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Object shape-based optical sensing methodology and system for condition monitoring of contaminated engine lubricants

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ABSTRACT

Presence of contaminants, such as gasoline, moisture, and coolant in the engine lubricant indicates mechanical failure within the engine and significantly reduces lubricant quality. This paper describes a novel sensing system, its methodology and experimental verifications for analysis of the presence of contaminants in the engine lubricants. The sensing methodology is based on the statistical shape analysis methodology utilizing optical analysis of the distortion effect when an object image is obtained through a thin random optical medium. The novelty of the proposed sensing system lies within the employed methodology which an object with a known periodic shape is introduced behind a thin film of the contaminated lubricant. In this case, an acquired image represents a combined lubricant–object optical appearance, where an *a priori* known periodical structure of the object is distorted by a contaminated lubricant. The object, e.g. a stainless steel woven wire cloth with a mesh size of $65 \times 65\ \mu m^2$ and a circular wire diameter of 33 μm was placed behind a microfluidic channel, containing engine lubricant and optical images of flowing lubricant with stationary object were acquired and analyzed. 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, gasoline and water contamination individually and in a combination form of coolant (0%–5%) and gasoline (0%–5%).

1. Introduction

The function of engine lubrication system is to reduce friction and wear, dissipate heat and energy, prevent corrosion, control contamination, ensure engine internal cleanliness, and reduce the environmental impact. Within the last decade, on-line condition monitoring of automotive fluids and lubricants has gained substantial interest. Environmental and safety regulations are the principle drivers in increasing the demand for automotive monitoring systems.

The current trends in the automotive industry indicate that engine lubricant condition monitoring through the direct and indirect measurements of the engine lubricant properties is highly desirable [1]. Developments in novel lubricant sensors has shifted from “quantity-based” to “quality-based” approach focusing mainly on oil condition monitoring through 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. In a study by Jakoby et al. [4] analyzed the kinematic viscosity using parameters that were measured using a microacoustic viscosity sensor. The sensor utilizes bulk and surface waves which are due to a liquid load cause a change in resonance characteristics, e.g. resonance frequency and damping of the oscillations. These characteristics were used for calculations of a viscosity value for fresh and used oil samples.

Change in engine lubricant electro-magnetic property of engine lubricant is the results of organic compounds partially exposed to oxygen in high temperature and pressures. There are a wide variety of by-products 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

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engine lubricant condition. Wang et al. [5] have detected a glycol contamination in the engine lubricant by studying the a.c. impedance within a wide range of frequencies. It was found that the bulk-layer resistance declines abruptly as the glycol concentration increased from 50 ppm to 150 ppm and a glycol leakage can be detected at the early stages. A capacitive sensor was proposed by Na et al. [6] and it was used to monitor the deterioration of automobile engine lubricant by measuring changes in the permittivity. It was observed that the sensor capacitance was typically increased at about 3% per 1000 km. Turner and Austin [7] have studied the changes to the dielectric and magnetic properties of the lubrication oil due to its degradation. It was concluded that a simple distance traveled is not a good indicator of the state of oil, as estimated by measuring its viscosity. The magnetic characteristics of lubricating oil (i.e. its magnetic permeability) are changing as the oil degrades, but the measurements were poorly correlated with viscosity values. In contrast, the dielectric properties of lubricating oil were reasonably well correlated with viscosity and therefore they can be effectively applicable for developing an on-line monitoring system.

Optical methodologies offer a very precise and accurate approach to monitor lubricant conditions. During the degradation process of engine lubricant, its optical properties, e.g. color, transparency, refractive index, absorbance, *etc* change significantly. Measuring the changes in the optical properties and correlating them to the actual quality of the lubricant allows monitoring the engine and lubricant condition. Kumar et al. [8] studied the use of a 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 a correlation between sensor output and lubricant optical condition was found. Yin et al. [9] proposed an on-line monitoring system for analyzing wear particles in diesel engine lubricant. This research work has combined an inductive transducer to detect large ferrous and non-ferrous wear debris with a fiber optic transducer to monitor the presence of small particles and contaminant levels.

It is also necessary to address the recent developments in spectroscopic methods for monitoring of oil quality. Parvin et al. [10] have introduced a UV laser spectroscopic rapid diagnostic technique to detect the transformer malfunctions. In particular, simultaneous laser induced fluorescence and laser induced breakdown spectroscopy are used for hyper sensitive identification of the oil degradation. The spectroscopic characteristics of oil in paper substrate were obtained due to ArF laser irradiation. It was shown that the amplitude of fluorescence signal increases when the oil suffers aging and degradation. A new fluorescence emission measurement technology was introduced by Wicaksono et al. [11] and it was experimentally compared with other measurement methods, such as the titration method and IR spectroscopy. Method was validated for the oil oxidation measurement of electrical insulating oil. It was found that by using a fluorescence emission ratio the oxidation of oil can be detected relatively earlier than by other methods.

Surface plasmon resonance (SPR) measurement is an effective optical technique widely used for dynamical analysis of molecular affinity and drug screening due to its high sensitivity to the change of the refractive index of tested objects including liquid media [12,13]. In a recent study Aghayan et al. [14,15] analyzed the changes in the optical properties of engine lubricant as a liquid medium caused by the introduction of contaminants, which were measured using an SPR sensor and the SPR characteristics (optical reflectance vs angle of incidence). SPR phenomenon was described as a transfer function changing the amplitude and the phase angle of the incoming light wave. The parameters of the SPR characteristic, minimum reflectivity at resonance angle, of engine lubricant contaminated by coolant with a concentration of 1%–10% were analyzed experimentally.

Despite the fact that engine lubricant monitoring systems based in the optical properties are precise and accurate, they are not fully explored and implemented as yet [16]. In this work, development of a sensing system based on the object shape-based optical analysis method for the analysis of the contaminated engine lubricants has been proposed. The sensing methodology is based on the measurement and comparison of a set of parameters which defines the true shape of a deterministic object placed behind a thin layer of lubricant with random properties. Comparison between the extracted parameters from fresh and contaminated object–lubricant images leads to estimate and monitor the presence of contaminates in the lubricant. This approach also benefits from the theory of effect of random medium (e.g. engine lubricant) on the image quality to explain the evolution of the object caused by the random medium. A potential applicability of the developed sensing system for on-line monitoring and control of the engine lubricant condition is experimentally verified for 0%, 1%, 4%, 7%, and 10% concentrated coolant, gasoline and contaminants. Also, to extend the efficiency of this sensing method, a combined mixture of coolant (0–5%) and gasoline (0–5%) was added to the fresh lubricant and the change in the lubricant statistical optical properties was studied.

2. Object shape based optical sensing methodology

The field of statistical shape analysis involves methods for studying the geometrical properties of random objects invariant under translation, scaling and rotation [16,17]. It is often extremely useful to measure, compare and categorize the shape of objects in a wide variety of disciplines, ranging from code recognition to medicine, archeology, and geology.

The main goal of shape analysis is the description of the mean shape of a random object and the analysis of its stochastic fluctuation. Shape analysis studies how shape changes during growth, or during evolution. This is achieved by bringing the set of shape into a frame of reference and then describing variation within the frame. Statistical–geometrical techniques are employed to study and describe the patterns of change in a shape. Applications of shape analysis are indeed concentrated in the fields of biology, geology and medicine, however, the theory and techniques can be applied to appropriate configuration matrices regardless of the discipline from which they arise.

In classical shape analysis method, the focus is to study the geometrical properties of a random object invariant under translation, scaling and rotation despite of the context which the shape is embedded in. In the proposed methodology in this study, the goal is to study the geometrical properties of a deterministic object under evolution and its embedded context or medium. The embedded context or the medium which surrounds the shape is considered to be random and responsible for the evolution of the shape. In this condition, the changes in the medium directly influence the object's geometrical properties and study the pattern of change in the shape and comparing to the geometrical properties of the deterministic object enables to monitor and identify the variation in the medium.

In this case, since variation in the medium is the cause for the shape revolution, a close emphasize is needed to be put on the study of medium as well. From optical point of view, the distortion and disfiguration of the shape caused by the random medium can be studied by the theory of imaging in presence of randomly inhomogeneous medium [18,19]. In such an approach, when an object is placed behind a thin film of a random medium (e.g. contaminated lubricant) and an object image I_{OOI} obtained, the obtained object image is distorted by the medium acting as a distortion operator h. In this case, quality of the distorted object image I_{DOI} (DOI) will mainly depend on the actual condition of the lubricant. In this circumstance, only a distorted image I_{DOI} instead