



Designation: D7685 – 11 (Reapproved 2022)

Standard Practice for In-Line, Full Flow, Inductive Sensor for Ferromagnetic and Non-ferromagnetic Wear Debris Determination and Diagnostics for Aero-Derivative and Aircraft Gas Turbine Engine Bearings¹

This standard is issued under the fixed designation D7685; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

In-line wear debris sensors have been in operation since the early 1990s. There are now thousands of these devices operating in a wide variety of machinery applications accruing millions of operational hours. Wear debris sensors provide early warning for the abnormal conditions that lead to failure. Improved machine reliability is possible due to the enhanced sensor data granularity, which provides better diagnostics and prognostics of tribological problems from the initiating event through failure.

1. Scope

1.1 This practice covers the minimum requirements for an in-line, non-intrusive, through-flow oil debris monitoring system that monitors ferromagnetic and non-ferromagnetic metallic wear debris from both industrial aero-derivative and aircraft gas turbine engine bearings. Gas turbine engines are rotating machines fitted with high-speed ball and roller bearings that can be the cause of failure modes with high secondary damage potential. (1)²

1.2 Metallic wear debris considered in this practice range in size from 120 μm (micron) and greater. Metallic wear debris over 1000 μm are sized as over 1000 μm .

1.3 This practice is suitable for use with the following lubricants: polyol esters, phosphate esters, petroleum industrial gear oils and petroleum crankcase oils.

1.4 This practice is for metallic wear debris detection, not cleanliness.

1.5 The values stated in SI units are to be regarded as standard. The values given in parentheses are provided for information only.

¹ This practice is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants and is the direct responsibility of Subcommittee D02.96.07 on Integrated Testers, Instrumentation Techniques for In-Service Lubricants.

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² The boldface numbers in parentheses refer to a list of references at the end of this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *condition monitoring, n*—field of technical activity in which selected physical parameters associated with an operating machine are periodically or continuously sensed, measured and recorded for the interim purpose of reducing, analyzing, comparing and displaying the data and information so obtained and for the ultimate purpose of using interim result to support decisions related to the operation and maintenance of the machine. (2)

2.1.2 *control unit, n*—electronic controller assembly, which processes the raw signal from the sensor and extracts information about the size and type of the metallic debris detected.

2.1.2.1 *Discussion*—A computer(s), accessories, and data link equipment that an operator uses to control, communicate and receive data and information.

2.1.3 *full flow sensor, n*—monitoring device that installs in-line with the lubrication system and is capable of allowing

the full flow of the lubrication fluid to travel through the sensor. Also referred to as a through-flow sensor.

2.1.4 *inductive debris sensor, n*—device that creates an electromagnetic field as a medium to permit the detection and measurement of metallic wear debris via permeability for ferromagnetic debris and eddy current effects for non-ferromagnetic debris.

2.1.4.1 *Discussion*—A device that detects metallic wear debris that cause fluctuations of the magnetic field. A device that generates a signal proportional to the size and presence of metallic wear debris with respect to time.

2.1.5 *machinery health, n*—qualitative expression of the operational status of a machine sub-component, component or entire machine, used to communicate maintenance and operational recommendations or requirements in order to continue operation, schedule maintenance or take immediate maintenance action.

2.1.6 *metallic wear debris, n—in tribology*, metallic particles that have become detached in a wear or erosion process.

2.1.7 *sensor cable, n*—specialized cable that connects the sensor output to the electronic control module.

2.1.8 *trend analysis, n*—monitoring of the level and rate of change over operating time of measured parameters.

3. Summary of Practice

3.1 A full flow sensor is fitted in the oil line to detect metallic wear debris. The system counts wear debris, sizes debris, and calculates debris mass estimates as a function of time. This diagnostic information is then used to assess machine health relative to cumulative debris count, or estimated cumulative debris mass warning and alarm limits, or a combination thereof. From this information, estimates of remaining useful life of the machine can also be made.

4. Significance and Use

4.1 This practice is intended for the application of in-line, full-flow inductive wear debris sensors. According to (1), passing the entire lubrication oil flow for aircraft and aero-derivative gas turbines through a debris-monitoring device is a preferred approach to ensure sufficient detection efficiency.

4.2 Periodic sampling and analysis of lubricants have long been used as a means to determine overall machinery health (2). The implementation of smaller oil filter pore sizes for machinery operating at higher rotational speeds and energies has reduced the effectiveness of sampled oil analysis for determining abnormal wear prior to severe damage. In addition, sampled oil analysis for equipment that is remote or otherwise difficult to monitor or access is not practical. For these machinery systems, in-line wear debris sensors can be very useful to provide real-time and near-real-time condition monitoring data.

4.3 In-line full-flow inductive debris sensors have demonstrated the capability to detect and quantify both ferromagnetic and non-ferromagnetic metallic wear debris. These sensors record metallic wear debris according to size, count, and type (ferromagnetic or non-ferromagnetic). Sensors are available for a variety of oil pipe sizes. The sensors are designed

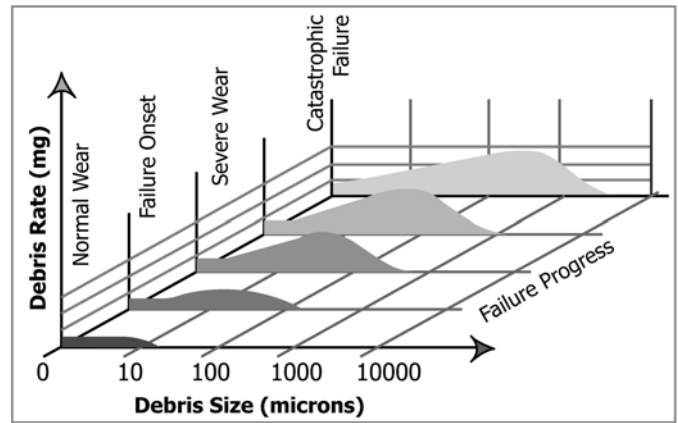


FIG. 1 Wear Debris Characterization

specifically for the protection of rolling element bearings and gears in critical machine applications. Bearings are key elements in machines since their failure often leads to significant secondary damage that can adversely affect safety, operational availability, or operational/maintenance costs, or a combination thereof.

4.4 The main advantage of the sensor is the ability to detect early bearing damage and to quantify the severity of damage and rate of progression of failure towards some predefined bearing surface fatigue damage limiting wear scar. Sensor capabilities are summarized as follows:

4.4.1 In-line full flow non-intrusive inductive metal detector with no moving parts.

4.4.2 Detects both ferromagnetic and non-ferromagnetic metallic wear debris.

4.4.3 Detects 95 % or more of metallic wear debris above some minimum particle size threshold.

4.4.4 Counts and sizes wear debris detected.

4.5 Fig. 1 presents a widely used diagram (2) to describe the progress of metallic wear debris release from normal to catastrophic failure. It must be pointed out that this figure summarizes metallic wear debris observations from all the different wear modes that can range from polishing, rubbing, abrasion, adhesion, grinding, scoring, pitting, spalling, etc. As mentioned in numerous references (1-11), the predominant failure mode of rolling element bearings is spalling or macro pitting. When a bearing spalls, the contact stresses increase and cause more fatigue cracks to form within the bearing subsurface material. The propagation of existing subsurface cracks and creation of new subsurface cracks causes ongoing deterioration of the material that causes it to become a roughened contact surface as illustrated in Fig. 2. This deterioration process produces large numbers of metallic wear debris with a typical size range from 100 to 1000 microns or greater. Thus, rotating machines, such as gas turbines and transmissions, which contain rolling element bearings and gears made from hard steel tend to produce this kind of large metallic wear debris that eventually leads to failure of the machines.

4.6 In-line wear debris monitoring provides a more reliable and timely indication of bearing distress for a number of reasons:



FIG. 2 Typical Bearing Spall

4.6.1 Firstly, bearing failures on rotating machines tend to occur as events often without sufficient warning and could be missed by means of only periodic inspections or data sampling observations.

4.6.2 Secondly, since it is the larger wear metallic debris that are being detected, there is a lower probability of false indication from the normal rubbing wear that will be associated with smaller particles.

4.6.3 Thirdly, build or residual debris from manufacturing or maintenance actions can be differentiated from actual damage debris because the cumulative debris counts recorded due to the former tend to decrease while those due to the latter tend to increase.

4.6.4 Fourthly, bearing failure tests have shown that wear debris size distribution is independent of bearing size. (2-5) and (11).

5. Interferences

5.1 Wear debris counts may be invalid due to excessive noise from environmental influences. See 7.4.

6. Apparatus

6.1 *Sensor*³—A sensor system is identified that is a through-flow device that installs in-line with the lubrication oil system. The subsections in this section provide examples for a certain type of inductive debris sensor system. The sensor has no moving components. As seen in Fig. 3, the sensor incorporates a magnetic coil assembly and signal conditioning electronics that are capable of detecting and categorizing metallic wear

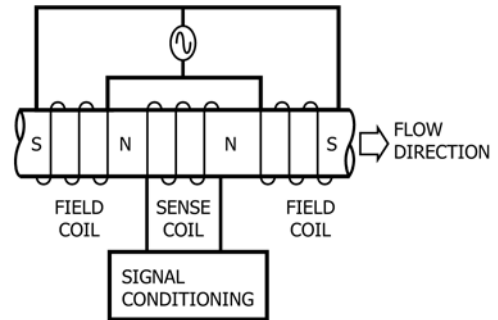


FIG. 3 Sensor Major Components (3)

debris by size and type. The magnetic coil assembly consists of three coils that surround a magnetically and electrically inert section of tubing. The two outside field coils are driven by a high frequency alternating current source such that their respective fields are nominally opposed or cancel each other at a point inside the tube at the center sensor coil. Signal conditioning electronics process the raw signal from the sensor and extract information about the size and type of the metallic debris detected. The sensor electronics perform several functions including: data processing, communication control, and Built-In-Test (BIT). Ferromagnetic and non-ferromagnetic wear debris counts are binned according to size. Signal conditioning using a threshold algorithm is used to categorize the metallic wear debris that pass through the sensor on the basis of size. Several size categories can be configured which allow the tracking of the distribution of debris.

6.2 *Principle of Operation*—The sensor operates by monitoring the disturbance to the alternating magnetic field caused by the passage of a metallic wear debris particle through the magnetic coil assembly as shown in Fig. 4 (12). The particle couples with the magnetic field to varying degrees as it traverses the sensing region, resulting in a characteristic output signature. The magnitude of the disturbance measured as a voltage defines the size of the metallic wear debris and the phase shift of the signal defines whether the wear debris is ferromagnetic or non-ferromagnetic. When a ferromagnetic particle passes by each field coil, it strengthens the magnetic field of that coil due to the high magnetic permeability of the particle relative to the surrounding fluid (oil). This disrupts the balance of the fields seen by the sense coil, resulting in a characteristic signal being generated as the particle passes through the entire sensing region of the sensor. The signal looks much like one period of a sine wave where the amplitude of the signal is proportional to the apparent size of the particle and the period of the signal is inversely proportional to the speed at which the particle passes through the sensor. For a ferromagnetic particle, the size, shape, and orientation of the particle and the magnetic susceptibility of the material determine the magnitude of the signal. When a non-ferromagnetic (conductive) particle passes by each field coil, the principle is similar except that the presence of the particle in the magnetic field weakens the field due to the eddy currents generated in the particle. This results in a difference in the signal phase allowing the processing electronics to differentiate between ferromagnetic and non-ferromagnetic particles passing through the

³ The sole source of supply of the apparatus known to the committee at this time is GasTOPS, Ltd., Polytek St., Ottawa, Ontario K1J 9J3, Canada. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,¹ which you may attend.

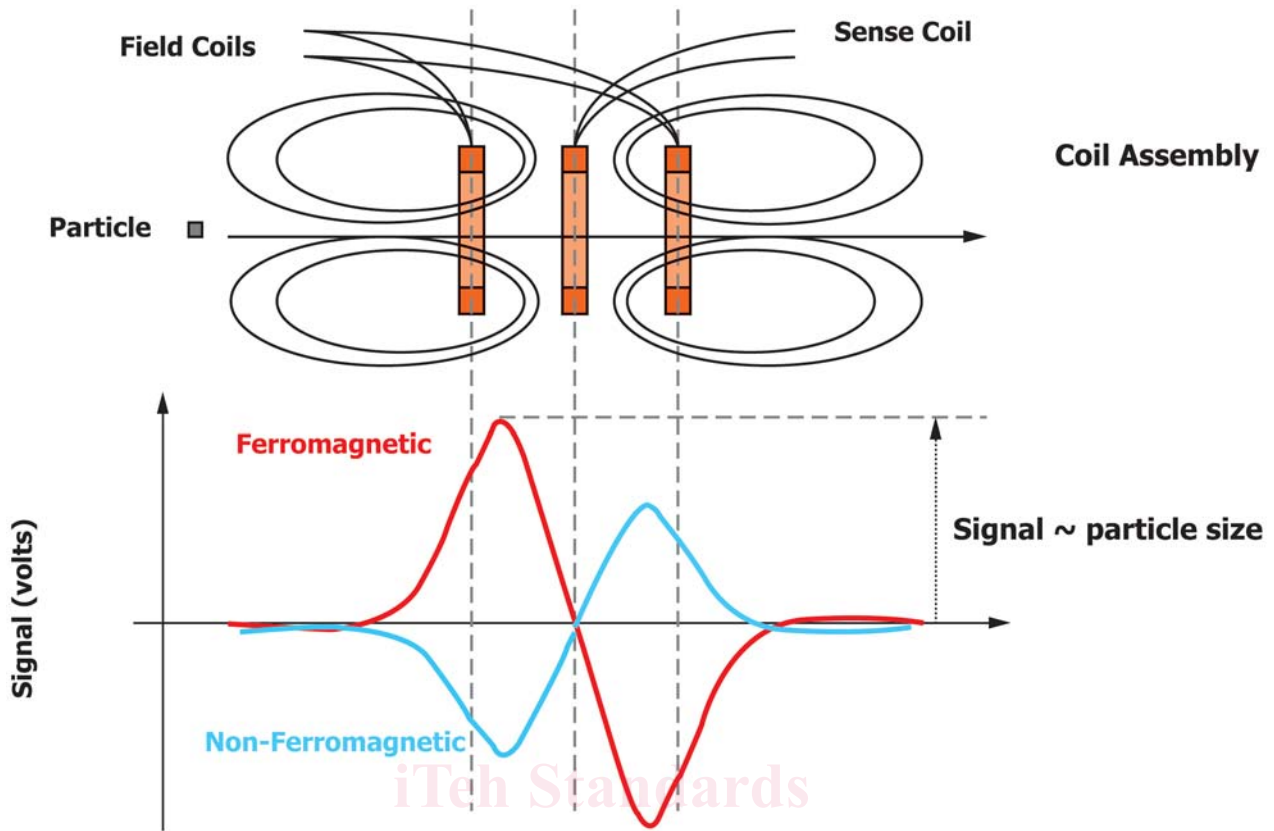


FIG. 4 Principle of Operation (12)

sensor. For a non-ferromagnetic particle, the surface area and orientation of the particle and the conductivity of the material, determine the magnitude of the signal. Also, for a given size of particle, the amount of disturbance caused to the magnetic field by a ferromagnetic particle is considerably greater than that caused by a non-ferromagnetic particle resulting in the sensor being able to detect smaller ferromagnetic than non-ferromagnetic particles. Note that the detection capability of the sensor is limited to distinguishing ferromagnetic materials from non-ferromagnetic (conductive) materials. It does not have the capability to distinguish different materials of the same type from each other (for example, it cannot distinguish aluminum from copper). Although the sensor electronics have the capability of processing metallic wear debris rates of 60 particles per second, this far exceeds the metallic wear debris rates that have actually been observed from bearing failure tests under conditions of severe wear progression. Metallic wear debris rates have typically been observed in a range from less than 1 to 5 particles per second for metallic wear debris particles that are 100 μm or larger. Hence, dead time and the likelihood of particles arriving at the same time is not an issue of concern.

6.3 *Particle Characteristics*—Several factors in addition to the size of the metallic wear debris particle, affect the magnitude of the signal generated (1), including:

- (1) Particle shape,
- (2) Particle orientation, and
- (3) Particle path.

Through field experience and laboratory testing it is known that ferromagnetic flake shaped particles, on average, produce larger signals than spherical particles of the same mass. Fig. 5 (12) shows the results of tests in which a specific ferromagnetic flake was passed through a sensor aligned in each of three orientations at both the center and the wall of the sensor bore. The particle used to represent typical bearing damage metallic wear debris was a ferromagnetic flake, rectangular in shape with the thickness being considerably less than the length and width. The particle orientation refers to the axis of the particle that is parallel to the flow direction. Also shown in the graph is the signal generated by a spherical particle with the same mass as the flake tested. It can be seen from this figure that there is a significant variation in the signal generated by an individual particle depending upon its shape and orientation. While there is some variation of the signal due to the position of the particle in the sensor, this effect is minor. Also shown in Fig. 5, is the distribution of the particle signal when the same particle was passed through the sensor many times, in a flow loop, to measure the variation of the signal caused by the “naturally occurring” orientation of a particle carried in a fluid flow. At the system level, particle size is determined by comparing the magnitude of the particle signal with preset thresholds associated with specific equivalent spherical particle sizes. In reality, due to the varying shapes of actual damage particles, a signal of particular level cannot be associated absolutely with a specific size of particle; rather, there is a definable statistical probability that a particle of a certain size will generate the

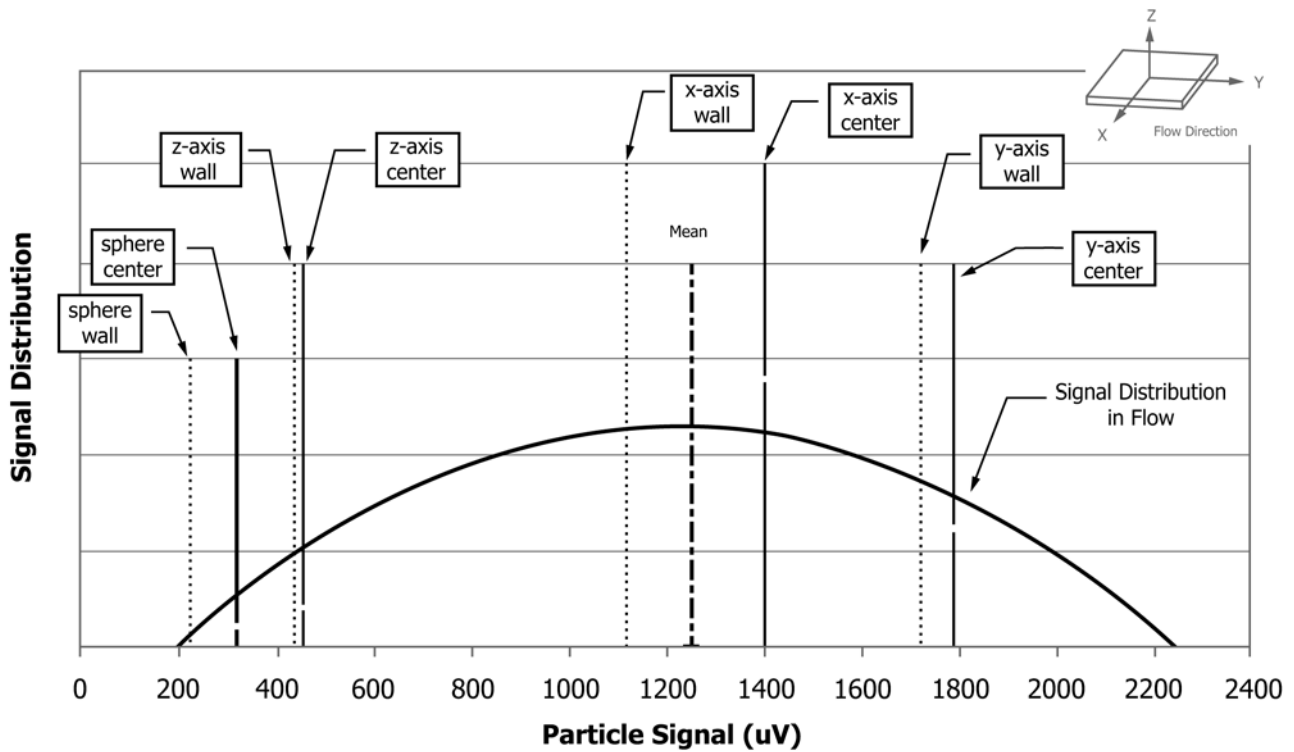


FIG. 5 Effects of Particle Shape/Orientation/Path for a Particle of Equivalent Mass (12)

mean signal. Given that large numbers of particles are usually released as bearings spall, a mean signal can be expected and it is usually at least 2 to 3 times larger than the one for a sphere of equivalent mass.

6.4 Material Magnetic Properties—All materials show some response to an applied magnetic field. In some materials, the magnetization is in the same direction as the applied magnetic field and the material is said to be paramagnetic. In other materials, the magnetization is in the opposite direction to the applied magnetic field and the material is said to be diamagnetic. For some metals, notably iron, nickel, cobalt, there exists a spontaneous magnetization even when the applied magnetic field is zero and the metals are said to be ferromagnetic. In an applied magnetic field, the magnetization of ferromagnetic metals is increased further in the same direction as the applied field. The magnetization due to paramagnetic and diamagnetic effects are very small by orders of magnitude compared with ferromagnetic effects. Thus, it is only in the ferromagnetic materials that the magnetization effects are large enough to be readily observable. Since rolling element bearings and gears contain largely iron as one of the elements, inductive sensing devices essentially detect the ferromagnetic wear debris from these components.

6.5 Metallic Wear Debris Detection Threshold:

6.5.1 Ferromagnetic Wear Debris—Particle detection threshold depends on the bore diameter of the sensor and whether the wear debris is ferromagnetic or non-ferromagnetic as defined in Table 1 and illustrated in Fig. 6. Particle detection thresholds are stated in terms of minimum spherical particle sizes that can be detected because the use of manufactured

precision spherical particles provides a traceable particle size reference that facilitates comparative measurements of sensor performance in development, qualification and production testing.

6.5.2 Non-ferromagnetic Wear Debris—Since eddy currents generated in a non-ferromagnetic particle are also proportional to the electrical conductivity of the material of the particle, different non-ferromagnetic materials will have different detection thresholds. As a default, the sensor conductivity is usually set for aluminum. Nonetheless, the conductivity can be selected as required to detect a specific non-ferromagnetic element for some applications.

6.6 Dynamic Range—The dynamic range depends on the nominal line diameter, 3/8 in., 3/4 in. and 1 1/4 in.; see Table 1.

6.7 Operating Temperature Range—A sensor can be mounted in harsh environments in the same space as the monitored machinery. Minimum ambient temperature range is -40 °F / -40 °C. Maximum ambient temperature range is 375 °F / 190 °C; see Table 2.

6.8 Operating Pressure Range—A sensor is installed directly into the fluid line without adversely affecting the lubrication system. The allowable maximum operating pressures depend on the bore size of the sensor; see Table 2.

6.9 Flow Rate—Minimum and maximum flow rates are necessary for accurate and repeatable sensor response; see Table 2.

6.10 Placement—The recommended location for the sensor is directly downstream of the system components subject to wear. Specifically, the sensors are placed after the component

TABLE 1 Metallic Wear Debris Size Range Detected for Specified Bore Diameter

Nominal Line Size	⅜ in.	¼ in.	1¼ in.
Bore	0.30 in. / 7.6 mm	0.7 in. / 18.0 mm	1.06 in. / 26.9 mm
Minimum Detectable Particle Size:			
Ferromagnetic (spherical equivalent)	120 µm	225 µm	330 µm
Non-ferromagnetic (spherical equivalent) (spherical aluminum)	440 µm	605 µm	900 µm



FIG. 6 Sensors with Different Bore Diameters

wear-generating source (bearing or gear) in the fluid return lines prior to the filtration system. The sensor is most effective when there are no traps or filters between the sensor and the components being monitored. The sensor can be mounted in harsh environments in the same space as the monitored machinery and can be installed in any physical orientation with the fluid flowing in either direction.

6.11 *Sensor Cable*—Sensors are electronically connected to the control unit using special low noise cables. The cabling and connectors play a significant part in achieving the level of sensitivity necessary for the system to operate properly.

6.12 *Vibration*—A sensor is designed to operate to a maximum of 6 g at 500 Hz.

6.13 *Safety*—A sensor system has been approved for use in Class 1, Division 2, Group D and ATEX Group IIA, Category 3 hazardous areas, and for electrical safety. It is NEMA 4 (IP66) protected.

6.14 *Power*—A system can be equipped with either an ac or a dc regulated power supply. The ac power supply can be nominal 120 V or 240 V ac, 50 Hz or 60 Hz; nevertheless, the voltage input at the sensor, taking cabling into consideration, must be in an operating range between 96 V and 132 V ac or between 192 V and 264 V ac, respectively. The dc power supply can be nominal 24 V dc; nevertheless, the voltage input at the sensor, taking cabling into consideration, must be in an operating range between 21 V and 29 V dc. In the event of total power failure, the host monitoring system reports a loss of data processing and communication.

7. Data Processing and Communication

7.1 For the through-flow sensor system identified,³ numerical data points are provided from which diagnostic information is interpreted. The host system can calculate machinery health indices and perform various functions as follows:

- (1) Total mass detected,
- (2) Number of metallic wear debris particles per size bin detected,

- (3) Rate of metallic wear debris detected,
- (4) Comparison of health indices to preset limits,
- (5) Annunciate warning/alarm,
- (6) Display time trends of metallic wear debris count and mass,
- (7) Display size distribution in the form of histogram plots,
- (8) Monitor and display system status, and
- (9) Display current particle counts and mass tables. Current particle counts or mass from the sensor show how many counts or how much mass have accumulated in each of the configured particle size bins since last reset. This includes a cumulative total of the counts or mass detected and the size distribution.

7.2 *Data Processing*—Data processing is performed by the electronics of the control unit including, metallic wear debris recognition; discrimination on the basis of material (ferromagnetic or non-ferromagnetic); and metallic wear debris size. Once the debris has been detected, classified, and sized, this information is passed to accumulating counters that record the total number of particles of a given type. The data can be segregated in user definable bins (for example, up to 16 size categories per type). The data is stored in non-volatile flash memory that retains the data in the event of a power interruption.

7.3 *Communication Control*—Sensor electronics can be connected to the machinery control and surveillance system for continuous monitoring of the machine. Within the control unit, a control module extracts data from the conditioning module and transmits this information to the external host monitoring system using communication protocols such as RS-232 or RS-485 serial communication, Modbus or other appropriate protocols. Multiple sensors may be polled to receive and record data on individual monitored components or machines. Polling is controlled by the host monitoring system that, in turn, time stamps the data for time trend presentations.

7.4 *Built-In-Test (BIT)*—System troubleshooting is augmented through the use of Built-In Test (BIT) functions. The BIT continuously monitors the health of the system circuits, and in the event of a detected fault, illuminates module LEDs and sends an error code to the host monitoring system.

- 7.4.1 The system includes two levels of BIT routines:
 - 7.4.1.1 Monitors three systems continuously—power supply, sensor field coil continuity and sensor performance, and
 - 7.4.1.2 Periodically monitors the circuitry at power-up and at regular 8 h intervals.

7.4.2 Particle counts may continue to be reported in a BIT fault condition. Depending on the nature of the fault one of the following situations could occur:

- 7.4.2.1 The counts are valid but system performance has degraded.

TABLE 2 Temperature, Pressure, and Flow Rate Requirements

Fluid Conditions	3/8 in.	1/4 in.	1/4 in.
Maximum Temperature	375 °F / 190 °C	375 °F / 190 °C	375 °F / 190 °C
Maximum Pressure	500 psi / 3500 kPa	500 psi / 3500 kPa	100 psi / 700 kPa
Minimum Flow Rate	0.056 US gpm / 0.21 L/min	0.50 US gpm / 1.9 L/min	2.1 US gpm / 8.0 L/min
Maximum Flow Rate	11.3 US gpm / 42.8 L/min	100.5 US gpm / 380 L/min	425 US gpm / 1600 L/min

7.4.2.2 The counts are invalid due to improper installation or from excessive noise from environmental influences.

7.4.2.3 The system stops counting particles due to failure of electrical components.

8. Calibration

8.1 *Calibration*—Particle size and amplitude of the waveform are proportional. To calibrate the output of the sensor, spherical particles are used to set the detection threshold of each sensor model. Calibration is performed during manufacturing and is achieved by using NIST 52100 chrome steel traceable particles by size for the ferromagnetic setting and using NIST aluminum traceable particles by size for the non-ferromagnetic setting. BITS provide verification that the sensor is operating correctly. There are no moving components or exposed components to go out of alignment.

8.2 As outlined in 6.3, several factors in addition to the size of the metallic wear debris affect the magnitude of the signal generated including debris shape, orientation, and path through the sensor. In reality, a signal of a particular level cannot be associated absolutely with a specific particle, but a definable statistical probability that a particle of certain size will generate a mean signal, can be determined. To verify sensor functionality and capability to detect particles of a certain mean size equivalent to a sphere, particle calibration is performed using NIST traceable spherical particles by size. The precision of the calibration with NIST particles is within $\pm 10\%$ of the sensor-sensed signal, which is voltage.

9. Calculation of Results: Generating Alarm and Warning Limits

9.1 The total volume or mass of ferromagnetic wear debris material removed from a rolling element bearing is directly related to mechanical condition. When monitoring rolling element bearings, research has shown a strong correlation between the accumulated ferromagnetic wear debris counts and/or ferromagnetic mass measured using the in-line full flow inductive sensor and the degree of bearing damage (2-5).

9.2 In general, the depth of spall damage on the bearing races is very shallow and can be considered to be approximately the same on average regardless of bearing size. In the determination of bearing stresses and deflections, the relative conformities of rolling elements to their contacting raceways is important. Loads acting between rolling elements and raceways in rolling element bearings develop only small areas of contact between the mating members. Consequently, although the elemental loading may only be moderate, stresses induced on the surfaces of the rolling elements and raceways are usually large. Since the effective area over which load is supported rapidly increases with depth below the rolling

surface of the bearing, the high compressive stress occurring at the surface does not permeate the entire bearing element. Although bulk failure of rolling members is generally not a significant factor in rolling element bearing design, destruction of the rolling surfaces to some limited depth is a significant concern. Fatigue failure observations on rolling element bearings from various sources reveal that the average depth of spall is usually some value in a range from 100 μm to 200 μm (7, 8, 10, 13, and 14).

9.3 If we imagine unfolding the spall in Fig. 7, it is essentially a rectangular area of damage with some average thickness for the missing material where the width of the spall is proportional to bearing roller width and the length of the spall is a function of the bearing mean diameter and the angle of spall. Thus, formulas can be derived to estimate bearing damage severity in terms of accumulated metallic wear debris counts or mass as functions of bearing geometry that include bearing pitch diameter, rolling element width, and number of rolling elements.

9.4 The alarm limit is a damage severity level where it is recommended that the machine be shutdown for inspection and servicing because continued operation may result in secondary damage to the machine. In order to quantify bearing degradation severity in terms of a suitable alarm limit, it is necessary to represent severity in terms of an equivalent angle of spall. An angle of spall of concern is considered to be the point where the supported shaft begins to experience some loss of position when two rolling elements have begun to simultaneously roll over the spalled area. This is equivalent to a spall angle of approximately 360° divided by the number of rolling elements as shown in Fig. 8. This criterion for setting the alarm limit has been found to be a conservative limit that has been validated on a number of applications, some of which have been included in Annex A1.

9.5 The formulas derived are independent of bearing size. Formulas define alarm limits for rolling element bearings in terms of accumulated mass or accumulated counts of metallic wear debris. The formulas correspond to a bearing spall wear scar size equivalent to the length between two rolling elements (Fig. 8).

$$M_{ALARM} = Km (360/N) D w \quad (1)$$

where:

- M = Mass detected by sensor (mg),
- Km = Calibration constant relating sensor detected debris mass for a specific bore size sensor to bearing spall geometry characteristics (mg/deg mm^2),
- N = Number of rolling elements,
- D = Bearing pitch diameter (mm), and
- w = Rolling element width (mm).