Viscosity Monitoring Using a Solid-State Sensor

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Introduction

Lubricants are essential in maintaining the condition of fixed or mobile assets. Any degradation in the lubricant's properties impairs its ability to protect the equipments' dynamic components. By having the ability to monitor oil condition real-time and on equipment, the user can change the oil at the optimum schedule and when unexpected contaminants are detected.

Contaminated oil can degrade and corrode dynamic gearbox components. Thus, oil changing timing becomes critical as left unchecked degraded oil can damage critical parts the longer it remains in the equipment. Contamination of oil can also cause seals to expand and develop fire hazards.

Currently, to ascertain an asset's comprehensive operating oil condition, manufacturing personnel must send a sample to an oil analysis laboratory. Depending on the distance the laboratory is from the manufacturing plant the process can take several days. Conversely, an on-line oil monitoring system will produce results instantaneously, not days. In a scenario when contaminants are found in the oil by the lab, maintenance personnel at the plant must flush the system, change the oil, take a sample, and send it to the lab for analysis. If the lab determines the oil's condition is still unacceptable, the maintenance personnel are required to repeat the above course of action until the oil meets specifications. Such an operation can potentially consume weeks, while having the oil analysis on the asset itself potentially reduces the process to no more than the time it takes to flush and change the oil for this iterative process.

Measuring the viscosity of oil is a rapid method of determining oil condition, and is considered an important parameter in assessing asset readiness. Conventional mechanical and electro-mechanical viscometers designed primarily for laboratory measurements are difficult to integrate into the control and monitoring environment. As a consequence, many companies rely on decisions based on intermittent "snapshot" data acquired from periodic sampling where conventional instrumentation can be affected by temperature, shear rate and other variables.

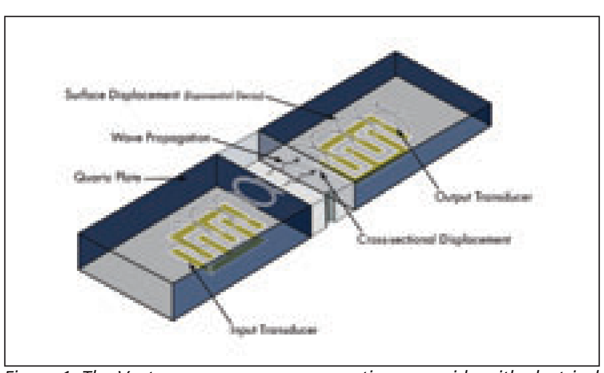

Figure 1. The Vectron sensor uses an acoustic waveguide with electrical transducers on one surface and being in contact with the fluid on the other surface.

Acoustic wave (AW) sensors offer a number of advantages over conventional mechanical and electromechanical viscometers as they are small solid-state devices that can be completely immersed in the oil providing an instantaneous viscosity data stream for embedded OEM or end-user spot-check applications. The sensors are unaffected by shock or vibration or by flow conditions so they can be used in harsh operating conditions with a temperature range of -25˚C to 125˚C with a high degree of accuracy. At the same time, sensor measurements are not affected by particulates in the oil.

The viscosity sensor which can compliment IR spectroscopy and other bulk property sensors can provide instantaneous on-line viscosity and temperature data and offers universal plug-n-play connectivity for integration to control platforms. The sensors have been tested in actual commercial specified oils in order for a correlation function to be established between the ASTM methods acquired dataset and the sensor generated viscosity values; these correlation functions can be stored on any handheld for automatic conversion. The viscosity sensor is currently installed in commercial markets applications in rigorous environments where ROI benefits have been realized, and are now been evaluated for mobile and fixed assets where oil condition monitoring is of paramount importance.

Figure 2. Vectron threaded bolt solid-state ViSmart™ sensor.

The function of oil is to enable a mechanism to transfer heat from moving components, protect the various parts of the asset from external contaminants and provide a hydrodynamic layer for smooth operation. Given that the degradation of viscosity is an important indicator of these characteristics, it important to not just rely on snapshot data. For the proper operation of machinery, the viscosity of the oil has to be kept to the specifications determined by the manufacturer and plant personnel relevant to the operating conditions of the equipment. Knowledge of viscosity in real time provide a significant benefit to measure aging of oil, ingress of contaminants during commercial operations and prevent incipient mechanical failure due to loss of oil lubrication properties.

This article shows a next generation sensor that is packaged as a in-line real-time threaded bolt solution (Figure 2) that is targeted at embedded integration to fixed and mobile equipment. Also presented will be data from a customer that has tested the next generation sensor on three specific oils for application into industrial gearboxes. The data has been correlated to lab measurements by this and other customers thereby resulting in viscosity data which bridges the traditional dataset to the new methods of measurement.

Technology

Vectron, a designer and and manufacturer of acoustic wave (AW) based sensor products, has developed a unique method to offer a viscosity sensor with a wide dynamic range (air to several thousand cP) in a single sensor (Figure 1).

Acoustic wave devices have played an important role in consumer and communication systems over the last 50 years due to their high performance, small size and high reproducibility. The telecommunications industry is the largest user of acoustic wave devices including filters in mobile cell phones and base stations. These are typically surface acoustic wave (SAW) devices and function as band-pass filters in both the radio frequency and intermediate frequency sections of the transceiver electronics.

Acoustic wave technology also lends itself very well to sensing applications. This emerging market holds the potential of equaling, and even exceeding the demand of the telecommunications market, across multiple application sectors. Applications include automotive applications (tire pressure and oil condition monitoring sensors) and industrial and commercial applications (temperature, chemical/gas sensors). Acoustic wave sensors are competitively priced due to mature manufacturing methodologies, inherently rugged because of the implementation of advanced packaging techniques and very sensitive and intrinsically reliable given the inherent design principles. Further, they are complemented by additional functionalities such as low or no power requirements and the ability to communicate wirelessly through use of RF interrogation.(no sensor power source required).

The shear horizontal acoustic plate mode (SH-APM) device combines the best properties of both the BAW (bulk acoustic wave) and SAW (surface acoustic wave) devices. It employs separate input and output transducers in order to allow differential signal measurements like the SAW structures but also allows the sensor crystal to be employed as a physical barrier between the electronics and the sensing medium.

The wave is a waveguide mode with energy throughout the bulk of the crystal and is dependent on the thickness of the substrate. Like all the previous surface launched acoustic wave devices, the SH-APM device uses input and output IDTs to launch and receive the acoustic wave. Similar to the BAW thickness shear mode device, the maximum displacements occur on the top and bottom surfaces of the plate. Similar to the STW and Love Mode devices, the surface displacement is shear and in the plane of the plate so it can be used for liquid-based applications. The waveguide modes have energy distributed between the two surfaces as a standing wave as in the BAW sensor but traveling along the surface as in a SAW. The continuous exchange of energy between the two surfaces allows the signal between the IDTs to be influenced by changes on the opposite surface.

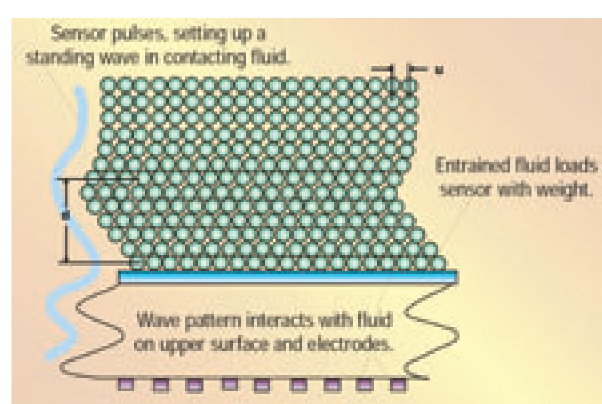

Figure 3. Cross section of the sensor showing transducers on the lower surface and liquid molecules (gold balls) on the upper surface.

Since the wave interacts with both surfaces of the plate, either surface can be used as the sensing surface. For liquid sensing applications and for corrosive or explosive gases, this is a great advantage over the STW (shear transverse mode) and Love Mode device because you can isolate the sensing medium from the electrodes by making the bottom surface of the SH-APM device the sensing surface.

The Vectron ViSmart™ is a commercially available, robust, reliable and cost-effective surface acoustic wave solid-state viscometer for integration into in-line, real-time monitoring and process control systems for scalable applications via a threaded interface design (Figure 2).

The sensor has no moving parts (other than the atomic scale vibration of the surface) and, due to the high frequency of the vibration, several millions of vibrations per second, is independent of flow conditions of the liquid and immune to vibration effects of the environment. High temperature electronics are utilized that allow a very wide operating temperature range for the sensor.

The importance of these acoustic sensors lies in the distinctly different measurement principle. Whereas one class of mechanical devices measures kinematic (flow) viscosity and the other class measures intrinsic (friction) viscosity, the acoustic wave (AW) sensors measure acoustic impedance, (ωρη)1/2, where ω is the radian frequency (2πf), ρ is the density and η is the intrinsic viscosity.

The viscosity measurement is made by placing the quartz crystal wave resonator in contact with liquid. The liquid's viscosity determines the thickness of the fluid hydro-dynamically coupled to the surface of the sensor. The sensor surface is in uniform motion at frequency, ω =2πf, with amplitude, U. The frequency is known by design and amplitude is determined by the power level of the electrical signal applied to the sensor. As the shear wave penetrates into the adjacent fluid to a depth, d, determined by the frequency, viscosity and density of the liquid as d=(2η/ωρ)1/2, as depicted in Figure 3.

Acoustic viscosity is calculated using power loss from the quartz resonator into the fluid. The unit of measure is acoustic viscosity (AV) and is equal to ρη, (g/cm3 • cP) (density times dynamic viscosity).

The acoustic wave resonator supports a standing wave through its thickness. The wave pattern interacts with electrodes on the lower surface (hermetically sealed from the liquid) and interacts with the fluid on the upper surface. The bulk of the liquid is unaffected by the acoustic signal and a thin layer (on the order of microns or micro inches) is moved by the vibrating surface. Also present is a proprietary hard coat surface that is scratch proof and abrasion resistant which allows the sensor to be operable in extreme environments and enabling AW sensor to be a suitable candidate for oil condition based monitoring applications in mobile and fixed asset markets.

Testing for the Evaluation of the Oils

Significant testing as been accomplished by a commercial customer in order to ascertain the performance for the solid-state viscometer. The tested oils are Mobil SHC XMP 320, Kluber GH 6-220 and Aral Degol BG 68 and represent a wide variety of viscosity values and lubrication characteristics. The viscosity values for the oils are measured at ASTM approved rheometer equipment (at 512 1/s shear rate) and with the solid-state sensor over a temperature range from 20 to 100 °C. Based on this data, functions are generated to interpolate the viscosity for intermediate temperatures.

Mobil SHC XMP 320

Temperature (Centigrade)	Acoustic Viscosity (Vectron Sensor)	Kinematic Viscosity (Vectron Sensor)	Kinematic Viscosity (Laboratory Data)
30	172.15	155.45145	
40	100.6	90.8418	325.63
50	66.5	60.0495	
60	47.77	43.13631	
70	35.31	31.86493	
80	26.13	23.59539	
90	20.61	18.61063	
100	16.4	14.8092	36.72

Figure 7. A chart demonstrating the methodology of creating a correlation function

The goals of the customer testing are two-fold: First, to observe the performance of the sensor over a temperature and validate that the sensor can differentiate between the oil types and be able to track the change of viscosity over temperature. And second, to verify if the sensor can provide the same data as from a lab instrument via the implementation of a correlation function.

The Vectron low shear solid-state viscosity sensor measures the acoustic viscosity (AV), which is the product of dynamic viscosity and mass density. Dynamic or kinematic viscosity is more commonly used in industry. The goal by customers is to establish correlation between acoustic viscosity and dynamic viscosity.

Correlation with All Oil Samples

The change of viscosity as a function of temperature for the three oils is presented below. It important to keep in mind that Mobil SHC XMP 320 is a synthetic gear oil, Kluber GH 6-220 is a synthetic gear oil for spur, worm and planetary gears, and Aral Degol BG 68 is a zinc-free, closed loop transmissions (CLP) type gear oil.

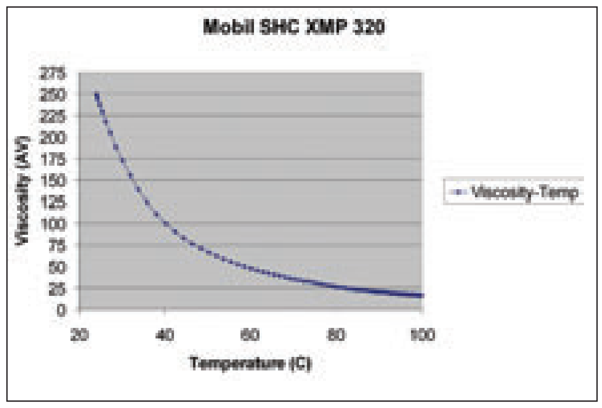

Figure 4. Viscosity-temperature data for Mobil SHC XMP 320

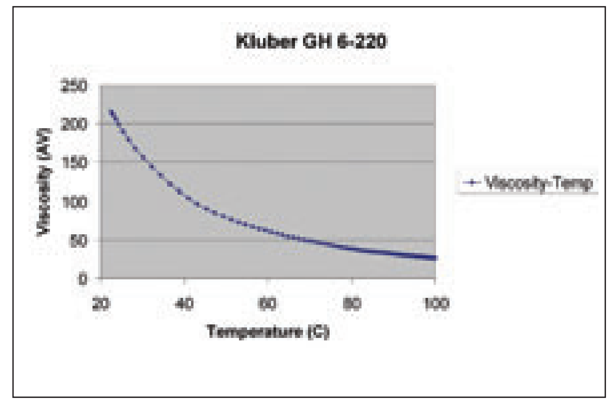

Figure 5. Viscosity-temperature data for Kluber GH 6-220

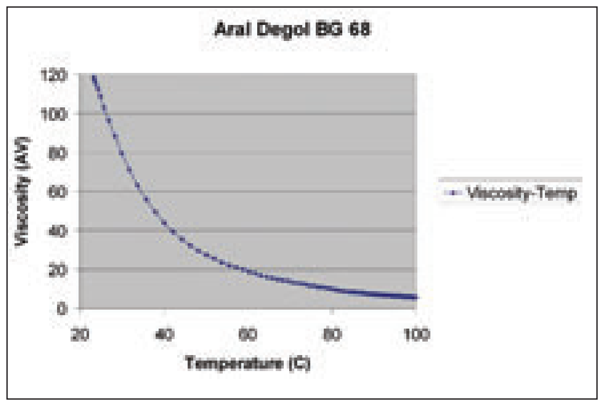

Figure 6. Viscosity-temperature data for Aral Degol 68

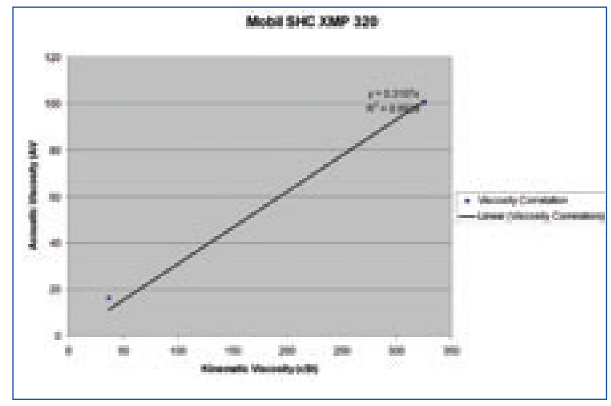

Figure 8. Correlation of solid-state sensor to lab data for Mobil SHC XMP 320

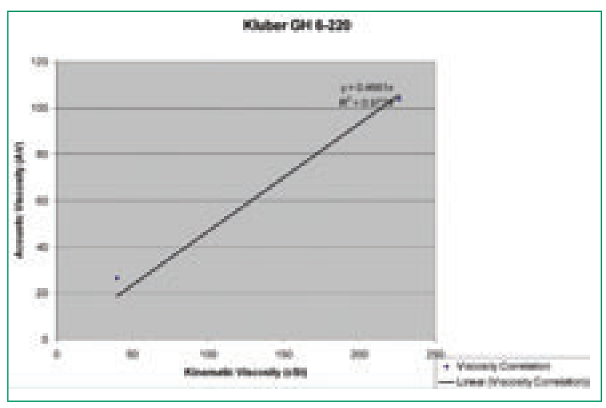

Figure 9. Correlation of solid-state sensor to lab data for Kluber GH 6-220

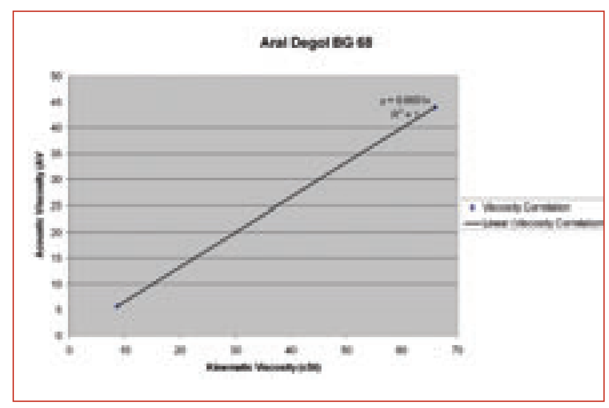

Figure 10. Correlation of solid-state sensor to lab data for Aral Degol BG 68

It is seen that the sensor can track the viscosity change as a function of temperature and can also differentiate between the sensors. This performance characteristic clearly demonstrates that solid-state viscometers can operate in the environments and be an important tool for the industry in its efforts to bring oil condition monitoring online for real-time decision making.

In order to create the correlation function, a simple methodology can be employed as shown in the table below. The key to the methodology is:

1. Acquiring the lab instrument data for the viscosity (and density) for the oil either via the manufacturers specification sheet, or by independent testing (needs to be done only once).
2. Converting the native measurements acoustic viscosity for the solid-state sensor to kinematic viscosity with the relationship noted above.
3. Plotting the lab and solid-state sensor kinematic viscosity value and observed the accuracy of fit.

The results for the three oils are demonstrated below. As seen the R-squared value for the oils indicates an accuracy level of 97% or better.

Employing the correlation function in a database that can be embedded into any host control platform, manufacturing personnel can track the performance of the oil as a function of it's viscosity value and take care preventative or corrective action as deemed necessary.

It is also important to note that correlation functions do not need to be created for scenarios where a given relative shift from an established baseline value is deemed acceptable for purposes of conducting oil condition monitoring activities.

If Vectron does not have any information about oil type, commercial testing has shown that will global correlation functions that are specific to the families of oils, functions with correlation R-squared values of 0.9107 and better can be created.

Conclusions

The conclusions that can be drawn from the data above and the customer testing are:

1. There is correlation between lab method and Vectron viscosity sensor for each oil (or group of oil), and that a library of "fresh oil" correlations is practical.
2. The Vectron ViSmart™ viscosity sensors operate at repeatable shear rates that are relevant to the assets being lubricated under normal operating conditions.
3. The ViSmart™ sensors offer acceptable correlation to lab measurements at these shear rates.
4. The correlation created from virgin oil provides the reference points from which changes in viscosity due to aging and contamination of the oil can be easily determined.
5. Deviations of the oil from a predefined interpolation function at any temperature is a significant means of screening oil quality and is more accurate than "compensating" to 40°C.
6. Evaluating deviations in "acoustic viscosity" is of comparable value to using kinematic viscosity. That is, independent and accurate knowledge of density is only important for correlation between on-site sensor testing and lab data.

Benefits

The viscosity sensor can indeed provide a measurement of the resistance of the lubricant to flow. Changes in viscosity level indicate contamination by having the incorrect oil, fuel or oxidation by-products.

Keeping in mind that solid-state viscometers leverage standard semiconductor manufacturing processes, the results are commercially available products that are robust and reliable, high quality to yield repeatable products and scalable for embedded applications where cost, functionality and space limitations are paramount considerations. With these benefit, solid-state viscometers are an additional tool the industry can utilize in addressing end-customer needs. Such efforts yield the addition of value-added features that extend the life cycle of the components and equipment and increase operational efficiency for the industry at large.