 10^6}\ m^2 = 225.23 \text{ x } 10^{-6} \text{ m2}$$

In this research the dimension of the transducer as illustrated in Fig.4 was proposed. Its cross sectional area is 282.6 mm^2 which is slightly greater than the minimum area.

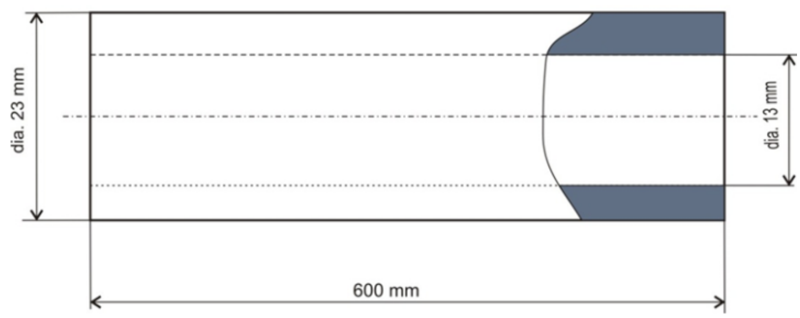

Figure 4. Design of transducer body

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3.1.3. Design of instrumentation. The type of the strain gage chosen in this research is KFG-2-120-C1-23 [2] with bellow specification:
Gage factor : 2.09 ± 1.0%
Gage length : 2 mm
Gage resistance : 119.6 ± 0.4 ohm

The 4-gage-system Wheatstone bridge configuration was chosen in order to have good sensitivity due to its capability to detect strains in lateral and longitudinal directions.

The output voltage signal from the Wheatstone bridge is amplified in interval of 10 times, 100 times, 1,000 times, and 10,000 times and processed in microcontroller. The amplified data voltage can be directly displayed or stored in a data storage.

3.2 Transducer fabrication

The fabrication of the force transducer was done in Mechanical Engineering Laboratory UPI Bandung including machining of the transducer body, strain gage installation, preparation of the instrumentation, and setting up of dynamic testing mechanism.

A transducer body was built from aluminum rod of diameter 1 in machined to become 23 mm of its outer diameter. It was then drilled with diameter 13 mm and cut off until the proper dimension was established.

Strain gage installation was done according to the bonding procedure recommended by the gage's manufacturer. For the purpose of strain measurement at normal temperature, a quick-curing cyanoacrylate adhesive CC-33A was used. The strain-gage bonding area was polished using a sand cloth (#200 – 300) and followed by removing grease from bonding surface using an industrial tissue paper dipped in acetone. After deciding bonding position at the transducer body, the four strain-gages were bonded one by one by applying a drop of the adhesive. Finally, it let curing for about 60 minutes to make sure that the strain gauge was securely bonded. The final transducer is shown in Fig.5 bellow.

Figure 5. A force transducer

The instrumentation for the 4-gage-system configuration according to Fig.5 was set up and a 6 volt d.c. power supply was applied to the circuit to see its output response.

3.3 Loading test

A loading test was performed on a universal testing machine to see the voltage outputs of the transducer upon applying load which varied from 0 to 10 kN with interval of 500 Newton. Some output parameters including drift, sensitivity, and transducer response to small load were also observed during the test.

The instrument was tested for different amplification set up started from 10 times up to 10,000 times to select the proper amplification required to obtain clear voltage outputs. It was found that 1000 times output amplification gave a good result.

4. Results and discussion

4.1 Loading test result

The output data in the form of electrical voltage resulted from the loading test is presented in Table 2 bellow.

Table 2. Loading test results

Load (N)	Voltage (mV)			
	#1	#2	#3	AVG
0	0	0	0	0
500	130	142	136	136
1,000	260	255	242	252
1,500	293	400	387	360
2,000	510	520	513	514
2,500	640	644	639	641
3,000	772	776	745	764
3,500	885	875	891	884
4,000	1,030	1,022	1,034	1,029
4,500	1,147	1,153	1,132	1,144
5,000	1,270	1,265	1,258	1,264
5,500	1,400	1,413	1,384	1,399
6,000	1,494	1,499	1,523	1,505
6,500	1,653	1,664	1,635	1,651
7,000	1,782	1,765	1,777	1,775
7,500	1,915	1,910	1,886	1,904
8,000	1,998	2,034	2,014	2,015
8,500	2,165	2,175	2,160	2,167
9,000	2,298	2,285	2,266	2,283
9,500	2,404	2,401	2,432	2,412
10,000	2,516	2,520	2,523	2,520

The average data taken from 3 times loading tests will be used for transducer calibration. The average output voltages (mV) versus load (N) are plotted in Fig.6.

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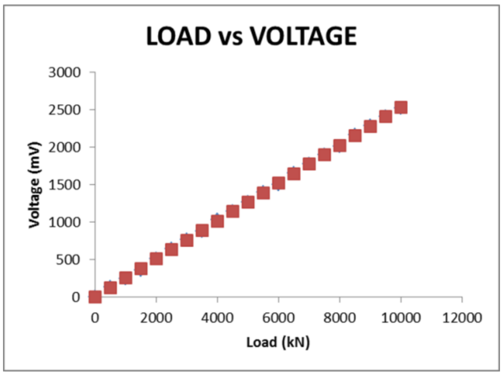

Figure 6. Data plotted: load vs voltage

4.2 Research findings

According to equation (5) the output voltages for every loading values can be determined as follow: Let take the maximum load applied is 10,000 N, from the aluminum alloy's data sheet [8] we have the Poisson's ratio is 0.34, the modulus of elasticity is 73 GPa, the gage factor is 2.09 [2] and d.c. power supply of the input voltage is 6 volts and the amplification is 1000 times, then the output voltage is:

$$e_0 = \frac{1}{4}.Ks.(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)E$$

$$e_0 = \frac{1}{2}.Ks.\varepsilon_1(1 - \vartheta).E$$

$$e_0 = \frac{1}{2}x2.09x608x10^{-6}(1 - 0.34)x6$$

$$e_0 = 2{,}516\ x\ 10^{-6}\ x1000\ = 2{,}516\ mV$$

Thus it is expected that the voltage reading of the transducer is 2,516 mV.

It can be seen from the Table 2 the average voltage of 10 kN load is 2,520 mV which are very close. This indicates that the force transducer gives accurate data if compared with the theory.

The data plot in Fig.9 shows that the voltage output is proportional to the applied load and almost straight line can be drawn from the data plot. A regression analyses of the dependent variable (voltage) and independent variable (load) confirms the proportionality. It has the regression equation as:

$$Y = 0.2531\ X + 2.0433$$

Where Y is output voltage (mV) and X is applied load (N). The multiple R value is 0.9999, R square is 0.9998, and the standard error of estimation is 9.39 mV. It can be concluded that the voltage outputs can be used to predict the value of load being applied with small error.

According to the equation of regression above the transformation formula to determine load is then:

$$Load = (3.951\ x\ Voltage) – 8.0731$$

The sensitivity of the transducer after 1000 times amplification is 0.2531 mV/N which shows that the transducer instrument amplification of 1,000 times can be used to display voltage outputs for every load below 10 kN.

The closeness of output readings when the same input is applied repetitively over a short period of time with same measurement conditions, same instrument, and observer known as repeatability shows that the output voltages in Table 2 during three times loading cycle are very close one to the others. It means that the transducer has good repeatability.

However, the output voltage data described above were obtained upon applying static load or gradually applied load. To elaborate its performance upon applying dynamic load it will be conducted in next research. It is planned to apply sudden loads from the body which is dropped from certain heights. The transducer will be used to sense the impact load resulted from the moving body by recording a sudden voltage output and with the transformation formula derived earlier the impact load can be calculated.

5. Conclusion

A strain gage load sensor or force transducer made from aluminum alloy Al601-T6 shows promising performances. It can withstand static loads up to 10 kN without damage during the loading process. The voltage data outputs have good proportionality and repeatability with small standard error of estimation and significant R value. Those meet with the design specification expected in this research.

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