The impact of stiffness increasing in construction of tire measuring device to measured results

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Abstract. The article analyzes the influence of the construction stiffness of the measuring device and its effort to the resulting measured results. The article deals with the possibility of increasing the accuracy of measurement and at the same time reducing the measurement deviation on the measuring device by increasing the rigidity of the structure of the device. In the introduction, the article describes the stiffness, errors and analyzes the possibilities of increasing the accuracy of measurement on the measuring device and examines the causes of measurement deviations. In the next part, the article offers the possibilities of increasing the rigidity and strength of the measuring device. In the practical part, the structural modification of the device increasing the overall rigidity and strength of the structure is presented. In the practical part we made a simulation of old device frame and modified frame. In the last part, the article compares the results of measurements before the structural modification and after the structural modification of the increase in stiffness.

1. Introduction
Measurement is an important part of our daily lives. People constantly use measurements for various quantities such as times, lengths, weights and others. But measurement helps the most with different types of product design. After finishing the products, it is necessary to verify the correct dimensions. Various measuring devices are used for that. Using these devices, we can mathematically determine the quality of the product. After obtaining the data from the measuring device, these values must be evaluated. Various value processing methodologies are used to evaluate them. Various measurement methods are used to measure diameters. In the optical method we use, the construction of the measuring device is very important. The design of the measuring device can significantly influence the measured values.

2. Stiffness of devices
In general, most of the machines determined for measuring or even for machining had to deliver specified work and power. Stiffness is a gauge of machine or device ability to keep a accuracy when doing a mechanical work or accelerating(deceleration) of mechanical parts and also has a special significance when force components are common with force loop.[1]
For a precise application a request for rigid construction lead to small deformation in components of an
force loop, so it’s necessary to take into account to stiffness. However, big constructions and machine
frames tend to weight more because of a higher stiffness. Bigger weight can cause lower dynamic
response, which is not required, this could be a significant problem.[2]
It’s difficult to predict character of forces which could occur in complex mechanism, therefore is often
necessary to consider the impact of force and moment structures in many coordinated directions. For
many mechanisms its necessary to take into account three-dimensional stiffness of the structure exposed
to all possible forces and moments.
In some cases, a low stiffens is necessary. An example could be a controlled machining process, for
example polishing. The aim of this process is to generate a constant force between workpiece and
polishing layer. A gravity force is used very often, and it provides effective force vector of zero
stiffness.[3]

3. Measurement error
The measurement error is the difference between the actual value of the measured quantity and the value
determined by the measurement. [4] Every measuring contains a certain error and only approaches to
the correct value. During the measurement, the influences are applied, which are reflected by the
deviation between the actual and the measured value of the real measured dimension. The difference
between measured value and real value depends on the accuracy of the measuring instrument and the
accuracy of the measuring method.[5]

Always when we repeat a measurement with a sensitive instrument, we obtain slightly different results.
We know three types of errors which can occur during the measurement:[6]
- Gross errors are caused by inattention, mistake, fatigue of the observer. Measured
  value is very different from other values, such values are then excluded in the
  following processing;[6]
- Random errors are caused by fluctuating disturbances, they cannot be removed (eg.
  accidental rubbing into the measuring instrument, wind, vibrations) and it is difficult
to find then. We do not always get the same value of the quantity, if we measure
repeatedly, their effect is reduced when we repeat the measure more times (5 to 10
times) and then make an arithmetic mean of these values;[6]
- Systematic errors are related to the used measurement method and the properties of
  the gauges used. The measured value is either slightly smaller or larger (the measured
  value is inclined to only one side). Systematic error can be reduced by using a better
  measurement method or a better gauge.[6]
4. Tire measuring device
The measuring device has been developed to measure the dimensions and tolerances of bead wire used in car tires. An exploded view of car tire is shown in Fig.1a below.

![Fig. 1. Car tire, a) exploded view of tire [7], b) detailed view of bead wire [8]](image)

The bead wire shown in Fig. 1b is a part of tire which ensures that the tire fits properly in the rim. It also ensures the tightness of the connection with the rim and the transmission of longitudinal forces (because of the friction between the rim and the tire bead)[8]. The bead wire is basically a rubberized bundle of steel wires and can be in size of different diameters and can be in different shapes.[9] In our measuring device we can measure the inner diameter, the profile of the rope and the total weight. The device is designed for bead wires with a diameter from 8 to 22 inches (20.32-50.8 cm). The operation of the measuring device is ensured by PLC SIEMENS SIMATIC. The measuring device consists of three main parts. The first part of the device is the supporting frame; the second part is a turntable on which the measured bead wire is placed during measuring and the last part is the measuring head assembly equipped with laser sensors.[1]
4.1 Turntable
The turntable shown in Fig. 2.a is an assembly where the bead wire is placed during measuring. Wire is placed on a circular plate which is mounted on strain gauges where the weight of bead wire rope is measured. The measured wire must be precisely centred with respect to the axis of rotation of the table. Three centering pins which are automatically extended by solenoids are used for centering to the desired position of bead wire on table. The drive of the centering pin and solenoid assembly is provided by a toothed belt driven by servomotor. The toothed belt ensures the same position of all three centering pins. The rotation of the entire table during the measurement is also ensured by a servomotor with a planetary gearbox.

4.2 Measuring device positioning assembly
The measuring head shown in Fig. 2.b is an assembly formed of positioning units which ensure the displacement of the measuring head in the horizontal and vertical position. Positioning is performed by sets of linear travels and servomotors with a planetary gearbox. A measuring head bracket is mounted on the horizontal guide, on which three laser sensors are mounted which measure the bead wire.

4.3 The frame of measuring device
In Fig. 3 it is possible to see the assembly of a measuring device without a protective PLEXIGLAS cover. The frame of the device is composed of aluminium BOSCH profiles 45x45mm. The profiles are connected by L-elements and screws with nuts. The frame is firmly fixed to the floor.

4.4 Measuring process and occurrence of measurement errors
The process consists in placing the bead wire on a rotary table which is located on the strain gauges which measures the weight of the wire. The bead wire can’t be held by force, it must be positioned loosely so as not to distort the measurement results due to tension or other deformation of the bead wire. After placing the bead wire, the linear unit positions the group of sensors to the exact required distance of the given bead wire for the measurement to be successful. After placing the bead wire and positioning the sensors with the linear unit, the measurement starts. The measurement takes entire rotation of table. The measurement takes place in one turn of the table clockwise and after braking in the other turn counterclockwise.

In the optical method of measuring the diameter of the heel rope on the device, errors occur:

- Due to vibration of the whole device, if sufficient rigidity is not ensured during the measurement, the device will vibrate, and the wire will move during the measurement. This movement can cause distortion of the measurement results; therefore, it is important to ensure the highest possible rigidity of the whole structure.
- Measuring errors can also occur if the measured wire isn’t correctly placed on the table. When the table rotates and the wire isn’t correctly centred, the wire will not form an ellipse instead of a circle.
- A measuring error can also occur when turning and stopping the measuring table again, if the speed of rotation is not constant and the resulting shape after the measurement would not correspond to the actual shape of the measured rope.
- A measurement error can also occur due to insufficient illumination during the measurement as laser sensors require specific lighting conditions.

5. Determining the frame rigidity

![Fig. 4. A CAD model of measuring device with applied forces](image-url)
To determine the rigidity of the frame, we will proceed by creating a simplified model of the frame of the measuring device and determining the boundary conditions that we apply in the FEM software Ansys Workbench 2020 where we apply static structural analysis.[10] We used a total deformation calculation and then we have quantified the maximal displacement. On CAD model in Fig.4 is possible to see that on the bottom of the frame, there is a height adjustment but in real machine, the frame is firmly attached to the floor. After creating a cubic mesh shown in Fig.5a on the model and determining the boundary conditions of the simulation, we load the frame model with external forces acting in various places on the frame. Frame with applied forces is shown in in Fig. 5b we find out the maximum displacement of the frame and then we determine the rigidity of the whole structure.

We have determined as boundary conditions:

- The measuring device frame is firmly attached to the floor.
- On the vertical cross struts in the frame, the vertical force and torque from the turntable is acting.
- A vertical force from the actuators acts on the upper cross struts in the frame.
In order to determine the displacement and rigidity of the structure, we perform a simulation where the external force was acting in different places, P1-P4, on frame as can be seen on Fig.4. In each analysis, we apply an external force of F=100N acting on the frame and gradually change the position, so four analyses were performed. The magnitude of the external force of F=100N is equal to twice the magnitude of the force required to close the door on the device. The magnitude of this force corresponds to the force required to engage the used door lock, as specified by the manufacturer. The weight of the measuring table is about 45 kg, so choose the force FT=450 N. The weight of the measuring head assembly is about 9.89 kg, we choose the force FA=100 N. The torque moment created from the rotation of the table is M=10M.m, size is determined from the technical sheet of the motor. The applied forces and boundary conditions for the simulation are shown in the figure Fig.4.

The Fig.6 shows the result of a simulation created in Ansys Workbench 20.2. With the specified boundary conditions and with the force F applied in various positions on the frame, the maximum displacement of the structure was $d_{\text{max}}=22.278 \mu\text{m}$ in a simulation with the force $F_{P3}=100$ N acting in $P_3$. According to the maximum value of the displacement, we adjusted the resulting display scale for each analysis to a value from 0 to 24 µm.

5.1 Existing frame modification

When designing a structural modification to increase the rigidity of the frame, we considered several options:

1. Production of an identical frame by welding from steel profiles
2. Production of a frame of the same shape but using larger profiles
3. By inserting a reinforcing element into an existing frame.
From a technological and financial point of view, we have chosen option 3 as the most suitable option. The proposed design of reinforcing element (orange colour) can be seen in Fig. 7a. The reinforcement is used to make a rigid connection between cross struts. The reinforcing already installed in measuring device is shown in Fig. 7b.

![Fig. 7. Reinforcement element, a) CAD Design, b) reinforcement installed in measuring device](image)

The reinforcing element consists of a square steel profile of dimension 40x20mm which is welded into one unit. The element connects the cross struts that hold the measuring table and the measuring head assembly with screws. The insertion of such an element has the task of connecting the two moving parts into one part and increasing the rigidity and reduce the vibrations of the whole structure during the measurement. This design modification will have a major impact on the accuracy and reduction of the deviation of the measured results.

### 6. COMPARISON OF A FRAME STIFFNESS BEFORE AND AFTER MODIFICATION

The strength analysis of modified frame was performed in the same way and with the same boundary conditions as for the original frame design.

The results from simulation before and after the structural modification are compared in the Table 1 where we can see the overall decrease in the maximal displacement of the frame structure while same boundary conditions on the frame was used.

| Acting force        | F_{P1} | F_{P2} | F_{P3} | F_{P4} |
|---------------------|--------|--------|--------|--------|
| Old Frame           | 11.968 | 15.787 | 22.278 | 18.524 |
| Reinforced frame    | 6.1389 | 8.400  | 19.173 | 16.786 |
| **Stiffness Increasing [%]** | **48.71%** | **46.79%** | **13.94%** | **9.38%** |

Table 1. Results of maximal displacement of frame in simulation
In the Table 1 can be seen, the addition of reinforcement to the frame of the structure reduced the overall displacement of the frame parts in the simulation result, and we can say that the overall rigidity of the structure increased. In the individual simulations, the increasing of stiffness in ranged from 9.38% to 48.71%. In the Fig. 8 to Fig. 11 is shown a comparison of the results of simulation in the original structure - left side of picture and on the reinforced structure - right side of picture. In each picture can be seen significant decrease in maximal displacement.

Fig. 8. Simulation result with force $F_{P1}$ acting in P1

Fig. 9. Simulation result with force $F_{P2}$ acting in P2
As can be seen in the simulation in the figures above, the addition of reinforcement to the construction of the measuring device resulted in an increase in the resulting stiffness. This increase in stiffness will result in an increase in the quality of the measurement and a reduction in possible measurement error and deviation.
7. COMPARISON OF A MEASURED RESULTS BEFORE AND AFTER MODIFICATION
When measuring the bead wire before the construction modification, we achieved the measurement results with insufficient accuracy of the measured results. In order to be able to compare the results from the measurement before and after the design modification, we had to select a suitable type of measurement by the optical method [11]. We have selected two types of measurements, which will be described in more detail below:

7.1 Movement of a point in the plane
The first method is based on measuring the position of a point in a plane. We placed a cone-shaped part on the turntable, we measured the position of the point located at the tip. We performed the measurement 50 times, between each measurement the door was always opened and then closed. Opening and closing doors between measurement caused the vibration and movement of the measuring device. Fig. 12.a shows the position of the measured cone on the table. Fig. 12.b shows the principle of measuring and evaluating the position. The measurement was performed by subtracting the coordinates of the position of the measured point and then creating a "POINTCLOUD", after creating a "POINTCLOUD", we determined the position of the point zero – P. From the point “P” we measured individual distances.

![Image](https://via.placeholder.com/150)

**Fig. 12.** a) Position of a measured cone on turntable, b) Measuring method

On the Fig.13 is possible to see a graph and the measurement results. The columns on the graph show the intervals of the measured values. When measuring on the old frame, the measured values of the displacement ΔX of the points with respect to the zero point “P” ranged from ΔX_{min} = 0mm, ΔX_{max} = 1.2122mm, while the mean value of the deviation in the old frame is ΔX_{STD} = 0.26249mm. After performing the reinforcing, we performed the measurement again and evaluated it. When measuring on a reinforced frame, the measured values ΔX of the points with respect to the zero point “P” ranged from ΔX_{min} = 0mm, ΔX_{max} = 0.2264mm, while the mean value of the deviation in the reinforced frame is ΔX_{STD} = 0.046822mm.
After evaluating the method of measuring the position of a point in the plane, we improved the measurement results with a reinforced frame, from the original deviation with an old frame $\Delta X_{STD}=0.26249\text{mm}$ we got to value $\Delta X_{STD}=0.046822\text{mm}$ in reinforced frame, which represents an improvement in measurement accuracy of 82.16%.

### 7.2 Measuring the radius of the circular caliber.

As the second method of comparing the measured results, we chose to measure the radius of the circular caliber body, which has a nominal dimension $D=291.9856\pm0.001\text{mm}$. The measurement was performed 150 times with the old frame and 50 times with the reinforced frame. The measurement was performed by turning turntable clockwise, always recording the average value of the radius. **Fig. 14** shows the measurement method.

**Fig. 14.** a) Position of a measured gauge on turntable, b) Measuring method
On the Fig. 15a can be seen the measurement results with the old frame. During the measurement, we recorded the values of the radius of the caliber. For the original frame, the values ranged from $m_{\text{umin}}=145.925\text{mm}$ to $m_{\text{umax}}=146.1505\text{mm}$. The nominal value of the radius of the caliber is $m_0=D/2=145.9928\text{mm}$. With an unreinforced frame, we achieved an average deviation of $\Delta m_{\text{STD}}=0.037172\text{mm}$ from the nominal value. On the Fig. 15b can be seen the measurement results with the reinforced frame. After the measurement, with the reinforced frame the values ranged from $m_{\text{umin}}=145.9785\text{mm}$ to $m_{\text{umax}}=146.0066\text{mm}$. With an reinforced frame, we achieved an average deviation of $\Delta m_{\text{STD}}=0.0046874\text{mm}$ from the nominal value.

![Fig. 15a](image1)

![Fig. 15b](image2)

**Fig. 15.** a) results of measuring a caliber in old frame, b) results of measuring a caliber in reinforced frame

After evaluating the method of measuring the radius of caliber, we also improved the measurement results with a reinforced structure, from the original mean deviation with an unreinforced frame $\Delta m_{\text{STD}}=0.037172\text{mm}$ we got to the value $\Delta m_{\text{STD}}=0.0046874\text{mm}$, which represents an improvement in measurement accuracy of 87.39%.

**Conclusion**

As the demands on the accuracy and quality of the final product are increasing, so same does the demand for the quality and accuracy of the components and semi-finished products used in the production process. The bead wire is part of the tire and it is very important that the required parameters and dimensions are observed as a faulty piece of bead rope could cause fatal consequences if it is damaged during riding on the vehicle. For this reason, high demands are placed on the exact dimensions and shape of the bead wire. This is the reason why it is very important to inspect each piece of bead wire before further use in the manufacturing process. With the requirement for inspection, there is also a requirement for an accurate measuring device. We had to additionally modify the measuring device that we created at our workplace to ensure better measurement accuracy. By increasing the rigidity of the device, we were able to increase the resulting measurement accuracy and confirmed that the rigidity of the device frame has a significant effect on the measured values.
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References
1. Kumičáková D, Rengevič A, Čísar M, Tlach V (2017) Utilisation of Kinect Sensors for the Design of a Human-Robot Collaborative Workcell. Adv Sci Technol Res J 11:270–278. https://doi.org/10.12913/22998624/80937
2. Pástor M, Živčák J, Puškár M, et al (2020) Application of Advanced Measuring Methods for Identification of Stresses and Deformations of Automotive Structures. Appl Sci 10:. https://doi.org/10.3390/app10217510
3. Leach R, Smith ST (2018) Basics of Precision Engineering. CRC Press
4. Kuric I, Tlach V, Čísar M, et al (2020) Examination of industrial robot performance parameters utilizing machine tool diagnostic methods. Int J Adv Robot Syst 17:. https://doi.org/10.1177/1729881420905723
5. Dodge Y, Institute IS, Commenges D (2006) The Oxford Dictionary of Statistical Terms. Oxford University Press
6. Taylor JR (1982) An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. University Science Books
7. Les Schwab Tire Center (2021) Tire FAQ. https://www.leschwab.com/article/tire-faq.html
8. AMG CENTRUM (2012) Konstrukce pneumatiky, druhy , typy. https://www.stk-valmez.cz/news/konstrukce-pneumatiky-druhy-typy/
9. Kuric I, Gorobchenko O, Litikova O, et al (2020) Research of vehicle control informative functioning capacity. IOP Conf Ser Mater Sci Eng 776:. https://doi.org/10.1088/1757-899X/776/1/012036
10. Kuric I, Klačková I, Nikitin YR, et al (2021) Analysis of Diagnostic Methods and Energy of Production Systems Drives. Processes 9:. https://doi.org/10.3390/pr9050843
11. Figiel A, Klačková A (2020) Safety requirements for mining systems controlled in automatic mode. / Acta Montan Slovaca 25:417–426. https://doi.org/10.46544/AMS.v25i3.13
12. Hrubos M, Svetlik J, et al. 2016 Searching for collisions between mobile robot and environment Int. J. of Adv. Robotic Systems 13(5) DOI10.1177/1729881416667500
13. Kelemen M Virgula I et al. 2018 A novel approach for a inverse kinematics solution of a redundant manipulator Appl Scie - Basel 8(11) 1-14 DOI: 10.3390/app8112229
14. Stejskal T Dovica M Svetlik J et al. 2019 Experimental assessment of the static stiffness of machine parts and structures by changing the magnitude of the hysteresis as a function of loading Open Eng. 9(1) 655-659 DOI10.1515/eng-2019-0078