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INVESTIGATION OF CHARACTERISTICS OF THE OIL SYSTEM WITH ELECTRICALLY DRIVEN PUMPS FOR GAS TURBINE ENGINE

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Abstract

It describes the results of experimental and computational studies of the characteristics of demonstration system lubrication of aircraft gas turbine engine (GTE) with using one supply and scavenges electrically driven oil pumps. Analysis of the features of working process in the lubrication systems units is executed and the possibility of using a homogenous model to describe the flow finely dispersed oil-air mixtures is evaluated. The mathematical model verified by comparing the calculated and experimental processes.

1 Introduction

The necessity to develop the oil system of GTE with electrically driven units associated with the prospects of creating an "electric aircraft" and the engine for it - "electric" gas turbine engine (EGTE), which can be performed without mechanical accessory gearbox of aircraft and engine (pumps, constant speed drives, etc.). It's possible some variants of the suspension rotor engine: the suspension with conventional rolling bearings and lubrication system either the suspension with magnetic bearings, which don't need lubrication. The second variant relates to the longer term, due to difficulties in obtaining an acceptable weight of magnetic bearings with current technology.

The oil system comprising pumps with controlled electric drives in the feed circuit, the scavenge circuit and the ventilation circuit, is closer to realization. Its application will improve the quality of lubrication and bearing life, increase the reliability run in sub-zero air temperature, and after stopping the engine, reduce the loss of oil and other.

One of the problems arising in the development of such system is to define of pumps speed control laws. Control of the lubrication system units becomes additional objective of the automatic control system (ACS) of engine, and efficiency of this control is determined by the interaction of lubrication system, fuel supply system and ACS.

When choosing the characteristics and control laws of such multivariable system is necessary into account the peculiarities of working processes in the system at different engine operating modes. The experimental research with using visual-spectral method was the complex carried out and dvnamic mathematical model was developed for the study of a number of specific effects, that occur during operation lubrication systems such as filling the space between the gear teeth in the area of the suction of gear pump, flow and mixing of two-phase mixture et al. Principles of creation and identification of this model are described below.

This complex model is used for a comparative study of the control laws in the oil system, affecting both the functional characteristics of this system and the fuel supply system, which interact with oil system.

2 Experimental studies of characteristics of oil system

In CIAM the demonstration oil system with electrical motor-driven pumps [1] is developed in order to assess the effectiveness of this system and experimental development of ways to control operation of the pump.

The system comprises an oil tank (OT), from which oil is supplied to the input of the supply pump, which supplies oil to the oil chamber (OC) of the bearing. Pumps ScP_1 and ScP₂ provide pumping oil from the OT to the AGB. Pump ScP₃ pumps oil from the AGB to the oil tank. Compressor supplies air (Gair) to the oil chamber. There is a breather system (Gbreath). Each pump is rotated by a controlled ED change in speed which provides inverter power (IP). Digital control system generates control signals for the IP. Transparent inserts installed in the path of pumping fluid for visual assessment of the nature of the flow. Scheme of demonstration oil system with electrically driven pumps on the seminatural test bench with a simulator oil chamber and its connections are shown in the fig. 1.



Fig. 1. Schematic diagram of the demonstration electric motor-driven oil system

When tested the demonstration oil system, excess pressure in the oil chamber was 0.01...0.03 MPa, pressure on outlet of the supply oil pump was 0.3...0.5 MPa, oil flow rate through it was 10...20 l/min and through the scavenge pumps less than 60 l/min, the temperature oil-air mixture was ranged from 20 to 70 °C. The ratio of the scavenge pump performance to the performance of supply pump ranged from 2 to 4, while real volumetric gas content (α_p) was 0.2...0.5. Rotor speed in the oil chamber varied from 4000 to 12000 rev / min.

Tests were carried out by the following procedure. Electric drive of scavenge pumps was turned on at first to empty the oil chamber, then air fed to oil chamber. Next, the electric drive of supply oil pump and the electric drive of oil chamber rotor bearings were turned on. Parameters registration and video recording of the flow pattern of flow in the pipes upstream and downstream exhaust pump carried out, when running at preset mode.

Experimental studies of the demonstration oil system with electrically driven pumps show that its characteristics and operability depend on the properties of the fluid, which is a finedispersed oil-gas mixture which is not subject to the processes of coalescence (fusion of air bubbles). A characteristic feature of the oil-air mixture flow considered in the work is the ability to involve to the flow a different amount of air depending on the oil properties, the engine mode of operation and the rotation frequency of the electric oil pump.

In the experiments, the establishment of thermal equilibrium in the system was slow (60 ... 65 sec), and times response of flow rate and oil pressure were also large (tens of seconds) when changing modes of operation.

If the pump is working on pure oil (without fraction of air), the stable operation of the pump with the ability to change the pumping tenfold is ensured. If set the stepwise disturbance on rotational speed of scavenge oil pump, then transients in the system are aperiodic. If scavenge oil pump operating at oilair mixture, transients have an oscillatory nature and possible of overshoot of the parameters (pressure, flow, etc.) and an increase in power consumption.

The appearance of these unwanted dynamic phenomena in units of GTE oil system, related to the complexity of the physical processes, caused the need for the experimental study and the mathematical modeling of these phenomena for taking them into account in the design of control systems. The visual-spectral analysis of system parameters used for the experimental determination of oil-air mixture characteristics.



Fig. 2. The structures of the flows of working medium: A - the stratified flow; B - dispersed flow; C - the slug flow

Video analysis showed that the increase in the flow rate of scavenge pump leads to following basic flow structures: the stratified flow (Fig. 2, A), with the oil-air mixture in the lower part tube, transits to the dispersed flow (Fig. 2, B), and further, to the slug flow (Fig. 2, C) consisting of a dispersed oil-air mixture in the lower part tube and the bubbles in the upper part tube.

In plug flow, as shown by visualization, the bubbles float to the top of the pipe and occupy a portion of the flow cross section without interrupting the flow radially. At the same time the bubbles under the influence of Archimedean force and the pressure difference gradually moving streamwise at a speed slightly greater velocity of the liquid phase.

One of the main reasons for of this flow is the use in lubrication systems GTE gear pump (positive displacement pump). Oil-air mixture flow rate in the hydraulic circuit is formed by the flow characteristics of the pump, which reflects the dependence of the volume flow at the pump outlet Q_p rotational speed n_p. Flow characteristic pump selected from the conditions required to ensure pumping of the working medium at the calculated value of gas content (α_{calc}) at the specified rotational speed pump. Volumetric flow rate of the pump on the other rotational speed will also correspond to the flow characteristic. This specificity of the pump determined by its construction in which a gear pair delivers the volume of working medium from input to output of pump equal to volume between gear teeth in the suction zone. The value of the volume flow at the output (input) of the pump at the current rotational speed characterizes its capacity.

If the gear pump delivers the oil-air mixture at a constant rotational speed, then the

following modes of operation are possible depending on the volumetric gas content (α_p) at the inlet of the pump:

I. The real volumetric gas content of the oil-air mixture at the inlet of the pump is equal to the estimated value ($\alpha_p = \alpha_{calc}$), and the pump is pumping it with the volume flow Q_p , corresponding to the current pump delivery at n_p .

II. The real volumetric gas content lower than the calculated value ($\alpha_p < \alpha_{calc}$). In this case, the oil-air mixture supplied to inlet of the pump with a higher density, and since the pump delivery is higher, then there is an effect of emptying the pump suction nozzle. This leads to a reduction in the inlet pressure to the pump and to increase α_p . The process ends, when the value of α_p at the pump inlet is at equilibrium state. At a certain pressure value is broken continuity of oil-air mixture, which results in the stratified flow where the disperse flow is in the bottom (or inclined) of the pipeline.

III. The real volumetric gas content higher than the calculated value ($\alpha_p > \alpha_{calc}$). The pump delivery is lower than the volumetric flow rate at the pump inlet, and there is a dynamic flow choking effect. Thus, there is the pulsating flow of the oil-air mixture in the hydraulic circuit with the pump.

Flow of oil-air mixture on modes I, II, III can be realized at the any pump rotational speed within flow characteristics pump.

The flow instability of the oil-air mixture on the mode III is associated with the formation of density waves (kinematic wave) in the hydraulic circuit, which are distributed at a flow rate [2]. When $\alpha_p > \alpha_{calc}$ the gear pump cannot pump over oil-air mixture from inlet to outlet, and mixture accumulation starts at the pump inlet, resulting in a pressure increase and as a



Fig. 3. The character of the pressure fluctuations on the path of pumping working medium $(P_{oc_bot} - below the bottom of OC, P_{sc1_out} - at the outlet of ScP_1, P_{out1} - at the inlet of AGB)$

consequence, the reducing size of bubbles, the increasing density and the decreasing volume of the mixture. Then, the pump delivers a portion of oil-air mixture with greater density, which results in a pressure drop at the entrance, the density reduction, flow choking, etc.

As a result, the flow is formed at the pump outlet, divided into portions with different density. This iterative process of change in density leads to polyharmonic parameter fluctuations. Regular oscillations of pressure with a frequency of 0.2 ... 0.5 Hz and 3...8 Hz and damped oscillations with a frequency of 60 ... 110 Hz at the pump outlet P_{sc1} out observed in the experiment. The excitation of density waves reduces the efficiency of the breather system and leads to the accumulation of air in the oil, its foaming and air emissions. Processes for oil supply mode 18 1 / min and at the ratio of the exhaust flow rate to the supply flow rate (Ksc) equal 2 are shown in Fig. 3.

Pressure measurements were performed in the upper part of the oil chamber (P_{oc_up}) and in the pipeline of 0.2 m below the bottom of OC (P_{oc_bot}) to determine the characteristics of the oil-air mixture in the OC. Spectra and temporary recording of pressure without rotation of the bearing rotor shown in Fig. 4.

Pressure at the top of the OC P_{oc_up} has mean value of the oscillation amplitude of 0.002 ... 0.003 atmospheres (0.2 ... 0.3%), recording





Qsupply = 4.8 l/min and Qscavenge = 19.2 l/min has a noisy appearance, and the spectrum of pressure is a "white noise". This may reflect the chaotic nature of the processes in the upper part of the oil chamber.

Dense oil-air mixture is in the bottom of the oil chamber where the hydrodynamic processes are with large amplitude fluctuations, as evidenced by the temporary records of pressures and their spectra at frequencies of more than 5...10 Hz. The amplitude of the pressure oscillations at the bottom of the OC (P_{oc_bot}) is 0.012...0.018 atmospheres (1.2 ... 1.8%), which is almost an order of magnitude higher than the amplitude at the top.

Fluctuations with polyharmonic character are observed in temporary records of pressure Poc bot. This fact is evident in the spectra of the presence of numerous harmonics whose amplitude at frequencies above 20 Hz are several times higher than the amplitudes at the top of OC. Increasing the speed of the rotor bearings increases the intensity of the processes at the bottom OC. 3-fold increase amplitudes of harmonics was observed in pressure spectrum Poc bot at frequencies 40 ... 80 Hz, as compared with a mode without rotation. This indicates that formation process of oil-air mixture with a small size bubbles is intensifying.



Fig. 5. The color change of oil-air mix in the different moments of transient (the ScP1 outlet in the upper part of frame, the inlet - at the bottom)



Fig. 6. The color change of oil-air mix when turn on / off the pumps: 1 - after the pump start, 2 - 30 seconds after switching on the pump; 3 - after the pump shutdown

With increasing speed bearings from 4000 to 12000 rev / min, there is a darkening of oilair mixture, which also indicates a decrease in bubble size.

A video footage at Fig. 5 shows the color change of the working medium in the process of transition demonstration oil system at preset mode. In the initial state (time 0 sec), the oil are in the pipeline at the inlet of scavenge pump (Frame 0 in Fig. 5). Frame 10 (time 10 seconds) shows that the dark color of oil-air mixture is practically the same at the inlet and outlet of exhaust pump after switching pump, and after 20 seconds the mixture at the pump inlet began to lighten (lower part on frame 20), and it can be characterized as a finely dispersed. After switching on the drive of bearing the clarification process is accelerated (Frame 30). At steady state operation the oil-air mixture at the inlet and outlet of the pump becomes milky color throughout the piping diameter (Frame 60), but at the outlet is a bit darker. Increasing the pump pressure at 0.02 MPa leads to darkening of oil-air mixture in the pipeline at the scavenge pump outlet (Frame 90).

The oil-air mixture color varies depending on the ratio of these components and the size of the bubbles: pure oil - liquid dark yellow, air colorless, and gas emulsion - milky dispersion medium. The darker color of oil-air mixture in the pipeline at the pump outlet is due to the higher pressure at the pump outlet and, as a consequence, the smaller size of the bubbles, which increases the influence of the darkcolored oil.

The color of oil-air mixture was determined for evaluating the occurrence in the hydraulic circuit of oil system the stable finely dispersed mixture: after 30 seconds the color of oil-air mixture became lighter and stabilized after 40 ... 60 sec.; after stopping pump light color of oil-air mixture is observed even for some time (Fig. 6). Thus, it was noted that during operation the mixture remains finely dispersed despite local compression processes of oil-air mixture in the pump and its expansion in the pipes.

Decrease (increase) the size of the bubbles, when the pressure changes, characterizes the oil-air mixture as an elastic continuous medium. There is no coalescence processes in a moving stream. Resistance of oilair mixture to the coalescence of bubbles is caused by the presence in the oil surfactants as additives. Their influence is evident in the change of the surface tension of the oil at the oil-air interface, resulting in a slowdown of oil deaeration, i.e. process air outlet of oil.

Under static conditions, the dispersed air in 5 minutes is almost completely exposed to coalescence. The residence time of air in the oil when ascending of bubbles continues a few minutes, while the residence time of oil-air mixture in the entire oil pipeline circuit is much smaller - 5 ... 12 seconds.

Thus, the presence of surfactants in the oil, and the possibility of air entrainment changes depending on the oil properties fundamentally distinguishes the streams in the oil systems of GTE from the air-water streams in power plants, in which bubbles can form a larger connection.

The fact that the finely dispersed flow of oil-air mixture is in the hydraulic circuit of lubrication system, is also supported by a small value of the sound speed in the pipes. The sound speed is determined by analyzing the temporary records of pressure on the transient operation of the system. Fig. 7 shows the transition process when disconnecting the electric supply pump, when there is a hydraulic shock with damped oscillations at the natural frequency of 2.4 Hz.



turned off

The length of the single-lane pipeline from oil tank to the pump inlet is 2.5 m, then for the oscillation frequency 2.4 Hz is needed sound speed of oil-air mixture equal 24 m / s. This low sound speed can be realized in the finely dispersed flow of oil-air mixture [3], which has the characteristics of a homogeneous continuous medium. The low-frequency harmonic of 2.4 Hz there is also in the spectrum of the pressure fluctuations, along with the other harmonics: 17 and 34 Hz -1st and 2nd rotary harmonics, 170 and 340 Hz -1st and 2nd harmonics of teeth.

3 Mathematical modeling of the oil system

Dynamic mathematical model of the system [4] designed to investigate the causes of these phenomena, and select the electrical-driven pumps control laws. Mathematical model can count on steady and transient operating pressure, temperature, flow rate of the working fluid content in the nodes of the air entering the cavity of the oil-gas path of the engine, taking into account the thermal characteristics of the liquid and gas depending on the temperature, pressure and volumetric gas content

Mathematical model is based on a modular principle, representing a set of differential, integral and algebraic equations that reflects the relationship occurring in the system of hydraulic, gas and thermal processes based on discharge and power characteristics of pumps and actuators. Solution of the system model is carried out in a computer program by direct numerical calculation without iterations. Homogeneous model is used to describe a twophase mixture in the pipeline, which is considered as a homogeneous compressible Newtonian liquid and an ideal gas.

The assumptions of the mathematical model: the pressure, temperature and flow rate are equal in both phases over the pipe section; there are no phase transitions; not taken into account evaporation and condensation; the mass fraction of gas in the nodes at the entrance of the piping and pressure loss its length (travel, local, etc.) are subject to the additivity rule.

The basic equations of oil system are the equations of motion of two-phase mixture in the pipe to the pressure drop on the lumped



Fig. 8. Pressure transients when changing the supply pump delivery (calculation red)

resistance and inertia of the mixture. Also takes into account the change in pressure in the gasliquid chamber with inlet / outlet air flow working environment gear pump with variable volume and hydraulic efficiency and equation of calculate the rotor speed transmission "pumpmotor."

Testing of the developed mathematical model is made by filing the stepwise control signal to change discharge of supply and discharge pump with subsequent comparison of experimental and computational processes.

The calculated and experimental transients of pressures in the pumping path from the oil tank to P_{out1} when the rotor speed of bearings 8000 r / min are shown in Fig. 8. The initial value of the motor supply frequency of the supply pump was 18.7 Hz, and then frequency stepwise changed to 34.7 Hz. The frequency of scavenge pumps during these tests kept constant 25.6 Hz.



When changing the flow rate of the supply pump, the transients of pressure in the hydraulic path of the demonstration oil system are close to aperiodic. In the experiment / calculation the response time of supply pump pressure P_s is 1.9 / 1.9 sec. This time is determined mainly by inertial properties of the motor rotor. This time for the scavenge pump pressure P_{scl_out} and the pressure to AGB (P_{out1}) is greater and equal to 7.3 / 6.1 (time is determined from the beginning of growth to the steady state mode).

A characteristic feature of the processes when changing of the flow rate of the supply pump is the presence of a significant delay of the parameters growth in the pumping out path, equal ~3 sec. Such time was caused weak growth of pressure in the upper part of the OC $(P_{oc_up}) - 2$ sec, and yet slower growth P_{oc_bot} in the lower part of the OC – 3 sec, in additional there is a delay – 1 sec with respect to pressure P_{oc_up} .

Slow growth pressure P_{oc_up} and P_{oc_bot} due to the compressibility of the working fluid in the oil chamber, and the growth delay of pressures in the pumping out path - the advent of the increased density of mixture to the scavenge pump outlet through 0.9 sec (kinematic wave). At change of flow rate of scavenge pump the experimental and calculated transients are significantly different from the processes when was changed the flow rate of supply pump (Fig. 9). The initial value of the motor supply frequency was 25.6 Hz (Ksc = 2), the stepwise transition to the frequency equal 40.6 Hz (Ksc=4).

It is seen that by increasing the scavenge pump delivery is observed the overshooting pressure is at the pump outlet and AGB (undershooting pressure at the pump inlet) and big response time. The most rapid processes of the pressure are at the pump inlet P_{sc1} in. The pressure time of drops in the experiment/calculations is equal to 0.56 / 0.55 seconds, and further pressure increase with time is equal to 1.5 / 2.5 seconds. The peak time of pressure at the scavenge pump outlet and pressure at the inlet of AGB is almost three times higher and is equal to 1.9/1.1 seconds, and settling time is 7.2 / 6.1 seconds. Such processes are due to the compressibility of the mixture.

The cause of overshooting (undershooting) parameters is a slow change of volumetric gas content in the system - in 4.5 seconds. The mixture of high-density first comes after a disturbance and forms the front edge of pressure. After 2 seconds, the density decreases and the trailing edge of parameters change is realized.

The values of the parameters obtained by calculation and experiment, close to both the duration and magnitude of overshooting pressure, it's reflects the accuracy of the developed mathematical model of the lubrication system.

4 Conclusions

1. Visually-spectral analysis of flow oil-air mixture in the hydraulic circuit of the demonstration oil system with electrically driven gear pump, made with medium temperatures 20...70 °C and with real volumetric gas content in the oil-air mixture in the pumping out circuit $\alpha_n = 0.2$... 0.5 have shown that:

- The dispersed oil-air mixture has the properties of an elastic continuous medium, which explains the existence of elastic deformation in the process of enforced flow with the local expansion and compression the stream;
- The dispersed oil-air mixture has the properties of an elastic continuous medium, which explains the existence of elastic deformation in the process of enforced flow with the local expansion and compression the stream;
- In the oil chamber stable finely dispersed oil-air mixture (bubbles exit time 5 minutes) is formed, whereby when finding oil-air mixture in the pipeline of lubrication system for 5-12 seconds coalescence of air bubbles is not observed.
- The presence of surfactants in the oil, and the possibility of air entrainment changes depending on the oil properties fundamentally distinguishes the streams in the oil systems of GTE from the airwater streams in power plants, in which bubbles can form a larger connection;
- In the upper part of the oil chamber the oil-air mixture is formed, where due to the effect of gravitational forces on the oil film bubbles tend to rupture with subsequent coarsening. If the bubbles came to the pumping out circuit, then they clutter up the passage of the pipeline section and going a little bit faster relative to oil-air mixture without mass transfer with it;
- flow structure of the dispersed oil-air mixture is formed by the flow characteristic of gear pump; the stratified flow can be realized when there is an effect of emptying the pump suction nozzle, and on the modes of dynamic flow choking the pulsating flow can be realized with forming density waves in the pumping out circuit from oil chamber to the oil tank with excitation of polyharmonic fluctuations;
- If set up the stepwise signal of pump speed, then if the pump is operating on

pure oil (without air inclusions), then transients in the system will be stable and aperiodic, but if the pump is operating on the oil-air mixture, then transients are oscillatory, possible overshooting parameters (pressure, flow et al.) and increased power consumption of the pump.

2. Numerical and experimental study of characteristics of the oil system with electrically driven supply and scavenge pumps showed that the mathematical modeling of such systems must take into account the inertia and compressibility of a working environment, which varies depending on the volumetric gas content, which is variable over path of pumping. Satisfactory convergence of calculated and experimental data was obtained by using the homogeneous model without the relative velocity of the liquid and gas phases for description of the two-phase mixture, for gear description was accounted partial pump compression of liquid and gas. The ability to use a homogeneous model is proved by the analysis of acoustic vibrations in the system.

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