3 Engine Lubrication System

3.1 General

Within a turbofan engine the lubrication system serves several functions essential to the safe and reliable operation of the engine. These functions are:

- Lubrication of the rotor bearings
- Lubrication of the gears and bearings of the gearboxes
- Cooling of the bearings especially in the turbine area
- Removal of the contaminants from the lubricant
- Support of the sealing of the carbon bearing seals
- Supplying of a squeeze film between the bearing outer races and their housings for oil dampened bearings. Oil damping dampens the transmission of dynamic loads of the rotors to the casings. This feature reduces the vibration levels and the fatigue loads for the casings.

The lubricant reduces friction by replacing solid friction with fluid friction. Thus it must be able to provide a stable film between metal surfaces moving relative to each other at high relative velocities under high loads and high temperatures.

3.1.1 Properties of Engine Oil

Generally low viscosity synthetic lubricants and no mineral oils are used in turbine engines because synthetic oils retain their lubricating properties and are more resistant to oxidation at high temperatures. These oils also have better characteristics concerning thermal stability and the viscosity.

The oils used for turbine engines are required to operate over a wide range of temperatures. Temperatures from minus 40°C to more than 250°C for maximum bearing temperatures are possible.

Today oil of the fourth generation of synthetic oils is available. According to the development generation the oils are designated as Type 2, Type 3 or Type 4 oils. Type 2 oils are still available and in use.

The main characteristics of engine oil are:

- Viscosity
- Pour point
- Flash point
- Pressure resistance
- Oxidation resistance
- Thermal stability

3.1.1.1 Viscosity

The viscosity is the most important characteristic of engine oil. It is a measure of the internal resistance of a fluid to deform under shear stress. It is commonly perceived as “thickness” or resistance to flow. Viscosity describes a fluid’s internal resistance to flow and may be thought of as a measure of fluid friction.

The viscosity of the oil depends on the temperature of the oil. It is high at low temperatures and vice versa. This means that warm oil with a low viscosity has a low internal resistance. A low internal resistance is an advantage, but if the viscosity gets too low, the load carrying capability of the oil decreases and the oil film can no longer separate the moving surfaces. Thus the lubrication capability is no longer ensured. The viscosity is usually measured in centistokes (cS). The viscosity of a typical Type 3 oil is around 5.3 centistokes at 99° C and higher than 12,000 centistokes at a temperature of –40° C.

3.1.1.2 Pour Point

The pour point of the oil is reached if it is cooled down to a temperature at which the oil becomes so thick that it stops flowing. Typical Type 3 oils for jet engines have a pour point of –62° C (-80°F). Thus, if the temperature is lower, the oil stops to flow.

3.1.1.3 Flash Point

The flash point of a flammable liquid (here engine oil) is the lowest temperature at which it can form an ignitable mixture with air. It should be as high as possible to avoid fire in the oil system. Typical Type 3 oils have a flashpoint higher than 250° C (482°F).

3.1.1.4 Pressure Resistance

The pressure resistance or load carrying capability of the oil is an important factor for the formation of an oil film between the moving parts. This film resists the loads on the moving surfaces of bearings and gears and prevents contact between the surfaces.

If the loads are higher than the pressure resistance capability of the oil, the surfaces come into contact and heavy material wear occurs. A typical value for a Type 3 oil is 2,715,114 Ryder Gear, av. lb/in % Hercolube A.

3.1.1.5 Oxidation Resistance

Oxidation is the reaction between oil and oxygen. When the oil reacts with oxygen it gets thicker and increases its viscosity due to the formation of acids and sludge. This reaction reduces the lubrication capability of the oil. The reaction rate with oxygen increases when the oil temperature and the extent of contamination increase.

Therefore the oxidation resistance is an important characteristic of oil because it influences the durability of the oil. Typical Type 3 oils are resistant to oxidation at oil temperatures up to 220° C (428°F).

3.1.1.6 Thermal Stability

The term thermal stability describes the resistance of the oil to decomposition of the oil compounds at high temperatures. The oil molecules are made of several individual compounds. At high temperatures these molecules can break apart and the chemical composition and the lubrication capability of the oil changes.

This decomposition usually occurs at very high temperatures, well above the normal operating temperatures of the engine oil. Type 3 oils can resist chemical decomposition at temperatures of up to 340° C (662°F).

3.1.2 System Design and Components

The lubrication systems generally used in commercial turbofan engines to serve above-mentioned objectives are self-contained recirculatory systems. In such systems the oil is distributed to the locations where it is needed and returned to the tank by pumps. Three subsystems are essential for the circulation of the oil. These are:

- Storage and supply system
- Scavenge system
- Venting system

The function of the storage and supply system is to deliver the required amount of oil to the bearings and gears in a condition that achieves good

lubrication. Thus the oil must be filtered and its temperature has to be in the proper range. The system uses the amount of oil stored in the oil tank. The function of the scavenge system is to return the oil from the sumps in the bearing compartments and the gearboxes to the oil tank. In many oil systems the scavenge oil passes a filter before it enters the tank. Due to the operation of the bearing compartment seals an airflow into the bearing compartments across the seals is necessary. The vent system ensures the venting of this air to the atmosphere. It keeps most of the oil droplets from the vent air within the oil system.
The major components of a typical lubrication system are (see Fig. 3.1):

- An oil tank
- An oil pressure pump and supply lines
- Scavenge pumps and return lines
- Filters and strainers
- An oil cooler
- A venting system
- Sensors for flight deck indication and condition monitoring.

Additionally servicing provisions are installed. These are the oil tank fill port and hose connections for remote filling of the oil tank.

As each area that needs lubrication has its specific requirement concerning the amount of oil for proper lubrication and cooling, the oil flow to the

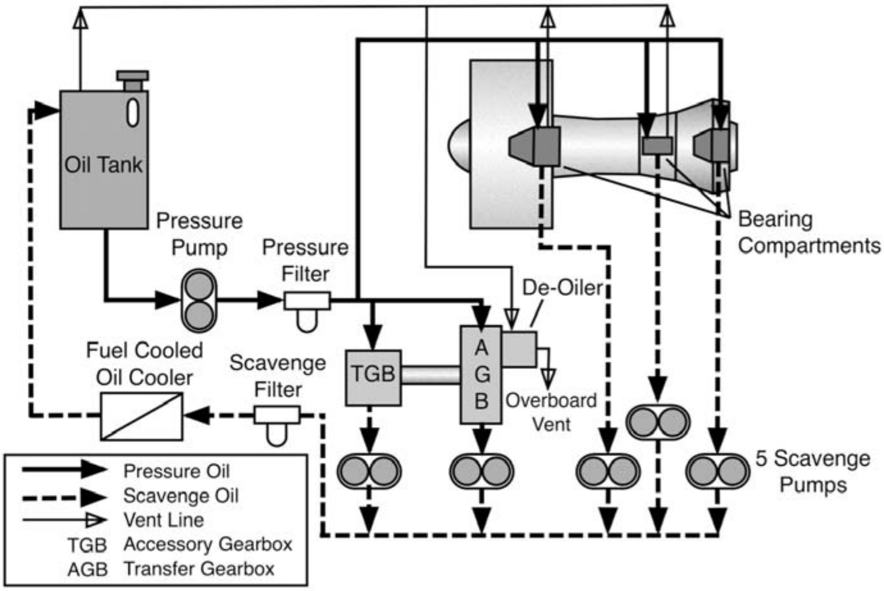

Fig. 3.1 A typical lubrication system for an engine with 3 bearing compartments

lubricated areas has to be matched with their demand. This matching is achieved by the cross section of the supply lines and the oil nozzles.

Concerning the pressure regulation, two types of systems are in use. The *relief valve system*, also called the constant pressure system, and the *full flow system*. In the relief valve system the pressure at the pump exit is maintained at a specific value over the engine operating range by a relief valve that returns excessive oil into the tank.

The full flow system operates without any pressure regulation device. Thus the oil flow in the supply lines is a function of the operating speed of the pressure pump, the supply line and oil nozzle cross sections and of the oil viscosity. This leads to a changing oil pressure with changing engine shaft speeds.

The pump of a relief valve system also supplies the part of the oil flow that is returned to the tank to keep the pressure constant. It has to be larger and requires more power for operation than the pump of a full flow system.

Most systems are designed as full flow systems. This type of system uses smaller pumps compared to the constant pressure system. Such a system saves weight and is easier to adjust, because it has no pressure regulating valve.

Independent of the method of supply oil pressure regulation the subsystems of both system types are practically identical. Figure 3.1 shows the main components of a typical lubrication system. This example shows a full flow system with a fuel cooled oil cooler. The vent (or breather) system uses a central de-oiler installed on the accessory gearbox.

3.2 Lubricated Areas

The rotor bearings used in turbofan engines are ball bearings and roller bearings. They are located within sealed bearing compartments. Oil supplied by the pressure pump is directed through individual supply lines and sprayed on the bearings through one or more nozzles per bearing. Figure 3.2 shows the arrangement of the oil nozzles for the front ball bearing of a CFM56-3. The oil-wetted areas are only inside the bearing compartments. The oil has no contact to the rotor components outside the bearing compartments and to the gas path. To ensure this the walls of the bearing compartments are sealed against the rotating shafts. For this sealing two types of seals are used: The carbon seal and the labyrinth seal. To have a constant sealing efficiency an airflow exists across the seals into the bearing compartments as shown in Fig. 3.3.

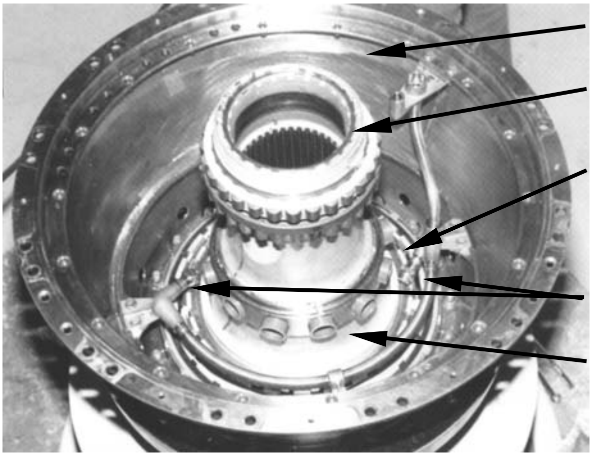

Fig. 3.2 The view from the rear into the front half of the front bearing compartment of a CFM56-3 after its removal from the engine. The oil nozzles for Bearing No.1 and its supply line are visible (LTT)

In the gearboxes ball and roller bearings are used to support the gear shafts. The gears and the bearings are supplied with oil through oil nozzles like the engine rotor bearings. The oil that drips off the bearings and gears is collected on the bottom of the bearing compartments and the gearboxes. These areas are called the sumps. Through return lines scavenge pumps take the oil out of the sumps with a higher capacity than the pressure pump delivers the fresh oil into the bearing compartments or gearbox. Thus the scavenge pump prevents the accumulation of oil in the sumps. Due to the

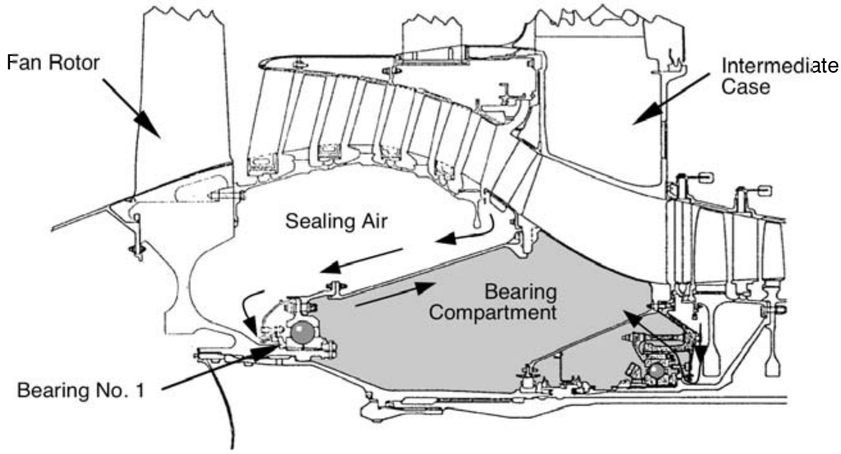

Fig. 3.3 The front bearing compartment of a PW4000 with the 3 forward bearings of the engine. The sealing airflow into the compartment is shown (Pratt & Whitney)

higher capacity of the scavenge pump it returns oil with a substantial amount of sealing air from each sump to the oil tank. The return lines and scavenge pumps must be properly sized and designed to handle the oil/air mixture. This generally requires an individual scavenge pump for each sump and the venting of the oil tank.

3.3 System Components

3.3.1 Oil Tanks

The oil of the lubrication system is stored in a tank. To allow servicing, devices for filling and draining the oil tank are provided. For the check of the oil level a sight glass or dipstick is installed. For the remote indication of the oil level an electrical quantity sensor is located in the oil tank.

The recirculatory system generally provides two different locations for the oil coolers in the system. If the oil is returned from the sumps directly to the tank without cooling, the system is called a *hot tank system*. If the oil passes the oil cooler before it enters the oil tank, the system is called a *cold tank system*.

Typical locations for the oil tanks on the engine are either the fan case or the accessory gearbox. If the engine has a core engine-mounted accessory gearbox with an oil tank, the access to the oil tank for servicing is not as good as the access to a fan case-mounted oil tank. The oil tank of the PW4000 for example requires an access door in the inner barrel of the thrust reverser structure because this oil tank is mounted on the gearbox of this engine. This variant is possible on engines with short duct nacelles only. A fan case-mounted oil tank can be used on every engine design.

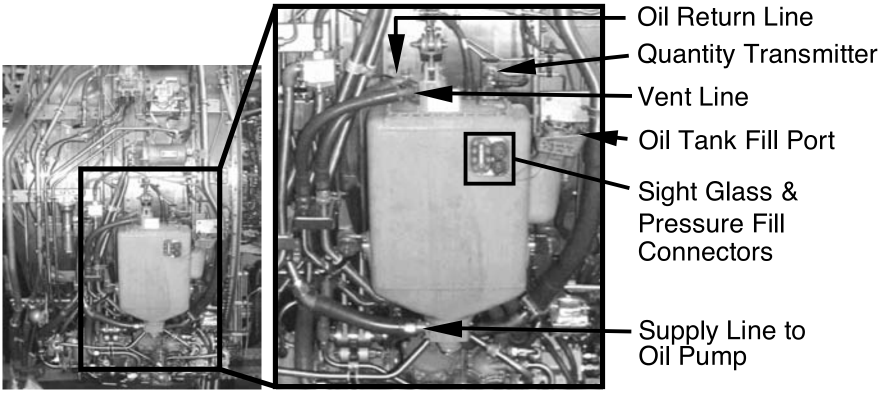

Fig. 3.4 The oil tank of a CFM56-5C on the left side of the fan case (LTT)

The typical oil tank has three connections to the lubrication system. These are the oil supply line to the pressure oil pump, the oil return line from the scavenge pumps and the vent line. The scavenge pumps deliver a scavenge oil/air mixture into the tank. This air is vented through a static de-oiler within the tank to the de-oiler or into one of the bearing compartments. On some oil tanks a pressurization valve is installed in the vent line connection. This valve keeps an air pressure slightly above the ambient pressure in the tank after engine shutdown. This facilitates the oil supply to the pressure pump during engine start.

For the remote sensing of the oil quantity a sensor is installed in the oil tank and connected to the assigned computer.

The oil tank can be filled directly with oil through the fill port or via remote fill connections. To check the oil level a sight glass is installed in the oil tank wall. If the pressure fill ports are used for refilling the oil tank, the oil is pumped into the tank until it is visible in the overflow hose.

The capacity of oil tanks depends mainly on the engine size. Here are three examples for oil tank capacities:

CFM56-7B: 23 US quarts, 22 litres
PW4000 (94 inch): 37 US quarts, 35 litres
GE90: 28 US quarts, 30 litres

3.3.2 Pumps and Filters

The oil pumps used in lubrication systems are gear type pumps or vane pumps. The gear type pumps are of the classic type with parallel shafts or they are of the gerotor type with coaxial gears. Usually one pressure pump

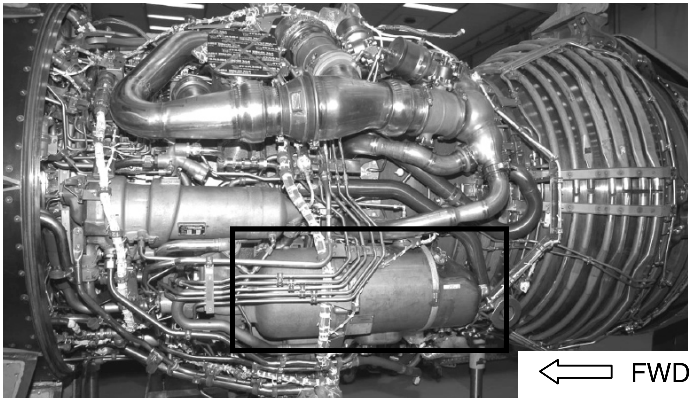

Fig. 3.5 The oil tank of a PW4000 on the core engine-mounted accessory gearbox. All connections to the lubrication system are integrated into the gearbox (LTT)

and for each sump one scavenge pump are used in a lubrication system. This leads to a number of four to six scavenge pumps. The pumps are either arranged in separate units – one for the pressure pump and the other for the scavenge pumps, or all the necessary pumps for a system are integrated into one unit. They are installed on the assigned pads of the accessory gearbox. On engines from GE and CFM the oil pumps are integrated together with the oil filters in one unit. Here these units are called *lubrication units*. Figure 3.6 shows the installation on a CFM56-5A.

The magnetic chip detectors for debris monitoring are installed in the scavenge pump inlets or in the scavenge oil lines upstream of the pumps where easy access is ensured.

The filter system is a very important element for the reliability of a recirculatory lubrication system. Because the oil has to pass through small holes and passages, even very small particles contaminating the oil could block the oil flow resulting in a lubrication failure. The normal contaminant is abrasive material and is released by the bearings and gears during their normal operation. It is flushed away from the bearings and gears by the oil and carried with the scavenge oilflow away from the sump. In the filters of the system the contaminants are removed nearly completely from the oil. Thus the oil can be supplied again to the bearings and gears. If a bearing or gear failure develops, larger than normal particles will be found in the filters and on the *magnetic chip detectors*.

A classic filter arrangement in a lubrication system is one pressure filter downstream of the pressure pump and one scavenge filter downstream of the scavenge pumps. In this arrangement the scavenge filter has the finest

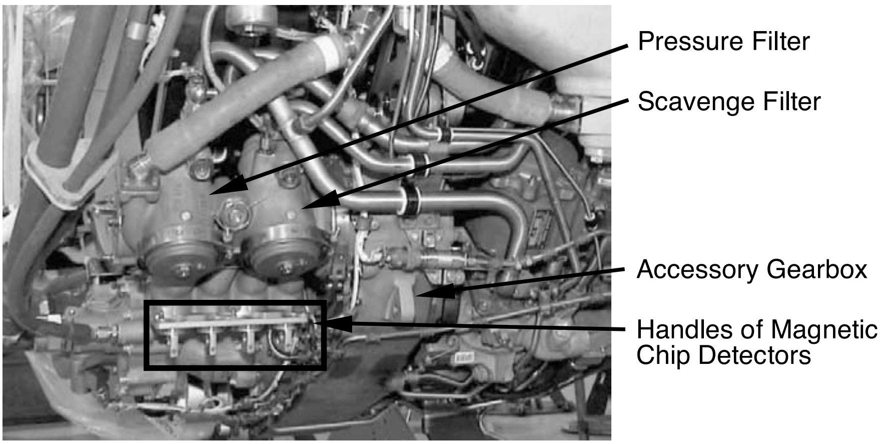

Fig. 3.6 The lubrication unit of a CFM56-5A. It contains one pressure pump and 4 scavenge pumps. The Pumps are gerotor pumps (LTT)

filter element. Also in use are systems with one filter in the pressure system only (e.g.:PW4000, CFM56-5B, -5C). In these systems a back-up filter is installed to ensure oil filtering if the main filter is clogged. Every oil filter is equipped with a bypass valve to sustain the oil flow while the filter element is clogged. The filter elements used in the oil filters have mesh sizes between 15 and 65 Microns (0.015 to 0.065 mm).

The finest filter in the system is monitored with a differential pressure switch for clogging. The resulting clogging warning informs the flight crew about the limited filtering efficiency in the system.

In some systems additional filter screens are installed upstream of the oil nozzles in the supply lines. These screens are called last chance screens (or last chance filters). They prevent a clogging of the oil nozzles by particles that can reach the nozzles if the filter bypass valve is open.

3.3.3 Oil Cooling

During the lubrication process heat is transferred from the engine components to the oil. It has subsequently to be removed from the oil to keep the oil temperature within the set limits. This requires the installation of an oil cooler in the system. The cooling medium may be fuel or air and in some designs a combination of a fuel-cooled and an air-cooled heat exchanger is used. The cooler may be located either on the feed side or the return side of the lubrication system resulting either in a hot tank system or a cold tank system.

The typical oil cooler used on turbofan engines is the fuel-oil heat exchanger. It has a smaller volume compared to an air-oil heat exchanger of the same cooling capacity and the use of fuel as the cooling medium results in a heating of the cold fuel delivered by the aircraft fuel system. The fuel-oil heat exchanger is also effective during ground operation and need not be exposed to the airflow. The lubrication systems on some engines use additional air-cooled oil coolers to control the temperatures of oil and fuel during the operation with low fuel flows (see also Chapter 4.4).

In some fuel-cooled oil coolers a thermostatic bypass valve is installed. It maintains a proper oil temperature by varying the portion of the oil passing, respectively bypassing, the oil cooler. This valve allows changes to the cooling effect in response to the changes in fuel flow in different phases of engine operation. All other oil cooler designs have a bypass valve responding to the differential pressure across the cooler. The highest differential pressure develops with the coldest oil. Thus the cooler is bypassed when the oil temperature is low.

3.3.4 Vent System Components

In order to maintain a continuous flow of air from outside the bearing compartment through the shaft seal into the bearing compartment, the sealing air has to be vented through vent lines out of the bearing compartment. When this *vent air* or *breather air* leaves the bearing compartment, it contains a large amount of oil droplets. Furthermore the sealing air mixes with the scavenge oil, which is pumped through the return lines into the oil tank. Thus means must be provided to separate the oil from the air to retain the oil within the system and vent almost clean air into the atmosphere.

After the vent air has left the lubrication system it flows through a *de-oiler* (it is also called *de-aerator*). This is a centrifugal device for the separation of oil and air. The vent air of the oil tank also flows through the de-oiler to the atmosphere. Figure 3.7 shows the de-oiler and its vent air outlet on the gearbox of a V2500-A5.

Within the de-oiler the vent air flows through radial passages in the rotor towards the center of the shaft. Most of the oil droplets are thrown out of the rotor and against the walls of the housing by the centrifugal force. At the bottom of the de-oiler housing the oil droplets are collected and returned to the oil tank via the scavenge pump. The air from the center of the shaft is vented into the atmosphere via the vent air outlet. A small amount of oil is released with the air leaving the system. It represents the normal oil consumption of the engine (0.1 to 0.5 US quarts/hour).

When the vent air leaves the bearing compartments through the engine shaft (in engines of CFM and GE) to the rear, the de-oiler is called *air/oil separator*. In fig. 3.2 the radial tubes of the air/oil separator are visible. No vent air lines to a central de-oiler are necessary when an air/oil separator in each bearing compartment is used.

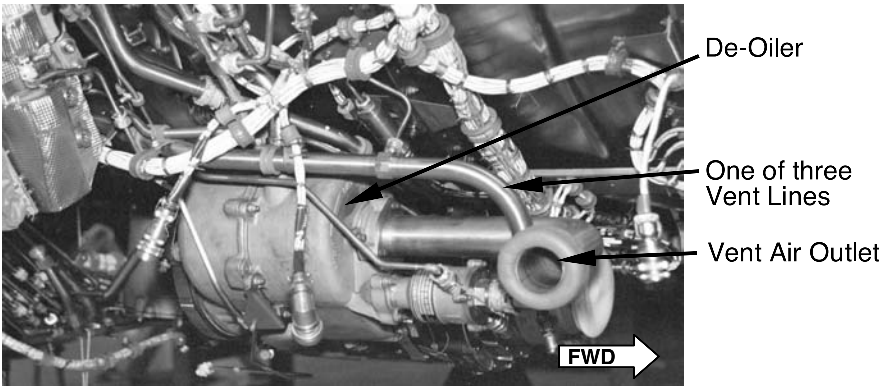

Fig. 3.7 The de-oiler of a V2500-A5 on the front side of the accessory gearbox (LTT)

3.4 System Indications and Monitoring

3.4.1 Indication of Operating Data

The indications of a typical lubrication system show the pilots the main operating data of the system for monitoring purposes. According to EASA CS 25.1305 and FAR 25.1305 the following data must be indicated:

- Oil Quantity
- Oil Pressure
- Oil Temperature
- Low Oil Pressure Warning
- Oil Filter Clogging

The indication system provides also a warning of high oil temperature and of a low oil level in the oil tank. The sensors for these data are located at assigned locations within the lubrication system. Figure 3.8 shows the oil system indications on the display screen of an A330.

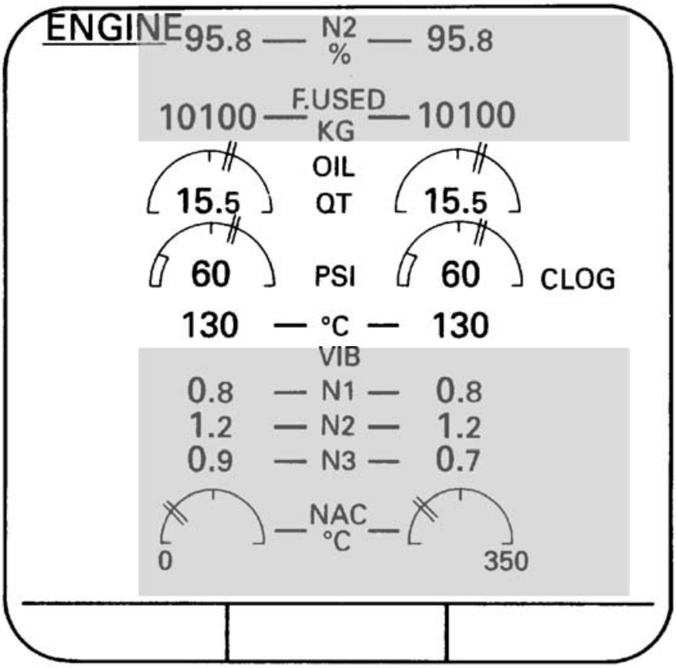

Fig. 3.8 The lubrication system indications on the ECAM display of an A330. The word *clog* indicates a clogged filter in the respective system and appears only if the respective filter clogging switch has signaled the clogged condition (LTT)

The following table shows the lubrication system indication data of 2 engines as an example. The reason for the higher oil pressure during cruise of the V2500 is the large decrease in the vent pressure connected to the pressure transmitter. The change of the vent pressure from take-off to cruise is larger on the V2500 than on the PW4000:

Table 3.1 Indication data of the PW4000 and the V2500-A5

	PW4000	V2500-A5
Min Oil Press.	4.8 bar (70 psi)	4.1 bar (60 psi)
Oil Press. at Idle	6.2 to 8.6 bar (90 to 125 psi)	7.9 bar (115 psi)
Oil Press. at Cruise	14.5 to 17.2 bar (210 to 250 psi)	17.9 bar (260 psi)
Oil Press. at T.O.	17.9 to 19 bar (260 to 275 psi)	16.6 bar (240 psi)
Max. Oil Temp Cont.	163 °C	156 °C
Max. Oil Temp. Transient	177 °C	165 °C
Typ. Cruise Oil Temp.	120 to 125 °C	110 to 120 °C

3.4.2 Indication System Sensors

The indication system sensors are located at specific locations within the lubrication system. Its output is not used for indication only. The sensor output data is also continuously collected for system monitoring. Additionally to the indication sensors, the chip detectors for debris monitoring purposes are installed in the scavenge system.

On all engines the oil quantity sensor is located in the oil tank. It is installed into the tank from the top and mounted to the ceiling of the tank. So it can be replaced without draining the oil tank. For the oil quantity measurement sensors of the capacitance type and the reed switch type are used.

The oil pressure transmitter is connected to an oil line of the supply system and to the vent pressure of the lubrication system. If the vent pressure level is very different between the bearing compartments, the vent pressure of the bearing compartment with the highest pressure is used. Due to this way of connecting the pressure sensor to the system, the indicated value shows the pressure difference between the absolute oil pressure and the absolute vent pressure.

The oil temperature sensor can be located in the scavenge system or in the supply system. The position in the individual system is selected by the designer to keep the maximum indicated values at approximately 150°C.

For the triggering of the low oil pressure warning a low oil pressure switch is installed parallel to the oil pressure transmitter, or the dedicated computer triggers the warning based on the oil pressure sensed with the oil pressure transmitter. In the latter configuration the threshold value for the low oil pressure warning can increase with the engine shaft speed.

3.4.3 Data Processing, System Monitoring

The sensors of the indication system are connected to computers located within the airframe or to the FADEC computer. Which variant is used depends on the computing power of the FADEC computer. If the sensors are connected to the aircraft computers, these are mainly the interface computers, which also handle the data transmissions between the FADEC computer and the airframe systems.

Besides the collection of sensor data for flight deck indication there is also a collection of data that is later evaluated on the ground only to detect the development of a trend. A very common example is the monitoring of the oil consumption of an engine.

The monitoring of the oil consumption is done to sample information about the efficiency of the bearing compartment seals and for the early detection of leaks. This is achieved by using the oil quantity data delivered in regular intervals by the system. When the bearing compartment seals suffer from increased wear, the amount of sealing air flowing across the seals increases. In an early state this does not result in a leak at the affected seal. The resulting effect is a higher flow of vent air through the de-oiler. This reduces the efficiency of the de-oiler and increases the oil consumption. If the wear of the seals progresses, leakages may occur.

The oil leaking out of a bearing compartment may enter the gas path of the engine. This leads to an oil contamination of the compressor airfoils and to an oil contamination of the bleed air delivered to the aircraft. An oil smell in the cabin will be the result. Because this is not acceptable, an operation with a leaking bearing compartment must be prevented. Oil consumption monitoring is an effective tool to achieve this.

3.4.4 Debris Monitoring

Fresh oil filled into the lubrication system will gradually dissolve contaminants and holds microscopic particles in suspension. Bearings, seals and gears wear, erode and corrode introducing traces of these components into the oil flow. Thus the condition of the oil, which has been circulated in the

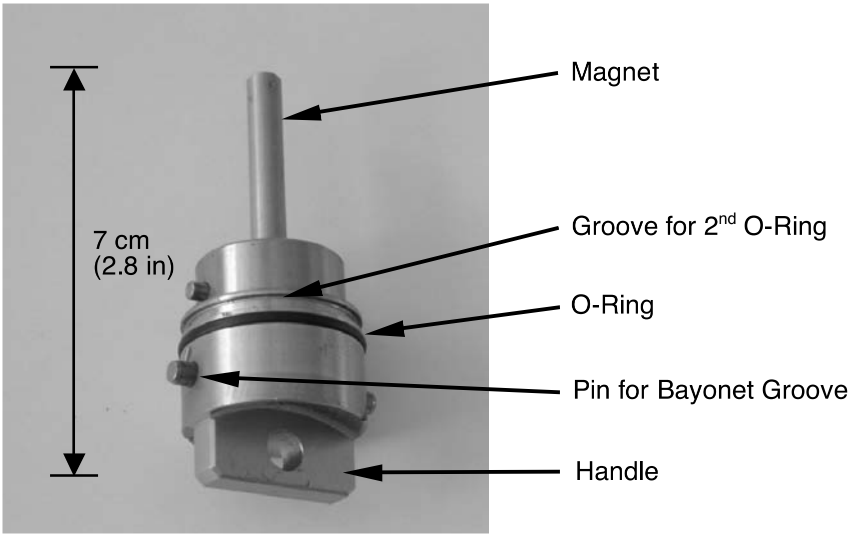

Fig. 3.9 A Magnetic chip detector for the installation in a lubrication unit. The O-rings are replaced with new ones before each installation

lubrication system for some time, very exactly reflects the condition of the system. If the system operates normally, the oil contains the amount of particles, which is typical of the system. The size of the particles is typical of abrasive contamination. During the development of a bearing or gear damage the size and the amount of the particles become larger. With the detection of these particles in the oil a bearing or gear damage can be recognized in its early stage. These particles are also collected by the oil filter, but the filter inspection intervals are too long to detect a damage early. To facilitate the check of the oil system for particles in shorter intervals, magnetic chip detectors are installed in the scavenge oil flow of each sump or as a master chip detector in the common scavenge line downstream of the scavenge pumps. Because the gears and bearings are made of steel, the magnets of the chip detectors are able to collect the particles (or chips) of these parts. These chip detectors collect particles from 0.02 to 1 mm in size. The whole arrangement of magnetic chip detectors is often called *debris monitoring system.* In its simplest design the magnetic chip detector is a tiny bar magnet which protrudes into the scavenge oil flow. Figure 3.9 shows such a chip detector. The check of the chip detectors for collected particles in fixed time intervals is part of the maintenance checks. To facilitate the check of these detectors they can be removed from their housing without a tool. If particles are found on the chip detector, they can be analyzed in a laboratory to exactly determine the component releasing these particles into the oil.

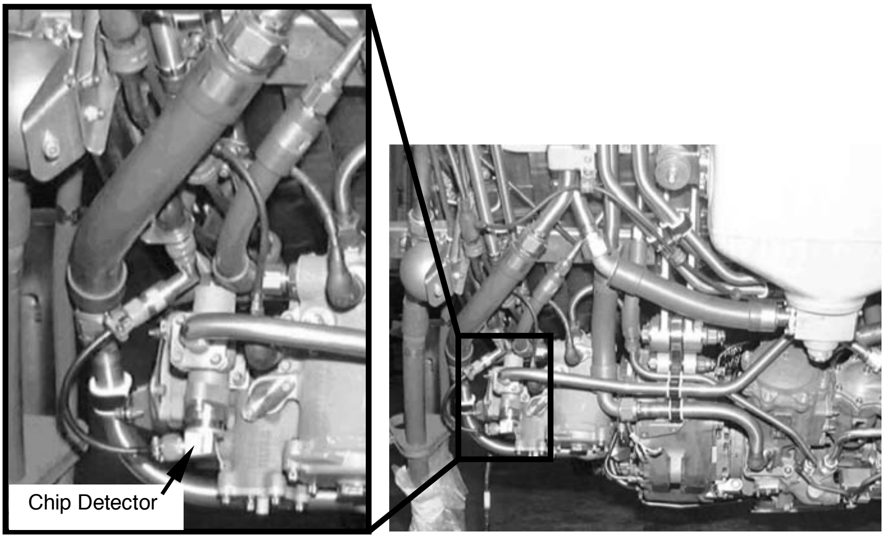

Fig. 3.10 The electrically monitored chip detector of a CFM56-5C. It is installed in the scavenge oil outlet of the lubrication unit (LTT)

The more sophisticated variant of the magnetic chip detector is the electrically monitored chip detector as shown in Figure 3.10. Such a chip detector comprises a set of two magnets. The FADEC computer monitors the resistance between these two magnets. A check and removal of the electrical monitored chip detector is not necessary until the FADEC computer sends the corresponding maintenance message.

For the particle monitoring of modern engines *oil debris monitors* (ODM) are used. These sensors are based on an inductive measurement technique which enables the system to detect, count and classify wear metal particles by size and type (ferromagnetic or non-ferromagnetic). This allows the system to determine the trend for the amount of particles in the oil. The ODMs are connected to the FADEC computer or another computer assigned to this function.

Another tool for the monitoring of the oil-wetted parts is the *spectrographic oil analysis program (SOAP)*. Through this analysis the concentration of particles of the size from 0.001 to 0.02 mm and its specific elements can be identified. The metal type and concentration may indicate to the analyst and engineers which part of an engine is failing if a direct assignment to an engine part is possible. SOAP is used if this program is part of the engine maintenance schedule. It may be used temporarily if uncertainties exist about the reliability of engine bearings or gears. Some turbine engine manufacturers mandate SOAP in certain turbine engine maintenance schedules.

For the monitoring of particle concentration in the oil a periodic analysis of oil samples, taken from the engine, is made in a laboratory. When the amount of particles for an element or an element combination increases, this indicates an increase in wear. If the trend continues, the development of a damage is imminent. In this phase the particle size also increases and the presence of the particles can be verified by the magnetic chip detectors. The verification with the help of a chip detector is important if an assignment of the analyzed elements to an engine part is not possible.

If SOAP is used, the airline engineering has more time for the observation of a failure development. This allows a longer planning period for the engine removal necessary in such case.

http://www.springer.com/978-3-540-73618-9

Systems of Commercial Turbofan Engines
An Introduction to Systems Functions
Linke-Diesinger, A.
2008, XV, 234 p., Hardcover
ISBN: 978-3-540-73618-9