Liquid Level Sensor in Automotive Design

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***Abstract*—New materials and technological developments in electronics and computers have changed all of the industries, as well as the world itself. These technological advancements have evolved automotive industry by redefining the concepts like: performance, efficiency, fuel consumption, driving dynamics, ergonomics etc. to a level far beyond expected. In this paper, the development stages; including the finite element analysis of the current sensors, using finite element analysis to design a new sensor, is elaborated. The new model designed in this study is computationally validated for production purposes and is planned to be experimentally tested. Also, in this paper a novel liquid level sensing device development strategy is presented in detail.**

Keywords – sensor; finite element analysis;modal analysis; durability analysis; whispering gallery mode (WGM).

I. INTRODUCTION

Oil sensors and analyzers are used in automotive and industrial applications to gather or send valuable information to ensure that the level of the engine oil does not become dangerously low without being noticed. The sensor monitors the oil level continuously during the entire engine operation, which means that the oil level can be prevented from falling below the minimum level during operation, which in turn means the oil film is not interrupted (which would lead to engine damage). Secondary influences such as the slope of the vehicle's lateral and longitudinal accelerations are compensated by the vehicle control unit calculating a mean value [1].

There are many oil level sensors in automotive, but most common approaches are ultrasound and resistance sensors [29]. Sensors using a resistance wire work with the principle of changing resistance and temperature of the wire between under and over the liquid. Sensor sends a current to the wire, and the output voltage differs by changing liquid levels.

The ultrasonic level sensor, however, works on the principle of measuring the time-frame between transmitting and receiving of ultrasound waves. The ultrasound wave travels through material [2]. The sensors emit high frequency (20 to 200 kHz) acoustic waves that are reflected back to and detected by the emitting transducer affected by the changing speed of sound according to moisture, temperature, and pressures. Correction factors can be applied to the measurement level to improve the accuracy of measurement [3]. Ultrasonic sensors have advantages in dynamic measurements; nevertheless they are more complex and more expensive when compared with the resistance wire type level sensors.

At this point, new approaches were searched and a possibility of applying Whispering Gallery Mode (WGM) theory into liquid level sensing is considered [14] [19].

II. LIQUID LEVEL SENSOR DEVELOPMENTS IN HISTORY

There are many different techniques in literature for measuring the liquid levels. Although, the concept development of sensors is parallel with the technological developments in electronics, some applications are much older than the electronics, like the Archimedes’ principle.

Archimedes’ principle also works for liquid level measurement. A cantilever beam is mounted into the liquid tank, and Archimedes’ principle raises the beam through the liquid, and load cell measures the deflection [4].

Another method which uses ultrasonic lambda waves, was developed in Russia (2002). The principle of this study is based on the changing characteristics of lambda waves in the liquid environment [5].

Ultrasonic level sensor for liquids working under high pressure [6] was developed and performed by NASA Langley research center and Old Dominion University. The basic principle can be explained as follows; the ultrasonic waves sent by a transducer propagate and are reflected from the liquid surface, and the time between transmission and reception is converted to distance.

An ultrasonic wave propagation method was developed in 2001 by BFGoodrich airplane advanced sensors department [7]. The principle is the same with the study before, sending and collecting ultrasonic waves, and finding the liquid levels according to the wave transfer times.

A totally different method is the usage of fiber optics in liquid level measurement [8]. Fiber optic cables reflect the laser/light signal when in the air. However, when the density difference reduces, it transfers the laser light to the liquid environment, and thus, the sensor detects the liquid environment.

Fiber optics is used again in another study [8]. The methodology used in [8] is as follows. While in air, most of the light rays reflect back, but in water light rays continue their way. The decrease in the level of reflected signals indicates that the optical fiber tip is inside water. The simplicity of the methodology implies that within the material property boundaries (between -20C and +70C) usage of optical fibers is easy, accurate and inexpensive.

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In the case for automotive engine applications, however, although all of the above methods have different advantages, a new method is required. The design must have high precision, and needs to be small enough to be located into the engine and must be durable enough for working under flammable liquids or gasses safely.

III. New Oil Level Sensor DEsign

A. *Hella Sensor Design*

This study was first started with the idea of generation and development of a new oil level sensor which is integrated inside an oil pan (Fig. 1). The initial plan was to study with the engineers in Hella Company's (Hella KGaA Hueck & Co.) automotive sensors division [26].

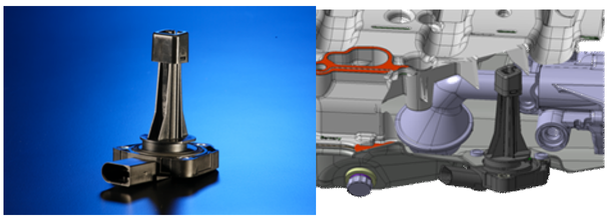

Figure 1. The current Hella oil level sensor, the picture in the right shows the sensor in it's assembled position and Target of OLS Design [25].

According to the mutual study plan, available information is shared. The information include previous three dimensional (3D) computer aided design (CAD) models, design and finite element analysis (FEA) studies, as well as the test results of the previous ultrasonic oil level sensor. For this aim, Hella Company has been visited, and during this visit details of the ultrasound sensor, its development, production and validation stages have been evaluated. Design validation tests of the sensor are thoroughly investigated to setup a relevant computational model.

The target of the Hella cooperated study is to work on the mechanical designs (material, sealing, mounting) in order to integrate the ultrasonic oil level sensor inside the vehicles oil pan.

For design verification purposes, a FEA simulation model is developed to study overall thermo-mechanical performance and vibration influence. Following the computational verification of the model developed, rapid prototypes of the model are planned to be produced to perform the first functional tests by Hella.

The main details of the FEA analysis are; the vibration profile and mechanical properties of the new sensor design under various temperature ranges, which are between -40C up to +150C. The endurance of the new design will be evaluated by using computer aided engineering (CAE) methods.

Following the verification of an acceptable design, the physical samples made out-of rapid prototyping will be prepared, and tested submerged in oil within the real world experimental setup. The target is to reach an accuracy of -/+ 0,2mm for sensing the oil levels.

In the present the study, several sensor models have been analyzed, and a new, reliable design proposal is developed (Fig. 2)

IV. Finite Element Analysis and evaluation of Results

During the FEA analysis, material properties of PA66-GF35 [25] is assigned for the main sensor parts, while fixings are CuZn39Pb3 and grounding is CuNi10Fe1Mn [24]. Several meshing structures are tested and an optimum mesh structure is reached. Final mesh structure consists of over 76.000 tetrahedral elements and around 22.000 nodes. Following the "meshing" stage of parts, all the individual parts are assembled with an attention to the rigidity of each part and the model. During the analysis it is assumed that the oil level is low, which also demonstrates the worst case by minimizing the damping effect of oil in the sump.

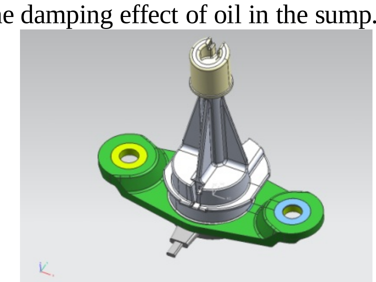

Figure 2. New oil level sensor design according to the results of FE analysis and the requirements of Hella GmbH.

A. *Modal Analysis*

The goal of modal analysis [27] is to determine the natural mode shapes and frequencies of an object or structure during free vibration. Since the model developed is of complex structure it is customary to use the finite element method (FEM) to perform this analysis,

The types of equations which arise from modal analysis are those seen in Eigen systems. The physical interpretation of the eigenvalues and eigenvectors, which are determined by solving the system, correspond to the natural frequencies and related mode shapes. Usually, the modes that are dominant are the lowest frequencies which are the most prominent modes at which the object will vibrate, dominating all the higher frequency modes [23].

A sample of the results evaluated is presented in Fig 3. The results indicate very high strain and stress values only in 7th, 8th and 9th modes, where the frequencies are 1635 Hz, 2187Hz, and 2413Hz.

All of the above frequencies are higher than the testing limits: (According to DIN EN 60068-2-6) [26], and our design is completely safe according to natural frequencies found in the modal analysis.

The above conclusion is demonstrated in depth in the next section, which summarizes the stress analysis results under the testing conditions.

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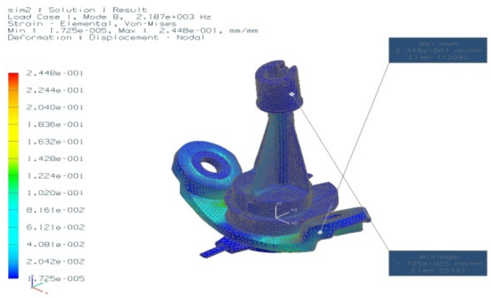

Figure 3. The mode 2 shape and the elemental strain values of the FE analysis.

B. *Stress-Strain Analysis in Freqency-vs-Acceleration*

Frequency vs. acceleration values obtained from the Volkswagen Automotive test spec [26] in Table 1., are applied to the new sensor model designed and meshed as summarized in Part A.

TABLE I. THE FREQUENCY VS ACCELERATION VALUES

Frequenz [Hz]	**Amplitude der Beschleunigung [m/s^2]**
100	100
150	150
200	200
240	200
255	150
440	150

Results of the stress-strain analysis under test conditions (Fig. 4) show that the oil level sensor faces a stress value of not more than 0.21 MPa, which makes no deformation when compared with its Yield Stress and Ultimate Tensile Strength values which ranges within 150-200MPa. Also the results show that there are no significant strain values.

In summary, computational results indicate that, in these test conditions, the new design is assessed to be safe.

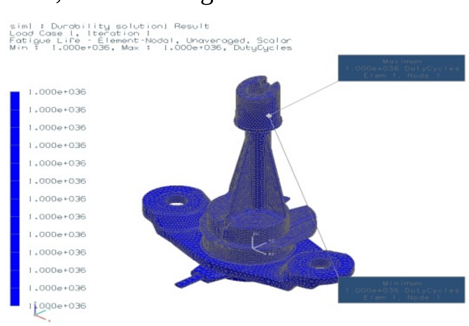

Figure 4. Fatigue Analysis Sample Results

C. *Fatigue Analysis*

Post processing of the results obtained show that, the stress values may not harm the design. However, the new model needs to be analyzed according to fatigue conditions to see the effects of cycling loads.

For this aim Fatigue Strength Coefficient, Fatigue Strength Exponent, Fatigue Ductility Coefficient and Fatigue Ductility Exponent values have been found and inserted into the materials' database of the computational model [24].

Same loading conditions are repeated for many times to see the life-time of the model under the test conditions. The results show that expected lifetime is above 10^36 cycles. Safety factors have minimum values of 25.76 for fatigue and 2.796 for strength. According to these findings it can be suggested that, the new design is absolutely safe according to both stress-strain and fatigue properties under cycling loading of test conditions.

V. WHISPERING GALLERY MODE PHENOMENON

A. *Theory*

Following the above study, exploring the capabilities of Southern Methodist University Mechanical Engineering Faculty's Micro Sensors Lab. a totally new type of liquid level sensor idea is activated.

This new sensor is planned to detect pressure/force by using whispering gallery mode (WGM) phenomenon, and capable of working nearly in everywhere including underwater.

The target is to develop sensor prototypes using the existing WGM theory. The test design includes equipments such as; laser as the signal source, micro sphere as the sensing element, fiber optics, and a liquid container as the test medium (Fig. 5). It is planned to perform the functional tests by using the Micro sensors laboratory of Southern Methodist University.

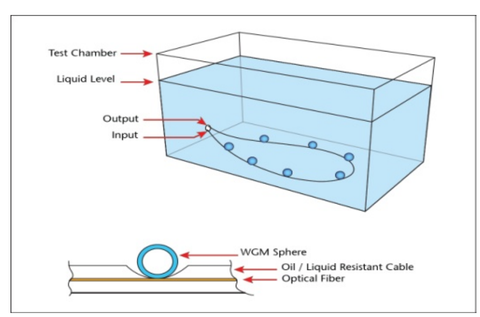

Figure 5. Planned experimental setup of liquid level sensor using WGM method

Fig. 5 and Fig. 6 show the proposed WGM pressure sensor experiment setup.

Fig. 5 shows the general experiment setup, while Fig. 6 shows detailed proposal of how to encapsulate the WGM sphere to make the sensor resistant to the medium including liquids [10].

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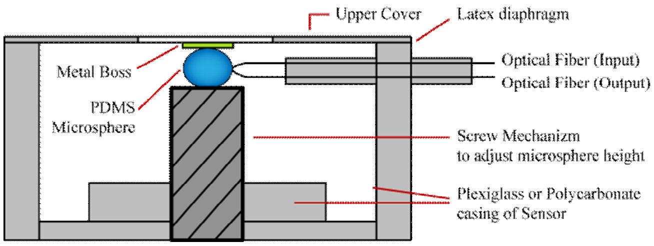

Figure 6. WGM sensor should be resistant to fluids therefore a latex type membrane will be planned and used in the experiments

As a summary; results of the present work is aimed to include not only a new level sensor, but also a new perspective into the WGM phenomenon will be evaluated to create a completely new sensor to be used in automotive as well as in many other branches of industry.

B. Equations

In the whispering gallery mode theory, light undergoes total internal reflection, and because it is trapped inside the sphere, WGMs are observed under certain conditions.

The details of the theory, the change in WGM spheres under pressure is as follows [19]:

For r >>λ, resonance condition (approximate):

$$2\pi r n_0 \approx \ell \lambda \qquad (\ell = \text{integer}) \tag{1}$$

n = Refractive index of the micro-sphere
λ= Wavelength
r = Micro-sphere radius

$$\frac{\Delta n}{n_0} + \frac{\Delta r}{r} \sim \frac{\Delta \lambda}{\lambda} \tag{2}$$

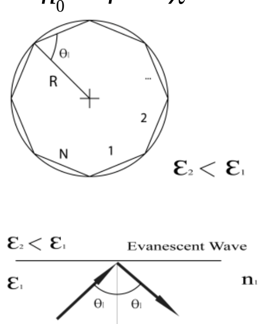

Figure 7. Total internal reflections of the sensor, according to basic optical physics.

When we look at Fig. 7 above, it can be seen that each time the light bounces off the inner surface of the sphere due to total internal reflection, the reflected wave experiences a "phase delay",ϕ. This phase delay is a function of the light wavelength, λ; and incidence angle; as well as the sphere-to surrounding refraction index ratio, n_1/n_2.

As it can be seen easily, the laser light comes into the microsphere in its contact point in the tapered film, and the light undergoes total internal reflections in the sphere, which causes the phase shifts or in other words WGM shifts.

As illustrated in Fig. 8, while light starts re-circulating in the sphere a resonance shift occurs in the light when compared with the reference light beam.

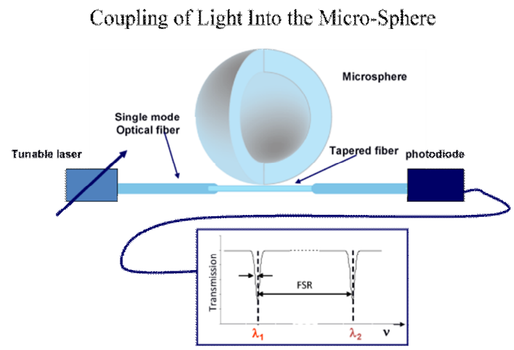

Figure 8. The WGM phenomenon, and the phase shift (or the WGM shifts) caused by the total internal reflections occured in the microsphere [19].

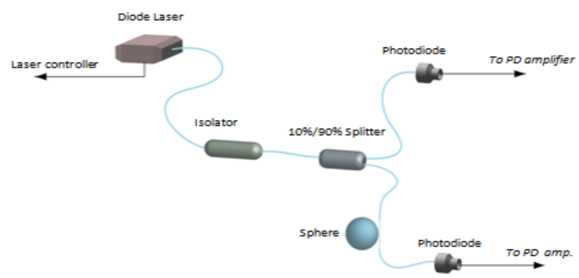

Figure 9. The experiment setup in it's general form. The light coming from the laser splits into two [19].

Fig. 9 presents the experiment setup in its general form. The light coming from the laser splits into two, leaving a small percentage for reference going directly to the photodiode, while keeping a high percentage (90% in this scenario) for WGM shift, which goes directly to the microsphere. So after the WGM phase shift occurs, it has been noticed by checking the differences between the reference light and WGM part of it

When force is applied to the resonator, a change occurs in both the shape and index of refraction of the resonator (Fig. 10). The formulas below demonstrate that we can measure the force by detecting the changes occurred in the shape and the index of refraction [19].

$$F = f(\Delta\lambda) \tag{3}$$

$$\frac{\Delta n}{n_0} + \frac{\Delta r}{r} = \frac{\Delta \lambda}{\lambda} \tag{4}$$

$$F = g(\Delta\lambda) = f\left(\frac{\Delta R}{R}, \frac{\Delta n}{n_0}\right) \tag{5}$$

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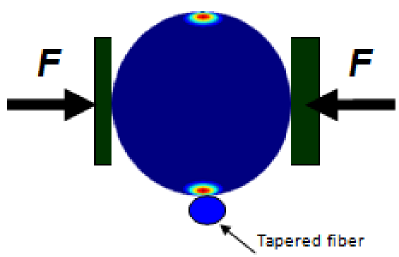

Figure 10. When force is applied to the resonator, a change occurs in both the shape and index of refraction of the resonator [16].

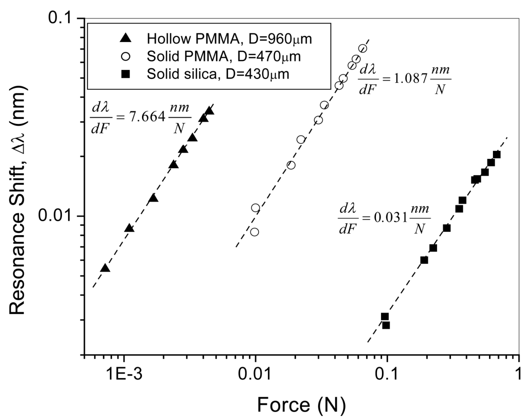

Figure 11. Force versus Resonance results for different spheres [16].

In this manner, there are different kinds of sphere materials showing different responses to the measurements. Fig. 11 shows the different sphere materials and their specific values like Young's modulus, index of refraction and Elasto-optical constant which all are related with the WGM measurement results.

It can be observed that, the force shifts the resonance, but more importantly according to different materials, resonance shift also differs.

Now if we use WGM phenomenon to develop a pressure sensor we can see that pressure changes of the medium surrounding the sphere will induce WGM shifts.

This means by using the same formula [19]:

$$\frac{\Delta n}{n_0} + \frac{\Delta a}{a} = \frac{\Delta \lambda}{\lambda} \qquad (6)$$

We can reach to the pressure as a function of the differences of sphere radius and index of refraction [19]:

$$P = g(\Delta\lambda) = f\left(\frac{\Delta a}{a}, \frac{\Delta n}{n_0}\right) \qquad (7)$$

If the stress and strain of a sphere is investigated, first the coordinate system should be defined (Fig. 12)

After many calculation steps, the formulas below can be achieved [16].

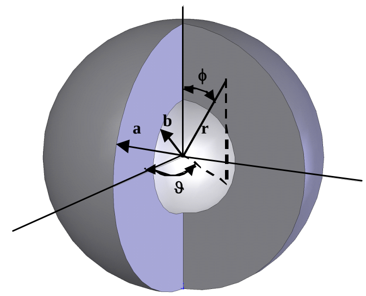

Figure 12. Coordinate System used [16].

$$\frac{dn}{n} = \frac{n_r - n_{0r}}{n_{0r}} = \frac{n_\vartheta - n_{0\vartheta}}{n_{0\vartheta}} = \frac{n_\phi - n_{0\phi}}{n_{0\phi}} = \frac{C(\sigma_{rr} + \sigma_{\vartheta\vartheta} + \sigma_{\phi\phi})}{n} \qquad (8)$$

By inserting the appropriate expression for the three principle stresses in $\frac{\Delta n}{n_0} + \frac{\Delta a}{a} = \frac{\Delta\lambda}{\lambda}$ we can obtain the dependence of the WGM shift on external pressure P_0 for a PMMA spherical resonator as follows [19]:

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{2G}\frac{P_0}{1-\left(\frac{b}{a}\right)^3}\left(\frac{\frac{1-2\nu}{1+\nu}+\frac{1}{2}}{2G\left[\left(\frac{a}{b}\right)^3-1\right]\frac{z}{3}+\frac{1}{2}\left(\frac{a}{b}\right)^3+\frac{1-2\nu}{1+\nu}}\left(\frac{1-2\nu}{1+\nu}+\frac{1}{2}+\frac{6GC}{n_0}\right)-\frac{1-2\nu}{1+\nu}-\frac{1}{2}\left(\frac{b}{a}\right)^3-\frac{6GC}{n_0}\right) \qquad (9)$$

This equation can be simplified - if the effect of p_i (Which denotes Inner Pressure) is ignored [19]:

(Please note that p_0 denotes External Pressure)

$$\frac{\Delta\lambda}{\lambda} = -\frac{1}{2G}\frac{1}{1-\left(\frac{b}{a}\right)^3}\left(\frac{1}{2}\left(\frac{b}{a}\right)^3 + \frac{1-2\nu}{1+\nu} + \frac{6CG}{n_0}\right)\cdot P_0 \qquad (10)$$

This equation indicates the dependence of WGM shifts on external pressure P_0.

Fig. 13 demonstrates the experimental results of a previous study [16] showing that the WGM resonances shift by applying force on the sphere.

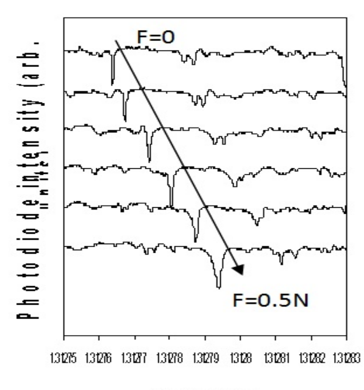

Figure 13. The experimental results can be seen as force terms in the resonance shift [19].

As a summary, WGM shifts can now be calculated according to the pressure changes of the medium, or in other words the external pressure changes.

VI. CONCLUSION AND FUTURE WORK

In this study, development and verification stages of a new, state of the art, oil level sensor was presented. Finite element analysis and modal analysis results indicate that the new design may be safely used within the oil pan of the engine. Safety factors, 25.76 for fatigue and 2.796 for strength, indicate that the model is ready to initiate production of prototypes for experimental verification purposes.

Research done within the scope of this study initiated an idea for developing a totally new liquid level sensor. The new sensor design is expected to detect pressure/force by using whispering gallery mode (WGM) phenomenon. This attempt is a new perspective into the WGM phenomenon. For this aim, the experimental set up outlined in this paper will be built and operated in SMU laboratories.

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