CALIBRATION TOOL FOR TILT SENSORS FOR CHECKING THE INSTABILITY OF MOTOR VEHICLES

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The article deals with the development and determination of the uncertainty of a calibration tool for tilt sensors for the control of motor vehicle instability. The stability of motor vehicles is critical, especially when driving on inclined terrain, when instability and overturning of the vehicle can occur. For this purpose, it is necessary to install and calibrate a suitable tilt sensor.

KEYWORDS

calibration, gauges, uncertainty, tilt sensor, vehicle stability

1 INTRODUCTION

When driving on inclined terrain, problems with sideway vehicle stability may occur, so along with dynamic effects, the influence of the vehicle's tilt angle is also an important parameter that needs to be monitored and evaluated (Fig. 1). It is based on the vehicle model and the location of the vehicle's centre of gravity. When the vehicle is driving slowly, it is sufficient to know the current tilt angle, but when driving fast, the dynamic effects of the vehicle's mass also have a significant impact.

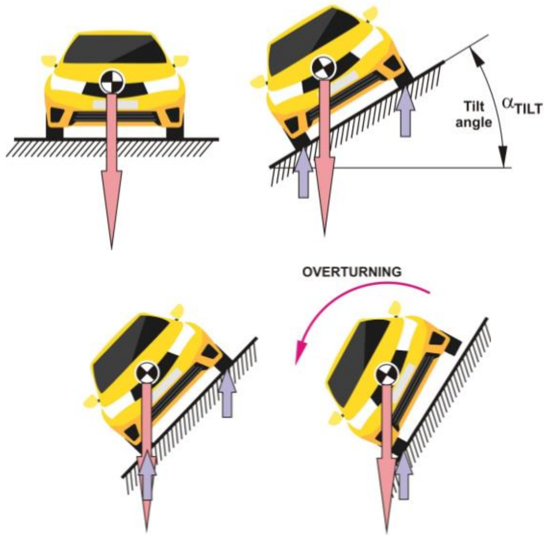

Figure 1. Measurement of tilt angle for detection of sideway vehicle instability

Low-cost sensors are usually used to measure vehicle inclination, but it is necessary to calibrate and verify their measurement accuracy [ACT 157/2018 2018, DECREE 161/2019 2019, DIRECTIVE 2009/34/EC 2009, DIRECTIVE 2014/32/EU 2014, EA-4/02 1999, JCGM 100 2008, JCGM 104 2009]. For this verification, it is necessary to develop a tool and methodology for the verification of such measuring devices [Bratan 2023, Hroncova 2022a, Hroncova 2022b, Huston 2014, Karnopp 2013, Kelemenova 2021a, Kelemenova 2021b, Klarak 2021].

Control stability and passive safety were solved in research [Vempaty 2017]. Also, many factors were observed which have influence to vehicle stability [Halko 2014].

Some authors addressed the danger of overturning of SUV vehicles as a frequent cause of accidents of these vehicles [Penny 2004]. The authors also tried to change the design concept of such vehicles [Krenicky 2018]. Rollover risk were analysed also in many other works [Farmer 2002, Hu 2023, MacLennan 2008, Piyabongkarn 2009, Yang 2011].

2 VERIFIED TILT SENSOR FOR VEHICLE INSTABILITY SENSING

The tested tilt sensor uses the principle of thermal field movement due to the acceleration and tilt of the measured object. The tilt of the object is detected using the temperature difference on the individual temperature sensors. By processing this information, it is then possible to determine a specific tilt value (Fig. 2).

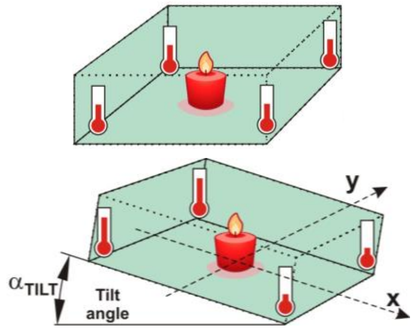

Figure 2. Tilt sensor principle.

The carrier of the tilt information is the output signal of the sensor in the form of a pulse width modulated signal. It is a low-cost sensor, so it is necessary to process its output information in the form of information about the tilt angle [Tlach 2017, Urban 2020]. The process of acquiring and processing information also introduces a certain uncertainty of obtaining this information about the angle of inclination. Maximum permissible errors (MPE) values are not known for the individual components used in this chain, so the only way to obtain them is experimental calibration and subsequent verification of the measuring chain.

3 THE MAXIMUM PERMISSIBLE ERROR OF THE TILT ANGLE ETALON - DETERMINATION USING A MATHEMATICAL MODEL

For the calibration and subsequent verification of the measuring chain, a methodology was proposed using a sine plate in combination with parallel gauge set. Tilt angle or the tilt angle standard was created using a sine plate and a block of parallel gauges (Fig. 3). The measurement was carried out on a granite base, which was adjusted using a coincidence spirit level. The earthenware slab represents the standard of a balanced plane.

Math model of sine plate is defined as:

$$\sin \alpha_{SP} = \frac{L_{ZMR}}{L_{SP}} . \tag{1}$$

From the point of view of taking into account the geometric deviations of the sine plate, the previous model is insufficient for the analysis of the maximum permissible error of this tilt angle standard. The influence of geometric deviations on the maximum permissible error of the sine plate can be partially assessed in two phases:

- Change or the maximum permissible error of the inclination angle is caused firstly by the geometric deviations of the contact rollers and the deviation of their relative position.

- Change or the maximum permissible error of the tilt angle is also caused by geometric deviations of the body of the sine ruler.

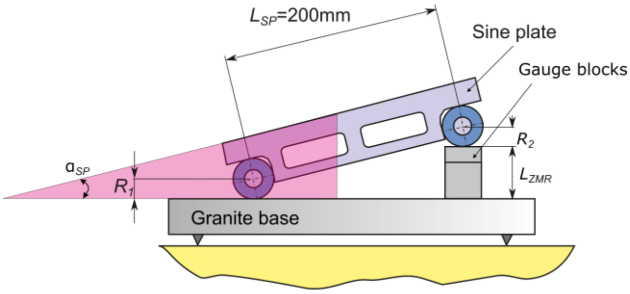

Figure 3. Tilt angle etalon.

Within these intentions, the angle standard model can be decomposed into two sub-models (Fig. 4):

- model of the contact angle of the contact rollers with the horizontal plane α_{SP1},

- model of the angle of the upper surface of the body of the sine plate α_{SP2}.

$$\alpha_{SP} = \alpha_{SP1} + \alpha_{SP2}\,. \quad (2)$$

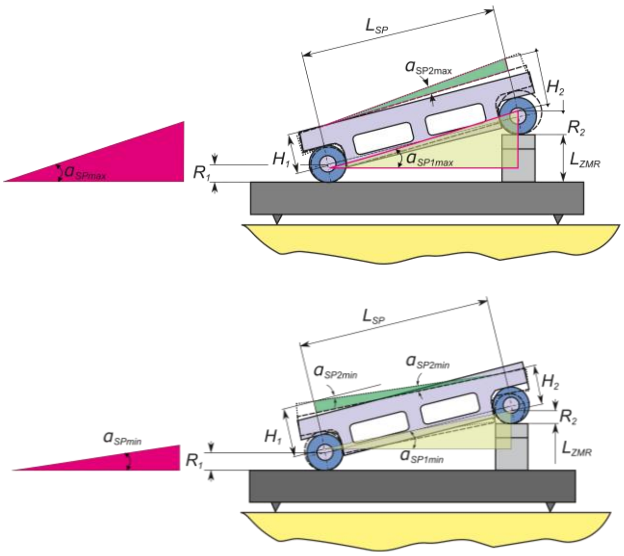

Figure 4. Model of the contact angle of the contact rollers with the horizontal plane α_{SP1} (upper figure) and model of the angle of the upper surface of the body of the sine plate α_{SP2} (lower figure).

Let us consider the maximum permissible errors guaranteed by the manufacturer of the sine plate. The maximum permissible error of the tilt angle etalon can then be determined as the difference between the upper and lower limit value of the set angle of the sine plate α_{SP}.

$$Z_{\max\,\alpha\,SP} = \alpha_{SP\max} - \alpha_{SP\min}\,. \quad (3)$$

The upper limit angle of the sine plate α_{SPmax} can be determined as the sum of the upper limit angles α_{SP1max} and α_{SP2max}. The lower limit angle of the sine plate α_{SPmin} can be determined as the sum of the lower limit angles α_{SP1min} and α_{SP2min}.

While for the given angles it is possible to write:

$$\alpha_{SP1\max,\,\min} = \arcsin\frac{L_{ZMR} + R_2 - R_1}{L_{SP}}\,. \quad (4)$$

$$\alpha_{SP2\max,\,\min} = \arctan\frac{H_2 - H_1}{L_{SP}}\,. \quad (5)$$

The upper limit dimension of the angle will be if:

- Deviation of the size of the contact cylinder $\delta_{R2} = +1\mu m$.

- Deviation of the size of the contact cylinder $\delta_{R1} = -1\mu m$.

- Deviation of the dimension of the contact roller axis distance $\delta_{LSP} = -1\mu m$.

The upper limit dimension of the angle $\alpha_{SP2\max}$ will be if:

- Deviation of the size (distance) of the axis of the contact rollers and the upper surface of the plate prism: $\delta_{H1} = -1\mu m$.

- Deviation of the size (distance) of the axis of the contact rollers and the upper surface of the plate prism: $\delta_{H2} = +1\mu m$.

The lower limit dimension of the angle $\alpha_{SP1\min}$ will be if:

- Deviation of the size of the contact cylinder $\delta_{R2} = -1\mu m$.

- Deviation of the size of the contact cylinder $\delta_{R1} = +1\mu m$.

- Deviation of the dimension of the contact roller axis distance $\delta_{LSP} = +1\mu m$.

The upper limit dimension of the angle $\alpha_{SP2\min}$ will be if:

- Deviation of the size (distance) of the axis of the contact rollers and the upper surface of the plate prism: $\delta_{H1} = +1\mu m$.

- Deviation of the size (distance) of the axis of the contact rollers and the upper surface of the plate prism: $\delta_{H2} = -1\mu m$.

After substituting the mentioned deviations, it is possible to obtain the relations:

$$\alpha_{SP1\max,\,\min} = \arcsin\frac{(L_{ZMR} + \delta_{ZMR}) + (R_2 + \delta_{R2}) - (R_1 + \delta_{R1})}{L_{SP} + \delta_{LSP}}\,. \quad (6)$$

$$\alpha_{SP2\max,\,\min} = \arctan\frac{(H_2 + \delta_{H2}) - (H_1 + \delta_{H1})}{L_{SP} + \delta_{LSP}}\,. \quad (7)$$

From these relations, it is possible to investigate the influence of the maximum permissible error of the value of the block of basic parallel scales on the maximum permissible error of the tilt angle standard.

For the purposes of this analysis, it is necessary to know the dimensions of the sine ruler LLSP, D1, D2, H1, H2. These dimensions (Fig. 5) were measured using a CARL ZEISS Contura G2 coordinate measuring machine (Fig. 6).

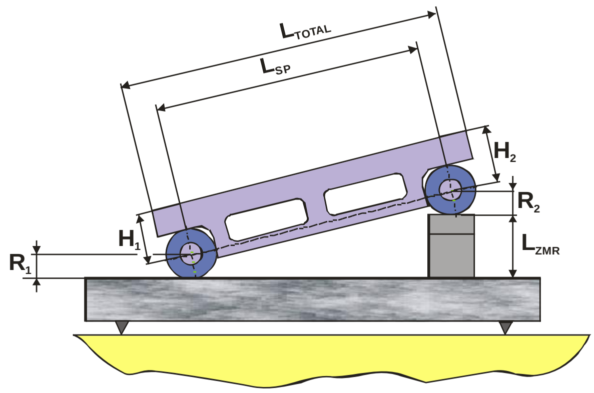

Figure 5. Dimensions measured using a coordinate measuring machine.

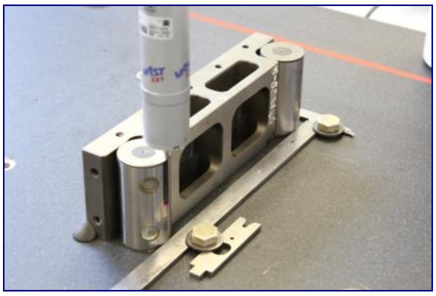

Figure 6. Measurement using a coordinate measuring machine.

A set of parallel gauges were used to set a specific tilt angle. Each nominal dimension of the L_{ZMR} block of gauges was corrected by the value of the systematic error, while this corrected value is further applied in the calculations.

The resulting uncertainty values of the blocks of gauges are also displayed graphically on (Fig. 7).

After all the listed values of the variables (dimensions) have been substituted, it is possible to determine the values of the maximum permissible error of the tilt angle etalon according to the value of the block of parallel gauges (Fig. 8). The values of the maximum permissible error are displayed in arc minutes.

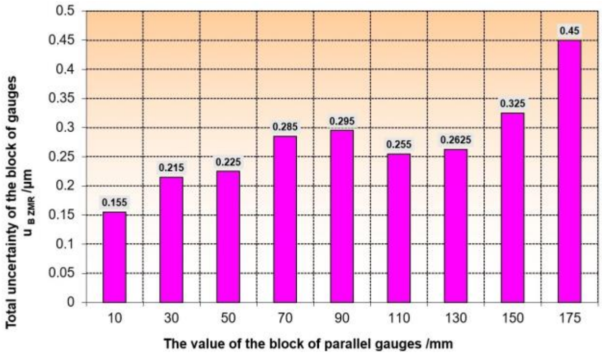

Figure 7. Total uncertainties of the block of parallel gauges.

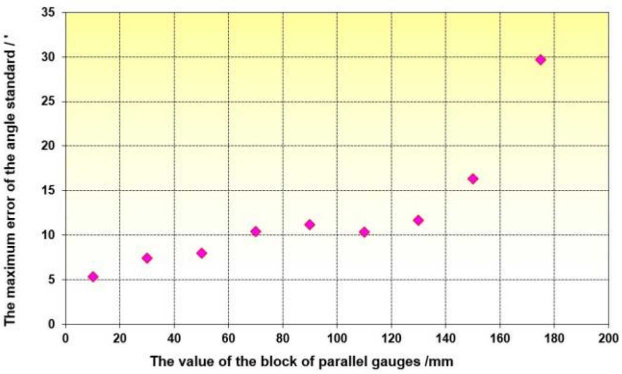

Figure 8. The maximum error of the tilt angle etalon at different values of the block of parallel gauges (or tilt angles) when considering the most unfavourable deviations of individual members of the tilt angle etalon.

It should be noted that these values are the result of the analysis assuming the most unfavourable situation in the individual partial deviations of the dimensional chain of the angle standard measurements [Krenicky 2022]. The maximum analytically determined tilt angle standard error is 29.6' (in arc minutes). In practice, however, the situation is usually not so unfavourable. One of the options for determining the maximum permissible error of the tilt angle standard is experimental identification.

4 CALIBRATION OF TILT SENSOR

The calibration was carried out in laboratory conditions (Fig. 9), while the tilt sensor was placed on the surface of the sine plate. The output of the sensor was displayed on a digital oscilloscope with the possibility of measuring the parameters of the pulse modulated signal. The measurements were carried out at ten evenly distributed selected values of the inclination angle in the range of 0° to 56°. For each set angle, ten observations were made under unchanged conditions.

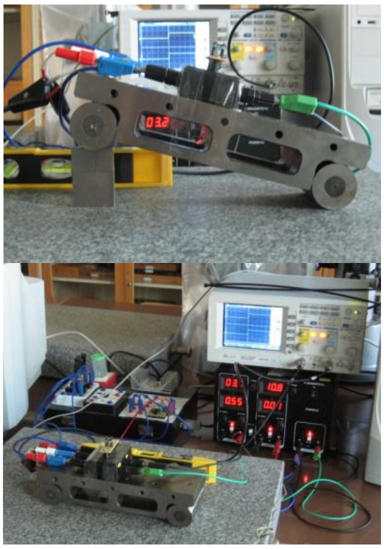

Figure 9. Calibration of tilt sensor.

The measured static characteristic has a non-linear course, but when using a mathematical model, the characteristic can be linearized (Fig. 10):

$$t_h = c_S \cdot \sin(\alpha_{TILT}) + 5. \qquad (8)$$

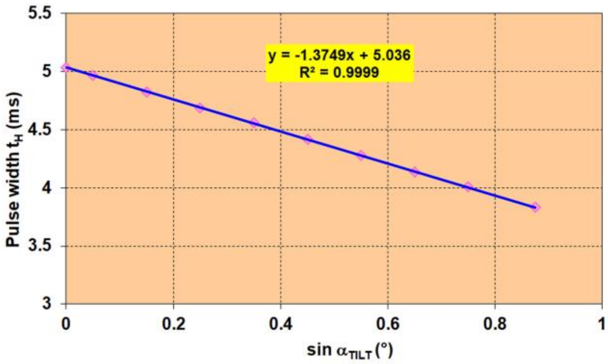

Figure 10. Static characteristic of the tilt sensor.

The linearized model was approximated by a regression linear function, where the sensitivity of the sensor was determined with the value c_S = -1.3749 ms and the zero shift has a value of z_S = 5.036 ms. The regression coefficient confirms the correctness of the linear model. From this model, it is possible to determine a calibration equation that can be used to convert pulse width values to tilt angle values:

$$\alpha_{TILTh} = \arcsin\left(\frac{5.036 - t_H}{1.3749}\right). \qquad (9)$$

For this resulting mathematical measurement model, it is then possible to further determine the uncertainties of the individual coefficients and the covariance. After the calculation, it is then possible to display the course of the standard uncertainties (Fig. 11) of the tilt angle measurement for the tested tilt sensor.

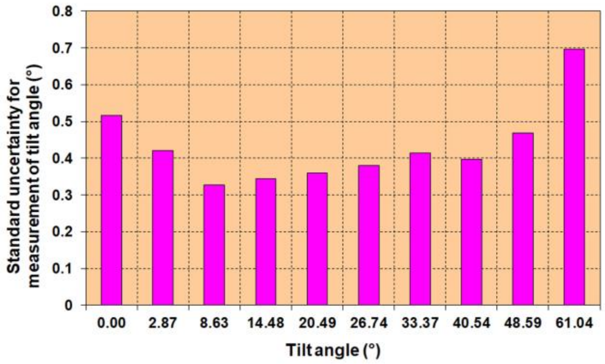

Figure 11. Static characteristic of the tilt sensor.

From the course of measurement uncertainties, it can be seen that the maximum measurement uncertainty is 0.7° on the investigated measurement range of the sensor. The measurement uncertainty is sufficient for the application requirement for detecting the vehicle's tilt angle as a prevention against side away overturning.

5 CONCLUSIONS

In mechatronic systems, sensors are key components that provide information about the state of the controlled system and the state of the environment. The process of calibration and determination of measurement uncertainty provides us with information about how we can trust the sensors and how correct the data obtained are. Control algorithms for control can be successfully used only in the case of correct and reliable data. On the basis of these data, the regulatory deviation is determined and the action intervention in the controlled system is determined [Blatnicky 2020, Bozek 2012, Bozek 2020, Bratan 2023, Domanski 2017, Kelemenova 2021b, Koniar 2014, Mascenik 2016, Mikova 2022, Lestach 2022, Olejarova 2021, Saga 2019, Segota 2021, Suder 2021, Peterka 2020, Pivarciova 2016, Vasko 2021, Zelnik 2021, Qazizada 2016].

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