

Reconstruction of Wheel Forces Using an Intelligent Bearing

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Abstract

Active vehicle safety and driving assistance systems can be made more efficient, more robust and less complex if wheel load information would be available. Although this information could be determined via numerous different methods, due to various reasons, no commercially feasible approach has yet been introduced. In this paper the approach of bearing load estimation is topic of interest. Using the bearing for load measurement has considerable advantages making it commercially attractive as: i) it can be performed on a non-rotating part, ii) all wheel loads can be measured and iii) usually the bearing serves the entire lifetime of the vehicle. This paper proposes a novel approach for the determination of wheel loading. This new approach, based on the strain variance on the surface of the bearing outer ring, is tested on a dedicated bearing test setup. The experimental results show that the approach allows for the determination of all three force vectors and two moments in different load conditions with sufficient accuracy and bandwidth suitable for the application in vehicle dynamics control.

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Introduction

Active safety systems have been actively developed during the past three decades. Starting as an equipment for luxury cars, nowadays systems as ABS and ESP are mandatory for all new passenger vehicles. Furthermore recent years also numerous Advanced Driver Assistance Systems (ADAS), such as collision avoidance systems and adaptive cruise control, have entered the automotive market. The introduction of all these electronic systems is accompanied by the implementation of numerous new sensors such as radar, laser and cameras within the vehicle.

All these new sensors are implemented to sense relevant information improving the working of stability control or driving assistance systems. However, for direct sensing of the interaction between road and tire, a key factor in vehicle dynamics, no commercially feasible sensor as a series component product is available. The control systems therefore predominantly use acceleration data or indirect estimations. Systems like ABS could be made more effective, less complex and more robust if an accurate high bandwidth wheel load estimate would be present [4]. Its development therefore is an interesting and active research area.

The unavailability of wheel load sensing in road vehicles reflects the difficulty in obtaining a measurement which is both accurate, robust and inexpensive. In theory however, all components carrying the load from tire contact patch towards the vehicle such as tire, rim, bearing and suspension would be suitable for determining (some of) the wheel loads. The available technical approaches and their main limitations can be summarized as follows:

Tire Inner Liner Accelerometer Based Approach

In this approach a MEMS accelerometer is fixed to the inner liner of the tire. The reconstruction of longitudinal and normal forces is demonstrated both in laboratory and road test conditions [1, 2]. Furthermore also the measurement of lateral contact forces is demonstrated [3]. The discontinuous measurement signal and durability of the approach due to the relatively short lifetime of tires are significant limitations.

Tire Sidewall Deformation

Force reconstruction using tire deformation measurement can be technologically achieved using an optical position detection sensor [6], a passive surface acoustic wave sensor [7] or by combination of a Hall sensor and magnet [8]. The common drawback of such kind of approach is the necessary adjustment and calibration after tire replacement.

Wheel Rim Strain Measurement

This approach is achieved by strain measurements in the wheel rim and is applied within commercial products from Kistler, MTS and other companies. Although it provides high accuracy and bandwidth, the application of wheel measurement hub as a standard vehicle sensor is too expensive even for premium class vehicles.

Suspension Bushing Deformation

The forces transmitted through the suspension bushing can be reconstructed via direct deformation measurement using eddy-current displacement sensors [8] or the estimation of the relative bushings

deformation based on acceleration measurement [9]. The complexity of the approach and the durability of the bushings are drawbacks of this method.

Deformation between Knuckle and Brake Calipers

This approach is based on the installation of a sensor bracket with strain resistance elements between knuckle and brake calipers to measure brake torque [10]. Main limitation is the fact that only the brake torque can be reconstructed.

Bearing Displacement or Deformation Based Approaches

For the reconstruction of forces and moments in the bearing two principally different approaches can be identified. On the one hand the displacement based approaches using i.e. eddy-current sensors [11,12] or Hall effect sensors [5] and on the other hand deformation based methods using strain gauges [13-15]. The first methodology is limited with respect to the number of loads to be reconstructed. The latter is thoroughly discussed and extended in this paper.

The bearing deformation based approach has several advantages compared to the other approaches which makes commercial implementation more feasible. First of all, the bearing outer-ring, at which the measurement takes a place, is non-rotating significantly simplifying data acquisition. Besides that, in contrast to tires, the bearing usually serves the entire lifetime of the vehicle. On top of that, the bearing based approach is robust to tire and rim changes. Furthermore, as the bearing is placed between the brake mount and its point of application, bearing load measurement allows for the measurement of the brake tangential force. This force can be used to reconstruct the applied brake torque, which is a very useful control variable in vehicle dynamics control. Lastly, due to the low weight of the sensory parts only a minimal increase of unsprung mass will result, such that the dynamic behavior is practically unaltered.

This paper focuses on a novel approach of bearing load measurement and in particular presents the results which have been obtained in the framework of the proposed methodology. In the first section a general introduction of bearing load measurement is presented discussing its main characteristics. The section thereafter discusses the currently known approaches focusing on their methodology, results and drawbacks. After this the novel approach is presented with a discussion on its novelty and advantages. Then the experimental setup for the performance assessment is presented, after which the experimental results and discussion section follows. The paper ends with a conclusion and a brief discussion of future work.

Basic Principle of Bearing Load Sensing

Loads applied to the inner-ring, or wheel side, of the bearing are transferred towards the outer-ring, or vehicle side, via rolling elements. These loads, either originating from the road-tire contact or the friction brakes, result in stress and strain within the structure. In bearing deformation based load-sensing, the resulting strain on the non-rotating part, the outer-ring, is measured using strain gauges and used to reconstruct the bearing loading.

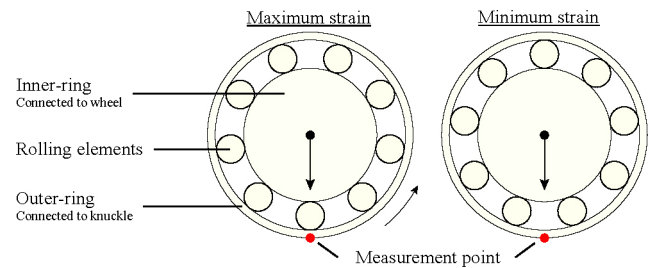


Figure 1. The strain at any measurement point varies significantly depending on the rolling element arrangement. When an element is in line with the measurement point a maximum is found, whilst a minimum is found when the measurement point is at the midpoint of two elements.

One of the difficulties in bearing load-sensing is the fact that the stresses and strains are not only influenced by the direction and magnitude of the loading, but are also heavily dependent on the arrangement of the rolling elements. If the bearing is in rotation, for any load an oscillating strain pattern will be found at each strain measurement location due to the changing arrangement of these elements. As shown in Fig. 1 a maximum will be found when a rolling element is in line with the strain gauge, whereas a minimum is measured when the measurement point is at the midpoint of two rolling elements.

While the bearing is rotating a varying strain will thus be observed even if the applied loading is constant. This constant loading case is presented in Fig. 2 for the passing of a single rolling element.

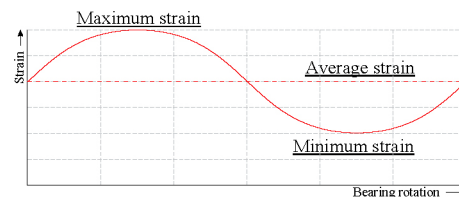


Figure 2. The resulting strain at a measurement point for constant loading and passing of one rolling element.

Note that vehicle wheel bearings often have two ball-rows closely located near each other, such that at the measurement location a superposition of this oscillating strain effect will be observed when both ball-rows are loaded. The axial placement of the strain gauge on the bearing outer-ring determines the strain sensitivity for either in- or outboard loading. In Fig. 3 the superposition phenomenon is presented for a measurement point axially located more closely to the inboard row.

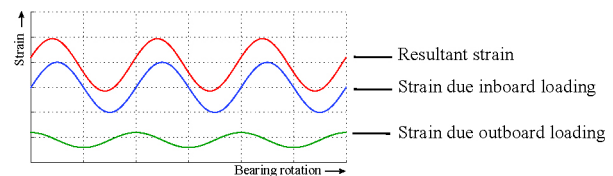


Figure 3. The resultant (measured) strain is a superposition of strain due to both inboard and outboard loading. The axial location of the measurement point determines in- and outboard sensitivity.

The strain signal can be characterized by the average strain, reflecting the structural deformation of the bearing, and a sinusoidal component, reflecting the local element deformation, due to the passing of elements. Both

components can potentially be used for bearing load measurement as both of them are load dependent. The novel field of bearing load measurement however is currently governed by approaches that are based on usage of the average strain or structural deformation [13, 14].

Structural Deformation Based Approaches

Currently two distinct studies on bearing load measurement based on structural deformation can be found in literature [13, 14]. Although in both studies a different approach is taken, the main issues addressed are identical. First of all, the structural deformation needs to be determined based on strain measurements. Secondly a correct set of strain-load mapping coefficients is determined for the final transformation to bearing loads. Fig. 4. presents the general scheme of load reconstruction.

The first step, the determination of structural deformation, both studies tackle from a different perspective. Where [14] uses a physical solution, by the addition of extra strain gauges and averaging, in [13] a signal processing approach is taken by notch filtering the strain signal at the ball-pass frequency. Although the latter approach is easier to implement and less expensive, the former approach allows for determination the average strain at any rotational speed and even at standstill.

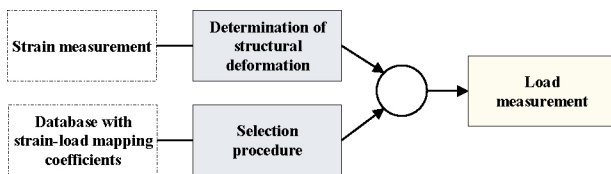


Figure 4. Schematic overview of the structural deformation based load-sensing approach.

As the relation between structural deformation and bearing load is highly non-linear, different sets of strain-load mapping coefficients are necessary for load determination under various load / driving situations (braking, accelerating, steering left, steering right etc.). In order to avoid a faulty load determination the selection of the correct set of strain-load mapping coefficients is a key step in this approach. Unfortunately the quality and robustness of this selection procedure cannot be analyzed as it is not thoroughly discussed in [14] and absent in [13] as only a single driving situation is considered.

In [14] it is stated that all three force vectors can be reconstructed where in [13] only the longitudinal force and braking torque are reconstructed. With respect to accuracy and bandwidth of these estimates unfortunately the former does not provide any clear results. In the latter study a good match is found between reference and estimated loading. The measured loads were furthermore used as control variables in real vehicle tests of a load based Anti-lock braking algorithm. This latter demonstrates that the approach provides enough accuracy and bandwidth for active vehicle dynamics control.

Although the presented research in [13, 14] is promising, showing an ability to accurately reconstruct loads on the bearing, there are still numerous drawbacks. Two of the most significant problems are i) the inability to reconstruct all loads and ii) the necessity of a selection

procedure of strain-load mapping coefficients. Where the first issue arises due to the lack of information within the structural deformation of the bearing, the second is related to the non-linearity of the structural strain with respect to the loading.

Inboard/outboard deformation based approach

In order to overcome these limitations in this paper a novel approach is presented and applied. This novel load-sensing approach aims for the reconstruction of all loads during various load / driving situations using only a single set of strain-load mapping coefficients. In contrast to the previously discussed approach, which is based on average strain of the combined in- and outboard loading, this approach focusses on the strain contribution of each individual row. Using this novel method more information can be extracted, enabling the determination of all wheel forces using only a single set of strain-load mapping coefficients.

As discussed in the basic principle section, the strain at each measurement point is a superposition of in- and outboard strain components. Depending on the axial position of the measurement point, the sensitivity to in- or outboard loading varies. As both rows are located close to each other, no single point can be found that measures only the in- or outboard strain contribution. However, by placement of two strain gauges at different axial positions, the difference in sensitivity of each measurement point for in- and outboard loading can be used to reconstruct the independent inboard and outboard strain contributions.

By comparison and analysis of strain patterns of two axially displaced strain gauges, a specially designed algorithm is able to reconstruct the relative strain contribution of each ball row. Instead of one measure for the combined in- and outboard average strain, the two measurement points hereby allow to determine an independent estimate for both in- and outboard strain contributions. Due to patent pending and industrial privacy reasons a more detailed description of the algorithm determining in- and outboard strain components will not be discussed.

Based on both in- and outboard strain components obtained by the numerous strain gauges on the circumference of the bearing outer-ring the load determination takes place by multiplication with a single set of strain-load mapping coefficients. A schematic overview of the approach is shown in Fig. 5. Only a single set of strain-load mapping coefficients is necessary as the in- and outboard strain components have a significantly less nonlinear relation with respect to the bearing loads.

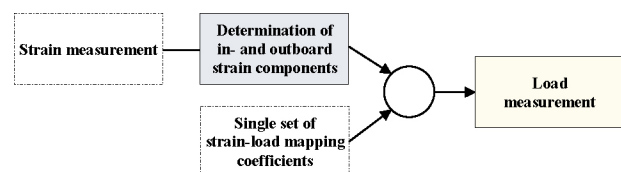


Figure 5. Schematic overview of load reconstruction based on inboard and outboard strain components.