Design and evaluation of portable flat-bed wheel and axle load scale for measuring lightweight vehicles

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Abstract. The balancing of the wheel and axle load ratio affects the vehicle performance. In this study, the flat-bed load scale was designed and fabricated using the ring transducer that detected the force in a range of 0-150 kg. The 48 mm ring transducers were bonded with the strain gauges in circuits of the quarter and full Wheatstone bridge. After that, the ring transducers were placed in the 3 patterns of P1, P2 and P3 and statically calibrated at the 3 positions i.e., centre (C1) and offset-centre (C2 and C3). The P3 type of force platform was found that it could be used to measure the vertical force accurately whereas the P1 pattern had highest percentage error in percentage.

1. Introduction

The balancing of the wheel load and the axle load ratios influences the vehicle performance. The automobiles distribute their weight to the beneath surface through the axle and wheel. In order to be the best performance of vehicle activities in daily life such as competition [1] and agricultural application [2, 3], the appropriate weight transfer ratio is considered necessary.

For the in-situ testing, the wheel loads of the heavyweight machineries are assessed using the portable weigh pads [4]. In contrast, the pads are unsuitably used on the lightweight vehicle and the 3-dimension force measurement.

The strain gauge, a device for measuring the material strain in elastic region, is applied to estimate the force, moment, and torque in term of the output voltage. The explicit data depend on the shape and the elastic behaviour of the studied material. Classical ring transducer has been studied, designed, and developed to determine the force in the vertical and other direction since 1980 [5]. The proper position for bonding strain gauge was regarded as the point that the maximum stress was appeared without interfering from another direction force. Accordingly, the half-height of the ring, which was the suitable point under bending load, was mounted the strain gauge in the circuit models of quarter, half and full Wheatstone bridge.

The simple force plate was made from the 4 pieces of quarter Wheatstone bridge rings that formed of the two of them were attached the strain gauge inside the ring, and the others were outer fastened the ring. Hence, the four circuits were intertwined being the full Wheatstone bridge [6]. Although the platform was actually used, the error from the external force acted on the surface was more interested, especially, at the edge of force plate [7]. Moreover, the ring transducers were modified as the multi-dimension force plate [8, 9] for measuring the force during milling or drilling provided that the degree of the inclined plane and the strain gauge mounting position were accurately adjusted. The load scale should calibrate and specify the contact area before usage, particularly, the field testing that has the several external factors i.e., installation, weather and field condition.
This article aims to present the design and fabrication of the simple flat-bed load scale for measuring the vertical force, including validating the proper transducer mounting pattern on the force plate. Therefore, the basic data of the ring transducer were determined in order to develop the new type of octagonal ring transducer flat-bed scale for estimating the tyre/surface interaction in all directions.

2. Materials and methods

2.1. Design of a flat-bed wheels and axle load scale

2.1.1. Flat-bed area load scale. The individual force platforms were designed for measuring the applied load beneath each wheel and axle. The physical characteristics of the lightweight and small vehicle were considered and shown in Table 1 that most automobiles had 1-4 wheels and 1-2 axles. Therefore, the upper side of the force plate should be greater than rear tractor tyre for utilizing in all vehicle types. The contact area of the platform, referred to the largest tyre sidewall, was 300×300 mm². The dimension of the flat-bed load scale and the ring transducer positions were illustrated in Figure 1.

Table 1. Characteristics of lightweight and small vehicle.

| Type of vehicle                  | Number of axle | Tyre size (mm) | Weight (kg) |
|---------------------------------|----------------|----------------|-------------|
|                                 |                | Front          | Rear        |             |
| Sidecar motorcycle*             | -              | 70/90-341.8    | 80/90-341.8 | 160         |
| Motorcycle                      | -              | 80/90-355.6    | 90/90-355.6 | 98          |
| Light weight tractors           | 2              | 127-355.6      | 228.6-406.4 | 600         |
| KMITL PCC formula student       | 1              | 190.5-254      | 190.5-254   | 230         |

*The tyre of the sidecar motorcycle same as the rear tyre of motorcycle.

![Figure 1. The schematic of the flat-bed load scale.](image-url)
2.1.2. **Elastic ring transducer.** The vertical ring transducer was designed and estimated by the linear static model with the finite element analysis (FEA) as shown in figure 2(a). The annular elastic elements with the inner diameter of 40 mm in figure 2(a) and 2(b) made of the aluminium 7075-T6, that had the tensile yield strength of 503 MPa, were shaped with a lathe. The thickness of prototype, strain gauge mounting position and maximum stress were analyzed by the FEA method. The achieved stress and the mechanical properties of the material were compared with the applied maximum vertical load of 150 kg (1471 N). Therefore, the appropriate ring wall thickness was 4 mm while the maximum stress at the mounting strain gauge point was 79.32 MPa that is about 15 % of the yield stresses. Figure 2(b) shows the dimension of the elastic ring transducer and the strain gauge bonding positions.

![Figure 2. Ring Transducer (a) analysed by FEA (b) Ring elastic element.](image)

2.1.3. **Flat-bed load scale unit measurement.** The system of the flat-bed load scale was shown in figure 3. The data acquisition (NI USB-6210), the 5 VDC of regulated power supply for Wheatstone bridge and the 12 VDC dual power supply were integrated and placed in the first force plate; whereas, the other plates were transmitted the signals to the first plate for processing and monitoring with LabVIEW 2014, and the data were recorded on a laptop. The output signal from the full Wheatstone bridge circuit before transmitted to the data acquisition was amplified 500 times for avoiding the surroundings’ noises [10] by the INA 128 amplifier that was connected following by the manufacturer manual.

![Figure 3. The system of flat-bed load scale.](image)
2.2. Calibration and evaluation of force plate

The 4 pieces of the ring transducer were placed in the 3 patterns followed by the Wheatstone bridge circuit and the Kyowa strain gauge (KFGS-5-120-C1-11-L1M2R) bonding points (inner at G2 and G4 or outer the ring wall at G1 and G3) as shown in figure 2 and table 2. Both P1 and P2 were the same quarter-bridge ring transducers, but the positions of the strain gauge, called L1, L2, L3 and L4 in figure 3, were changed. The P3 form consisted of the 4 full bridge ring transducers that not only measure in the vertical direction but also estimate the force in every axis if calibrated them in other directions [11].

| Table 2. The mounting position of the different elastic ring transducer. |
|---------------------------------------------------------------|
| **Ring transducer type** | **Pattern** | **Strain gauges bonding position** |
|-------------------------|------------|----------------------------------|
| Quarter-bridge per elastic ring | P1 | outside (G1) inside (G2) outside (G3) inside (G4) |
|                         | P2 | outside (G1) inside (G2) inside (G4) outside (G3) |
| Full bridge per elastic ring | P3 | Ref. figure 2(b) |

For the static calibration, the applied vertical force, from the handle screw jack, was detected by the 300 kg of load cell (model S-type, total error of ±0.02% F.S., ZEGA). The vertical force at the centre (as C1 point in figure 1) was compressed on the upper plates of the P1, P2 and P3 force platform for determining the correlation of the output voltage and the referenced weight. Therefore, the loading and unloading were varied in the range of 0-150 kg with a 5, 10 and 20-kg step in 0-30, 30-90 and 90-150 kg range, respectively. After the force was stable, each output voltage was recorded for the duration of 1 minute. The hysteresis and linear regression were estimated from the calibration data that shown in figure 4. The equation (1) was fitted as followed:

\[ y = mx + c \]  

where \( y \) is the voltage output ratio (V/V\text{max}), \( m \) is slope of the linear equation, \( x \) is the weight ratio (N/N\text{max}) and \( c \) is the constant.

Since the tyre/flat-bed load scale interface depends on the properties and size of tyre, the weight acting on the off-centre points of the plate (C2 and C3 shown in figure 1) were considered. The force was applied at the C2 position (between ring transducers of L1 and L2), whereas the static load was applied in the middle of two ring transducers (L2 and L3) which was C3 position. These calibrations were performed the same as the C1 condition.

3. Results and discussion

The curve fitting of the calibration data at the C1 position was performed with the linear regression as figure 4. Before the regression analysis was evaluated, the relationship of the independent variable (\( x \)) and the controlled variable (\( y \)) in equation (1) were arranged in term of dimensionless because of easier observation and consideration. Then the coefficient of determination (\( R^2 \)) and the hysteresis were calculated and presented in table 3. The \( R^2 \) values of all strain gauge mounting patterns were about 0.99-1, indicating that the flat-bed load scale, which was fitted with the ring transducers was reliable. These were similar to the vertical calibration results conducted by Yaldız et al. [9].

The hysteresis of all quarter Wheatstone bridge was considered to be the total error value; therefore, the P1 and P2 patterns had the error of 1.52 and 0.92%, respectively. On the other hand,
each ring transducer (L1, L2, L3 and L4) of the P3 force platform showed the hysteresis errors of 1.57, 0.53, 1.60 and 1.57%, respectively. From the hysteresis results, the ring configuration was a necessity for regarding the unloading forces.

![Figure 4. Typical calibration data for the loading.](image)

Table 3. Specification of the calibrated ring transducers.

| Pattern | Terminology | L1 | L2 | L3 | L4 |
|---------|-------------|----|----|----|----|
| P1      | Slope (m)   | 1.0103 | | | |
|         | Constant (c)| -0.018 | | | |
|         | R²          | 0.999 | | | |
|         | Hysteresis (%) | 1.52 | | | |
|         | Slope (m)   | 1.005 | | | |
| P2      | Constant (c)| 0.003 | | | |
|         | R²          | 0.999 | | | |
|         | Hysteresis (%) | 0.92 | | | |
|         | Slope (m)   | 1.0011 | 0.9988 | 0.996 | 1 |
|         | Constant (c)| -0.004 | 0.000 | -0.000 | -0.003 |
|         | R²          | 0.999 | 1 | 1 | 0.999 |
|         | Hysteresis (%) | 1.57 | 0.53 | 1.60 | 1.57 |

The calibration data on the positions of C2 and C3 were compared with the reference value of C1 point and represented as the relative error (figure 5). The standard error curve of the P3 pattern at the C2 and C3 spot showed the constant tendency to almost every load, but the error that occurred at C3 was greater than C2 and the mean absolute error was 2.84%. Sometimes, the transducers showed the higher values since the direction of the applied force was not straight to the strain gauges, therefore, the strain values were not detected. The P2 pattern with compressing at C2 provides the negative number due to understating, while the error curve of C3 provides the positive number and shows the steady trend along the studied period and the mean difference of 25.43%. Moreover, the trend lines of two compressed positions of the P1 force plate were appeared clearly that the positive (right) skewed curve and the highest value manifested at 25 kg.
Therefore, the P3 pattern could be used to measure the vertical force efficiently, providing the shorter height of the flat-bed scale [12]. In case of the P1 pattern, it was not usable because the error was greater and the data in all loading were unstable. Nevertheless, the P2 pattern of load scale might specify the measured area of tyre/plate interface for more accurate outcome.

![Figure 5](image)

**Figure 5.** The relative error of C2, C3 compared with the reference point C1.

4. Conclusion
The flat-bed load scale with the 4 ring transducers mounted the quarter Wheatstone bridge circuit in the P1 pattern was not suitable in use. For the P2 pattern, it could be measured precisely if the position of the loading contact area was specified on the platform. On the other hand, the force plate with each ring transducer bonded the full Wheatstone bridge (P3) could be used to evaluate the vertical force at all points and it is used in many applications such as in measuring in the 3-dimension of tyre/surface interaction, biomechanics and machinery operation.

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