Determination of boundary conditions for mathematical model of agricultural machine during transport ride

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Abstract. Agricultural tillage machines require large working widths. The maximum permissible width of the machine on public roads is 3 meters. For this reason, the machines for work have to be spread mostly by side frames. There is a force on the machine in the transport position than during the machine operation and therefore it is necessary to determine its boundary conditions, which are different from the machine in the working position. When designing the machine, it is therefore necessary to pay attention not only to the marginal conditions during the machine operation but also to the marginal conditions for the transport of the machine. During the transport of the machine, its frames and connecting frame pins are stressed by forces that cause tension in the structure. These forces arise from road surface unevenness, but since the machine often travels on farms, field crossings and various other obstacles are often the cause of machine design failures. In this work, the stress on the machine structure in the transport position was measured. Two strain gauges were used to measure the stress. The results obtained can be used for the design of agricultural machinery modifications.

1. Introduction

Machines with wide shots are used for tillage on large farms. The agricultural machine for wide tillage can move in two positions. The first position is transport and the second is working. Machines must meet the requirements for transport on public roads. For this reason, the machine side frames extend to a transport position around the centre frame. The middle frame and side frames are bolted together. Wide tillage machines achieve high weight. Designers try to minimize the weight of the machines, thereby reducing the overall cost of production while reducing machine load [1–3].

For machine design, designers are currently using mathematical models and machine boundary conditions during the work. The machine has completely different design requirements during machine operation and in transport position [4, 5]. The difference in these two machine positions is primarily in the different loads of the machine frames. When the machine is changed from the working position to
the transport position, the position of the machine frames changes and they are loaded in a different direction compared to the machine working position. Most agricultural machines are only suspended by tires [6, 7]. Measurements using strain gauges to determine the stress conditions that are inserted into mathematical models have been used, for example, to test wind turbine blades [8], testing and modelling in composites [9], crack initiation in alloys [10] or predicting the life of welds [11]. Strain gauges are performed on agricultural machines to determine tractor tensile strength measurements [12], operational dynamic tests on a polygon for an agricultural machine [13], fatigue life assessment of the machine [14]. Various strain gauge measurement methods were used to determine the stresses in the frames of agricultural machines [15–18].

The aim of this work was to create a methodical procedure for determining the boundary conditions of an agricultural machine in transport position. The resulting boundary conditions can be substituted for the mathematical model when designing an agricultural machine.

2. Material and methods

One part was selected for measurement on a soil tillage machine. The selected part is focused on the determination of tension during transport. The measurement started by sticking the strain gauges onto the machine. The measuring unit was assembled and connected with strain gauges on the machine. The assembled measuring device was verified by testing measurements at known loads. Experimental rides were performed after verification of the measuring system.

2.1. Strain gauge attachment to the machine

The places were selected on the machine with the highest load in the transport for sticking the strain gauges. The right (strain gauges 1 and 2) and left (strain gauges 3 and 4) sides of the machine were fitted with strain gauges mirrored. 4 places were measured in total. 2 strain gauges rotated 90° were used in one place. The resulting stress was then counted. The location of the strain gauges on the machine is shown in Fig. 1.

![Figure 1](image.png)

**Figure 1.** Measured machine in transport position: 1 - Strain gauge location 1, Strain gauge location 2, obstacle to crossing the machine, 4 - the location of the measuring device

2.2 Measuring device

The measuring device was designed to record the stress course during experimental rides – see Fig. 2. The miniPC was placed on a soil tillage machine. The MiniPC has been recharged from the tractor. The
measuring device was controlled via a computer located in the tractor. Wifi was used to control the miniPC.

![Measuring device for determining the stress at selected points during transport of the machine](image)

**Figure 2.** Measuring device for determining the stress at selected points during transport of the machine

### 2.3. Experimental rides

Test rides were performed on a flat surface. The road surface consisted of asphalt. Tractor and soil tillage machine created a kit for experimental rides. Stress at measuring points was measured for unloaded condition before experimental rides. The resulting stress values were shifted to 0 by reading the unloaded values. Obstacle (wood, sizes: 160 mm x 160 mm and 1000 mm long) was choose, which represents surface roughness in the field. The obstacle was inserted under the wheel of the soil tillage machine during experimental runs. Three speeds of experimental rides were measured 6 km h\(^{-1}\), 8 km h\(^{-1}\) and 10 km h\(^{-1}\). Higher speeds could not be tested because of machine stability. The obstacle was placed under the right wheel in the first three experimental rides and below the left wheel in the next three experimental rides. Two experimental rides were made for the driving back. Driving back were made only for the speed of 6 km h\(^{-1}\). Higher speeds were not used because of the drawbar limitations for driving back.

### 3. Results and discussion

All experimental rides were processed in dependence of stress (MPa) on time (s) and stress (MPa) on acceleration (m s\(^{-2}\)) for each strain gauges. The dependence for driving 8 km h\(^{-1}\) and the obstacle under the right wheel is shown in Fig. 3. Approaching the obstacle is shown in 1 second (Fig. 3 right), followed by the oscillation of the machine structure. The dependence of stress on acceleration is shown in Figure 3 on the left.

![Dependence on stress at the acceleration (left) and stress at the time (right) for ride 8 km h\(^{-1}\), obstacle under right wheel, strain gauge 2](image)

**Figure 3.** Dependence on stress at the acceleration (left) and stress at the time (right) for ride 8 km h\(^{-1}\), obstacle under right wheel, strain gauge 2
The dependence of stress on acceleration can be described by ellipse. The ellipse shape was developed for each experimental ride. The ellipse parameters describe the dependence (magnitude and direction) of stress on acceleration. The ellipse parameters are shown in Table 1. Abbreviation S.G. describes individual strain gauges. The angle describes the inclination of the ellipse along the y-axis (the left direction is a negative angle and the right direction is a positive angle). The a parameter describes half the width of the ellipse (acceleration magnitude range) and parameter b half the height of the ellipse (size range stress). Parameters m and n describe the offset of the centre of the ellipse from 0, where m is the x-axis offset (acceleration shift) and n is the displacement of stress during hitting the obstacle. The coefficients are described by the general ellipse 1 equation.

\[
\frac{(\cos \alpha \cdot x' + \sin \alpha \cdot y') - m}{a^2} + \frac{(-\sin \alpha \cdot x' + \cos \alpha \cdot y') - n}{b^2} = 1
\]

where \(x'\) – acceleration [m s\(^{-2}\)], \(y'\) – stress [MPa]

The procedure described in this work is for measuring the machine stress in the transport position. The results are used as boundary conditions for mathematical models.

The greatest acceleration difference measured is 0.38 m s\(^{-2}\) when comparing forward and reverse travel at 6 km h\(^{-1}\). Usually, the difference is about 0.1 m s\(^{-2}\). This difference increases with increasing experimental speed. However, it cannot be said that the greater the speed, the greater the difference in acceleration.

**Table 1. Coefficients of ellipse for all rides**

| Speed  | Parameters | Obstacle under left wheel | Obstacle under right wheel |
|--------|------------|---------------------------|---------------------------|
|        |            | S. G. 1                   | S. G. 2                   | S. G. 3                   | S. G. 4                   | S. G. 1                   | S. G. 2                   | S. G. 3                   | S. G. 4                   |
| 6 km h\(^{-1}\) | angle (°)  | -2.35                     | -2.85                     | -2.33                     | -1.92                     | -1.42                     | -3.62                     | -1.72                     | -3.58                     |
|        | a (m s\(^{-2}\)) | 0.68                      | 0.75                      | 0.68                      | 0.72                      | 0.54                      | 0.78                      | 0.85                      | 0.87                      |
|        | b (MPa)    | 9.60                      | 8.84                      | 15.28                     | 9.12                      | 12.78                     | 8.26                      | 9.78                      | 8.63                      |
|        | m (m s\(^{-2}\)) | -0.05                     | -0.12                     | 0.03                      | -0.38                     | 0.32                      | -0.25                     | -0.05                     | -0.13                     |
|        | n (MPa)    | -4.40                     | 14.07                     | 9.46                      | 0.51                      | -3.54                     | 18.63                     | 11.19                     | 0.39                      |
| 6 km h\(^{-1}\) | angle (°)  | -0.31                     | -4.18                     | -1.98                     | -3.74                     | -1.92                     | -3.42                     | -1.08                     | -2.09                     |
|        | a (m s\(^{-2}\)) | 0.75                      | 0.74                      | 0.69                      | 1.10                      | 0.72                      | 0.75                      | 0.82                      | 0.97                      |
|        | b (MPa)    | 9.02                      | 8.08                      | 13.69                     | 7.06                      | 13.95                     | 7.23                      | 9.54                      | 7.58                      |
|        | m (m s\(^{-2}\)) | -0.24                     | 0.04                      | -0.16                     | 0.12                      | -0.36                     | -0.10                     | -0.12                     | 0.19                      |
|        | n (MPa)    | -5.76                     | 5.52                      | 10.04                     | -4.95                     | -3.92                     | 8.82                      | 7.06                      | -2.14                     |
| 8 km h\(^{-1}\) | angle (°)  | -3.11                     | -3.84                     | -1.92                     | -0.72                     | -1.19                     | -4.45                     | -2.10                     | -2.81                     |
|        | a (m s\(^{-2}\)) | 0.65                      | 0.77                      | 0.78                      | 0.91                      | 0.99                      | 0.72                      | 1.24                      | 0.94                      |
|        | b (MPa)    | 9.88                      | 7.61                      | 20.80                     | 8.55                      | 20.58                     | 8.35                      | 16.85                     | 8.68                      |
|        | m (m s\(^{-2}\)) | 0.19                      | -0.34                     | 0.04                      | 0.05                      | 0.33                      | 0.33                      | 0.22                      | -0.08                     |
|        | n (MPa)    | -5.18                     | 11.88                     | 5.85                      | -0.11                     | -3.73                     | 18.31                     | 13.16                     | 0.50                      |
| 10 km h\(^{-1}\) | angle (°)  | -2.86                     | -1.56                     | -1.47                     | -0.49                     | -1.92                     | -3.10                     | -1.85                     | -4.41                     |
|        | a (m s\(^{-2}\)) | 0.75                      | 0.88                      | 0.84                      | 0.92                      | 0.83                      | 0.88                      | 1.10                      | 0.98                      |
|        | b (MPa)    | 14.95                     | 7.22                      | 24.20                     | 8.50                      | 23.07                     | 11.42                     | 20.58                     | 9.43                      |
|        | m (m s\(^{-2}\)) | 0.17                      | -0.22                     | 0.17                      | -0.21                     | 0.12                      | 0.06                      | 0.09                      | 0.22                      |
|        | n (MPa)    | -6.31                     | 8.99                      | 2.39                      | -3.17                     | -9.21                     | 13.65                     | 11.39                     | 1.43                      |
The dependence on the rates was verified. For example, the stress magnitude b parameter is approximately the same for the same forward and reverse speeds for strain gauges 1 and 3. The higher the experimental speed, the higher the stress. This is evident on the side where the obstacle is located under the wheel as well as under the absence of the obstacle. Acceleration values increase with higher speed.

The strain gauge for strain gauges 2 and 4 is lower compared to strain gauges 1 and 3. This is due to the placement of strain gauges on the top. However, lower values of these strain gauges do not necessarily mean their incorrect positioning, but rather the possibility to improve machine construction.

Acceleration and stress shifts are not important for mathematical models. This is the correct determination of the magnitude of acceleration and stress (ellipse placement) for a given strain gauge.

Kumar H et al. [19] describes the application of a torque transducer for measurement on agricultural machines. Torques were not measured in this work. The torques can be calculated at any location on the machine if the stress is known at one of the machine's locations. Stress can be calculated for any location on the machine. The torque for the selected location can then be calculated from this stress.

Subbaityan et. al. [20] presents a procedure for determining excavator design by measuring the stress during machine load. Their results show a good correlation between test data from a mathematical model and experimental measurement. This procedure will allow the design of the machine with less time and means for developing the machine. A similar procedure was created in this work for an agricultural machine. There is also a prerequisite for reducing machine development costs and optimizing it. This makes the machine lighter and less expensive to operate.

4. Conclusion

The procedure described in this work is used to determine the boundary conditions for mathematical models dealing with the design of agricultural machinery. Measured values of maximum stress at known locations during transport of the machine will help to calculate the stresses in other parts of the machine. The resulting stress values must always include the machine in the work position. The solution in this work can be used for the current solution, thus improving the machine design and designing the new machine. Specific results of average stress values show similar sizes of about 5 MPa. For the design of boundary conditions, the maximum values of the stresses attained during the passage to the obstacle, i.e. the upper and lower peaks are important.

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