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Applicability of Strain Gauge Methods for Experimental Determination of Operating Stress of Construction, Road and Agricultural Machines Attached to Tractors

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Abstract. The operating stress of construction, road and agricultural machines is determined during experimental and factory tests using force sensors. The aim of the research is to improve the methods of experimental determination of horizontal forces transferred by mobile implements using strain gauges combined with the elements of fastening of technological machines. The stress-strain state and deformations of measuring strain gauges at their different arrangements on strain gauge pins of circular cross-section are considered. When determining the horizontal load on the vehicle with the use of pre-calibrated strain gauge pins, it was experimentally established that the mentioned strain gauges can additionally react to the vertical load, which leads to the emergence of systematic errors in estimating the horizontal load. To eliminate this, it is proposed that before the main calibration of the horizontal force sensors, it is necessary to pre-determine the position at which the calibrated strain gauge will not respond to the vertical force, by rotating it relative to the longitudinal axis and then ensuring fixation in this position. The influence of axial forces on strain gauge pins, picked up by the strain gauges, can also lead to distortion of the stress field in the body of the strain gauge. Taking into account this influence on the strain gauge pins requires additional experimental studies.

Keywords: construction and road machines, horizontal load, loading, experimental determination, strain gauge pins

Conflicts of interest. The authors declare that there is no conflict of interest.

Authors' contribution: *Rogachev A.F.* — conceptualization, modelling, data analysis, writing; *Karsakov A.A.* — methodology, modelling, photographs, data analysis, writing; *Martynov A.A.* — experimental investigation

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Применимость тензометрических методов для экспериментального определения нагруженности строительных, дорожных и сельскохозяйственных машин, агрегатируемых с тракторами

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Аннотация. Силовая нагруженность строительных, дорожных и сельскохозяйственных машин определяется во время экспериментально-производственных испытаний с использованием датчиков усилий. Цель исследования — совершенствование методов экспериментального определения горизонтальных усилий, передаваемых в мобильных агрегатах с применением тензометрических датчиков, совмещаемых с элементами крепления технологических машин. Рассмотрены напряженно-деформируемое состояние и деформации измерительных тензорезисторов при различных схемах их расположения на тензометрических пальцах круглого сечения. При определении горизонтальной нагрузки на транспортное средство с использованием предварительно калибруемых тензометрических пальцев экспериментально установлено, что упомянутые тензорезисторы могут дополнительно реагировать и на вертикальную нагрузку, что приводит к появлению систематических погрешностей при оценке горизонтальной нагрузки. Для устранения этого явления предложено перед проведением основной калибровки датчиков горизонтального усилия предварительно определить положение, при котором калибруемый тензодатчик не будет реагировать на вертикальное усилие путем его поворота относительно продольной оси с последующим обеспечением фиксации в этом положении. Влияние осевых усилий на тензометрические пальцы, воспринимаемых тензорезисторами, также может приводить к искажению поля напряжений в теле тензопальца, учет влияния которого на тензометрические пальцы требует проведения дополнительных экспериментальных исследований.

Ключевые слова: строительные и дорожные машины, горизонтальная нагрузка, нагруженность, экспериментальное определение, тензометрические пальцы

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Вклад авторов: *Рогачев А.Ф.* — концепция исследования, подготовка расчетных схем, анализ данных, написание текста статьи; *Карсаков А.А.* — дизайн исследования, подготовка расчетных схем и фотографий, анализ данных, написание текста статьи; *Мартынов А.А.* — участие в проведении и анализе экспериментов.

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1. Introduction

Operating stress and efficiency of construction, road and agricultural machines [1; 2] are determined during experimental and factory tests, for which they can be equipped with force [3; 4], displacement, acceleration sensors, etc., which are part of data measurement systems [5–7].

The use of multi-purpose measuring instruments for determining operating stress of elements of such implements [8] changes their operating interaction pattern, which introduces errors in the measurement of forces, in particular, horizontal forces, the most important for traction and energy calculation. Such data

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measurement systems for assessing operating stress of various joints of mobile implements are based on fundamental methods of engineering mechanics [9], theory and experimental evaluation of stress of shells [10; 11] and other experimental and theoretical methods [12–14].

For experimental determination of operating stress of construction, road and agricultural machines, equipment, tractors, the use of special rig equipment [15], soil channels [12], the application of similarity theory methods to determine traction resistance of the attached technological machine [16], artificial intelligence (AI) algorithms [17] and other modern approaches [18; 19] are known. However, when measuring devices are combined with structural elements of the implements, negative effects may occur not only due to anisotropy of their materials [20; 21], but also as a result of the geometric inaccuracy of attaching strain gauges on the surfaces of force-measuring elements [18].

Therefore, experimental methods of determination of operating stress of construction and agricultural tractor attachments remain insufficiently investigated, including in terms of the applicability of force sensors combined with the elements of attachment of the implements, and require further experimental research and theoretical substantiation.

2. Methods

To measure internal forces, the strain gauge [22], which is a thin metal lattice inside a dielectric (Figure 1, *a*), has become widespread. Strain gauges are glued onto the tested part (one, two or four functional) and are connected by a bridge circuit according to Figure 1, *b*. When the resistance of resistors $R_1, ..., R_4$ is equal, the voltage between points *C* and *D* will be 0 and, accordingly, the current flowing along the diagonal *C* – *D* will also be equal to zero.

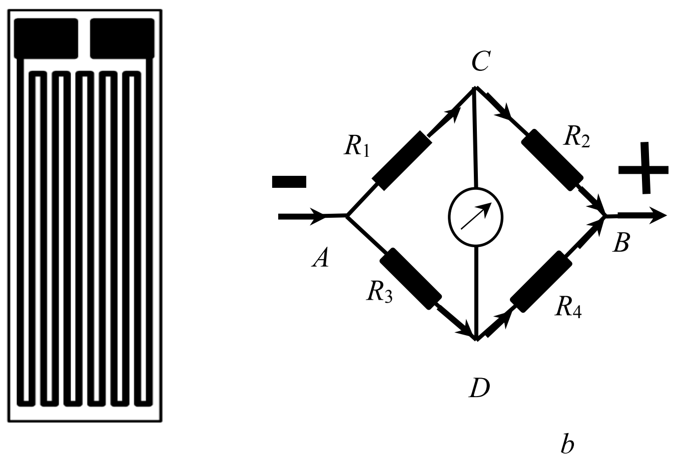

Figure 1. Structure and connection of strain gauges:
a — strain gage conductors; *b* — bridge connection diagram
Source: made by A.A. Karsakov

When the tested part is loaded, it is deformed (stretched or compressed) and the strain gauges are deformed, which leads to a change in their electrical resistance. By measuring the value of current flowing along the diagonal *C* – *D* or the voltage in it, it is possible to determine strain ε of the part, as well as normal stress

$$\sigma = \varepsilon \cdot E, \quad (1)$$

where σ is the normal stress of the part, N/m^2; ε is the strain of the part; *E* is the normal elastic modulus of the material of the part, N/m^2.

The arrangement of strain gauges on an axially loaded part is shown in Figure 2.

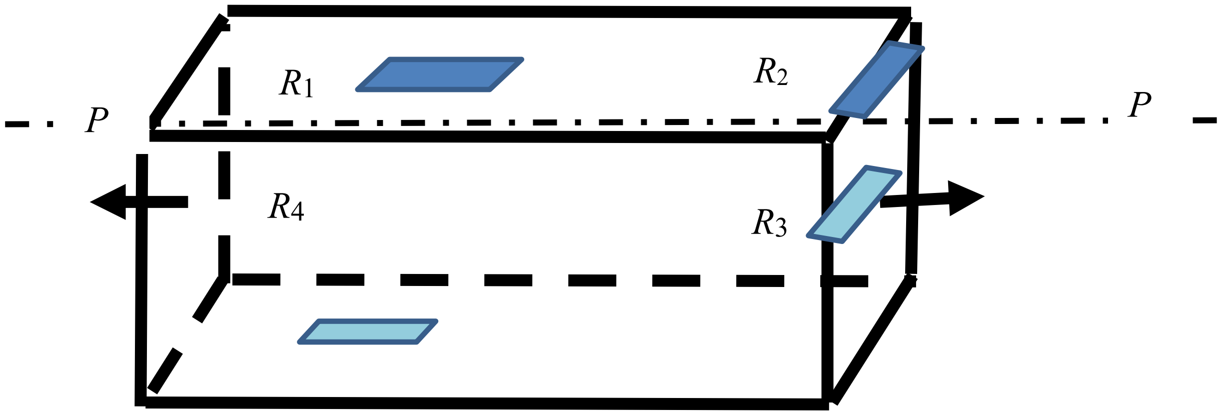

Figure 2. Arrangement of strain gauges on a part under axial loading
Source: made by A.A. Karsakov

In pure axial tension, strain gauges R_1 and R_4, fixed strictly parallel to the longitudinal axis of the bar, are stretched during loading with force P, and their resistance will increase. In turn, strain gauges R_2 and R_3, which are oriented perpendicular to the longitudinal axis of the bar, are partially compressed, and their resistance will decrease. At a sufficient distance from the point of application of force P, the stresses at any point of the cross-section of the bar will be the same and will be determined by the expression

$$\boldsymbol{\sigma} = P / A, \tag{2}$$

where P is the magnitude of the applied force, N; A is the cross-sectional area, m^2.

Strain $\boldsymbol{\varepsilon}$:

$$\boldsymbol{\varepsilon} = \boldsymbol{\sigma} \cdot E, \tag{3}$$

where E is the normal elastic modulus, m^2/N.

The case of loading a bar by moment M (Figure 3) is considered below.

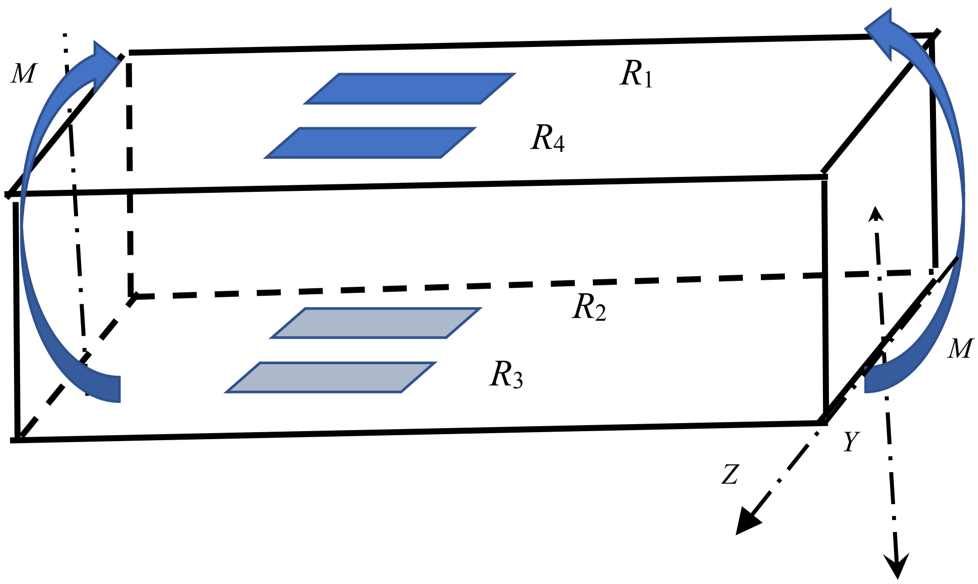

Figure 3. Model of loading a bar by moment M
Source: made by A.A. Karsakov

In the case of bending of the bar under moment M, strain gauges R_1 and R_4 are fixed parallel to the longitudinal axis of the bar. In the process of loading, their resistance will decrease, while gauges R_2 and R_3 are parallel to the longitudinal axis of the bar from the opposite side and their resistance will increase.

The stresses at the gauge attachment points are determined by (4), and they will be the same across the top and bottom faces.

$$\boldsymbol{\sigma} = \frac{M \cdot Y}{\boldsymbol{J}_z}, \tag{4}$$

where $\boldsymbol{J}_z$ is the moment of inertia of the cross-section with respect to Z-axis; Y is the coordinate of the point of measuring normal stress; M is the magnitude of the bending moment.

3. Results and Discussion

Circular strain gauge pins are sometimes used as force sensors during testing, installed at the joints of individual parts (Figure 4).

The transferred forces can act in three directions: horizontally P_H, vertically P_V and laterally P_L, whereas only one, for example horizontal P_H, is required (Figure 5). For this purpose, the longitudinal axes of the strain gauges must be parallel to each other and lie in the same centerline plane and be located at the same distance "*a*" from the supports.

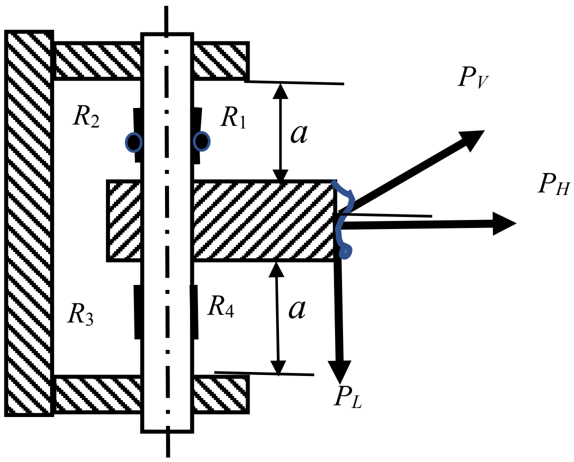

Figure 4. Diagram of forces acting on the strain gauge pin when installed at the junction of the parts

Source: made by A.F. Rogachev

The distribution of normal stress from horizontal P_H and vertical P_V forces is shown in Figure 5. The highest stress from the horizontal force P_H will be in the locations where the strain gauges are attached (points 1 and 2). In these locations, the stress from the vertical force P_V is equal to zero, while the vertical force P_V will not affect the readings from the horizontal force P_H. The lateral force P_L will cause the same strain of all four strain gauges, which will also not affect the readings from the horizontal force P_H. At the same time, in reality it is difficult to provide geometrically accurate attachment of the strain gauges. In addition, due to the anisotropy of the strain gauge pin material caused by preliminary thermal treatment and elastoplastic deformation, its physical properties vary at different points, which leads to changes and distortion of the real stress diagram.

This requires correcting the axial positioning of the strain gauge pin in the supports. For this purpose, a mark is made on the end of the pin, and the pin is installed in the rig such that the mark is positioned vertically. The strain gauge pin is loaded vertically. Then it is rotated several times around the longitudinal axis ϕ and a graph of the relationship between of the mV signal and the angle of rotation ϕ is plotted (Figure 6).

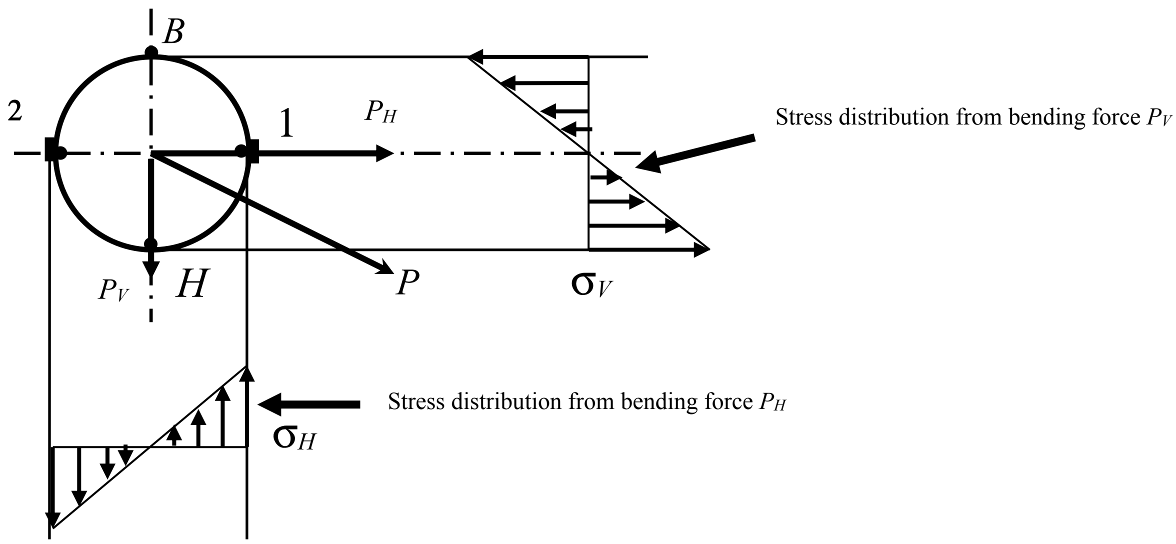

Figure 5. Distribution of normal stresses from horizontal P_H and vertical P_V forces
S o u r c e: made by A.A. Karsakov

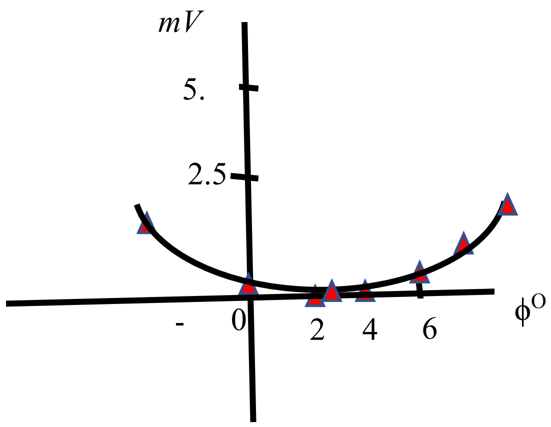

Figure 6. Plot of relationship between mV signal and rotation angle ϕ
S o u r c e: made by A.A. Karsakov

Figure 7. Installation of the strain gauge pin in the found position and locking it against rotation relative to the longitudinal axis
S o u r c e: made by A.A. Karsakov

Figure 8. Method of adjusting the angle of installation of the strain gauge pin in the "zero" position using a pull bar of variable length
S o u r c e: made by A.A. Karsakov

After that, the position of the strain gauge pin at which the signal is equal to zero is found. In this position, it is installed in the actual rig and secured against rotation (Figure 7).

Another way of correcting the angle of the strain gauge to the "zero" position is shown in Figure 8.

The pin is mounted in the support with the possibility of its rotation around the longitudinal axis. A lever is welded to the pin and an additional pin is welded to the support. A pull bar of variable length is installed between these two pins. By changing the length of this bar, the required "zero" position is found.

In addition to the investigated influence of vertical load on strain gauge pins when determining horizontal forces, it is possible that axial forces are also picked up by the strain gauges. Their emergence is possible during measurements in factory conditions and leads to distortion of the stress field in the strain gage pin body. This can cause additional error when measuring the horizontal force, which is difficult to estimate by numerical methods, such as FEM [23; 24]. In this regard, taking into account the influence of axial forces on strain gauge pins requires additional experimental and theoretical studies, including the use of various modern methods [25].

Thus, technical solutions allowing to practically eliminate the revealed undesirable phenomenon of mutual influence of different components of the total load acting on the strain gauge pin, when measuring the horizontal load, are proposed.

4. Conclusion

The conducted study allowed to draw the following conclusions about the aspects of application of strain gauge devices for determination of operating stress of implements.

1. During the experimental determination of the horizontal load on the vehicle from the side of the implement, using pre-calibrated strain gauge pins, it was found that the strain gauges of the pins can additionally react to the vertical load, which leads to the emergence of systematic errors in the estimation of the horizontal load.

2. To eliminate this disadvantage, it was proposed that before the main calibration of the sensors of the horizontal force, which is transferred to the transport machine from the side of the implement [26], it is necessary to pre-determine the position at which the calibrated strain gauge device will not react to the vertical force. This is performed by rotating it relative to the longitudinal axis and ensuring its fixation in this position afterwards (Russian Federation patent No. 2800400).

3. The influence of axial forces on strain gauge pins, which may emerge during measurements and are picked up by the strain gauges, leads to distortion of the stress field in the body of the strain gauge pin. This may cause additional error when measuring the horizontal force, which is difficult to estimate by numerical methods. In this regard, taking into account the influence of axial forces on strain gauge pins requires additional experimental studies.

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