NRC Publications Archive Archives des publications du CNRC

Object shape-based methodology for optical analysis of contaminated engine lubricants

Aghayan, Hamid R.; Yang, Jun; Bordatchev, Evgueni V.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

*ISOT 2010 International Symposium on Optomechatronic Technologies
[Proceedings], 2010-10-25*

NRC Publications Archive Record / Notice des Archives des publications du CNRC :

<https://nrc-publications.canada.ca/eng/view/object/?id=ea414122-1ea0-4133-aa46-fb59601f3fb5>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=ea414122-1ea0-4133-aa46-fb59601f3fb5>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Object shape-based methodology for optical analysis of contaminated engine lubricants

Hamid R. Aghayan

Jun Yang

Mechanical and Materials Engineering Department
The University of Western Ontario
London, Ontario, Canada
haghayan@uwo.ca, jyang@eng.uwo.ca

Evgueni V. Bordatchev*

Centre of Automotive Material and Manufacturing (CAMM)
Industrial Materials Institute (IMI)
National Research Council of Canada (NRC)
London, Ontario, Canada
evgueni.bordatchev@nrc.gc.ca

Abstract—Introduction of gasoline, water, coolant and other contaminants into the engine lubricant as well as the normal aging process affects the optical properties of liquid medium, such as transparency, absorption, and refractive index. A new methodology for optical analysis of contaminated engine lubricants is proposed and described in details in this paper. Novelty of the proposed methodology consists of obtaining and analysis of an optical image that combines an object with known periodical shape and lubricant. The object, e.g. a stainless steel woven wire cloth with a mesh size of $65 \times 65 \mu\text{m}$ and a circular wire diameter of $33 \mu\text{m}$ was placed behind a microfluidic channel, containing engine lubricant and optical images of flowing lubricant with stationary object were acquired and analysed. Several parameters of acquired optical images, such as, color of lubricant and object, object shape width at object and lubricant levels, object relative color, and object width non-uniformity coefficient, were proposed. Measured on-line parameters were used for optical analysis of fresh and contaminated lubricants. Estimation of contaminant presence and lubricant condition was performed by comparison of parameters for fresh and contaminated lubricants. Developed methodology was verified experimentally showing ability to distinguish lubricants with 1%, 4%, 7%, and 10% coolant contamination.

Keywords—engine; lubricant; contaminants; object; optics; color; image; analysis; coolant

I. INTRODUCTION

An automotive engine consists of several sub-systems, such as, intake and exhaust, fuel injection, ignition, engine cooling, engine lubrication, *etc.* Each of the sub-systems' function affects the performance of the engine. However, the most important factors that can reduce the performance and life expectancy of the engine of the motor vehicle are those related to the phenomena of friction and wear. These factors are controlled by the engine lubricant system and by the lubricant condition. The main function of the engine lubricant as a combination of base oil and chemical additives is to provide lubrication on the moving parts to reduce friction and wear, transferring heat and energy, preventing corrosion, contamination control, engine internal cleanliness, and reducing environmental impact. Operating conditions, such as, engine load, cold starts, driving habits, *etc.* significantly influence the properties of engine lubricant and its degradation

process irreversibly. This is why monitoring of engine lubricant condition has been always a vital task to the optimal performance of engine [1].

Increasing lubricant replacement intervals and monitoring required lubricant volume were the main goals of initially developed engine lubricant sensors. New developments in microfabrication technologies, micro-mechanics, and micro-opto-electro-mechanical systems are opening up completely new possibilities for development of intelligent, multi-functional, integrated sensing systems and technologies with enhanced functionality, e.g. on-line measurement and instantaneous analysis and control. Developments in novel lubricant sensors have shifted from "quantity-based" to "quality-based" approach focusing mainly on oil condition monitoring through direct and indirect measurements of physical-mechanical, chemical, optical, electrical and other properties of engine lubricant [2,3].

Physical-mechanical properties, such as, viscosity (including complex and dynamic viscosity) and specific density, have been always a first choice for estimation of actual lubricant condition monitoring. Agoston *et al.* [4] analyzed thermal aging of engine lubricant using a thickness shear mode microacoustic quartz resonator immersed into the lubricant samples. It was concluded that the sensor is potentially suited for the detection of the oxidation-induced viscosity changes caused by thermal deterioration of the lubricant. Jakby *et al.* [5,6] introduced a viscosity microacoustic sensor utilizing shear-polarized oscillation and surface acoustic waves. Engaging microacoustic sensor with liquid media led to effective mass loading causing a change in a sensor's resonance frequency. The sensor measurements in arbitrary units were compared to the viscosity measurements performed using an Ubbelohde viscometer, and the relationship between temperature and kinematics viscosity and the sensor output was studied.

In all lubricating systems, organic compounds exposed to high temperatures and pressures in the presence of oxygen will partially oxidize. Carboxylic acids contribute to the acidity of the lubricant and deplete its basic reserve as neutralization takes place. The net effect of prolonged oxidation is that chemically the lubricant becomes acidic. Measuring change in chemical properties of engine lubricant, such as, total acid

* corresponding author

number (TAN) and total base number (TBN) is the key index to monitoring engine lubricant condition. As lubricant ages, TAN increases slowly, while TBN tends to decrease. Moon *et al.* [7] developed a new approach that uses multiwall carbon nanotubes to monitor engine lubricant degradation using the change in the chemical properties of the engine lubricant. This study concluded that the engine lubricant sensor output corresponds to TAN concentration which potentially can be used to monitor engine lubricant condition.

Changes in electro-magnetic properties of engine lubricant are the results of organic compounds partially exposed to oxygen at high temperature and pressures. A wide variety of by-products are produced during the combustion process. Some of these compounds are highly polar and can remain suspended in the lubricant. Measuring the change in electro-magnetic properties of engine lubricant is another way to characterize and monitor the engine lubricant condition. In a study, Wang *et al.* [8] have shown how to detect glycol contamination in the engine lubricant by studying the a.c. impedance technique to measure the bulk-layer resistance of engine oil containing glycol. In this study, the impedance of engine lubricant was measured over the wide range of frequencies and it was found that the bulk-layer resistance declines abruptly as the glycol concentration increased from 50 to 150 ppm. Na *et al.* [9] proposed to monitor the deterioration of automobile engine lubricant using a capacitive sensor to measure changes in the permittivity of the engine lubricant. It was concluded that the capacitance of lubricant increases about 3% per 1000 km.

In addition to oxidation products, nitration and sulphation products are also formed when organic compounds are exposed to high temperatures and pressures in the presence of nitrogen, sulphur and oxygen. These products cause lubricant thickening and contribute to change in optical properties of lubricant. Engine lubricant optical property includes: color, transparency, reflection, refractive index, and absorbance. As lubricant degrades its color darkens, transparency decreases, refractive index increases, absorbance changes. Color, transparency, refractive index, and absorbance are the key optical measures in condition monitoring of engine lubricant. Kumar *et al.* [10] studied the use of color intensity sensor to monitor condition of engine lubricant on-line. In this study, the intensity of light emitted through a thin layer of lubricant was measured and correlation between sensor output and lubricant optical condition was found. On-line sensing of olive oil quality was developed by Gastón *et al.* [11], where optical power transmitted through a small polished zone of a single mode optical fiber immersed into the oil was measured. The results indicated that any process that could lead to changes in optical properties of olive oil would be susceptible by being traced by the proposed optical fiber sensor.

In this paper, a new methodology for optical analysis of contaminated engine lubricants is proposed and described in details. Novelty of the proposed methodology consists in obtaining and analysis of an optical image that combines an object with known periodical shape and lubricant. In such an optical image, the object shape is changing with introduction of contaminants and lubricant aging. Image parameters are proposed that quantify a synergetic effect of combined lubricant-object optical appearance. Estimation of contaminant

presence and lubricant condition was performed by comparison of parameters for fresh and contaminated lubricants. Developed methodology was verified experimentally showing the ability to distinguish lubricants with 1%, 4%, 7%, and 10% coolant contamination.

II. GENERALIZED APPROACH FOR OBJECT SHAPE-BASED OPTICAL ANALYSIS OF CONTAMINATED LUBRICANTS

Object shape-based optical analysis approach is based on the effect of thin random medium on the image quality that object shape will be distorted by a media (liquid or gas) located in front of the object. Recognition of the object with known or unknown properties of media is a typical task of statistical and non-linear optics[12], where media can be mathematically described as a statistical operator that describes light propagation through random media and transforms an original object into a media-distorted image.

As proposed in this paper object shape-based optical analysis approach, an object with known periodic shape is placed behind liquid medium, e.g. automotive engine lubricant, and parameters of the acquired optical image is examined as the properties of the optical medium varies. The novelty of the proposed methodology is in the introduction of an object with known periodic structure behind the optical medium, e.g. engine lubricant. In this case, an acquired image contains a synergetic effect of combined lubricant-object optical appearance, where known periodical structure of an object is distorted by a lubricant. Introduction of an object with known periodic structure significantly simplifies further lubricant condition monitoring through the analysis of lubricant-object combined image, because the object behind lubricant is already known. This arrangement is very similar to a classic task of identification of a dynamic system with known input and output. An additional advantage of the proposed approach is in a periodic structure of the object. In this case periodic structure represents a deterministic signal with known statistical characteristics. Therefore, by measuring statistical characteristics of the acquired image and comparing them with initially known characteristics of the object, the difference in characteristics represents properties of the lubricant and it can be analysed with respect to changes in the lubricant condition providing accurate and precise estimation of contaminant presence.

Figure 1 shows the generalized schematics of a proposed approach for optical analysis of contaminated lubricants. Initially, the light is sent through a lubricant and object with periodic structure and a combined optical image is recorded. According to the proposed logic for further comparison, initially, an optical image of a medium without distorting ingredients, e.g. fresh engine lubricant or lubricant right after oil change, will be acquired. Such an image from the undistorted optical medium and object represents the initial state or condition of the optical medium. As the engine runs, lubricant degradation process occurs leading to the breakdown in hydrocarbon chains, depletion of additives, and addition of contaminants. Optical images with operating lubricant and unchanged periodical object are acquired further delivering optical information with respect to degradation of lubricant condition.

Optical image analysis for both fresh and used engine lubricants consists in extraction of certain object shape related parameters and characteristics and their consecutive comparison. The acquired optical data from images requires initial image processing, such as, cross-sectioning, color normalization, averaging *etc.* making optical images and data more suitable for further statistical analysis pattern recognition. Final steps of the proposed approach are focused on a quantitative and qualitative analysis of contaminant presence and analysis of lubricant condition evolution.

Figure 1. Generalized schematics of a proposed approach for optical analysis of contaminated lubricants

III. EXPERIMENTAL SET-UP AND METHODOLOGY

The experimental set-up shown in Figure 2 used for object shape-based optical analysis of engine lubricant consists of a microfluidic chip with inlet and outlet connections, attached object with periodic shape, pumping system, and illumination source. The data acquisition system was composed of a CCD camera (Lumenera Infinity 1) with a magnifying lens (Keyence) having a focal length of 35-245 mm and connected to a PC equipped with imaging software (Infinity capture software by Lumenera). All optical components including camera, microfluidic chip and light source were mounted on an optical bench in order to avoid any external vibrations. The images were captured by the CCD camera with a magnification of 245x while running lubricant through the microfluidic chip made from two PMMA plastic plates with a thickness of 1.5 mm and forming a microfluidic channel with dimensions of 170 μm x 500 μm 50 mm (depth x width x length). The microfluidic channel provided a path to flow the contaminated engine lubricant positioned between CCD camera and light source. A medical syringe was used for pumping lubricant through the microfluidic channel. The object used in this set-up was a 10x10 mm stainless steel woven wire cloth (by Tech-Met-Canada) with a mesh size of 65x65 μm and a circular wire diameter of 33 μm . The purpose of stainless steel woven cloth

was to introduce a periodic structure into the image, suitable for shape-based optical analysis. The object was intentionally placed behind the microfluidic chip on opposite side of the CCD camera to avoid distortion of the laminar flow by the periodic structure. The visible light source (Stocker Yale, model 21AC) with a wavelength of 380-750 nm was used to illuminate the object and flowing lubricant using two fiber light guides. The images from the camera were acquired as 8-bit 640x480 pixel digital bitmap files and they were digitized at 256 grey scale.

Figure 2. Schematic (top) and a photograph (bottom) of the object shape-based optical analysis experimental set-up

Schematic of the experimental methodology for obtaining optical images and preliminary image analysis is shown in Figure 3. The goal of this experimental methodology is to extract, preliminary process, and deliver digital data suitable for further object shape-based analysis. Initially, an optical image of the flowing lubricant and object with periodic structure is acquired as a two-dimensional matrix with respect to the color of each pixel and its X-Y position. In the initially acquired optical image, the woven cloth provides a square grid represented by dark color having the engine lubricant flowing through within the grid with a constant period T .

During the next step, three image cross-sections at the mid-distance between two horizontal grid lines are selected and extracted to confirm statistically the validity of the measured data. Each image cross-section contains four intersections with

vertical grid lines surrounded by lubricant image on each side forming an object shape as a vector of 640 pixels. For better physical understanding of object shape, the pixel values of each image cross section are normalized ranging between 0 (black) to 1 (white). Then the three normalized image cross-sections are averaged into one image cross-section with respect its corresponding location. Mapping pixel color scale (between 0 and 1) vs pixel position forms the color cross-section. The color cross-section is pre-processed data ready for further analysis of lubricant condition and contaminant presence. Typically this cross-section has a number of peaks and valleys corresponding to the number of vertical lines representing the periodic structure of the object. The peak values (close to white color) correspond to the lubricant color passing through the microfluidic channel without interference with object, while the valleys correspond to the combined color of the object affected by lubricant.

Figure 3. Schematic of the experimental methodology for obtaining optical images and preliminary image analysis

IV. OBJECT SHAPE-BASED METHODOLOGY FOR OPTICAL ANALYSIS OF CONTAMINATED LUBRICANTS

Object shape-based optical analysis methodology consists in defining object shape parameters and in their measurement

and analysis with respect to analysis of lubricant condition and contaminant presence. Typical color optical cross section and object shape parameters are shown in Figure 4, where color cross-section, $C(x)$, is a function of pixel color scale (between 0 and 1) vs pixel position. Several parameters characterising the object shape are proposed and defined below. Within one period of the object structure, T , the amplitude to the highest plateau is defined as the color of lubricant, CL , passing through the microfluidic channel. The amplitude of the lowest plateau is the color of object distorted by the lubricant, CO . These are parameters that characterise the object amplitude. In addition, two parameters that characterize the object width are introduced to fully characterize the object shape. These two additional parameters are the object widths at lubricant level, WL , and the width at object level, WO , where lubricant level was chosen at 90% of lubricant color, $h_{WL} = 0.9CL$, whereas object level was set at 10% above the object color, $h_{WO} = 1.1CO$. Introduction of shape parameters allows representation of color optical cross section as a function of these parameters, $C(x) = f(x, T, CO, CL, WO, WL)$ along cross-section position.

Figure 4. Typical color optical cross sections and object shape parameters

Object shape-based optical analysis methodology is also based on a comparison of object shape parameters of fresh and used lubricants as it is shown in Figure 5. When fresh lubricant is introduced, earlier defined shape parameters are considered as constant parameters, $T, CO, CL, WO, WL = const$, to represent an optical medium with no change in its properties. That means the color cross-section of fresh lubricant is a deterministic function of independent variables with no variations in parameter values and it can be reproduced at any position, x , along color cross-section. Color cross section, $C(x)$, changes its character becoming a function with random variables, $C(x) = f(x, T_i, CO_i, CL_i, WO_i, WL_i)$, where $T_i, CO_i, CL_i, WO_i, WL_i = var$, and object shape parameters become interdependent with respect to lubricant condition and contaminant presence due to the changes in color, transparency, light absorption, and other optical characteristics.

In addition to the parameters proposed above, T, CO, CL, WO, WL , two relative object shape parameters are also proposed. To gauge the color divergence between lubricant, CL , and lubricant-object combination, CO , the relative lubricant-object color index, ΔC , is introduced and it is defined by the following expression:

$$\Delta C = CO/CL \quad (1)$$

In general, relative lubricant-object color, ΔC , shows how well object shape can be recognised at the background of lubricant and it is ranging from 0 to 1 (or from 0% to 100%). Critical limit of 100% optically indicates that the object can not be recognised because their colors are identical.

Figure 5. Object shape-based optical analysis methodology

During light propagation through the lubricant, in addition to the object color change represented by ΔC , the object image shape also changes the width of the periodic structure diluting the optical image. This phenomenon can be estimated by the introduction of a non-uniformity coefficient of object width, ΔW , and defined as the percentage change in the relative width of object shape by the following expression:

$$\Delta W = (WL - WO)/WL \quad (2)$$

This parameter quantifies the gradient of color degradation between two levels – at lubricant and object within the object shape. A non-uniformity coefficient of object width, ΔW , is also ranging from 0 to 1 (or from 0% to 100%), where critical limit of 100% optically indicates that optical image and shape of the object are deteriorating and the object totally loses its shape due to lubricant condition and/or contaminant presence and the object can not be recognised because their colors become identical.

V. EXPERIMENTAL VERIFICATION OF PROPOSED METHODOLOGY

In order to verify performance of the proposed object shape-based optical analysis methodology, coolant contamination of the engine lubricant was experimentally analysed. In particular, fresh lubricant (Pennzoil 5W30) was mixed with coolant with a concentration of 1%, 4%, 7%, and 10% forming coolant emulsion particles causing changes in color, transparency, and light absorption of the lubricant. Contaminated lubricant was pumped through the microfluidic channel and optical images were acquired. Measurements were

started with fresh lubricant, followed by the lowest to the highest contaminant concentration. Accordingly described in Section III experimental methodology, optical images were initially acquired and color cross-sections were calculated for each coolant concentration and they are shown in Figure 6. Preliminary visual analysis of color cross-sections clearly demonstrates that introduction of coolant into the lubricant significantly changes both color (represented by amplitude of color cross-section) and shape (represented by width of color cross-section) of the object with periodical structure.

Figure 6. Color cross-sections for different coolant concentration

In the next steps, object shape parameters introduced in Section III were analysed with respect to coolant concentration. Figure 8 illustrates the evolution of relative lubricant-object color index, ΔC , as an effect of coolant introduction. For example, introduction of even 1% of coolant immediately changes the color of the lubricant from $CL_{0\%} = 0.826$ to $CL_{1\%} = 0.812$ and color of lubricant-object combination from $CO_{0\%} = 0.209$ to $CO_{1\%} = 0.219$ resulting in a change of the relative lubricant-object color index $\Delta C_{0\%-1\%} = 1.87\%$. As coolant concentration increased to 4%, 7%, and 10%, the ΔC values decreased non-linearly to 65.63%, 50.68% and 27.71%, respectively. At the highest concentration of the coolant (10%), all color-related parameters of the object shape exhibited significant change in their values, e.g. $CL_{10\%} = 0.625$ which is a 24.33% change with respect to $CL_{0\%} = 0.826$. Also, $\Delta C_{10\%} = 27.71$ which is a 62.49% change with respect to $\Delta C_{0\%} = 73.88$.

Figure 7. Evolution of the relative lubricant-object color index with respect to coolant concentration

Width-related parameters of the object image shape have also exhibited good correlation with introduction of coolant

into the engine lubricant. As an example, Figure 8 shows the evolution of non-uniformity coefficient of object width, ΔW , with respect to the coolant concentration. However, addition of 1% coolant did not cause significant change in width-related parameters, e.g. non-uniformity coefficient was changed only for $\Delta W_{0\%-1\%} = 0.36\%$. Width-related parameters are more affected by quite sizeable coolant concentration, e.g. coolant concentration increased from 1% to 4%, 7% and 10% causes the lowering ΔW value from 59.84% to 57.77%, 49.21%, and 29.06%, respectively. Overall, introduction of 10% coolant contamination non-linearly changes the non-uniformity coefficient from $\Delta W_{0\%} = 60.02\%$ to $\Delta W_{10\%} = 29.06\%$ (difference of $\Delta W_{0\%-10\%} = 30.96\%$). It is also necessary to note that the change $\Delta W_{0\%-10\%}$ was mainly caused by the significant change of the object shape width at the object and lubricant levels, e.g. $WO_{0\%-10\%} = 24.00\mu\text{m}$ and $WL_{0\%-10\%} = 7.88\mu\text{m}$, respectively.

Figure 8. Evolution of the non-uniformity coefficient of object width with respect to coolant concentration

VI. SUMMARY AND CONCLUSION

This paper introduced and described a new object shape-based methodology for optical analysis of automotive lubricants. Novelty of the proposed methodology consists in obtaining and analysis of an optical image that combines an object with known periodical shape and lubricant. Several parameters of acquired optical images, such as, color of lubricant and object, object shape width at object and lubricant levels, object relative color, and object width non-uniformity coefficient, were proposed. Object shape-based optical analysis methodology is also based on comparison of object shape parameters of fresh and used lubricants. Developed methodology was verified experimentally showing ability to distinguish lubricants with 1%, 4%, 7%, and 10% coolant contamination. From the results obtained, the following conclusion can be drawn:

- Developed object shape-based optical analysis methodology is a novel approach for analysis of a synergetic effect of combined lubricant-object optical appearance. It opens up new opportunities for on-line monitoring, diagnostics and control of engine lubricant condition and engine performance.
- Developed methodology was verified experimentally showing the ability to distinguish lubricants with 1%, 4%, 7%, and 10% coolant contamination with respect to fresh lubricant. This proves that object shape introduced into

lubricant is susceptible and sensitive to the changes of optical properties of lubricant. Methodology can be also applied for analysis of different contaminants and lubricants.

- Developed approach ties together color- and width-related object shape parameters, although color-related parameters are more sensitive to introduction of coolant into the engine lubricant than width-related parameters.
- Future use of the developed methodology will be focused on detailed analysis of the effect of specific contaminants and as well as combined effect of different contaminants on lubricant optical properties and condition.

ACKNOWLEDGMENT

This paper is the result of collaboration between The University of Western Ontario, Ontario, Canada and NRC-IMI-CAMM, London, Ontario, Canada. The author thanks Hugo Reshef, Marco Zeman, Mike Meinert, Suwas Nikumb and Sylvain Pelletier for their continued technical and partial financial support in this work. The financial support was also provided in part by Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

- [1] J. Marek, H.-P. Trah, Y. Suzuki, and I. Yokomori (editors), *Sensors for Automotive Technology*. WILEY VCH Verlag GmbH & KGaA, Weinheim, 2003.
- [2] S. Prosser, "Automotive sensors: past, present and future," *Journal of Physics: Conference series*, 2007, vol. 76, paper # 012001, 6 p.
- [3] W. Fleming, "New automotive sensors - a review," *IEEE Sensors Journal*, 2008, vol. 8(11), pp.1900-21.
- [4] A. Agoston, C. Ötsch, and B. Jakoby, "Application of microacoustic viscosity sensors for online oil condition monitoring," *VDI Berichte*, 2004, vol. 1829, pp. 833-6.
- [5] B. Jakoby, H. Eisenschmid, and O. Schatz, "On-Board evaluation of engine oil using physical sensors," *VDI-Berichte*, 2001, vol. 1646, pp. 699-707.
- [6] B. Jakoby, M. Scherer, M. Buskies, and H. Eisenschmid, "An automotive engine oil viscosity sensor," *IEEE Sensors journal*, vol. 3(5), pp. 562-8.
- [7] S.-I. Moon, K.-K. Paek, Y.-H. Lee, J.-K. Kim, S.-W. Kim, and B.-K. Jua, "Multiwall Carbon nanotube sensor for monitoring engine oil degradation," *Electrochemical and Solid-State Letters*, 2006, vol. 9(8), pp. H78-H80.
- [8] S. Wang and H.-S. Lee, 1997 "The application of a.c. impedance technique for detecting glycol contamination in engine oil," *Sensors and Actuators B*, vol. 40, pp.193-7.
- [9] D. Na, S. Kim, and S. Park, "Capacitive microsensor for monitoring the deterioration of automobile engine oil," *Proceedings of SPIE*, 2002, vol. 4936, pp. 387-93.
- [10] S. Kumar and P.S. Mukherjee, "Online condition monitoring of engine oil," *Industrial Lubrication and Tribology*, 2005, vol. 57(6), pp. 260-7.
- [11] A. Gastón, I. Lozano, and J. Sevilla, "A novel approach to on line oil quality sensing through side-polished optical fiber," *IMTC 2006 – Instrumentation and Measurement Technology Conference*, Sorrento, Italy, April 24-27, 2006, pp. 2066-9.
- [12] J. W. Goodman, *Statistical Optics*. John Wiley and sons, New York, 2000.