ADVANCED OIL SYSTEM FOR THE ANTLE/POA DEMONSTRATION PLATFORMS

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Abstract

Fuel price and environmental policies of European government push aircraft manufacturers and aircraft motorists to improve the efficiency of their products. In this aim, European projects and different aeronautical companies have joined their efforts to optimize and therefore improved their know-how. This paper present the Techspace Aero participation among these projects and particularly the results obtained through the ANTLE and POA engine demonstrators. The electrically driven and distributed oil system developed to optimize the cooling and the lubrication of the engine is described. The results of the project are detailed with particular emphasis on the four-month engine test campaign. Future works and challenges for MEE will also be given.

1 Introduction

The ANTLE[1] engine demonstrator was successfully rig tested during the spring of 2005. This experimental platform which was part of the EU funded EEFAE[2] programme aimed at demonstrating mid-term aircraft engine technology. Techspace Aero, a company of the SAFRAN group, was responsible for the design, manufacturing and integration of an innovative advanced electrically driven oil system.

Traditional aero-engine lubrication units are mechanically driven by the external gearbox. The rotation speed of the lubrication units is thus strictly proportional to the engine high pressure shaft speed. As a consequence, the pumps have to be designed for the single most demanding condition (generally Take-Off). The oil system operation for other engine rates is not optimised. Further than energy loss, excessive lubrication results in higher heat dissipation in some bearing compartments and can even contribute to adverse phenomena like churning effect. This inability for mechanically driven pumps to match all the engine conditions of cooling need is particularly true for MEE. Indeed, the additional cooling needs of the More Electric Engine due to the integration of high power electric generator strongly differs from the conventional bearing compartments and gearboxes needs, both quantitatively and qualitatively. Mechanically driven pumps would then lead to lubrication exceeds or even unaffordable flows for most engine rates. MEE will thus strongly benefit of the full flexibility of the electrically driven and distributed oil system.

The ANTLE oil system consists of 5 independent electrically driven pumps (1 feed pump and 4 scavenge pumps – see Figure 1) which are controlled by the OSC (Oil System Controller – see Figure 2). By controlling the pump speeds independently, the OSC optimises

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[1] ANTLE stands for Affordable Near Term Low Emissions.

[2] EEFAE stands for Efficient and Environmentally Friendly Aircraft Engine – the largest ever EU funded aero-engine
research programme. EEFAE aims at the reduction of CO_2 emissions (between 12 and 20%) and of NO_x emissions
(80%).

the oil cooling flow for any engine rating. This optimisation can either be strictly based on the predictions of the ANTLE engine oil system model computed by Techspace Aero (open loop control laws) or be fine tuned by closed loop control feedback which is computed from real time engine sensor measurements. By appropriate selection the objective function, the closed loop control laws enable the optimisation of different variables whose weights may be varied for different engine rates.

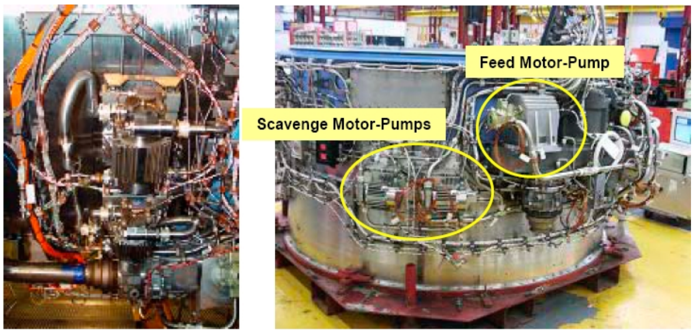

Figure 1 - ANTLE Electrically Driven Distributed Lubrication System (left: close-up on 2 scavenge motorpumps

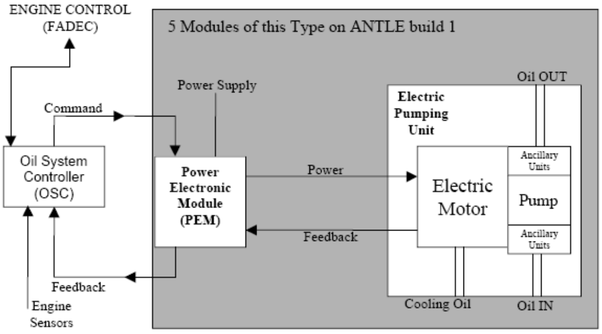

Figure 2 - Oil System Control Schematic

The first part of this paper is the description of the architecture of the distributed and electrically driven lubrication system. It includes a presentation of challenges faced during the motor-pumps conception as well as an overview of the control system. The oil system model predictions (steady-state and transient) are also presented.

The second section of the paper is dedicated to the presentation of the ANTLE oil system test results. Throughout the 4-month ANTLE test campaign, various OSC control laws – open and closed loops – were successfully tested and adjusted to meet the specific engine requirements. The impact of the oil feed flow variations is compared to the oil system model predictions.

In the third and final part, the future and the challenges for the oil systems of the More Electric Engine are presented. Different issues are addressed upon the additional cooling required by the MEE like availability of heat sinks and electrical power for the cooling before start and after stop. The sharing of oil system equipment for engine lubrication and electrical equipment cooling is also considered, as on the POA-ESVR[3] platform (part of the EU funded EEFAE programme) for which Techspace Aero is the supplier of an electrically driven oil system derived from ANTLE.

2 Description of the architecture of the lubrication system

2.1 Lubrication unit composition

The oil system (OS) circulates oil to a set of engine chambers or housing to perform lubrication, thermal, and pollution control function.

The ANTLE demonstrator engine is based on the Rolls Royce TRENT 500 three spool engine. It has the following seven chambers/housings which must be serviced by the OS:

1. The Front Bearing Housing : FBH
2. The Intermediate Gearbox : IGB
3. The High Pressure / Intermediate Pressure Bearing Chamber : HP/IP

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[3] POA stands for Power Optimised Aircraft – ESVR stands for Engine Systems Validation Rig. ESVR tests are scheduled for 2006.

4. the Tail Bearing Housing : TBH
5. The Step-Aside Gearbox / Lower Bevel Box : SABG
6. The External Gearbox : EGB
7. The air/oil Breather : BSE

It retrieves the oil from all the above chambers with a quantity of entrained air which is then purified, cooled and stored (not necessarily in that order) before being re-circulated.

The ANTLE OS has two separate pumping systems:

- The first system consists of a set of pumps mechanically driven by the EGB. Inherited from Trent 500, this system is required for the equipment still driven by EGB and that will disappear with the EGB in a MEE. This system is thus out of interest for this document.
- The second system consists of a set of separate electrically driven pumping units. Oil supply to the seven chambers/housings is provided by the main electric oil pumping unit. Oil is scavenged from the four chambers/housings: FBH, IGB, HP/IP, and the TBH individually using four electric oil pumping units.

Each pumping unit will have its own power electronics and the co-ordination of pumping operation is done by an oil system controller (OSC) based on:

- Information gathered directly from on-engine sensors
- Messages received from the engine controller (VECS) through the dual CAN bus.

2.2 Location of Units

The supply unit was fixed on the ANTLE EGB. The FBH and the IGB scavenge pumping units were also located on the fan case but were clamped to flanges. The two other scavenge pumps were located on the engine intercase.

The aim of ANTLE/POA was that a single design be used for all the four scavenge pumps. The requirement for these two environments were very different, the core being the hottest (up to 330°C during soak back) and the fan case experiencing the highest vibration loads (40g). The T500 can be considered as hot with report to other commercial engines of similar power (oil temperature at the scavenge pumps requirement being as high as 280°C transiently). This combination of harsh environment resulted in a challenging specification for an electric equipment.

Designing a reliable electronic motor in this engine environment was a real challenge since it exceeds the usual limits of the components, the maximal operating temperature of the windings being 220°C and the one of SM-CO magnets being 350°C. An innovative internal cooling strategy has thus been set up.

This distributed electric oil system proposed on ANTLE/POA allows placing pumping units at the vicinity of the associated housing, simplifying the piping network. This distributed architecture was also selected for meeting the high flexibility requirements of a test campaign. The weight of mass and reliability factors being higher for production engine, the trade-off versus flexibility would probably lead to merge the scavenge pumps in a single unit.

2.3. Pumping requirements

Generally speaking, the oil system aims to cool and lubricate the bearing chambers, the gearboxes and the electric equipment. The pumping elements supply the oil flow from the tank to the housings and scavenge an air-oil mixture from the housings back to the tank. The separation of air and oil is performed in the tank and de-oiler. The cooling of the oil is performed by heat exchange with fuel and/or air.

The requirement for the oil system can therefore be divided in two separate demands of oil cooling. The first is the conventional bearing cooling depending of the bearing load, and usually requiring high pressure due to injectors at the housing inlet. The second is dedicated to the electrical generator cooling requiring high flows independently of the engine rate.

The combination of challenging values for these two major drivers of the pump design had to lead to advanced answers in the optimization of the pumping elements:

- Flow is of course a major driver for the design of a pump. The cooling of the generators involved a 64% increase of the cooling flow to be delivered by the supply pump.
- Further than the high pressure required by the bearing chamber cooling, the high flow required by the generators still increases the pump outlet pressure. The supply circuit had to be redesigned in order to limit the pump pressure outlet increase due to the dramatic flow augmentation.

2.4 The Oil System Controller

Designing lubrication units usually consists in choosing the most demanding operating point of the engine to allow mechanically driven units to deliver enough oil for all engine speeds. Indeed the lube systems speed is proportional to the engine shaft speed. It results in a mismatching of oil requirements and oil delivering for other points that the design point.

To vary the pumps speeds independently from each others and from NHP and therefore match exactly and continuously the oil requirements whatever are the condition and engine speed, electrically driven units have been produced

A first step is to replace the constant reduction speed ratio between NHP and pump speed by a variable parameter that can be optimized for the whole engine operation. As a second benefit, the electronically driven system can monitor external conditions and select in real time the best curve associating the NHP to the pumps speeds according to these external conditions. Final improvement is the implementation of closed loops to perform real time optimisation based on engine operating conditions and engine operating variables. The OSC allows the operator to select different closed-loop laws where some physical objectives are defined. For example, instead of defining a pump speed for a shaft speed, an oil flow objective is defined for the shaft speed. Based on a flowmeter signal, the OSC, thanks to a PID closed loops, calculate the exact pump speed needed to reach the oil need. Three different closed-loop have been programmed, the first influencing the oil flow, the second the oil temperature and the third the heat flow.

The four scavenge pumping units speeds are defined to obtain the required air-oil mixture. Nevertheless, the operator may activate a closed-loop law which drives the pumping unit to alter the pressure value in the housing.

2.5 The oil circuit model

Techspace Aero has developed an analysis tool able to model the thermal and pressure behaviour of any jet lubrication system. Parametric models are available for the main components of the system: oil tank, feed pump, filter, heat exchanger, injector, bearing housings (including gearboxes), scavenge pumps and oil/air separation devices. The three main piping networks (the feed circuit, the scavenge circuit and the ventilation circuit) are also modeled through a combination of straight pipe elements, bends and orifices, essentially.

The ANTLE/POA demonstrator engine is based on a Rolls-Royce Trent 500 as the tank the supply and scavenge pumps, pressure filter,… are inherited from the TRENT 500 Rolls-Royce engine. Some components, not included in atypical Trent 500 engine, are added to ANTLE/POA oil system:

- An oil/water heat exchanger (also called “Slave Cooler”) is located upstream from the FCOC. The purpose of this additional heat exchanger is to match the very high loads likely to be encountered on POA.

- The feed pump and the four scavenge pumps are electrically driven.
- Two air riding axial carbon seals are installed in the FBH. These seals replace the labyrinth seals used on the Trent 500 engine.

The four electric motors associated to the scavenge pumps need a cooling oil supply. Therefore, four additional cooling circuits are added to the existing feed circuit (small flow rates are extracted downstream from the FCOC).

This tool is based on three modeling principles:

- Only steady-state models are considered;
- The modeling is based on conservation of mass and energy (within a specific component model and between the system components);
- "Semi-empirical" models are built which means that some parameters are added to each model. These parameters are adjusted in order to allow the model to accurately reproduce the behaviour of the actual device.

A special subroutine is used to connect the models of the individual components and to solve the compatibility equations.

The modular nature of the simulation tool allows to analyse easily different architectures of a given oil system. It is possible to carry out analysis of the component locations (heat exchanger, oil tank, etc.) and to compare the different options.

The lubrication system model is included in a Graphical User Interface (GUI). All the inputs required by the modeling (geometrical data, operating conditions, etc.) can be specified by the user through this GUI. The GUI can also be used to run the simulation process and to visualize the results.

The complete ANTLE lubrication system is built by means of the GUI. The lubrication system is depicted in Figure 3. Some particular points must be mentioned:

- The "injector" elements are used to connect the oil feed circuit to the components to be lubricated within the housings (bearings, squeeze films, pinion, bevel gear and hydraulic seal).
- The lubrication system is simplified by merging the three gearboxes (EGB, LBB, and SAGB) in a single gearbox.

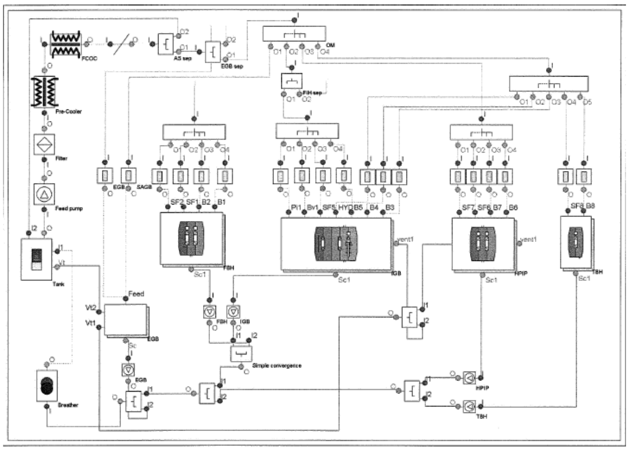

Figure 3 - ANTLE OIL SYSTEM MODEL

3. ANTLE oil system results

3.1 ANTLE OSC testing at INTA

The ANTLE engine demonstrator was rig tested at INTA (Spain). We will explain, in this paragraph, events and challenges addressed by the Oil System, explaining their consequences and showing how the flexibility of electrically driven pumping system supported the success of the demonstrator.

The ANTLE test campaign can be divided in three phases from the Oil System point of view:

1. Early testing : dry cranks, wet cranks and run attempts
2. Engine runs
3. Engine runs with the Oil System operating as an engine life support system

The first phase has shown during the cranking the full versatility of the OSC. The first solved issue was the priming procedure. With usual lube system, the engine has to be cranked to drive the pumps and fill the piping. Presently with electrically driven system, the supply pump may fill the pipes to prime all the scavenge pumps without any NHP speed.

The second issue was the high outlet pressure due to low temperature (increasing the oil viscosity). It has been solved in the simplest way by decreasing the supply pump speed. Indeed, low temperature of the oil means less flow to ensure a perfect cooling of the bearings. It shows that this concept allows a lot of flexibility for the operational specifications as it can adapt to the peculiar situation.

During the second phase, the ANTLE engine reached ground idle speed (63% of the shaft speed at take-off). Some correction factors were assigned on the supply pump and scavenge pumps speed in order to ensure not to attain over pressure (proportional law). Once the engine was running at ground idle, these correction factors were deactivated as the temperature of the oil was sufficient to obtain a low viscosity. This phase has thus shown the efficiency of the Oil system Controller to drive the motor pump during starting sequence of an airplane engine.

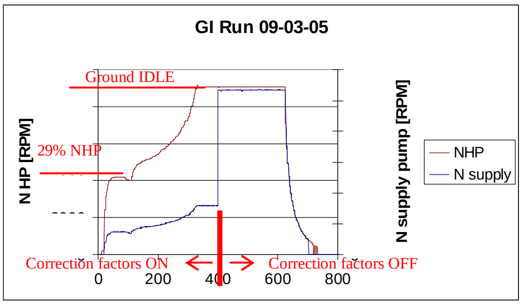

Figure 4 : GI Run - N_{HP} and N_{supply} profiles

The OSC has even proven capacity to solve issue not directly related to oil system. During this phase, leakages appeared, more air than expected was therefore present in the bearing housings. Correction factors were affected to the pumps speed to deal with these extra volumes. During these phase, the non linear laws and the closed-loop laws were also successfully tested, meaning that the pumps speed were correctly following the OSC command signals. But during the shutdown of the engine, smoke has appeared in the exhaust gazes. It was caused by oil fires due to leakage of oil out of the FBH compartment and to a crack in the HP/IP oil feed line. To cope with this matter, modification has been done in the main laws driving the motor pumps. It means that correction factors were needed to be assigned on motor speeds. Once again, the adaptability of the pumps speed has permit to cope with problems coming from parts of the engine external to the OSC. This proves the efficiency of the adaptive speed and thus flow to regulate the operating conditions of the engine.

The third phase of the test allowed the OSC to run as life support system for the engine. Indeed, the oil fires observed previously during the tests were due to cracks in the pipes and leakages. The OSC might control the oil flow to ensure that these fires couldn’t occur anymore and therefore permit the completion of the ANTLE testing program.

As said previously, the fires were due to oil present outside the bearing housing after high power run. These have occurred during shutdown. The solution implemented to deal with this problem was to reduce the oil flow and principally for low engine speed. The default law was a linear interpolation setting the supply pump speed proportionally to the high pressure shaft speed. Thus, to avoid leaking and especially at low engine speed (as fires occurred during shutdown), a multilinear laws has been defined as shown on Figure 5.

During this phase, the oil fire safe mode has been engaged when reducing speed from cruise to ground idle. As no more fire has happened, the OSC has proved its efficiency as a life support system.

The ANTLE Oil System was successfully tested on the ANTLE demonstrator. The tests highlighted the very high adaptability of electrically driven lubrication systems, in particular for demonstration and development engines.

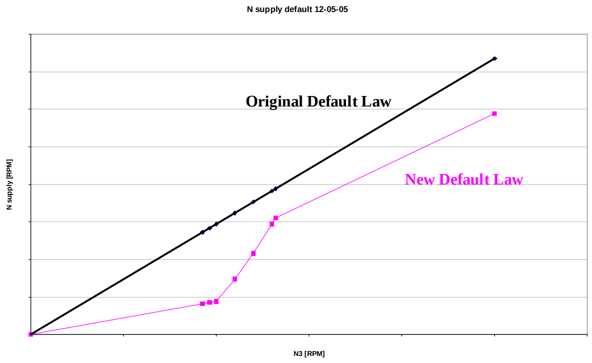

Figure 5 : Supply Pump Default Laws

Feed and scavenge pump speed variations were safely implemented throughout the various test phases. Thanks to the versatility of the oil system, engine runs could be conducted until the end of the scheduled test campaign despite an oil leak resulting from a cracked oil pipe in the IP torsion box which would have led to the cancellation of the tests because oil fire risks if a conventional lubrication unit had been used.

3.2. Oil system model prediction

As said previously, the model contains a series of parameters to be tuned on the basis of the experimental data available. Whenever possible, the model uses physically meaningful parameters. These parameters have been tuned thanks to the first experimental data. Afterwards, a global simulation of the oil system has been carried out. The results are satisfactory.

The parameters to be tuned are numerous and defining them all is out of the scope of this paper. Nevertheless, it is interesting to explore some of them.

For example, the scavenge flow (air/oil mix) is mixed with the anti-siphon flow in the oil tank. The experimental data show that the mixing inside the tank is not an adiabatic process; heat is lost to the surrounding air which leads to an oil cooling. Therefore, the heat transfer is modeled by means of an equivalent “AU” value (A is the heat transfer area and U is the overall heat transfer coefficient).

The feed pump behavior simulation needs several input parameters to predict the resulting oil flow. These are principally geometrical parameters tuned thanks to data acquisition. The same kind of model is used for the scavenge pumping units but with extended parameters due to the diphasique flow passing through them.
The oil injectors model is a polynomial function based on a more complex model. The coefficient and correction parameters may be tuned following the experiments.

The net heat generation inside a bearing housing can be deduced from the measurements on both oil and air sides (i.e. measurements located at the housing inlets and outlets). The air contribution is usually small compared to the oil contribution. The net heat generation can also be deduced from the estimation of:
1) The heats generated by the housing components (bearings, seals, bevel gear, pinion, etc.) [this term has always a positive value];
2) The heat exchanged by convection between the air/oil mixture and the surrounding air [positive value if heat provided to the air/oil mixture inside the housing].

The gearbox model is a very simplified housing model. The gearbox is composed of a single internal zone and one scavenge outlet. The oil is not injected on a specific component but is rather injected inside the zone. The heat generated in the gearbox has to be provided by the user as heat input to the zone. As explained above, EGB, LBB and SAGB are modelled as a single gear box.

A global simulation of the oil system has been carried out. Table 1 summarises the main results:

- Mtot: Total mass flow rate to feed pump

- Pin_pump & Pout_pump: Feed pump inlet & outlet pressures
- Tin_pump: Feed pump inlet temperature
- Tout_FCOC: FCOC outlet temperature
- Tscav_*: Scavenge temperatures
- CSOT : Common scavenge oil temperature

These predictions are compared to the measurements.

Mtot [kg/s]	Pin_pump [bar abs]	Pout_pump [bar abs]	Tin_pump [C]	Tout_FCOC [C]
+0.4%	-0.09 bar	+0.75 bar	+4.7 K	+3.0 K

Tscav_FBH [C]	Tscav_IGB [C]	Tscav_HPIP [C]	Tscav_TBH [C]	Tscav_EGB+LBB+SAGB [C]	CSOT [C]
+1.8 K	-0.7K	+0.4K	+0.9K	+2.7K	+4.8K

Table 1 : Comparison between measured and predicted values

The results are very satisfactory. Pressure and temperature levels are close to their measured values. The error is somewhat higher concerning the prediction of the CSOT (and, consequently, Tin_pump and Tout_FCOC). This is due to the fact that the heat dissipation in the scavenge lines is not modelled.

The important amount of experimental data allows us to validate our feed pump model in real operating conditions. This is a crucial point since development and manufacturing of gerotor pumps is one of TA[4]'s main activities. The measurements inside and around the bearing housings were also very useful in order to better understand and quantify the various heat transfer phenomena. The oil system model developed by TA is now able to predict the ANTLE engine behaviour in terms of lubrication requirements. However, some further work is still required in order to assess the overall model accuracy. The model will be essentially used in a near future to help with defining and validating the oil system control strategies for POA (for instance, definition of the pump control laws).

It would be interesting to add some parasitic heat dissipations to the oil model (mainly, heat transfers between the piping network and the surrounding air). This would allow the model to better describe the actual system performance.

4. Future and challenges for the oil systems

Some of the technologies developed in the frame of the MEE aim at decreasing or even deleting the lubrication need. Active magnetic bearings technology will be tested on the TBH of POA. With this technology, shafts are sustained by magnetic field. Therefore, no frictional forces exist, and then the traditional lubrication aim of oil disappears.

The main difference between ANTLE and POA ESVR demonstrators is the presence of two high-power (two times 150 kW) embedded generators (see Figure 6), the FSDG designed by Goodrich is situated in the TBH and the HPSG designed by Thales which have also for purpose the engine starting situating in the IGB. The embedded generators are oil-cooled, such that the oil system on the ESVR serves two conflicting purposes. One is to cool and lubricate the traditional bearings and gears (critical design point at high engine power), and the other one is to cool the embedded generators (critical design point at low engine power). The heat load from the generators and engine is very high (up to 43 kW) and this heat is dissipated into the atmosphere via a slave cooling system.

Thus, instead of a decrease, as the first experience of a MEE POA experienced a dramatic increase of the lubrication needs due to the integration of these generators. Furthermore, the torque needed to operate these generators can't be taken from a single shaft without compromising the total efficiency of the engine. Then, a system of shaft coupling is required or an ancillary turbine, having for consequence the

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[4] TA stands for Techspace Aero

apparition of new gears finally resulting in a further increase of cooling requirements.

The challenge for the oil system is to adapt to these new requirements and to identify the appropriate architecture to accommodate bearing chamber lubrication and generator cooling. On the ESVR, a complete sharing of every equipment (tank, pump, exchanger…) has been considered, the integration of the generators in the housing being an opportunity to combine two circuits into one. This solution is elegant and associated reliability figures are good since the number of ancillary equipments decreases.

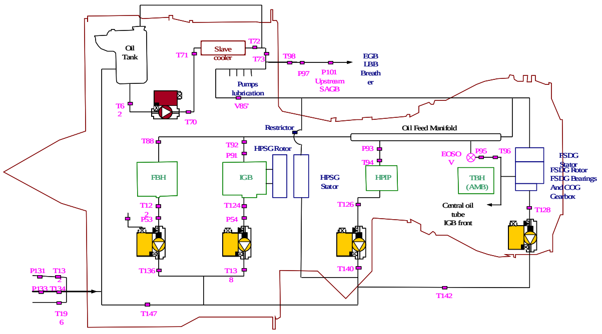

Figure 6 : ESVR/POA oil system architecture showing the two embedded generators.

In order to limit the impact of this architecture on the oil pump, a first adaptation to this new architecture could be to separate the feeding function in two parts, a high pressure pump to feed the bearing compartments and a low pressure pump for cooling the generators.

The retained solution is a shut off valve added in the central oil tube to enable the oil system to cool the generators while the engine is stationary, without pumping oil into the HP compressor drum via the central oil tube oil jets (which rely on IP shaft rotation to transfer oil to the bearings).

Thanks to the adaptative possibility of the OSC, a complex sequence of supply pump speed to reduce oil flow before closing the shut-off valve to avoid a water hammer effect has been programmed. This has been done in synchronicity with the command of the valve shutting/opening, an impossible task for a mechanically driven lube unit.

For electric generators, the cooling need is more or less constant except during starting (due to the starter function) and stopping (thermal soak back). An electrical cooling device is therefore a mandatory. The advantage of electrically driven oil cooling system is its total flexibility but it needs an alternative power source when the engine is stopped; that can be the APU or ground electric network but switch will have to be closely tested like it is considered on ESVR.

As cooling needs, an additional heat sink has to be identified. The impossibility in future more composite aircraft structure to send back heated fuel to the wings will make this issue even more outstanding. This need of a cold source will be crucial at starting and after stop as no fuel or limited fuel flow is available. To palliate this issue, a slave oil cooling system is present on POA demonstrator engine. This slave cooler is an oil/water heat exchanger. It is of shell/tube counter-flow construction. The water runs through the tubes, and the oil runs through the shell. Finally, heat rejection to the atmosphere is via a large fin/tube radiator. The heat transfer to the atmosphere is enhanced using a set of 4 air-blast fans. This kind of system to exchange heat with the atmosphere has to be designed for the future as heat generation will increase. This emphasise the importance of an ACOC in the MEE which would have to work in stand still conditions maybe thanks to an ancillary fan.

Another issue due to electrically driven pumps is the limited torque. During a cold day start, the oil viscosity is great, introducing an extremely high torque as the pressure loss in the piping increase. Currently, this is not an issue as the power is provided by the engine through the shaft, but with electrically driven pumps, a particular starting sequence has to be built. During this procedure, the oilflow would be reduced to reach a certain temperature for which oil viscosity is low enough not to reach a critical pressure and then torque. Once again, the complete versatility of the system with its electronic drives and control laws has been proved to be able to automate the starting sequence and therefore to reduce the risks due to human intervention.

5. Conclusion

This paper has presented the oil system conceived by TA in the framework of European projects. This oil system is an innovative concept as it is based on two completely new principles.

The first one is the distributed oil system. It permits the reduction of piping, reducing the mass and the possible leakage, increasing then the reliability and the safety.

The second innovation is the electrically driven device. The lube unit is there independent of the shaft speed. It has proved its full flexibility allowing:

- coping with off-specification oilflow,
- working as a safety device reducing the fire risks,
- proving the possibility to have a closed loop regulation of physical engine parameters without risks for the engine.

An oil system model has also been set up. It has shown its efficiency in correctly predicting the oil demand of the ANTLE test engine. In the future, this model would be used to predict engine behaviour and therefore to conceive the oil system based on these predictions to match perfectly with the oil demand for every engine rating.

The last paragraph was an overview of the future challenges forecasted for the lube system manufacturer. The increase of cooling needs raises more and more crucial challenges that TA is wiling to take up. The system tested on ANTLE enabled to validate the feasibility of electric lubrication pump in turbo-engines without matching the weight objective for a flight operation anyway. POA platform offered Techspace Aero the opportunity to demonstrate a second generation electric pumping unit with flight compliant reliability and mass figures. This new pumping device is around 4kg with a redundant-winding DC brushless highly integrated motor and will be tested at the end of the year 2006 on the POA/ESRV engine.

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