Master Thesis at SKF:

Lateral force estimation acting at a vehicle wheel using a hub bearing unit equipped with strain gauges and Eddy-current sensors

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Presentation overview

- Introduction
- Research goals
- Strain gauge measurements
- Eddy-current sensor measurements
- Field- / validation measurements
- BETSY calibration method
- Conclusions

1

Introduction

Introduction: Load Sensing Bearing (LSB)

- Why would we like to measure forces?

  - Monitoring the mechanical loads of a bearing.
  - Control the active safety systems in vehicles like the ABS (longitudinal force) and ESC (lateral force).
  - Measure the vertical load in, for instance, trucks.

Introduction: Load Sensing Bearing (LSB)

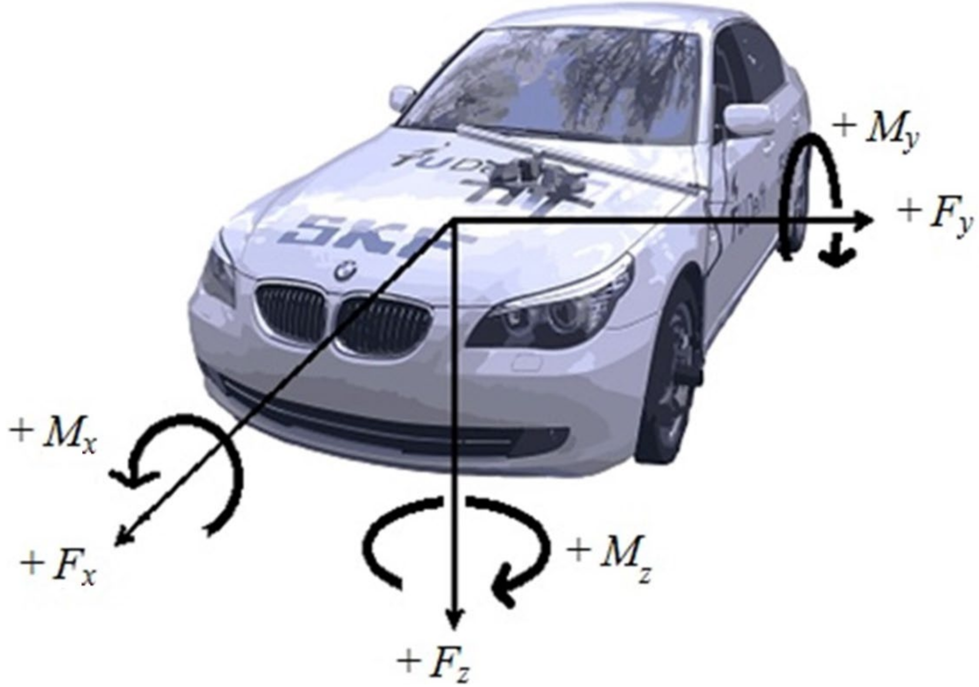
- How? → A load sensing hub bearing unit instrumented with:
  - 6 strain gauges: deformation of the bearing outer ring.
  - 2 Eddy-current sensors: tilting movement of the ABS-ring.

2

Research goals

Research goals

1) Lateral force estimation, acting at a vehicle wheel, using strain gauges and Eddy-current sensors.
2) Calibration of the load sensing bearing using the Bearing Test System (BETSY)



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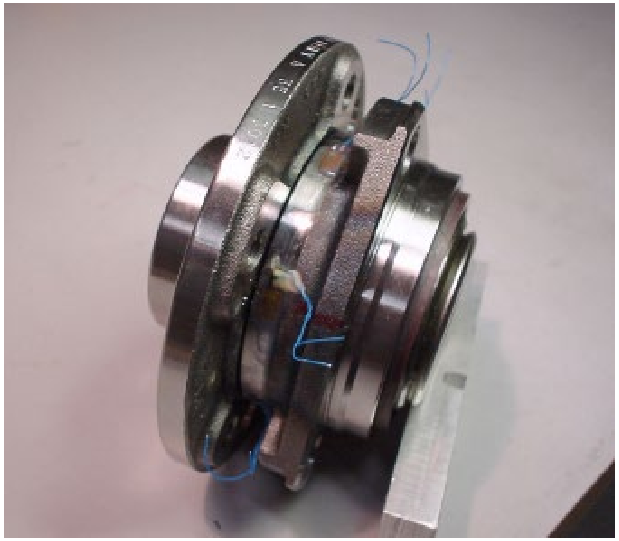
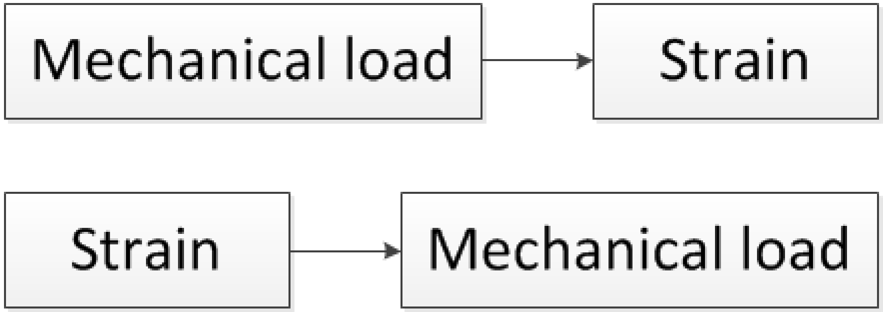
Strain gauge measurements

Strain gauge measurements

- The strain gauges measure the deformation of the bearing outer ring at six places along the circumference.

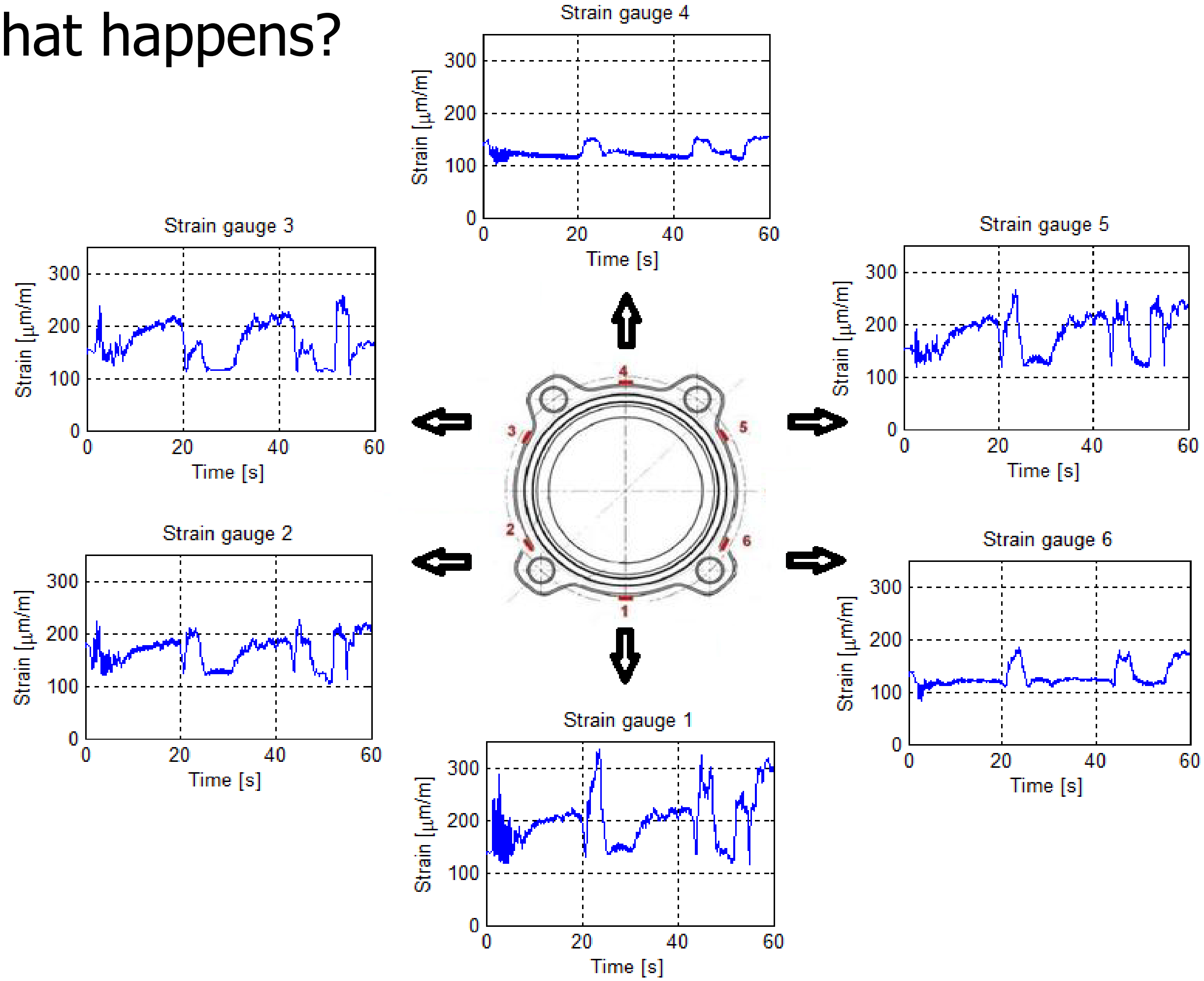
- The deformation provides information about the loads acting on the bearing.





Strain gauge measurements

- So what happens?



Warning

The following slide features a mathematical trick performed by a professional and under the supervision of a professional.

Accordingly, the TU Delft and the students must insist that no one attempt to recreate of re-enact any trick or activity performed on this slide.

Strain gauge measurements: MLRA

- Multivariate Linear Regression Analysis (MLRA): The output is assumed to be a linear combination of the input and higher order terms of the input.

- For one single dimension:

$$\longrightarrow \quad F_y = \beta_0 + \beta_1\varepsilon + \beta_0\varepsilon^2 + \ldots + \beta_n\varepsilon^n + \mathrm{E}$$

- For multi input multi output

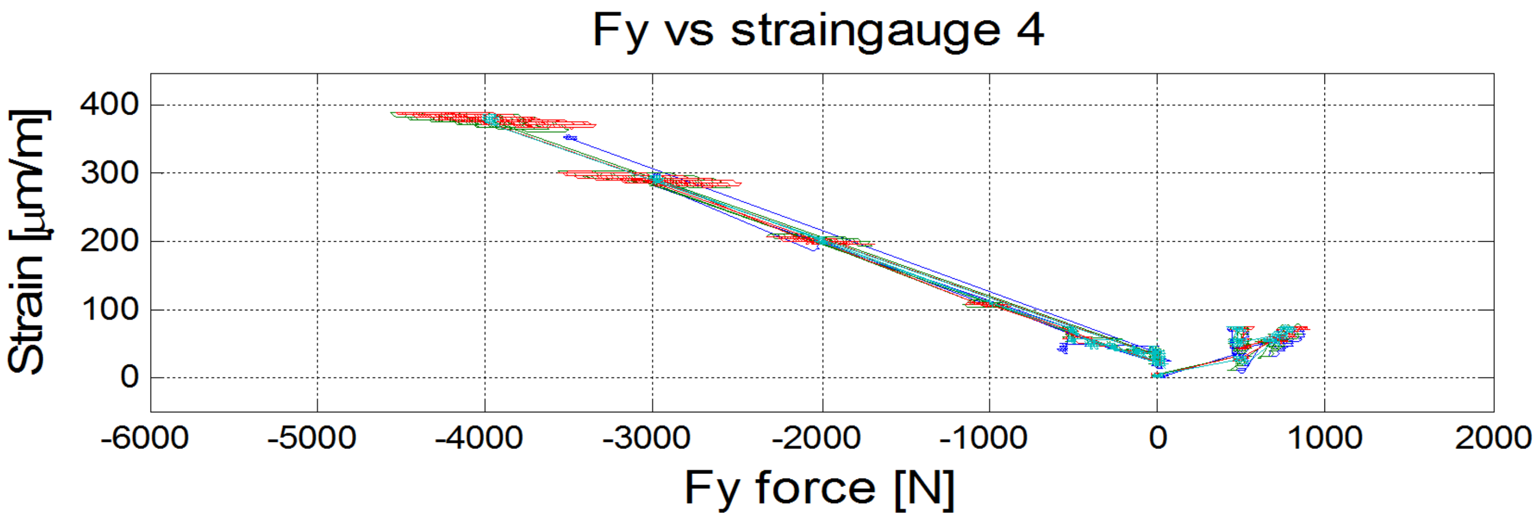
$$\longrightarrow \quad \begin{bmatrix} F_y \\ F_z \end{bmatrix} = \begin{bmatrix} \beta_{F_y} \\ \beta_{F_z} \end{bmatrix} \begin{bmatrix} 1 \\ \varepsilon \\ \varepsilon^2 \\ \ldots \\ \varepsilon^n \end{bmatrix} \quad \longrightarrow \quad [\beta] = [F][\varepsilon]^T([\varepsilon][\varepsilon]^T)^{-1}$$

The entries of F have dimensions [1 x N] with N the number of samples

The entries of β have dimensions [1 x $(6n+1)$] with n the order the polynomial

The entries of ε have dimensions [$(6n+1)$ x N] with n the order the polynomial

Strain gauge measurements: MLRA

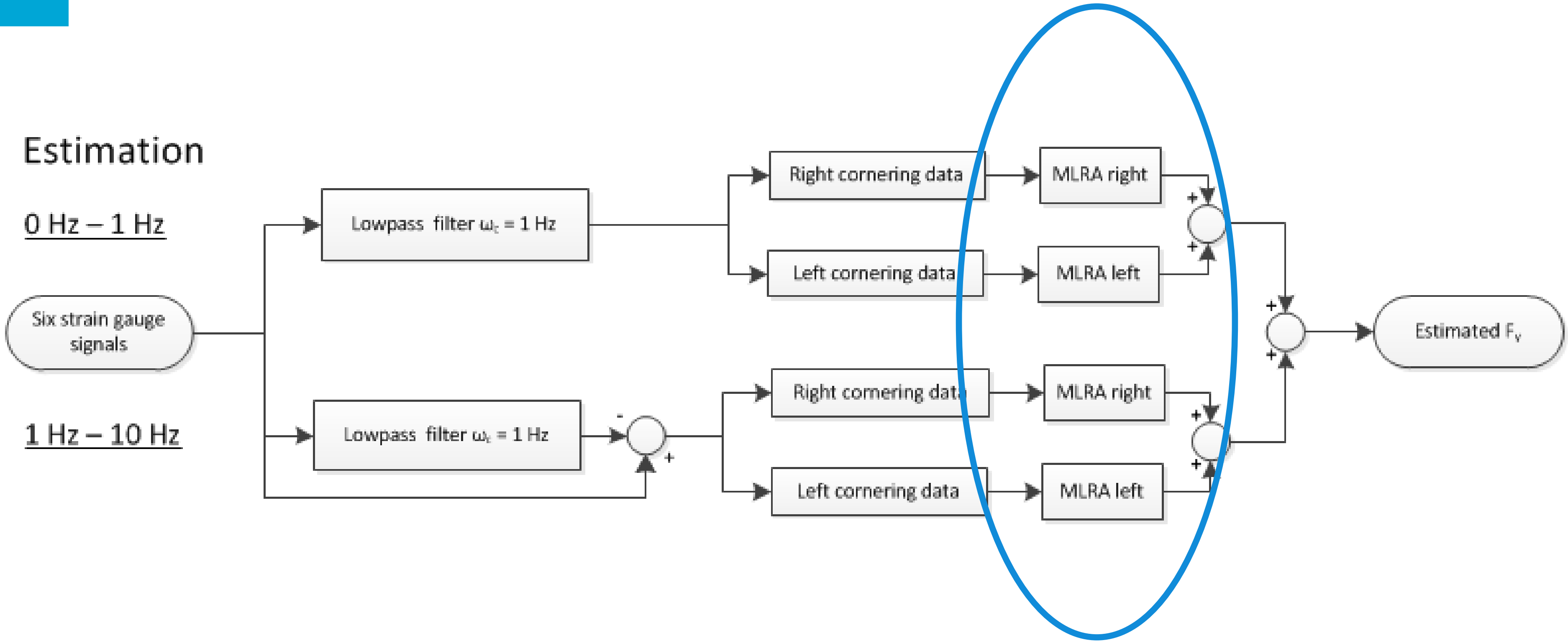


1) Absolute value problem

2) Difference in sensitivity for $F_y < 0$ N and $F_y > 0$ N

3) Difference in response for 0 Hz < f < 1 Hz and 1 Hz < f < 10 Hz

Strain gauge measurements: F_y estimation block diagram



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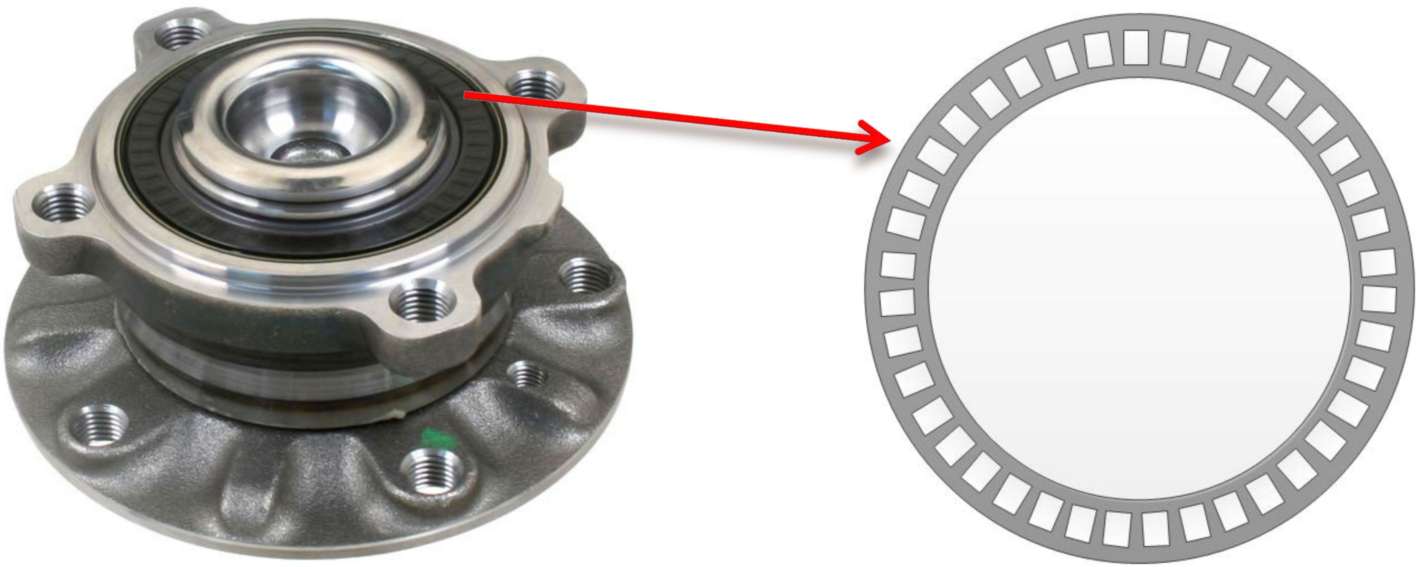
Eddy-current sensor measurements

Eddy-current sensor measurement

- Why (inductive) Eddy-current sensor measurements?
  - The strain gauges are subject to the absolute value problem.
  - Strain measurements are subject to low frequent thermal influences.

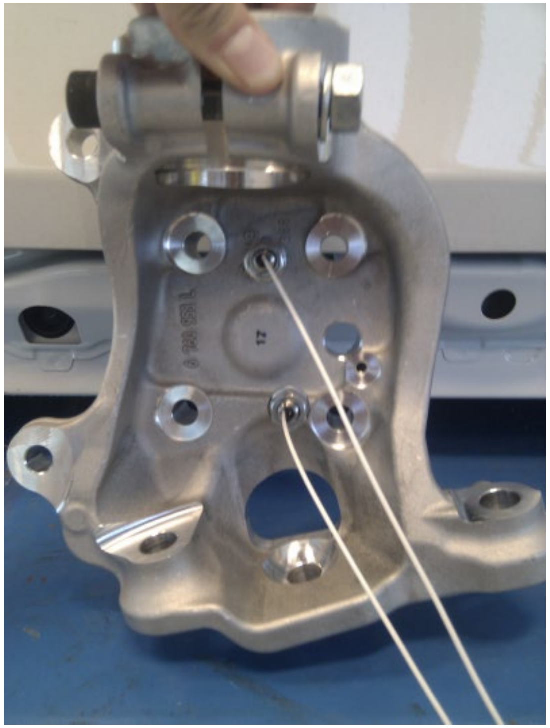
Eddy-current sensor measurement

- ABS-ring integrated in the seal of the bearing. 48 holes and 48 spokes.
- The tilting movement of the ABS-ring gives an estimate of the lateral force F_y acting on the bearing.



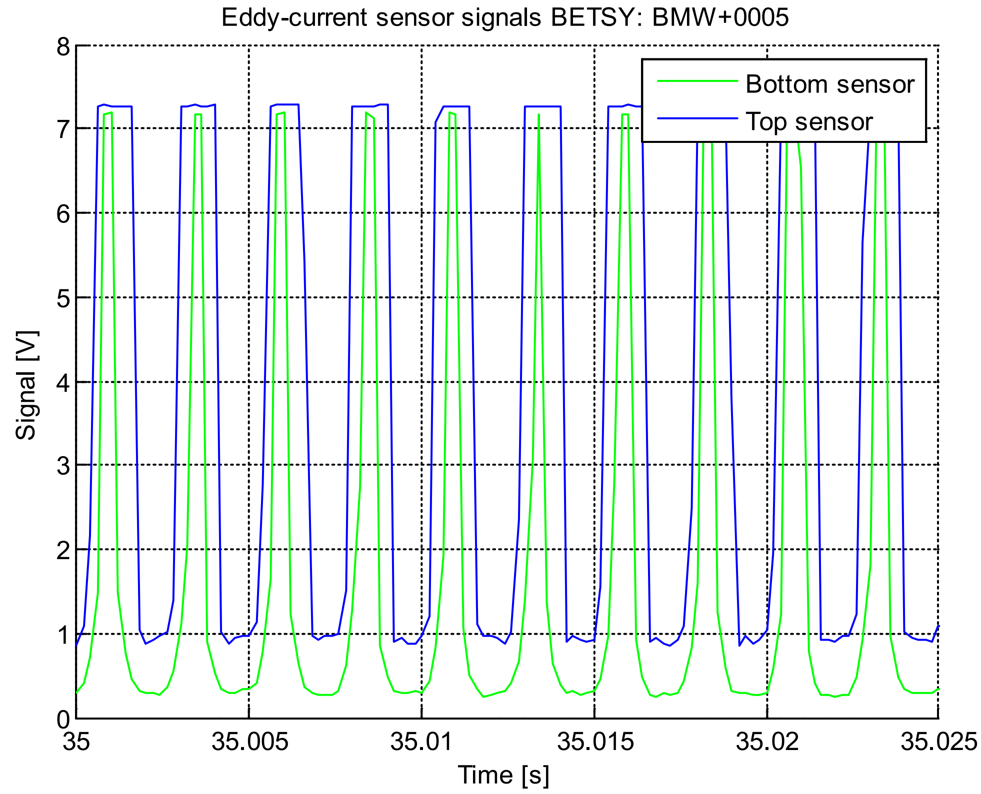
Eddy-current sensor measurement

- Two Eddy-current sensors are mounted into the knuckle.



Eddy-current sensor measurement: Signal

- The change in the lower values provides the information about F_y

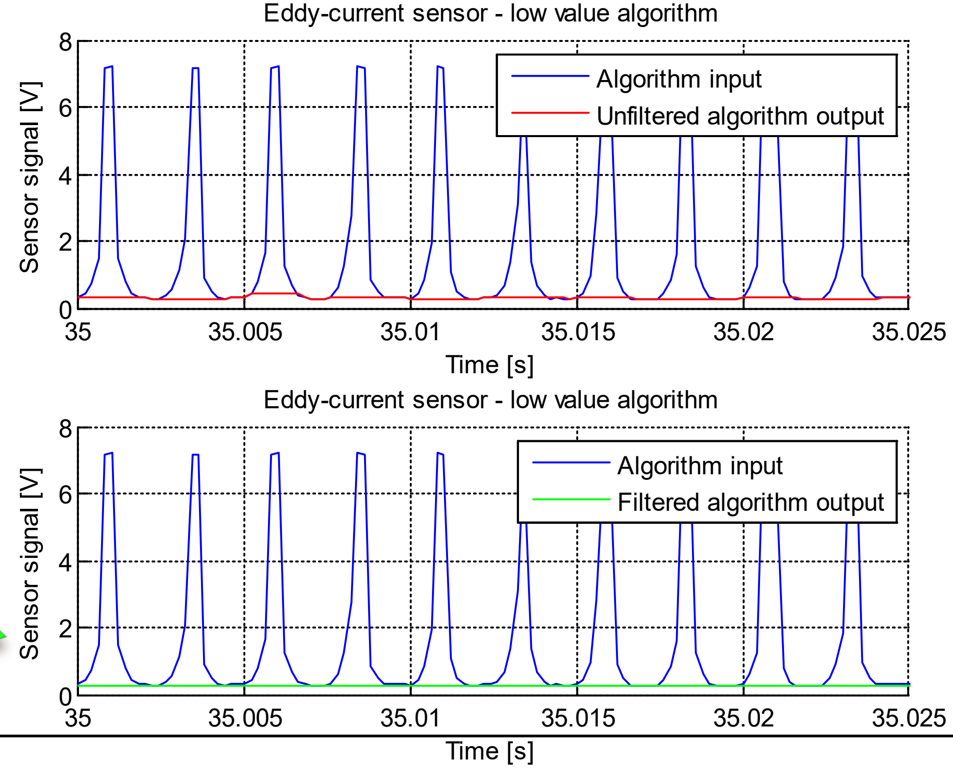


Eddy-current measurement: Low value algorithm

- Algorithm to retrieve these lower values.
  - Based signal derivative
  - Maximum change per time sample Δy_{max}
  - An initial condition y_0 (the equilibrium value)
  - The wheel speed

Discontinious output

Continuous output



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Field measurements

Field measurements

- The LSB equipment has been built in a BMW E60 and tests have been performed at the test track at SKF

Field measurements

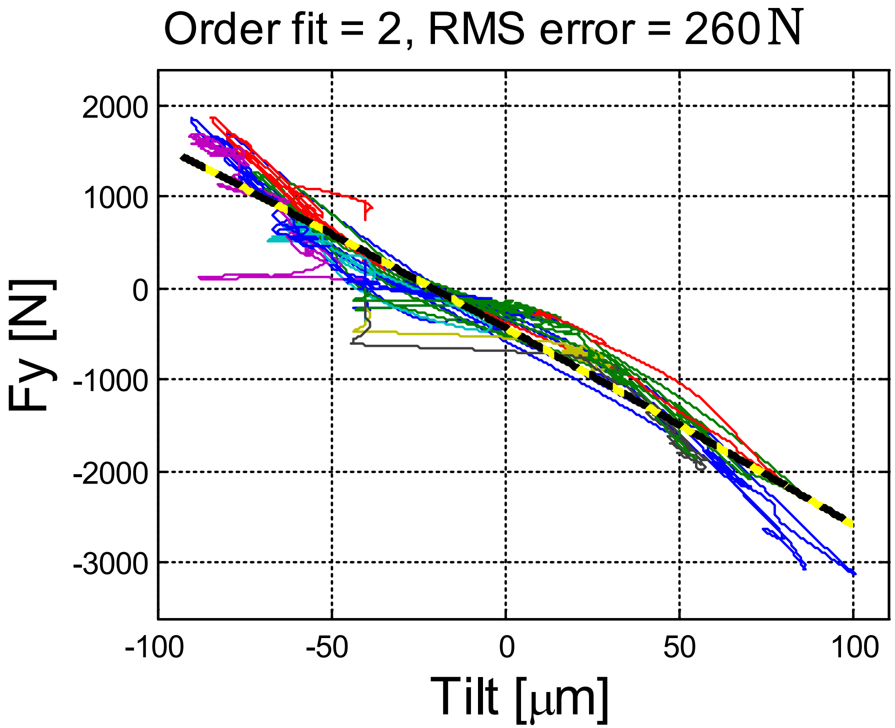
- Movie: Circle run at 30 km/h

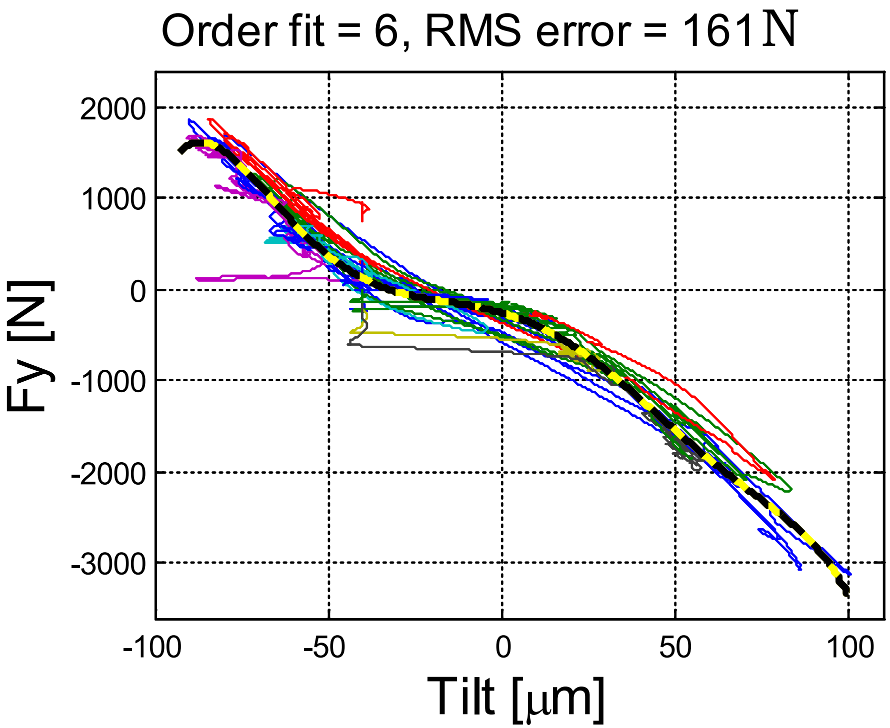
Field measurements

- A Kistler VELOS force measuring wheel is used as reference

Field measurements: Tilt vs F_y

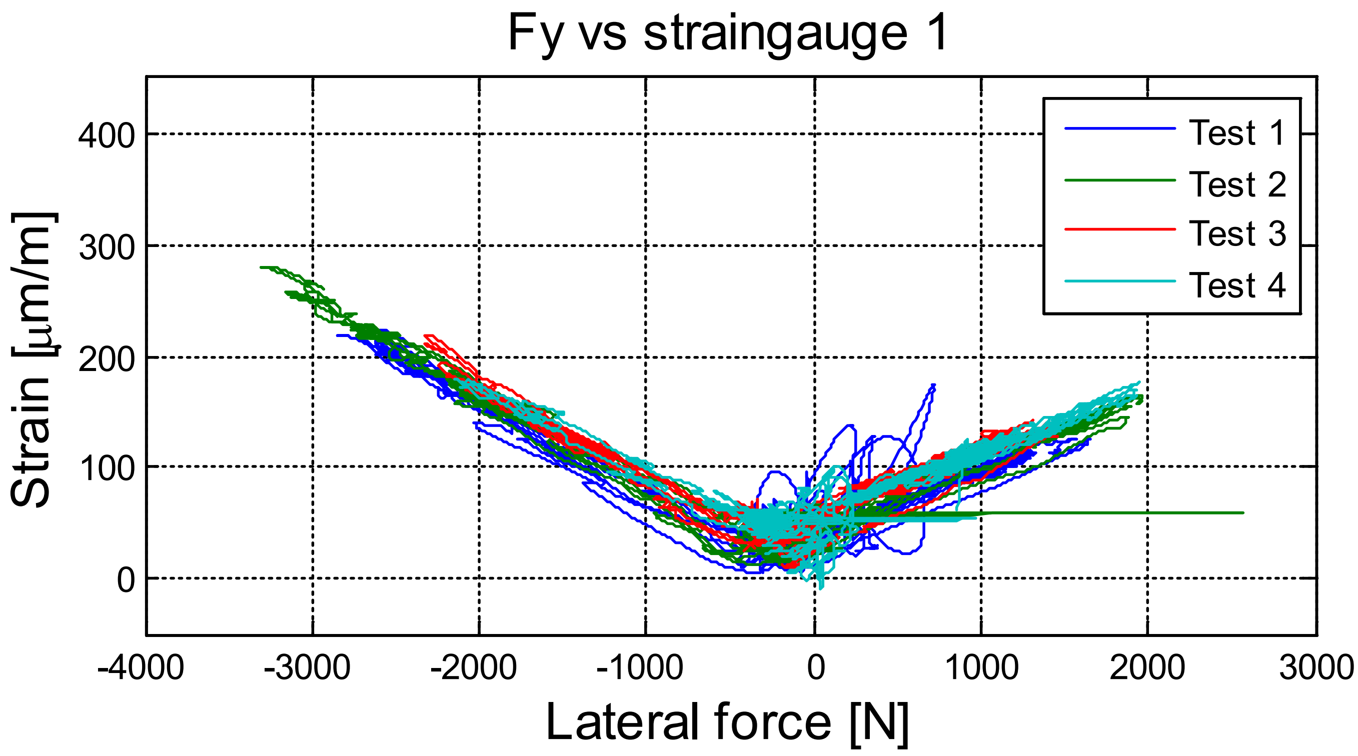
- Eddy-current sensor measurement.
- Data is approximated by a 2nd and a 6th order polynomial: Accuracy vs extrapolation characteristics





Field measurements

- Strain measurement



Field measurements : F_y estimation

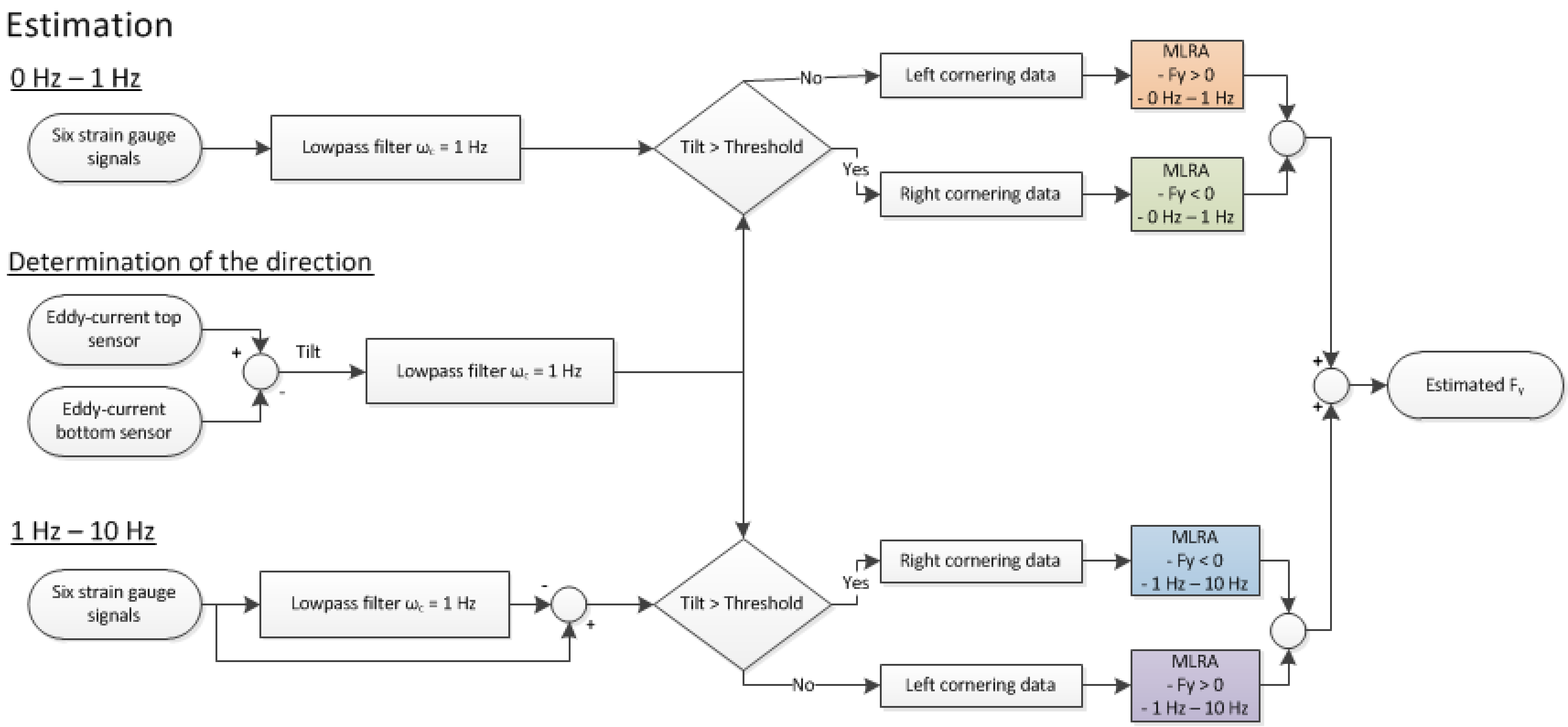
- Two force estimation algorithms. Both for an in-situ calibration and a BETSY calibration.

  1) Using 4 MLRA on the strain gauges and use the Eddy-current sensors for the determination of the direction.

  2) Using both the Eddy-current sensors and the strain gauges for the force estimation.

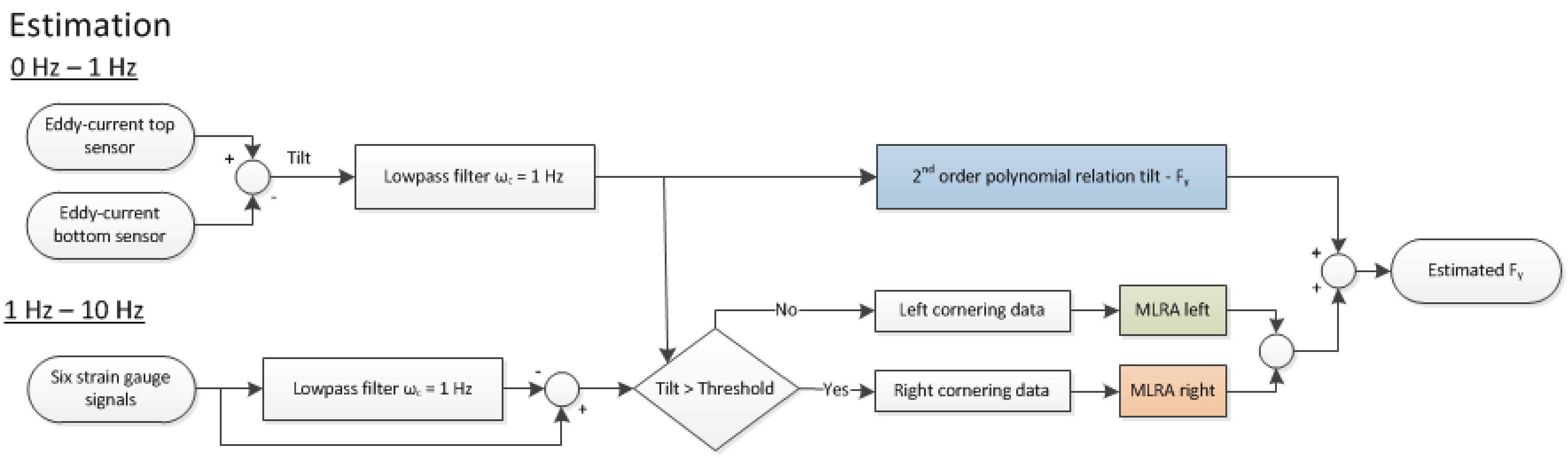
Field measurements : Algorithm 1

- Using 4 MLRA on the strain gauges and use the Eddy-current sensors for the determination of the direction.



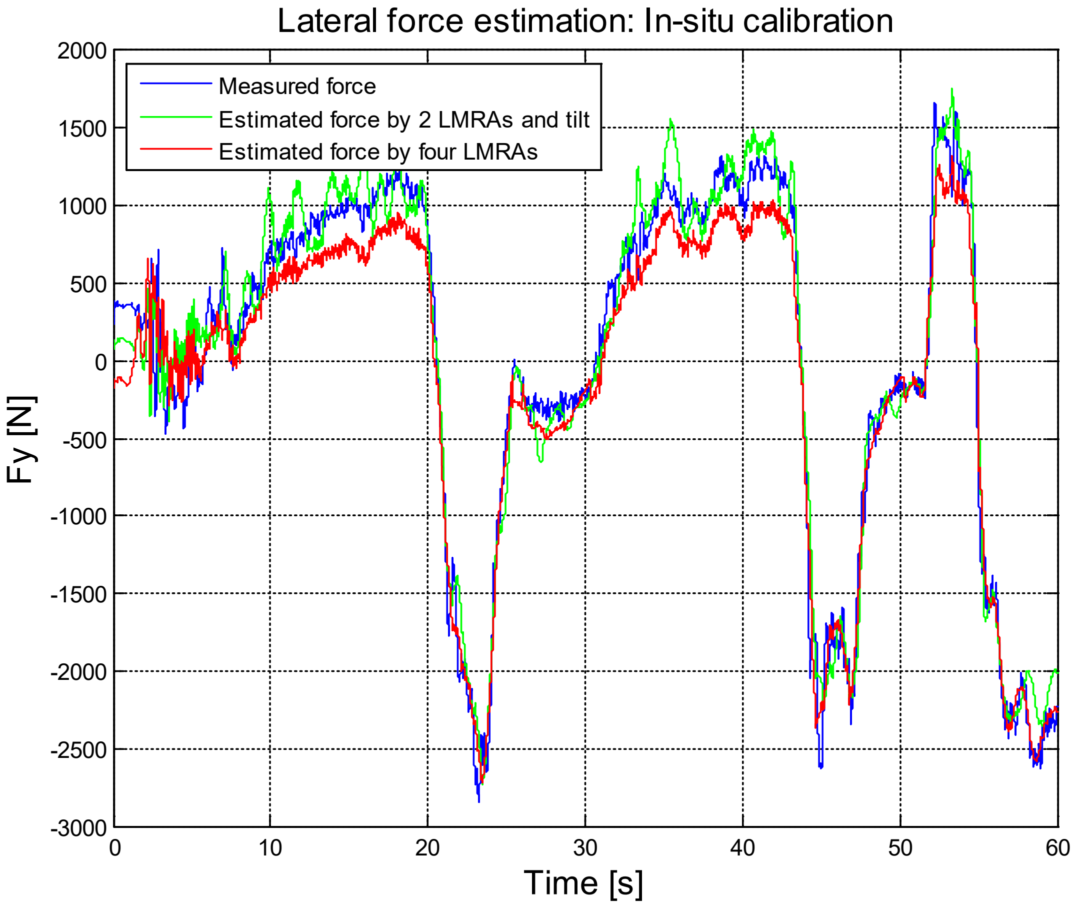
Field measurements: Algorithm 2

- Using both the Eddy-current sensors and the strain gauges for the force estimation



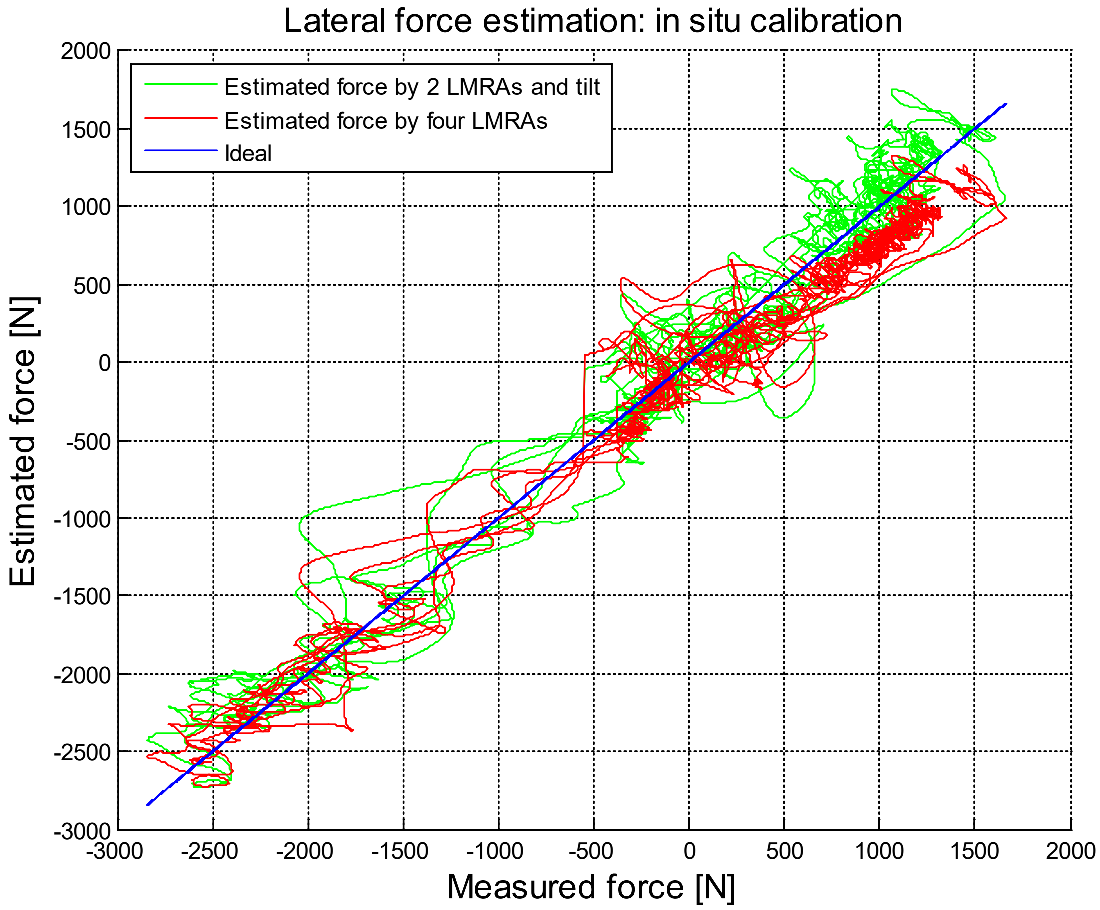
Field measurements : F_y estimation, result

- Estimated force vs time for both algorithms.



Field measurements : F_y estimation, result

- Estimated force vs measured force for both algorithms.



Field measurements : F_y estimation, result

- Estimation errors

Frequency content	Method	RMS Error [N]	Error [%]
0 Hz - 10 Hz	**Algorithm 1**	**232,00**	**20,09**
0 Hz - 10 Hz	**Algorithm 2**	**216,82**	**18,78**

Frequency content	Method	RMS Error [N]	Error [%]
0 Hz - 1 Hz	MLRA	188,82	16,46
	Tilt 2nd order	229,84	20,04
	Tilt 6th order	174,47	15,21

Frequency content	Method	RMS Error [N]	Error [%]
1 Hz - 10 Hz	MLRA	130,89	141,82

In-situ calibration

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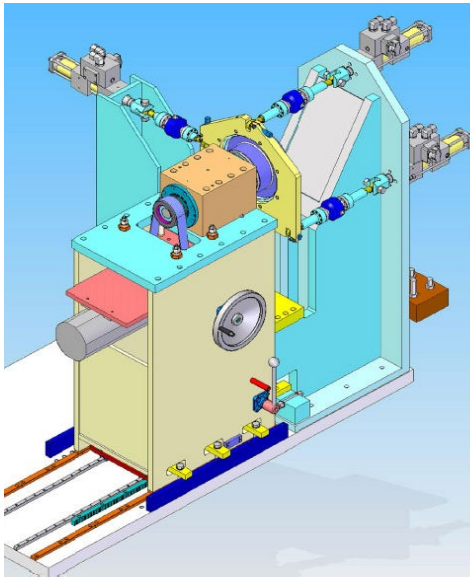
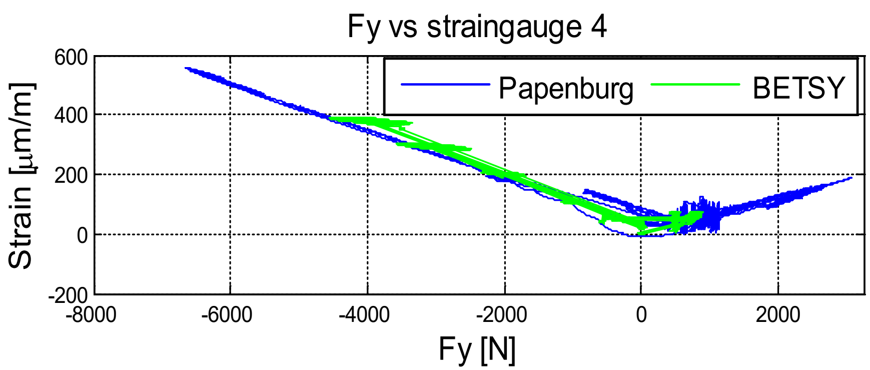
BETSY calibration

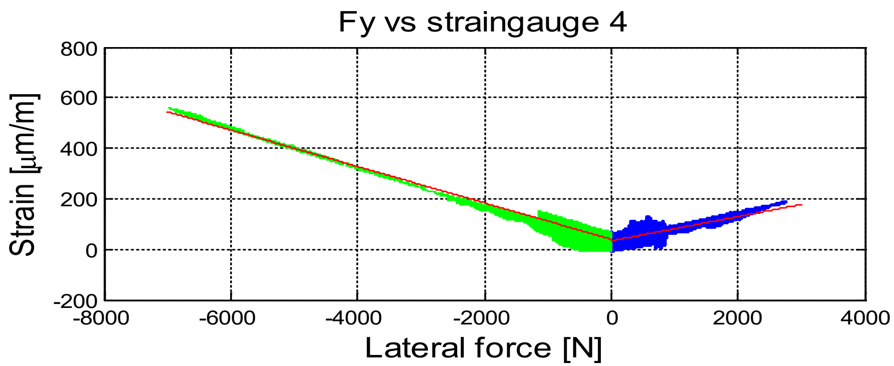
Strain gauge measurements: BETSY

- What is BETSY and why do we want to use it?
- The Bearing Test System is a 5 Degree of Freedom (DoF) system, where forces and moments are applied in 5 DoF by hydraulic actuators.



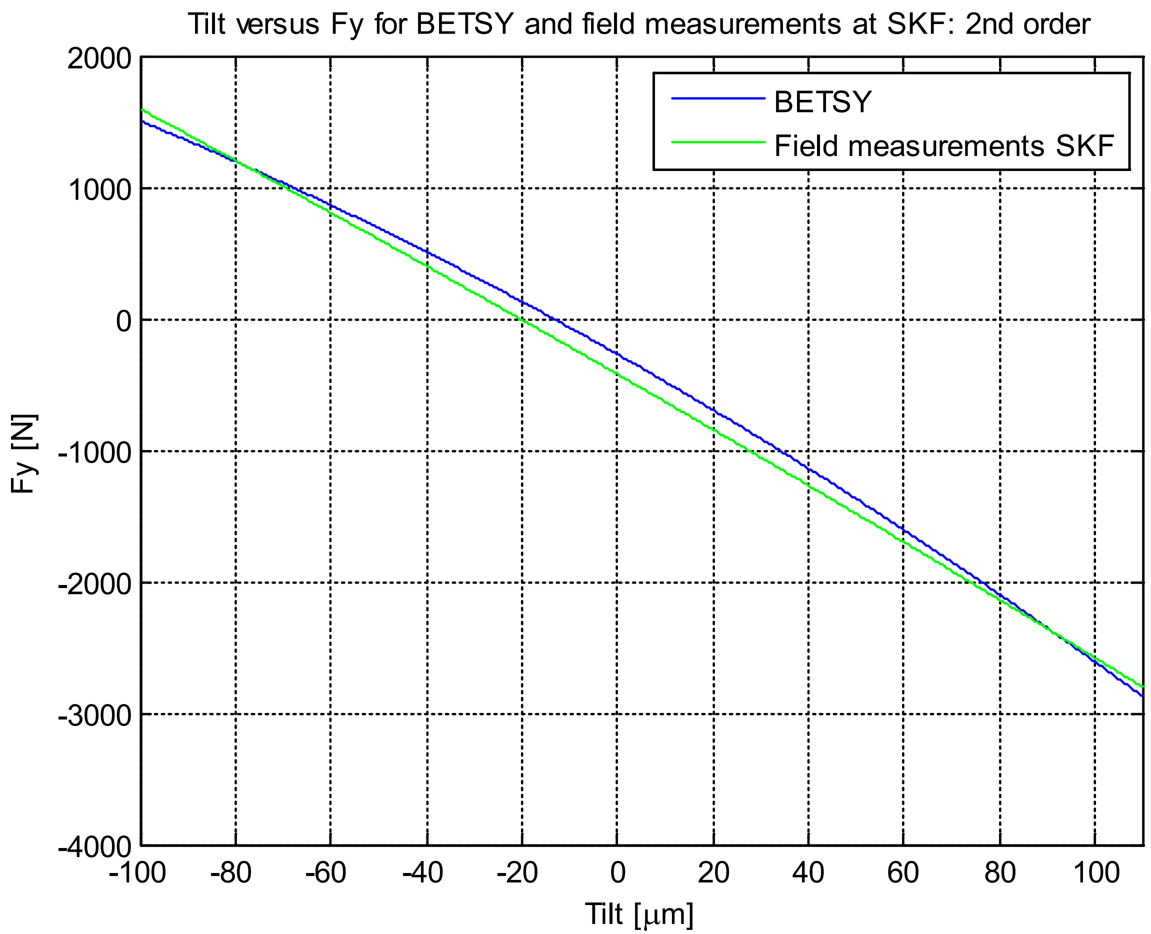
BETSY calibration: strain





- $\varepsilon_{vehicle} = c_1 \cdot F_y + c_2$ $\quad\quad$ $\varepsilon_{BETSY} = c_3 \cdot F_y + c_4$
- $$F_{y,test} = \frac{\varepsilon_{BETSY} - c_4}{c_3} = \frac{\varepsilon_{vehicle} - c_2}{c_1}$$
- $$\varepsilon_{BETSY} = \frac{c_3 \cdot \varepsilon_{vehicle} - c_3 \cdot c_2}{c_1} + c_4 = c_A \cdot \varepsilon_{vehicle} + c_B$$

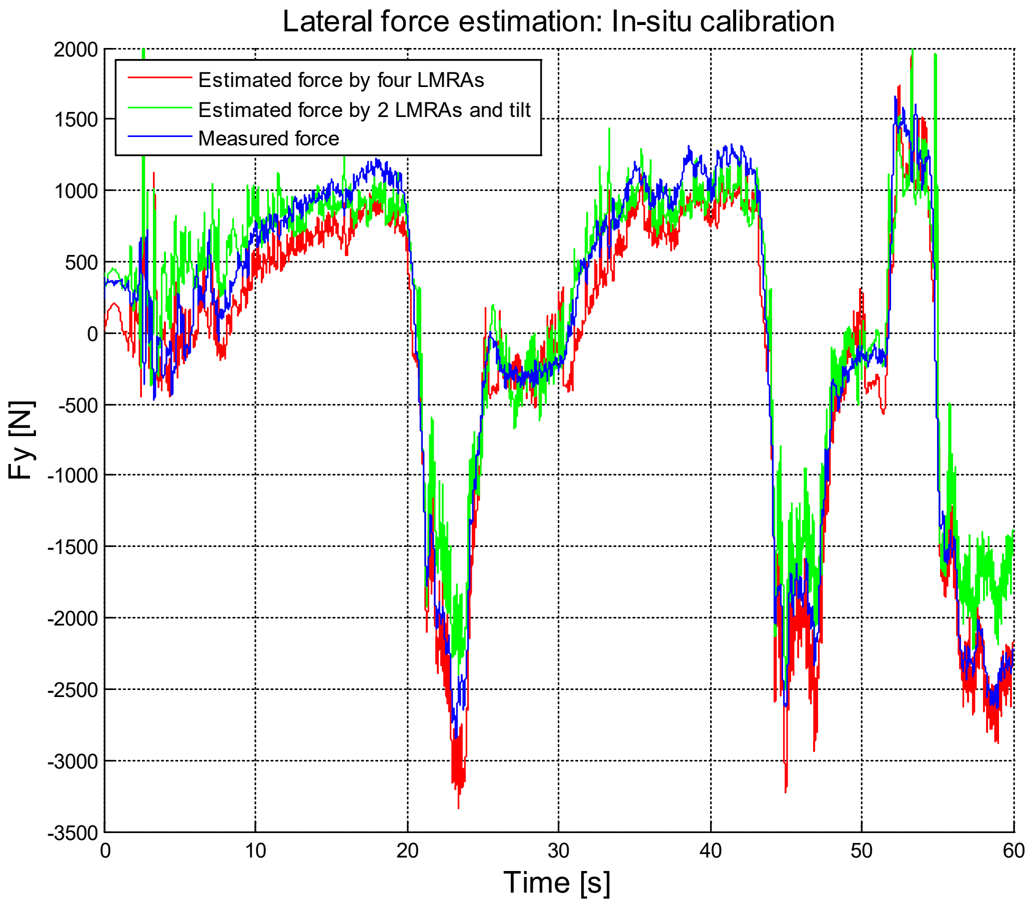
BETSY calibration: Eddy-current sensors



Good! ☺

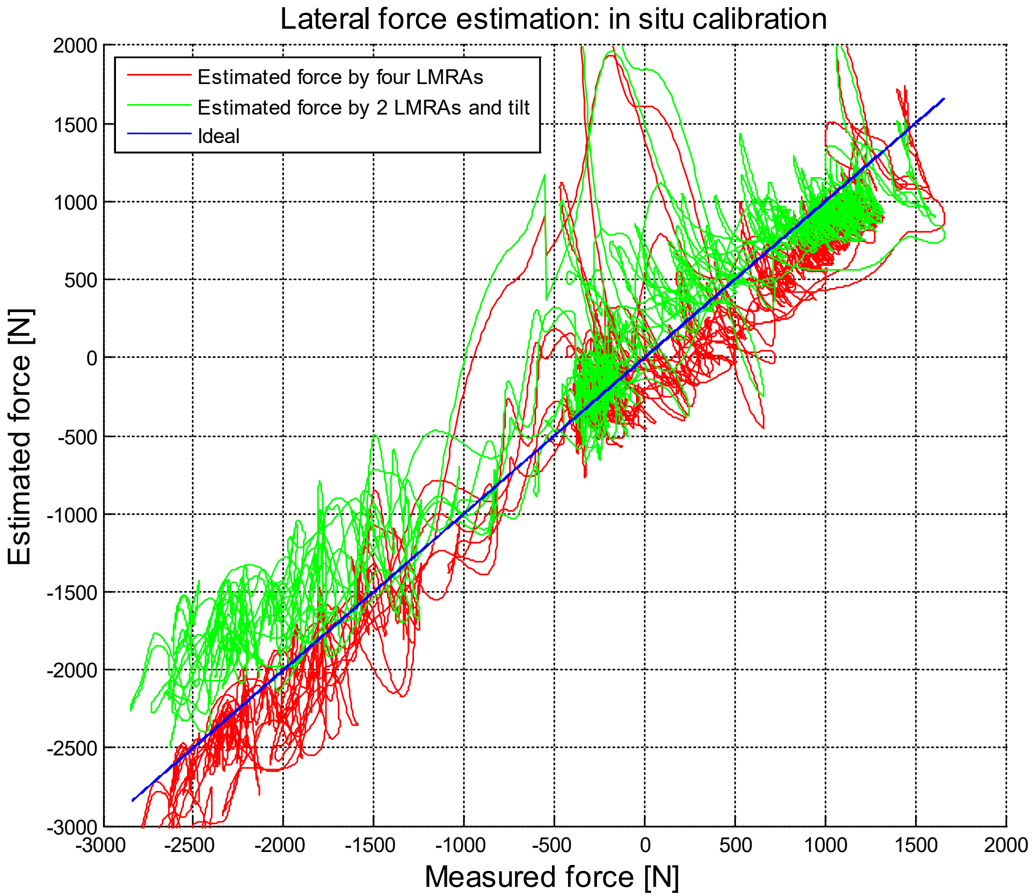
Field measurements : F_y estimation, result

- Estimated F_y vs time for both algorithms



Field measurements : F_y estimation, result

- Estimated F_y vs measured F_y for both algorithms.



Field measurements : F_y estimation, result

- Estimation errors using a BETSY calibration

Frequency content	Method	RMS Error [N]	Error [%]
0 Hz - 10 Hz	**Algorithm 1**	**335,29**	**29,04**
0 Hz - 10 Hz	**Algorithm 2**	**374,55**	**32,44**

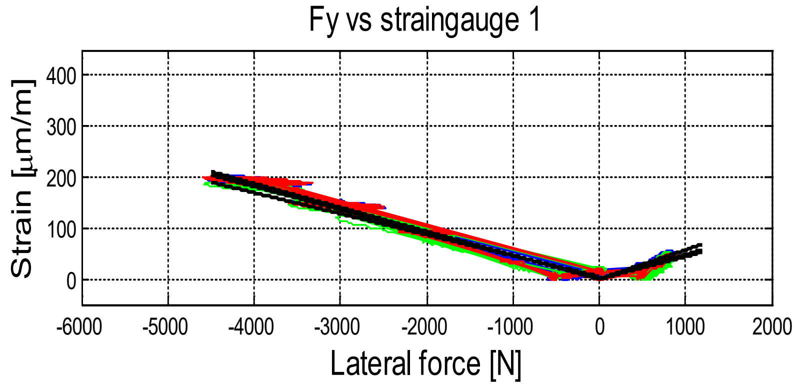
Frequency content	Method	RMS Error [N]	Error [%]
0 Hz - 1 Hz	MLRA	191,44	16,69
	Tilt 2nd order	261,23	22,78
	Tilt 6th order	342,64	29,88

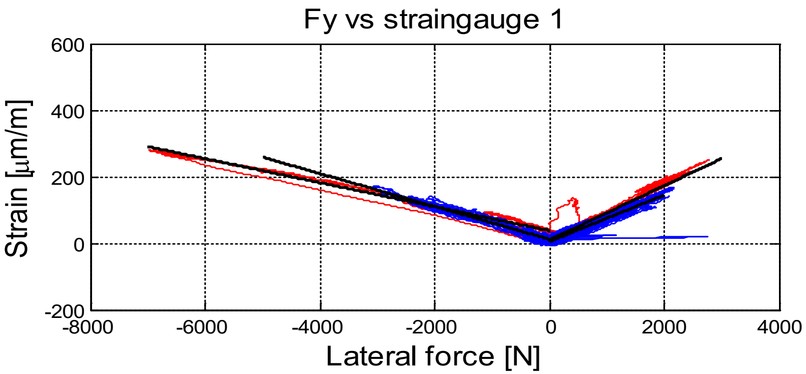
Frequency content	Method	RMS Error [N]	Error [%]
1 Hz - 10 Hz	MLRA	265,34	287,49

- So we can use BETSY for calibration?

Reproducibility: strain

- Reproducibility is necessary for calibration of a whole production line of LSB

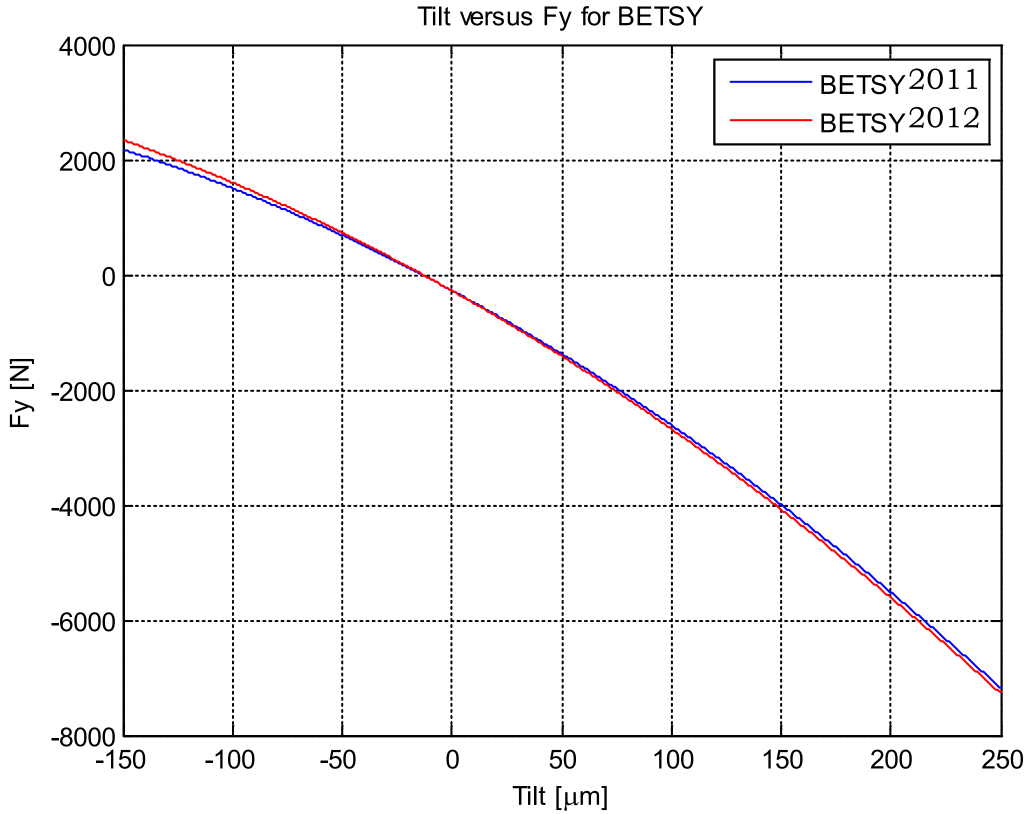




Not good! ☹

Reproducibility: Eddy-current sensors

- Reproducibility is necessary for calibration of a whole production line of LSB



Good! ☺

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Conclusions

Conclusions: lateral force estimation

- In the semi-static frequency range the strain gauges as well as the Eddy-current sensors can be used for force estimation with errors ranging from 15 % - 20 %.
- In the dynamic frequency range the lateral force is not correlated with the strain and ABS-ring deflection.
- Regarding the Eddy-current sensors BETSY can be used for calibration.
- Regarding the strain gauges sensors BETSY cannot be used for calibration.

Questions?

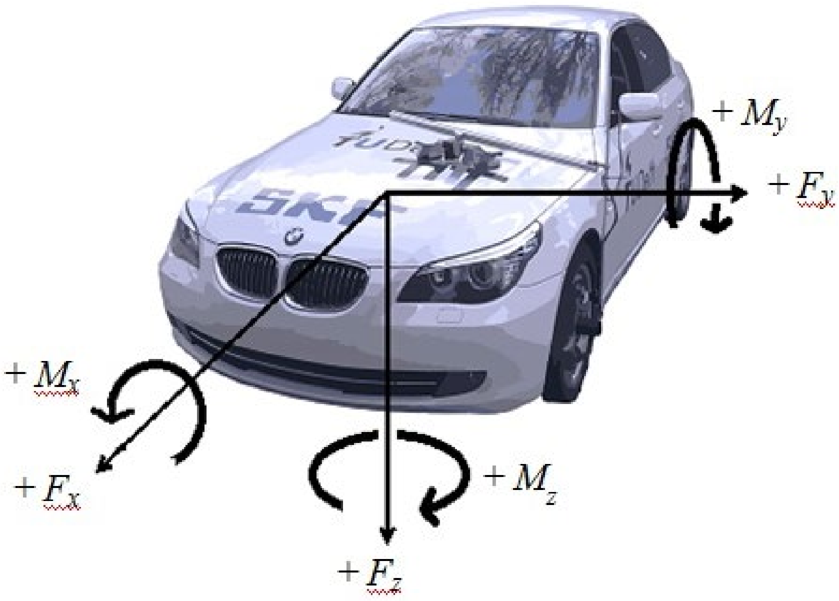
Thank you for your attention !

Backup slides

Introduction: Load Sensing Bearing

- What forces act on a vehicle?

- 3 forces:
  - F_x = longitudinal force
  - F_y = lateral force
  - F_z = vertical force



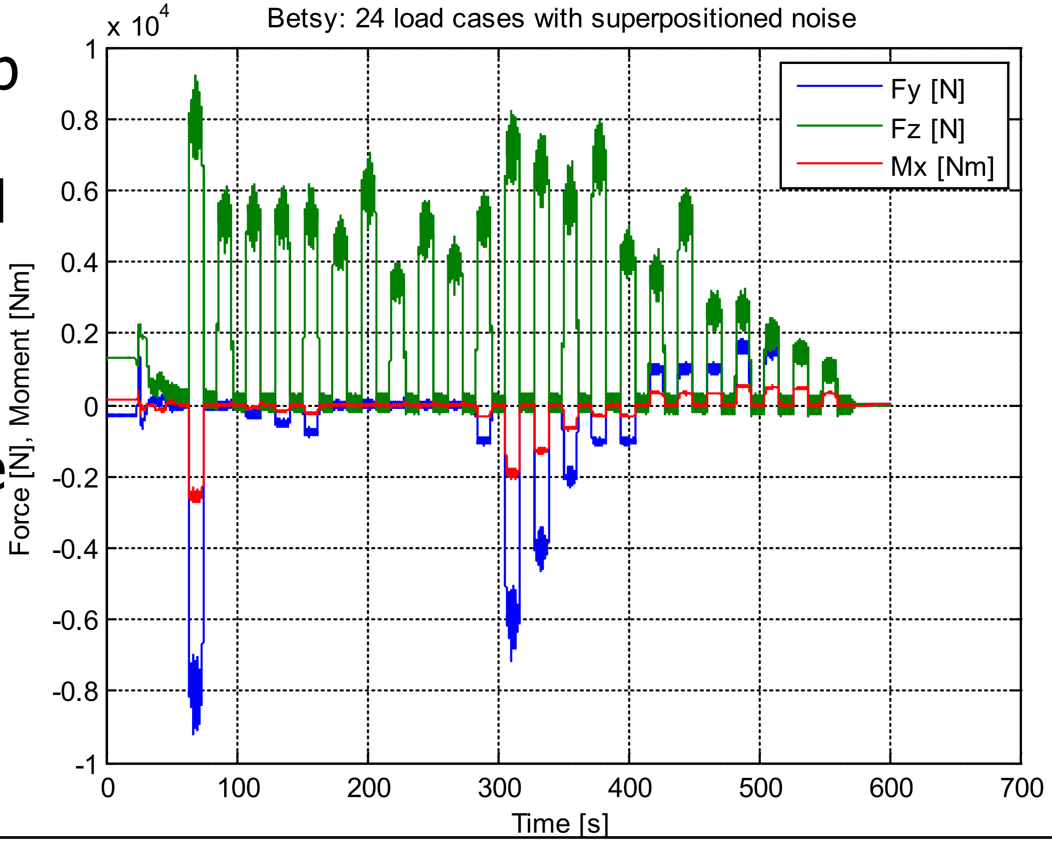
- 3 moments:
  - M_x = moment around the x-axis
  - M_y = moment around the y-axis
  - M_z = moment around the z-axis

Strain gauge measurements: Applied loads

- Cycle consisting of 24 load steps.
- Load steps with 10 seconds of duration.

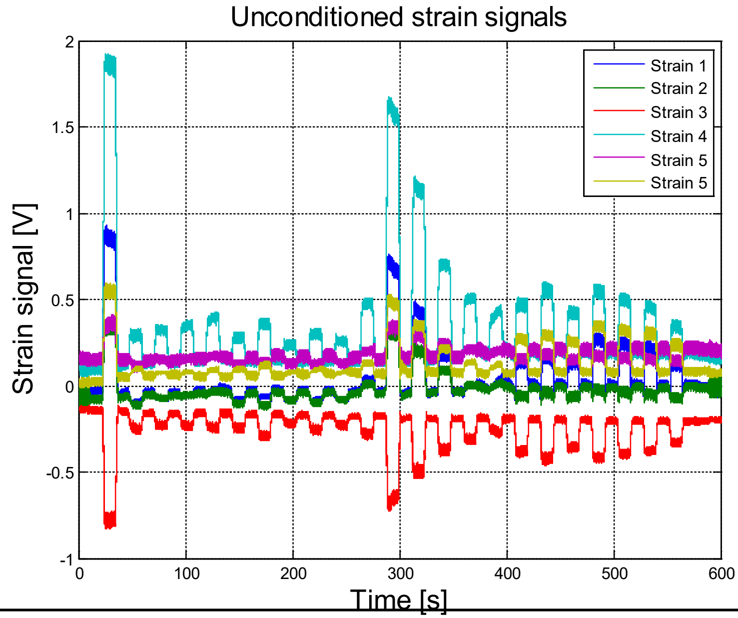
- Between each load step a 10 seconds interval of running without load is inserted.

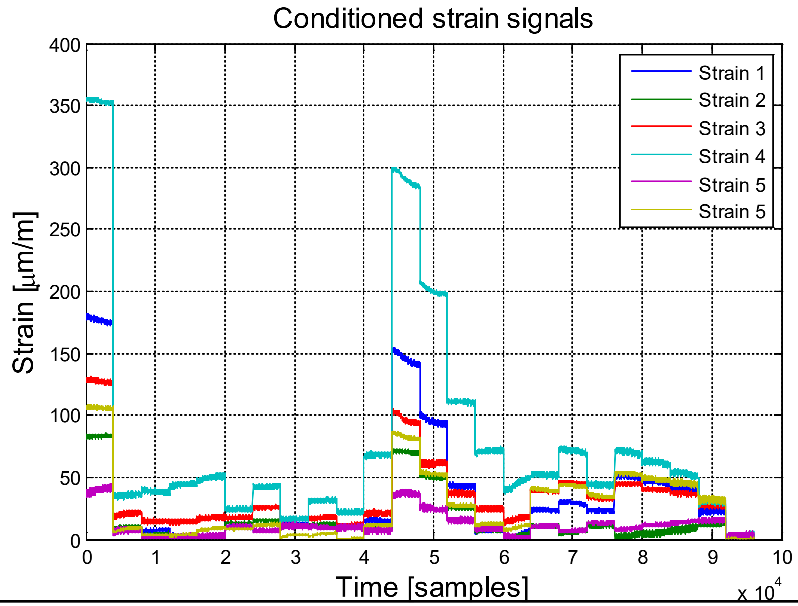
- Combinations of static and dynamic forces are applied.



Strain gauge measurements: Signal conditioning process

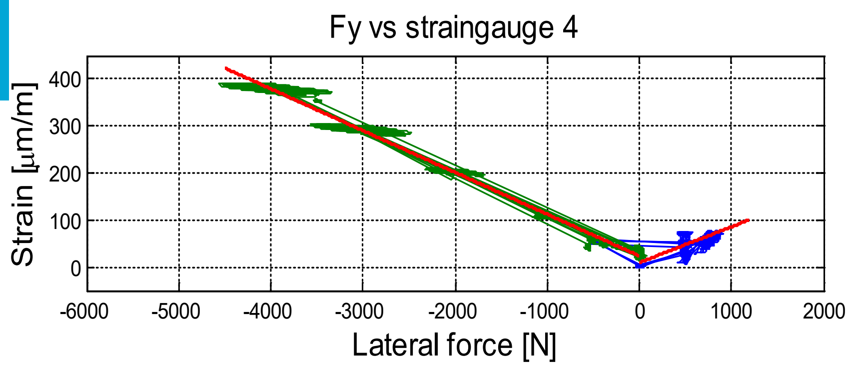
- Filtering
- Static offset and drift
- Inverted signal strain gauge 3
- No-load intervals
- Scaling to physical dimensions



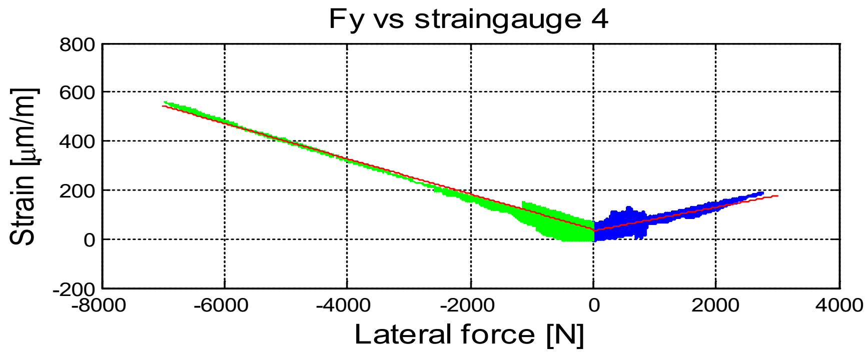


BETSY calibration

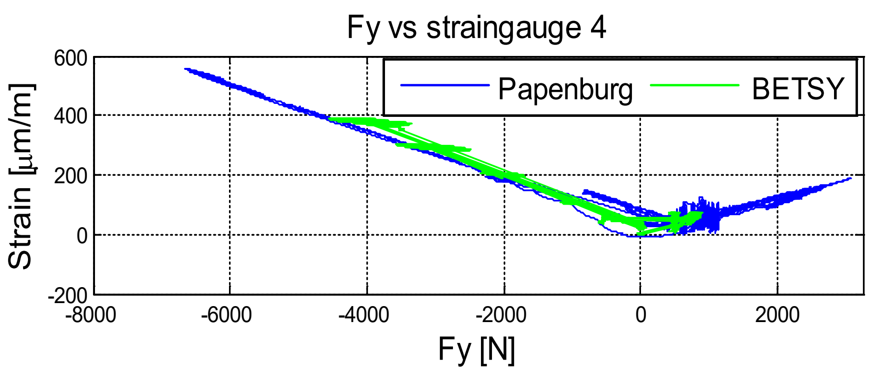
- BETSY



- Field



- BETSY and field



- Some differences are present
- How can we compensate for those differences.

BETSY calibration

By describing both sides of the V-shape by a 1st order polynomial two coefficients, C_a and C_b, can be derived for both positive and negative F_y to transform te one to the other. (So 4 coefficients in total).

BETSY $\varepsilon_{right,BETSY} = c_{1,right} \cdot F_{y,right} + c_{2,right}$ $E_{left,BETSY} = c_{1,left} \cdot F_{y,left} + c_{2,left}$

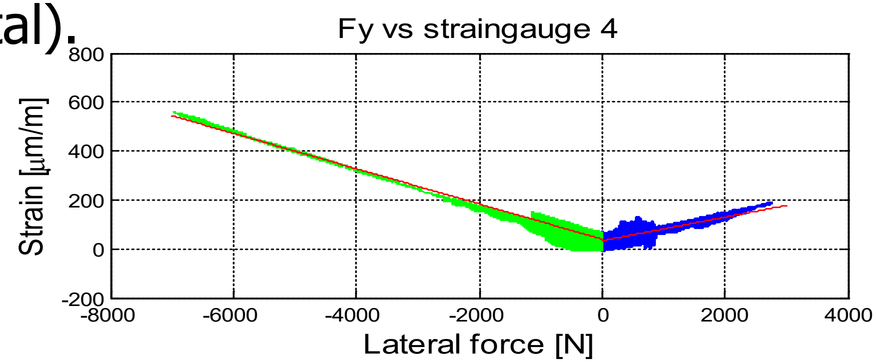
Field $\varepsilon_{right,Field} = c_{3,right} \cdot F_{y,right} + c_{4,right}$ $E_{left,field} = c_{3,left} \cdot F_{y,left} + c_{4,left}$

$$F_{y,right} = \frac{\varepsilon_{right,BETSY} - c_2}{c_1} = \frac{\varepsilon_{right,field} - c_4}{c_3}$$

$$\varepsilon_{BETSY} = \frac{c_1 \cdot (\varepsilon_{vehicle} - c_4)}{c_3} + c_2 = \frac{c_1 \cdot \varepsilon_{vehicle} - c_1 \cdot c_4}{c_3} + c_2 = c_{A,right} \cdot \varepsilon_{vehicle} + c_{B,right}$$

BETSY calibration

- By describing both sides of the V-shape by a 1st order polynomial two coefficients, C_a and C_b, can be derived for both positive and negative F_y to transform te one to the other. (So 4 coefficients in total).

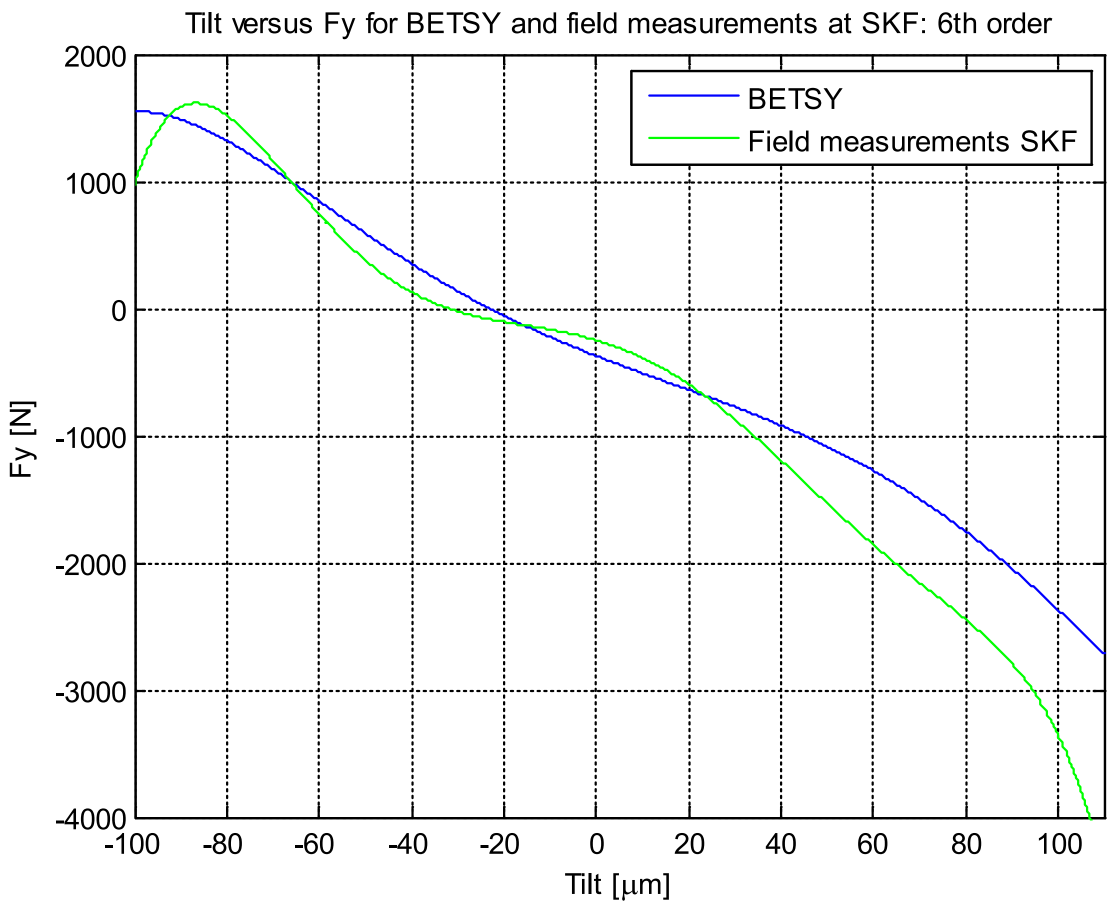


$$\varepsilon_{right} = c_{1,right} \cdot F_{y,right} + c_{2,right} \qquad \varepsilon_{left} = c_{1,left} \cdot F_{y,left} + c_{2,left}$$

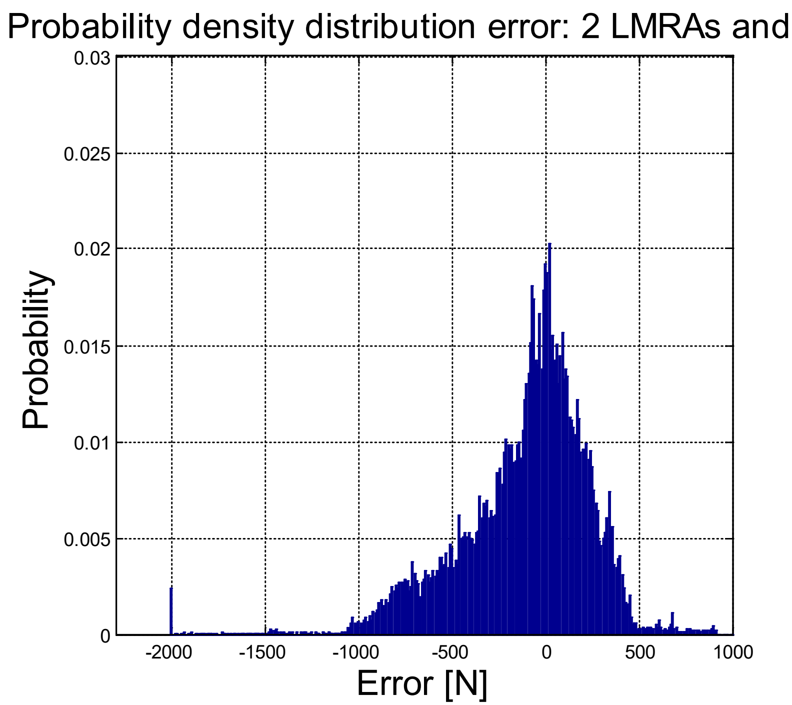
$$F_{y,test} = \frac{\varepsilon_{BETSY} - c_2}{c_1} = \frac{\varepsilon_{vehicle} - c_4}{c_3}$$

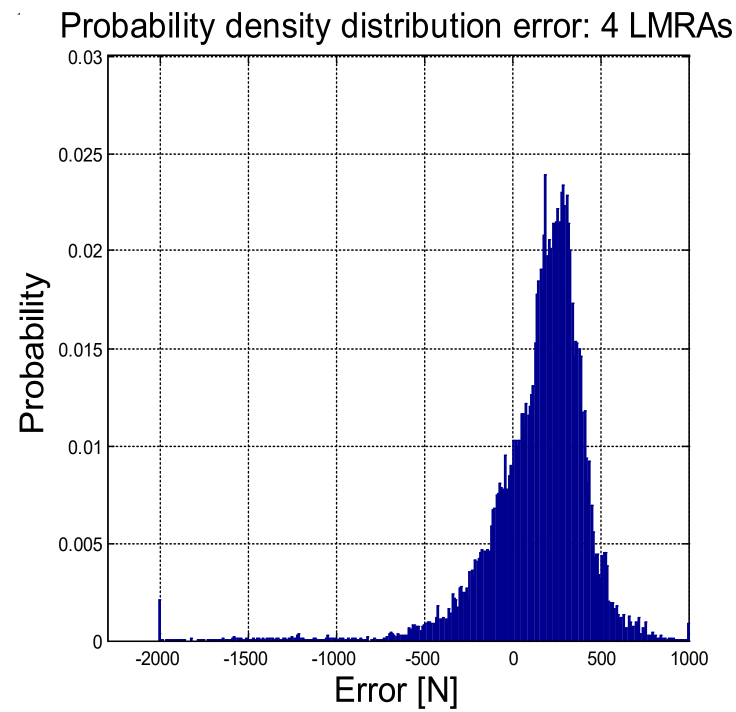
$$\varepsilon_{BETSY} = \frac{c_1 \cdot \left(\varepsilon_{vehicle} - c_4\right)}{c_3} + c_2 = \frac{c_1 \cdot \varepsilon_{vehicle} - c_1 \cdot c_4}{c_3} + c_2 = c_{A,right} \cdot \varepsilon_{vehicle} + c_{B,right}$$

BETSY calibration: Eddy-current sensors



Estimation errors distributions





Summary: lateral force estimation

- F_y estimation summary:

0 Hz – 1 Hz			
Calibration	Strain	Tilt 2nd order fit	Tilt 6th order fit
In-situ	16.5 %	20.0 %	15.2 %
BETSY	16.7 %*	22.8 %	29.9 %

Recommendations

- Errors obtained with estimation using the Eddy-current sensor are mainly caused by the rubber seal and low value algorithm.
- This research focused on F_y. Next: F_x, F_z
- Online testing
- Excite with higher amount of dynamic forces

Questions?

Thank you for your attention !

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