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Mechanical Design Aspects for Wheel Sensors of Tire Pressure Monitoring Systems – an Overview

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Introduction

For over 15 years, industry has been working on the development of Tire Pressure Monitoring Systems (TPMS) that can measure operating tire pressure while driving and warn the driver in the event of under-inflation or pressure loss.

Studies in America have shown, that 26% of cars and 29% of trucks were operating with tire pressure at least in one tire 25% or more below specification, which not only has a negative impact on fuel economy and tire wear, but poses a significant safety risk for the motorist.

The American TREAD act mandates that TPMS Systems be used on all passenger cars sold in the USA and so the subject of integrating TPMS Systems into existing and new car platforms has taken on a very high priority.

While a lot of attention is given to the electronic and RF design, the mechanical aspect of fixing the sensor unit to the wheel and the related safety aspects is sometimes neglected.

As a member of a German VDA task force, consisting of Audi, BMW, Daimler Chrysler, Porsche, Volkswagen and the electronics supplier Doduco, ALLIGATOR Ventilfabrik, one of the major manufacturers of tire valves in the world, has been involved in the development, production and continuous improvement of these systems for well over 15 years. In this article we want to share our experience regarding the mechanical design of these sensor units.

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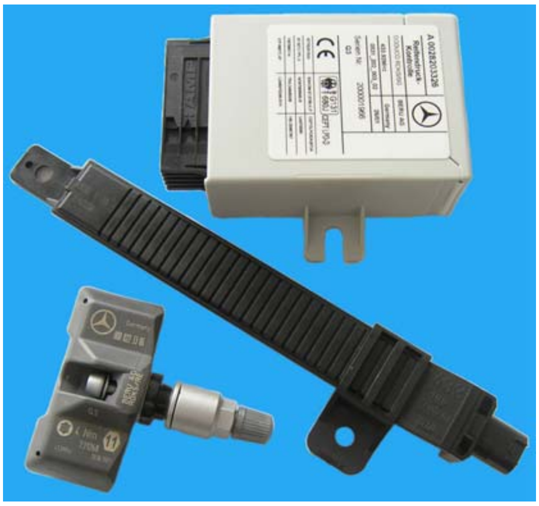
Basic description of TPMS systems



*The components of a typical TPMS system:
wheel sensor, antenna, and central electronics unit.*

All so-called active systems currently used in production employ an electronic sensor unit inside each wheel, measuring tire pressure and temperature. A Radio Frequency Transmitter transmits this information to a central unit inside the car which processes this data and informs the driver in the event of pressure loss. The fixation of the wheel sensor and the mechanical design of the sensor housing is the main focus of this article.

Different fixation –systems and mechanical requirements

Many means of permanently fixing the wheel sensor inside the tire have been developed and tested. The fixation has to hold the sensor securely in place at accelerations of up to 2000g (1g = 9,81 m/s²) and resist centrifugal forces of up to 600 Newtons (based on sensor mass of 30 grams).

Secure retention has to be guaranteed over the life of the vehicle, since a loose sensor tumbling around inside a tire at road speeds of 200 km/h and more would cause a major safety risk. Due to this inherent risk, certain methods of securing the sensor, like using adhesives, riveting etc. have been ruled out in the past.

Somewhat contrary to the requirement of secure and long-term fastening is the need for quick, simple and inexpensive installation at the OEM and simple replacement in the aftermarket.

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In vehicles currently being produced, a small number of sensor units are fixed to the drop bed with a strap going around the rim. In certain cases, where the sensor cannot be attached to the valve, e.g. on truck wheels, where there is not enough space directly behind the valve, a special dowel-type fastener is used.

Dowel-type fastening of wheel sensor in the case of insufficient space behind the valve.

The majority of wheel sensors however are attached to the back end of a specially designed metal tire valve.

Wheel sensor attached to back end of tire valve

This system offers the most advantages

- Quick, simple and inexpensive assembly at the OEM
- The valve hole is used to bolt the sensor securely to the rim. No additional holes need to be drilled that could cause air-leakage.
- No additional fastening elements, brackets, additional holes to be drilled – all of which would increase system cost
- Simple quality assurance on the mechanical fastening process (as compared to adhesive solutions etc.)
- Replacement in the garage does not require highly specialized training or expensive equipment

Mechanical and environmental requirements

In addition to the standard requirements for tire valves, an often neglected safety component on each car, a valve mounted TPMS sensor has to fulfil a multitude of special requirements:

- **Minimum size and weight to minimize imbalance of the wheel and mass-forces**
- **Resistance against damage during tire installation; ability to resist and securely transmit mounting forces into the rim.**
- **Sensor unit must not offer any sharp corners or protrusions on which the tire bead could catch during assembly.**

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- **Adjustability to wheel designs; ability to use the same sensor unit on different wheel designs.**
- **Resistance to operational forces and loads**
- **Operating temperature range and reliable sealing**
- **Environmental resistance**
- **Ease and low cost of assembly**

Minimum size and weight

The mass of the sensor unit is normally dictated by the size of the battery required. The weight of all other components has to be kept as low as possible in order to minimize the imbalance of the wheel and the size of the balancing weights needed. Especially since zinc has to be substituted for lead, heavy weights are undesirable due to the large size. Not only the weight of the sensor but also its geometrical size has to be minimized, so that its centre of gravity can be kept as close to the rim-shoulder as possible, in order to minimize torque loads on the valve and sealing grommet caused by centrifugal forces and lateral acceleration in service. Especially in designs where the sensor is not properly supported by the rim surface, this torque can lead to undue movement of the valve in the valve-hole and ultimately cause air-leakage.

Resistance against damage during tire installation

During assembly of the tire onto the wheel, the tire bead may slide over the assembled sensor. Special attention therefore has to be paid to a well rounded surface of the sensor housing to prevent the tire bead from catching on protrusions or sharp corners, which could cause severe damage. The transition between valve stem and sensor housing has to be smooth with no gap in which the tire bead could get caught.

The forces exerted onto the sensor housing by the tire bead sliding over it have been measured to be as high as 1700N. If the sensor housing is not properly supported by the drop-bed, (i.e. if it is “hanging in the air”) these forces may actually break the sensor housing off the valve stem. This risk is especially present in non-adjustable designs if used on a rim with different drop-centre angle.

Tire bead sliding over wheel sensor during tire-assembly

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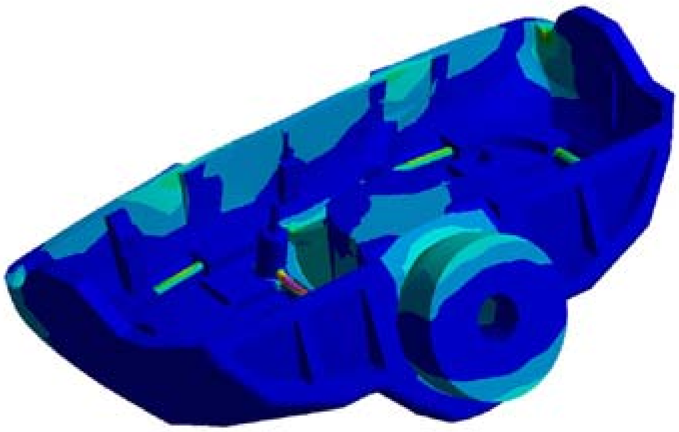
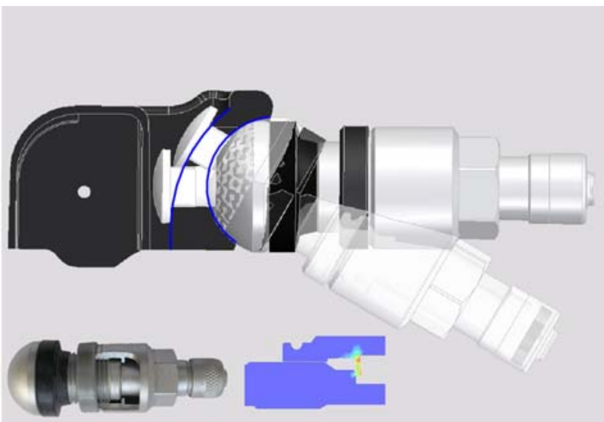
Just a fine hairline crack in the housing, occurring during this phase is even worse than the sensor housing breaking off completely. Such a crack normally goes unnoticed during tire assembly but will increase in size during service and may cause the sensor unit to become loose inside the tire and damage the inner liner. Extensive physical testing and optimization of the housing design using FEA methodology are necessary to ensure proper function.



Finite Element model of sensor unit used to optimize load absorption, resistance to operating forces and minimize distortion of sealing elements.

A special 3 point support system has been developed to ensure positive support of the sensor housing by the rim. The sensor housing is attached to the valve stem with an adjustable ball joint, allowing the housing to be fitted snugly against the drop-bed. The ball-joint not only compensates for angle variations caused by manufacturing tolerances but also allows the sensor unit to adjust to different rim designs, in order to eliminate the need for different sensor units to equip different rim designs.



Wheel sensor unit with self-adjusting ball-joint and 3 point support against drop-bed

The head of the screw which holds the sensor-housing to the valve base slides on a sloped surface which acts like a wedge and actually forces the sensor housing down against the rim-surface as the screw is tightened.

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The sensor housing features two feet which, together with the ball-joint, form a well defined 3 point support, preventing damage to the sensor as the tire bead slides over it. This also prevents tilting or excessive deformation of the housing due to centrifugal forces while in service.

Sensor designs with a fixed angle between valve-stem and housing, i.e. with the housing molded right onto the valve stem at a fixed angle seem to offer a cost advantage over the adjustable system. However, experience has shown that over time there could be a proliferation of rim designs with different angles and or different requirements for the valve length, leading to a potential logistical nightmare both at the OEM and especially in the aftermarket, if a different wheel sensor is needed for every single different wheel.

If wheel sensors with different but similar angles are used by the OEM, there is a high risk, especially in the case of repair in the garage, that the wrong sensor might be used, causing damage during tire assembly, as described above.

Resistance to operational forces and loads

In normal operation, depending on driving speed, suspension system of the vehicle and road surface conditions, the sensor is exposed to very high accelerations of up to 2000g, (2000 times normal gravity) resulting in forces of 600N on a sensor unit weighing 30 grams.

In addition to numerical simulations, high speed spin are used to observe the sensor units at simulated speeds of up to 350 km/h, with peaks of up to 480 km/h.

Despite mathematical simulations and laboratory tests carried out, it is ultimately recommended that the sensor unit be tested on the actual vehicle it is designed for, in order to ensure optimal mechanical performance over its entire lifetime.

Spin tester to simulate loading on wheel sensor up to 480 km/h

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Operating temperature range and reliable sealing

Minus 40 °C has been the standard for automotive components for a long time. Especially the sealing materials used on a tire valve (both on the so called outer grommet as well as on the seals of the valve core) have been selected to resist these low temperatures.

The high temperature limits, to which a valve mounted TPMS sensor has to be designed and tested, vary, however. Increasing brake-power on vans and passenger cars combined with ever more aerodynamic designs, mean ever hotter brake-discs that keep moving closer to the rim and to the tire valves, exposing these to ever higher operating temperatures.

Today’s OEM specifications require operating temperatures of up to 150 °C and more.

Especially the sealing grommets have to be designed to withstand these temperatures without hardening under the heat (which could cause them to crack and develop leakage paths) and without taking excessive compression set, which would reduce the preload on the seal and could again cause leakage, when the valve is flexed by operating forces. Sealing materials, specially formulated to function under these conditions, have to be used.

Clamp-In metal valves utilizing an O-Ring instead of sealing grommets have been designed to partly overcome the loss of preload described above. The O-Ring is encased in a metal gland, so that there is metal contact between nut and rim-surface, and the compression set of the O-Ring does not reduce the loosening torque of the nut and thus allow the valve to become loose and leak air.

This O-Ring design however has some major drawbacks: The air pressure inside the tire pushes the O-Ring towards the valve stem, and into the chamfer of the rim’s valve-hole. If this chamfer is too big (as is often the case) the O-Ring starts leaking air since it is no longer sufficiently compressed.
Also, many rims, especially after having been in service for a while, have damaged surfaces, burrs or are uneven around the valve hole. Due to the small volume of compressed rubber in the O-Ring seal, it is not able to seal securely under these adverse conditions.

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A special sealing concept, the so called ASC (Advanced Sealing Concept) has been developed to combine the advantages of a grommet seal with its large displaced rubber-volume on one hand and metal-to-metal contact on the other.

Different sealing concepts: O-Ring, standard grommet and ASC (Advanced Sealing Concept)

Environmental resistance

Due to weight considerations, as described above, aluminium is the material of choice for the valve components. In selecting the right alloy, consideration has to be given to the machinability of the material, especially with the extremely fine tolerances required on the valve components.

Since the corrosion resistance, even of materials with no or minimal copper-content, is not sufficient to protect the valve for a lifetime, it is necessary to use protective coatings, either resin based or special types of anodization. Automotive OEMs rely on various salt spray tests in an effort to simulate the harsh real-life environment. Depending on the exact specification, different surface treatments are available to achieve optimal results.

To prevent electro-chemical corrosion, only a special nickel plated version may be used in an aluminium valve, - not a standard brass valve core. The staff at tire shops have to be instructed not to substitute a standard brass valve core for the original nickel-plated version.

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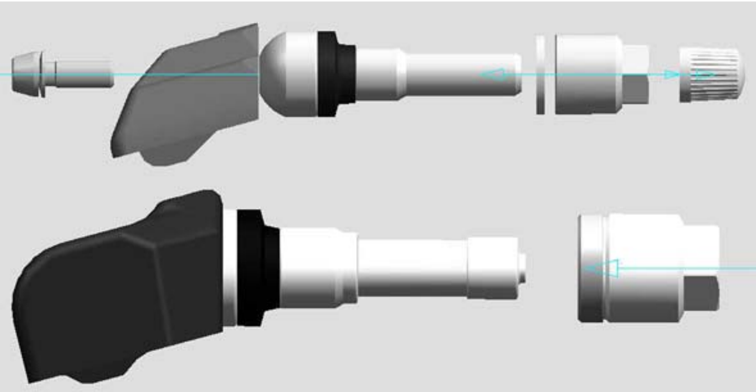
Ease of assembly

The adjustable design Generation 1, as described above has been used successfully by different OEMs since 1998. The assembly onto the wheel however is still quite labor intensive since there are several components that have to be mounted on site.

In order to reduce assembly time and cost, the so-called Generation 2 wheel-sensor has been developed.



Comparison: wheel-sensor Gen.1 vs. Gen.2:

The sensor unit is supplied with valve stem and housing already joined together. This preassembled unit is slid into the valve hole and the separate hexnut attached. This patented nut features a shear collar that rides against the shoulder of the valve stem. As the nut is tightened, it makes the whole valve stem spin and tightens the screw in the back, causing the sensor housing to tilt down against the drop-bed and become tightened.

As the maximum torque of the screw is reached, the shear collar breaks off and the nut threads itself onto the valve stem, tightening the valve in the rim hole. (See details in Fig. 6)

Therefore, with only one torquing process, the sensor housing is adjusted to the rim and fastened, while at the same time the whole sensor unit is tightened in the valve hole.

The screw has a square shank, which is guided inside the slot of the plastic housing, preventing it from spinning and thus from loosening in service.

Furthermore, unlike Generation 1, the valve-cap is small enough in diameter for the hexnut to slide over it, so that it is no longer necessary to remove it for assembly.

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The washer underneath the hexnut, which is needed to prevent damage to the rim surface, is permanently clipped to the nut, so that it can not be misplaced or forgotten during assembly.

This new design has become standard on many European, American and Asian platforms.

Conclusion

Due to the limited scope of this article we were only able to give a brief overview of the mechanical aspects of designing a valve mounted TPMS sensor and to barely scratch the surface of some of the challenges involved. We hope however that we have managed to make the reader more curious and encourage him or her to ask more questions, in order to avoid costly mistakes.