Wear evaluation methods for friction units of aircraft GTE oil systems: the on-line methods

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Abstract. On-line sensors based on optical, ultrasonic, electostatic and inductive principles are evaluated for use in determination of wear in oil systems of aircraft GTEs. This application is limited due to contraints of the high oil flow rate (40 – 60 L/min) and the flow diameter of 20-25 mm. Under such conditions, most sensors are unable to function efficiently and give incorrect readings. As such, creating on-line wear evaluation systems remains hardware-limited. Decrease of detection limit of non-ferrious particles for inductive type sensors is a possible way to solve the issue.

1. Introduction

Quantifying particles that are suspended in working oil can be useful for determining excessive wear of friction pairs that generated them, prevent further damage and thus reduce maintenance costs. However, in complex systems such as gas-turbine engine (GTE) oil systems there are many friction pairs, each generating normal wear particles, therefore simply measuring the particle content is insufficient to determine whether the wear of a system or a particular friction pair is excessive. As such, the source of each particle must also be localized.

In lab-based approach, this can be done by analysis of the elemental composition of the wear particles. If a material can be identified from analysis, it can be traced to a number of friction pairs that are made of the same material. Thus, most successful lab-based approaches to wear evaluation of complex tribo-systems consist of sensitive spectral equipment.

On-line wear sensors are a subject to rising interest of aircraft operators through last couple decades. Compared to lab-based methods, sensors require less maintenance costs due to no sampling, analysis or delays.

The problem is element-sensing equipment is currently bulky and can’t be used as an on-line sensor [1]. However, similar effect can be potentially achieved if multiple particle sensors are installed throughout the system (figure 1).

In the figure, cogs represent friction pairs that come in contact with a particular flow area and cameras represent sensors. Cog 1 generates the particle, which is detected by sensor 1. Cog 2 generates the second particle. Both particles are captured by the filter. If sensor 2 has readings from sensor 1, it would be able to differentiate the number of particles that came from cog 2 and thus excessive wear can be localized to within those areas.
2. Sensor types
On-line sensors differentiate mainly by underlying principle by which a particle is detected.

1. In optical [1-3] sensors, oil-particle flow is illuminated by a light source and registered by a photosensitive element or image sensor (figure 2). Particles are detected by either light intensity decrease or by image analysis. As such, size and particle quantity can be evaluated.

2. The general layout of ultrasonic sensors [4-6] is similar to the optical sensor layout. The difference is that the acoustic source and the detector are used instead of light-based counterparts.

The sensor readings are a subject to oil cleanliness, flow diameter and rate, excessive particle counts and presence of extraneous elements such as air or water bubbles. In small flows (1.2 x 1.6 mm, flow rate up to 1 liter per minute, L/min) particles 5 μm or above can be detected [1]. Oil flows in GTEs, however, can reach diameters of 20-25 mm and flow rates of 40 – 60 L/min. In these conditions, most particles are out of focus and cannot be reliably detected. To counter this, the common technique is to introduce microflow – a separate flow of lesser diameter with controllable oil flow rate. In this case, however, only a slight fraction of total particle count is detected which makes multi-sensor correction, and therefore, wear localization – impossible. This is because wear particle, generated by oil system controlled by one sensor can be ignored by it and detected by another sensor and vice-versa.

These circumstances limit the usefulness of optical sensor for GTE oil system wear control [1].
The size and particle quantity can be measured [5]. In hydraulic or oil systems, particles from 30 μm to 1000 μm can be detected [7]. Oil, air bubbles and metallic particles can be detected separately [8]. Work [4] shows that metallic particles with size of 75 μm or larger can be detected in flow with a rate of 400 μL/min and a diameter of 6.5 mm.

The ultrasonic equipment can be a useful tool for detecting excessive engine vibration. As an online sensor though, the application is limited due to dependency of the sensor reading on oil viscosity, speed, low throughput and mechanical vibration interference [1].

3. Wear particles accumulate charge through friction. This phenomenon is a base for the electrostatic sensor that represents a conductor put in controllable medium (oil).

Initially, sensors of this type were developed for control of the engine gas flow [9]. Then, potential application of electrostatic sensors in oil systems was shown using gear and bearing test machines [10], including roller bearing of the F100 jet engine [11]. One outstanding feature of electrostatic sensors is the ability to detect non-metallic particles, which is important for wear control of plastic and ceramic bearings. The material of the particle itself cannot be determined, though.

The sensor allows one to quantify particles of 20-50 μm in flows of 7 to 9 L/min using test machines [12]. An electrostatic sensor was able to detect roller bearing failure 18 hours before critical failure [11] in overload (200% nominal load) conditions and flow rate of 4 L/min.

In complex tribo-systems, such as the GTE oil system, however, the device did not receive industrial use. This is due to the issue with identifying charge sources and mechanisms in such systems [13].

4. The inductive sensors received most use in aircraft industry [14-16]. The ferrous and non-ferrous particles can be detected by fluctuation in the electromagnetic field of a coil when the particle passes through it.

The GasTOPS company has developed the MetalSCAN sensor which employs three coils, placed sequentially through the oil flow (figure 3) [14].

![Figure 3. MetalSCAN sensor layout](image)

Side coils are connected to AC source and their electromagnetic field is mutually compensated in the centre. When particle passes through, central coil detects field fluctuation of each coil.Signals from ferrous and non-ferrous particles can be differentiated by signal phase [14].

The sensor can determine size, mass of ferromagnetic particle larger than 125 μm, and non-ferrous of 1000 μm in a flow of 0.5 inch (12.7 mm) in diameter and rate of 3.7 L/min (1 Gallon/min). For a flow of 25 mm, minimal diameterr of ferromagnetic spherical particle is 275 μm. For a particle of irregular shape, detection limit is 180 μm (of equivalent spherical particle) [16].

The QDM® sensor counter consists of a single coil and a magnet for particle capture, which ensures the ability to extract particles and execute further analysis [17, 18]. The sensor can count particles in sizes ranging from 400 to 600 μm [19].
Most (>90%) metallic particles in the oil system are in a size range of 10 to 100 μm. But even engines that exhibit normal wear can generate particles 300 μm and above, therefore excessive wear potentially can be detected by QDM and MetalSCAN. High detection limit for ferrous particles makes the sensor blind to wear modes which do not generate particles of big sizes (fatigue). But in Russian aircraft, fatigue wear is rare compared to other wear modes.

Detection limit of non-ferrous particles of 1000 μm makes that feature almost entirely irrelevant, since particles of this size almost exclusively are a product of catastrophic failure.

The error in determining mass of specific particle for this type of sensors can reach 370%; size – up to 170%. This is because a signal from a particle depends on particle shape, trajectory and orientation [20]. Size detection error makes it harder to determine excessive wear by analysis of change in size distribution function.

The detection limit is proportional to flow size and speed. In extremely low flows (3 μL/min, 1 mm), 5 μm ferromagnetic particles can be detected [21]. To increase throughput, multiple sensing channels can be used. As such, using 3x3 sensing array can increase sensor throughput to 460 μL/min [22].

Using permanent magnets instead of coils can decrease detection limit due to higher density of the magnetic field. Device that uses permanent magnets [23] allows one to register ferromagnetic particles 83 μm or larger in flow of 20 L/min with diameter of 12 mm.

For MetalSCAN sensor, changing flow diameter from 7.6 mm to 26.9 mm (3.5 times), detection limit increases from 100 μm to 275 μm (2.75 times) [16]. Assuming the same would be true for permanent magnet sensor, the detection limit for 25 mm flow diameter can be evaluated as 170 to 250 μm i.e., 2-3 times bigger than detection limit for 12 mm flow.

Capabilities of QDM and MetalSCAN were tested in work [19]. Both were simultaneously installed on oil system test machine. Next, ferromagnetic particles of irregular shapes were introduced to the system. The size ranges of the particles were 850-1180 μm, 425-600 μm, 150-500 μm, 10 mg each, which amounted to tens of particles. The tests were repeated 10 times. Flow rate was 60 L/min, diameter – ½ inches (12.7 mm). Both sensors (QDM and MetalSCAN) were detecting 60-70% of particles in their nominal detection limits (250-1000 μm for MetalSCAN, 400-600 μm for QDM). This holds true even for larger particles (600-1000 μm).

This is a major issue, since detecting only a fraction of particles, as was noted above, breaks multisensor reading correction and wear localization. Also, accumulated mass will be measured with significant error.

Preliminary tests at UEC “Aviadvigatel” were performed to assess viability of MetalSCAN sensor as wear control device for new generation GTEs [24]. Tests were performed on engine test machines, equipped both with multiple MetalSCAN sensors and standard wear control equipment, such as filter-signalers, flak-signalers and particle detectors. At best, MetalSCAN sensors allowed one to detect impending failure 10 minutes before standard equipment would [25]. As such, currently there is no significant advantages to prefer MetalSCAN over widely available, much older equipment.

3. Conclusion

Despite more than thirty years of development of integrated on-line sensors, the application of sensors for wear evaluation of friction pairs in the aircraft gas turbine engine oil systems remains severely limited. The limitation is attributed to harsh environment that is oil system of GTE, which exhibits big flow diameters (25 mm) and flow-rates (40-60 L/min). Most sensors are unable to function efficiently under these constraints.

For inductive (or other type) sensors one major step to the solution of the problem could be increasing the fraction of detected particles up to 95-99%, making mutual correction of readings of multiple sensors less prone to error.

Another step would be to determine material of the particle, at least roughly. This would allow one to trace source of the particles in a way, used by lab-based methods and can be achieved by decreasing detection limit of non-ferrous 300 μm particles for inductive sensors.
Until at least those problems are solved, lab-based methods remain as the most reliable means for wear evaluation of GTE oil system friction pairs.

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