

Development of a load cell to measure axial force

Desarrollo de celda de carga para medir fuerza axial

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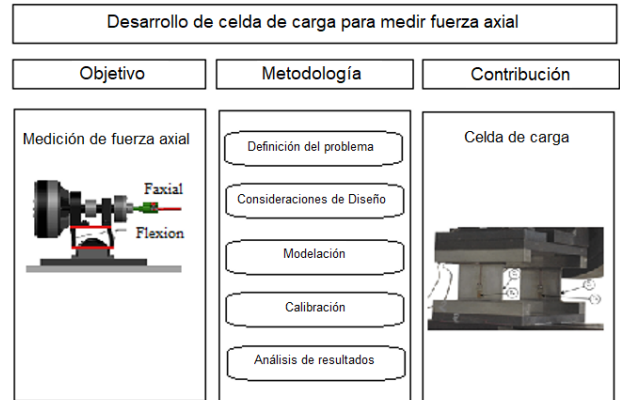
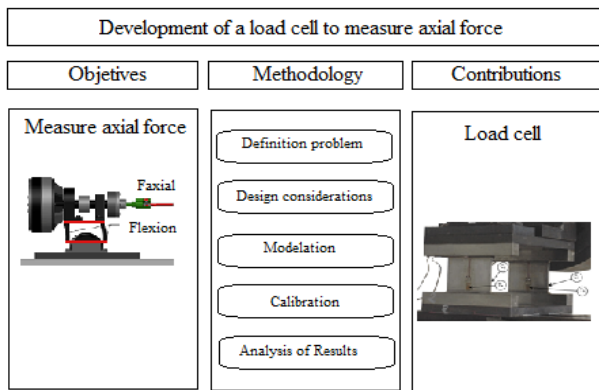
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Abstract

Original development of a load cell to reliably measure axial force in constant velocity axles and sliding constant velocity joints, which meets the characteristics to be installed especially in a dynamic Noise Vibration and hardness [NVH] test rig where parameters and variables similar to those present in vehicles under real conditions are reproduced; through the use of strain gages in a Wheatstone bridge arrangement and applying pure bending theory in the linear elastic range. The cell calibration results show linear behavior to measure the axial force value with an uncertainty of 0.5836 and a reliability value of 95% and an absolute error of 1.022 to ensure reliable measurement with errors less than 5%.

Resumen

Desarrollo original de celda carga para medir de manera confiable fuerza axial en flechas de velocidad constante y juntas homocinéticas del tipo deslizante, que cumpla con las características para ser instalada en especial en banco dinámico NVH donde se reproducen parámetros y variables semejantes a las presentes en los vehículos en condiciones reales; mediante el uso de strain gages en un arreglo de puente de Wheatstone y aplicando la teoría de flexión pura en el rango elástico lineal. Los resultados de calibración de la celda muestran un comportamiento lineal para medir el valor de la fuerza axial con una incertidumbre de 0.5836 y un valor de confiabilidad de 95% y un error absoluto de 1.022 para asegurar la medición confiable con errores menores del 5%.



Design, axial force, pure bending.

Diseño, fuerza axial, flexión pura.

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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## Introduction

The main objective is to create a design for a device or system that meets the particular need of this job. The products of mechanical design are useful in multiple fields. Designers use a wide variety of knowledge and skills in their work [engineering drawing, computer-aided design, material properties, manufacturing processes, statics, dynamics, strength of materials, kinetics, mechanisms, etc.]. The ultimate feature of mechanical design is, of course, to produce a useful device that is safe, efficient, and practical, [Measurement Groups, Inc., 1988].

Load cells are devices that measure force, these consist of two main parts: the deformable body and the strain gages. The first part is a piece, usually made of steel or another metal, with a known design, such that when a load [a force] is applied in a point or area, it deforms in a known manner [Bray et al. 1990].

Strain gage is a universal measuring device used for the electronic measurement of various mechanical quantities such as pressure, load, torque, deformation, position, etc. The strain gage is basically an electrical resistance. The variable parameter subject to measurement is the resistance of said gage. This variation in resistance depends on the deformation suffered by the gage. It starts with the hypothesis that the sensor experiences the same deformations as the surface on which it is glued [Khan et al. 2000].

Axial forces occur in Constant velocity Joints [CVJs] joints at constant velocity shafts, particularly in the sliding joint element. This allows the suspension to absorb sufficient lateral slip to prevent component disengagement. This has an impact on the noise and vibration characteristics of the CV joint and the vehicle. Shudder is a vibration phenomenon caused by these axial forces. [Genway et al. 1993].

Axial forces cause vibration in the engine and transmission; this vibration is transmitted to the vehicle body through the engine mounts, wheels, and suspension struts. Vibration increases if the frequency of the axial forces is equal to the natural frequency of a vehicle component. The magnitude of the axial force depends on the torque, angle, and speed of rotation. [Genway et al. 1993].

## Requirements

Constant velocity joints [CVJs] are used in vehicle traction. They are composed of three mechanical components: two constant velocity joints, one fixed and the other sliding, connected by a solid or hollow shaft, short on the right side and long on the left. The fixed joint on the wheel side allows free rotation on three axes, while the sliding joint on the transaxle side has three rotational movements and one sliding movement to compensate for the vehicle's axial movements.

The axial movement generates the force to be measured by the load cell, developed experimentally and theoretically on a dynamic NVH test bench. The axial force depends on the rotational speed, the inclination angle due to height variation, and the torque of the FVC [Flecha de velocidad constante]. These values range from 0 to 1500 rpm, from 0 to 27° inclination angle, and from 0 to 1500 Nm of torque, generating axial forces of 0 to 300 N.

## Load cell design considerations

The load cell for measuring axial force is a double support steel structure in the shape of an I-profile where the elastic part is used, it is instrumented with strain gages in the lower part to measure the effect of tension and compression by bending and form the complete Wheatstone bridge [8,9]. In this case the axial force applied to the upper part of the posts causes a bending in the area where the strain gage array is located to produce micro deformations directly proportional to the voltage they generate in millivolts and by means of a reader obtain the values of the applied axial force. The Wheatstone bridge arrangement [Bray, 1990] confirms the measurement quality and attenuates the error, See figure 1.

Due to the effect of pure bending, it was determined that the most appropriate area to locate the strain gages was at the bottom of the supports. In addition, these were replaced by others that were more sensitive to the force  $F$ , as shown in Figure 1. The dimensions and original shape of the supports were also established to fulfill this function and improve the sensitivity of the measurement, in addition to supporting the weight of the bearings, bases, head, shaft, and electromagnetic brake [70 kg] that make up the body of the cell.

## Box 1

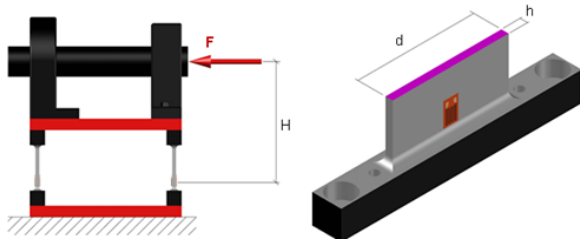


Figure 1

Load cell for measuring axial force by pure bending.

Source Author's own contribution

According to the direction of the force, the gages that would be subjected to tension would be  $T_4$  and  $T_2$ , the gages subjected to compression would be  $C_3$  and  $C_1$ , as can be seen in figure 2. The strain gages used for the cell are of the CEA-06-125UW type - with resistance in ohms at 24 °C  $350 \pm 0.4$ , gage factor:  $2.095 \pm 0.5$ , transverse sensitivity:  $0.6 \pm 0.2$ , [1,2]. The arrangement of the gages was configured to form a complete Wheatstone bridge, to ensure the measurement, as can be seen in figure 2.

## Box 2

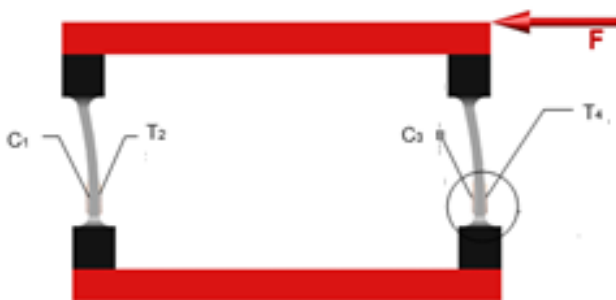


Figure 2

Instrumentation of supports with strain gages.

Source Author's own contribution

The Wheatstone bridge Figure 3 is a circuit used to determine the change in resistance subject to a deformation that can be static or dynamic.

The resulting unitary deformation is directly related to the change in voltage as mentioned above [8,9].

## Box 3

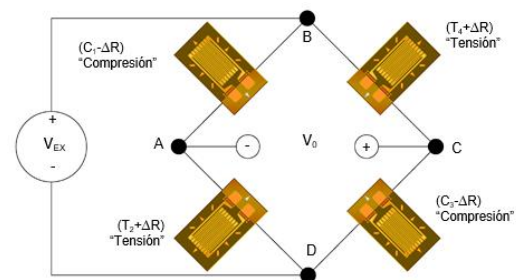


Figure 3

Strain gages Wheatstone bridge arrangement.

Measurement Groups, Inc., [1988]

## Theoretical model of stress and strains

To estimate the sensitivity and capacity of the equipment, it is necessary to obtain the theoretical model that represents the supports.

The sum of the forces acting on the supports is equal to the axial force [Gere, 2019].

The stress according to the bending theory and the proposed physical model is [Gere, 2019]:

$$\sigma = \frac{Mc}{I} \quad [1]$$

Where:  $\sigma$  is the normal stress,  $M$  the bending moment,  $c$  the maximum distance and  $I$  the moment of inertia.

The effort according to Hooke's Law is [Gere, 2019]:

$$\sigma = E\varepsilon \quad [2]$$

Where  $\varepsilon$  is the normal strain, the bending moment is calculated as [Gere, 2019]:

$$M = F_{\text{axial}} H \quad [3]$$

Where  $H$  is the distance from where the axial force is applied to the gage.

Considering the two supports of the cell, the centroidal moment of inertia is calculated as [Gere, 2019]:

$$I = \frac{d(2h)^3}{12} \quad [4]$$

Where  $h$  is the height and  $d$  is the width of the plate.

Eq.[3] and Eq.[4] are substituted in Eq.[1] and knowing that for this case  $c = h/2$ , we obtain:

$$\sigma = \frac{F_{axial}H[h/2]}{\frac{d[2h]^3}{12}} = \frac{3F_{axial}H}{4dh^2} \quad [5]$$

Equating eq.[5] with eq.[2], we obtain:

$$\sigma = 2E\varepsilon = \frac{3F_{axial}H}{4dh^2} \quad [6]$$

Solving  $F_{axial}$  from eq. [4.6], we obtain an equation in terms of  $\varepsilon$ :

$$F_{axial} = \frac{2Edh^2}{3H} \varepsilon \quad [7]$$

### Load Cell Calibration

To calibrate the load cell, a linear actuator was used that applies load in the axial direction, ensuring alignment from a top-down perspective.

The actuator stroke adjustment must be made with contact between the parallel plates. Under no circumstances should this situation be forced, to avoid inducing additional preload on the cell.

#### Box 4



**Figure 4**

Load cell calibration.

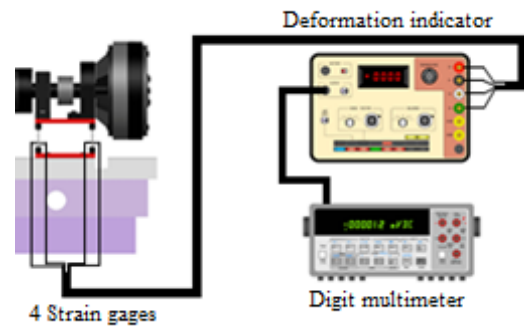
*Source Author's own contribution*

### Instrumentation for calibration

For the load cell instrumentation, a Wheatstone full-bridge strain gage array configuration was used. Figure 5 shows the connections to the strain gage. The connection between the strain gage and the digital multimeter is also shown.

The equipment used for calibration was: a linear actuator with a load of  $\pm 12$  KNm, a frequency of 9 Hz and a linear displacement of  $\pm 127$  mm, a manufactured axial force calibration support, square clamping screws and nuts, a micro deformation indicator, a digital multimeter, and coaxial cables for equipment connection.

#### Box 5



**Figure 5**

Load cell instrumentation for calibration.

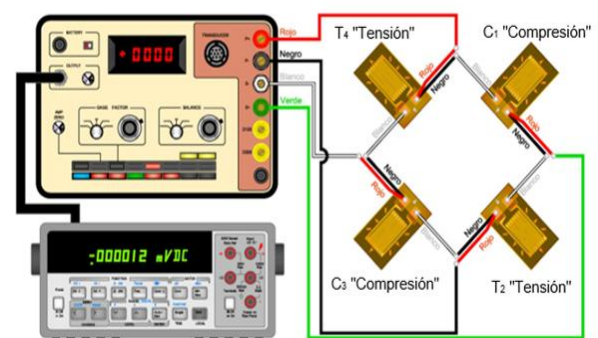
*Source Author's own contribution*

The exposed areas of the machine where the measuring instruments and interface cables will be mounted must be cleaned, since the cell height is a fixed parameter. The support serves to hold the linear actuator at the necessary height so that the center of the cylinder is centered with respect to the center of the shaft. Similarly, the system aligns the shaft that connects the cell to the actuator shaft from a top-down perspective.

The actuator stroke is adjusted and must be adjusted with contact between the parallel plates. Under no circumstances should it be loaded to avoid inducing additional preload on the cell.

As mentioned above, the load cell works under a Wheatstone full bridge configuration, the way in which the connections to the strain gage should be made is shown in Figure 6, the connection between the strain gage and the digital multimeter can also be seen.

#### Box 6



**Figure 6**

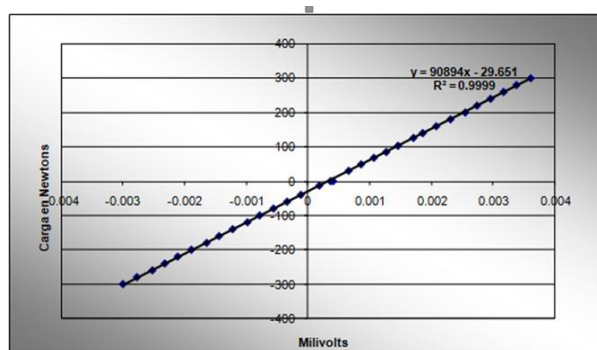
Wheatstone bridge connection diagram.

*Source Author's own contribution*

## Calibration Results

Once the equipment and instrumentation were assembled, the calibration procedure was performed, applying a load of -300 to 300 N in increments of 20 N. The load versus voltage results, expressed in microstrains, are shown in the graph in Figure 7.

### Box 7



**Figure 7**

Axial force load cell calibration graph.

*Source Author's own contribution*

The maximum value of microdeformation obtained was  $75 \mu\epsilon$ , taking as reference the data from the CEA type strain gages, the range of permissible microdeformations is  $\pm 1500 \mu\epsilon$ , this to comply with  $10^6$  cycles.

The values are programmed in the Displays according to the function obtained from the calibration as shown in figure 7, dividing them by a sensitivity factor of 1.15 by the resistance used of 60 Ohms, so the values to be programmed are:

$$Y = [90894X - 29.651] / 1.15 \quad [8]$$

When the values were run on the readers, they were found to be very close to the actual values. The obtained values have a relatively low error of 1.022, a measurement uncertainty of 0.5836, and a very acceptable reliability of 99.98%.

## Load cell installation on NVH test rig

Once the load cell was calibrated, the next step was to install it on the dynamic NVH test bench to perform the respective tests. Figure 8 provides an overview of the load cell installation.

### Box 8



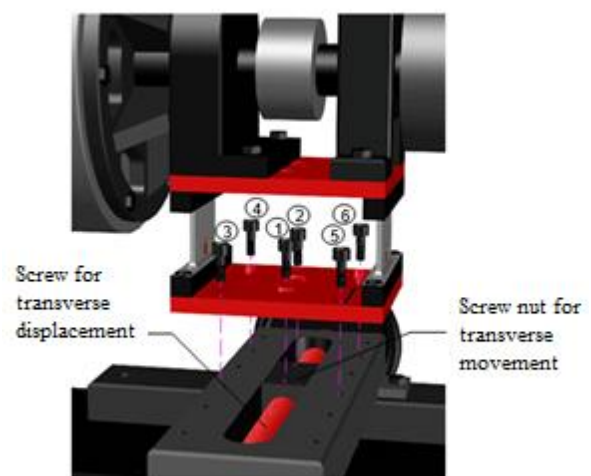
**Figure 8**

Load cell installation on NVH test rig.

*Source Author's own contribution*

The load cell is basically secured to the longitudinal motion support by bolt 1 and bolt 2. These are held in place by the nut on the transverse displacement screw. Once the FVC has been set to a certain angle by the transverse displacement screw, bolts 3, 4, 5, and 6 serve to hold the load cell in place in this direction, see Figure 9.

### Box 9



**Figure 9**

Load cell assembly.

*Source Author's own contribution*

## Experimental tests and results

To measure the axial force, the test was carried out with four constant speed arrows that, as seen previously, consist of a fixed joint on the wheel side, a solid or hollow shaft on the intermediate side and a sliding joint that generates the axial force at different angles, speed and torque.

Figure 8 shows the constant speed arrows already mounted on the NVH dynamic test rig. The test conditions were determined according to the Japanese Nem KD2 27003/1990-8 specification [11] in the values of the NVH bench capacities at 200 rpm, 100Nm and varying the angle to the values of 4°, 6°, 8°, 10° and 12°.

Within the test the parameters to control are:

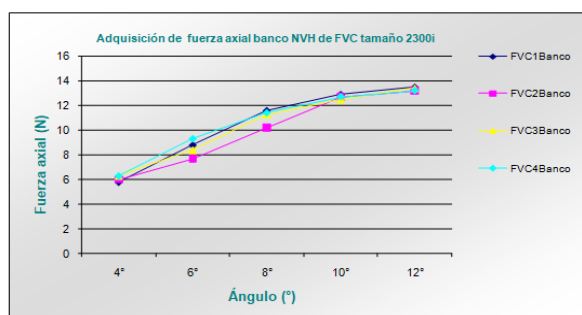
- Torque
- Angular velocity
- Joint angle

Within the test the parameters to monitor are:

- Axial force
- Torque
- Angular velocity
- Joint angle

The graph in Figure 10 shows that the value of axial force increases as the angle increases in a non-linear manner. It is worth mentioning that the torque induced to the system of 100 Nm and the speed of 200 rpm remain constant. It can be seen that there is repeatability as shown with the trend of the lines for each of the 4 constant speed arrows that were tested from the same model. It is observed that the axial force values are very small, they do not represent any risk.

### Box 10



**Figure 8**

Axial force measurement with load cell on NVH test rig.

*Source Author's own contribution*

According to the values obtained and graphed, it can be seen that the axial force recorded by the load cell for the 4 arrows of constant test speed under the same conditions of torque, angular speed and angle of inclination are practically the same. As shown in the graphs, the error values are small for an angle of 4°, for angles of 6° and 8° they increase and for angles of 10° and 12° they decrease significantly.

## Conclusions

Using an array of 4 Wheatstone full-bridge strain gages, a load cell was developed to measure the axial force generated by constant velocity arrows in tests carried out on a NVH dynamic test rig.

The adaptation modifications to the dynamic test rig were minimal, only the new supports for the load cell were designed and manufactured, which, unlike the originals, the geometries, dimensions and material were considered to be sensitive to axial force and facilitate data acquisition without exceeding the linear range. This expands the testing possibilities of the dynamic test rig, since the usual noise and vibration tests can be carried out and include axial force measurement and correlation and effect of the data.

The system was calibrated considering the weight of the brake [64 Kg], to avoid preloads and possible subsequent effects on the cell; Their inertias were not considered since the displacements and axial forces are considerably small. The errors in the calibration results obtained were very low, ranging from values of 1.022 %, uncertainty to 0.5836 and data reliability of 99.98 %.

The maximum value of micro deformation for a load of 300N was 75  $\mu\epsilon$ , comparing this value against the range of values offered by the manufacturer for the gages used [ $\pm 1500 \mu\epsilon$ ], it can be concluded that the cell will be able to have a good useful life, since the value of the maximum micro deformation that was presented is well below that allowed by the manufacturer.

The most important aspects that justify the development of the load cell to measure axial force: low cost compared to a commercial one, it is useful in this specific application and guarantee of operation and measurements.

The price of the commercial cell ranges between \$90,000 pesos, while the cost of the most representative materials [4 gages, 2 steel supports, 2 steel bases and screws] for the manufacture of the developed cell was \$5,000.00 pesos.

Finally, it is concluded that load cells can be developed that adapt to the particular needs of the equipment that requires it, with much lower cost, good quality, guarantee in measurement, knowing the principles of operation of strain gages in a Wheatstone bridge arrangement, among others. Science and technology are available to create, develop, and innovate in an original and limitless way.

### Declarations

### Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

### Author contribution

*Sánchez-Rodríguez, Alvaro*: Application of the idea, development of the design methodology.

*Aceves-Saborio, Salvador Martín*: Development Theoretical model of stress and strains

*Orozco-Mendoza, Horacio*: Load Cell Calibration and installation.

*Rodríguez-Castro, Ramón*: Experimental tests rig and results

### Availability of data and materials

Availability of data and materials is only that presented in this work.

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This work has been funded by Instituto Tecnológico de Celaya

### Abbreviations

CV	Constant velocity
CVJs	Constant velocity joints
FVC	Flecha de velocidad Constante
NVH	Noise vibration and harshness

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