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High speed visualizations of oil jet lubrication for aero-engine gearboxes

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Abstract

Augmenting gearing systems efficiency is a key issue in developing innovative aero-engines with low specific fuel consumption. The transmission system directly affects the engine overall efficiency, therefore it is essential maximizing its performance. In high speed applications fluid-dynamic losses become predominant and are directly connected to the lubrication method. Oil jet systems are generally used in order to achieve a proper cooling and lubrication of tooth surface.
A novel rotating test rig was exploited for investigating oil jet lubrication by means of high speed visualizations. An oil jet impinging radially on a single spur gear was generated by a spray-bar, assessing which parameters affect the oil jet behavior.

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Keywords: Gearbox; oil jet lubrication; high speed visualization; liquid break-up.

1. Introduction

The efforts made in the recent years in reducing the environmental and climate impact from air traffic are leading aero-engine industry and research community towards innovative engine technologies aimed at minimizing the

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specific fuel consumption (SFC). For turbofan engines, a bypass ratio enhancement is the way forward to successfully augmenting propulsion efficiency, as well as reducing jet noise and engine emissions [1]. Regardless of the identified engine concept, high performance gearing systems have a crucial role in achieving such goal; this moves the attention on the transmission efficiency, which directly affects the SFC. Nowadays gearboxes can reach efficiencies higher than 99% [2], nevertheless in high power applications research for power losses reduction is of primary importance.

A performance enhancement can be achieved developing a physical understanding of the losses within the transmission system. These are classified into load-dependent and load-independent groups [3]. The former are primarily related to a mechanical power loss due to friction at the gear contact, while the latter are related to fluid-dynamic effects, which includes bearing losses, gear windage, fluid trapping and squeezing between meshing gear teeth, inertial losses resulting by impinging oil jets. In high speed gearbox systems, in fact, lubrication is accomplished adopting nozzles to develop small oil jets heading for the gear teeth. A proper cooling and lubrication of tooth surface is mandatory for preventing gearbox failure. The understanding of the oil behaviour inside gearbox is therefore desirable, in order to minimize lubrication losses and reduce the oil volume involved, while retaining gearbox reliability. For a gearbox designer is very important realize how oil penetrates into the gear tooth space under dynamic conditions, to determine how much oil is involved in cooling and lubrication processes.

A pioneer work on this matter was done by Akin et al. [4], which used a high speed camera to observe the oil jet interaction with a rotating gear at different working pressures and rotating speeds. They found a strong influence of the air flow field generated by the gear movement with the jet break up and measured the jet penetration within two teeth to provide an experimental validation to numerical models.

A new rotating test rig, installed at the Department of Industrial Engineering of the University of Florence, was exploited to investigate oil jet lubrication by means of high speed visualizations. An oil jet impinging radially on a single spur gear was generated by a spray-bar, assessing how rotating speed affects the oil jet behaviour. Acquisitions made from two different points of view provided useful information on the oil jet break up as well as the oil film formation on the tooth surface as result of the oil jet impact.

Nomenclature

air	Air property
D	Diameter
L_j	Jet to teeth spacing
L_f	Gear face width
p	Pitch property
j	Jet property
q	Liquid to gas momentum ratio
U	Velocity
UR	Velocity ratio
We_{cf}	Crossflow Weber number
Z	Number of gear teeth
ρ	Density
σ	Surface tension coefficient

2. Experimental set-up

The test rig exploited for this experimental campaign allows a single gear to rotate at high speed within a box where pressure and temperature conditions can be set and monitored. As sketched in Fig. 1 an electric spindle imposes the rotation to a shaft which is connected to the gear through a bearingless torque-meter equipped with a speedometer providing the rotating velocity.

A lubricating circuit equipped with a flowmeter provides oil, at controlled mass flow rate, temperature and pressure, to the bearing chamber. Exploiting a gate valve, the same lubricating oil feeds another branch of the circuit which is equipped with a flowmeter and is connected to the spraybar placed within the test box; hydraulic oil ISO VG 46 has been used in this experimental survey. The oil jet axis was oriented perpendicularly to the wheel axis, while axial position of the spray bar was fixed so that the oil stream impinges the centre of the tooth face. Gear geometrical features and jet to teeth spacing, made dimensionless using the jet diameter, are summarized in Table 1.

Table 1 Characteristic dimensions.

D_p/D_j	L_f/D_j	L_j/D_j	Z
152	55	75	38

In order to perform tests at different pressure conditions, the test box is sealed and equipped with a pressure tap connected to one of the 16 silicon piezoresistive pressure sensors contained in the Netscanner 9116, differential pressure scanner which guarantees an accuracy up to ±0.05% of the full scale (1bar).

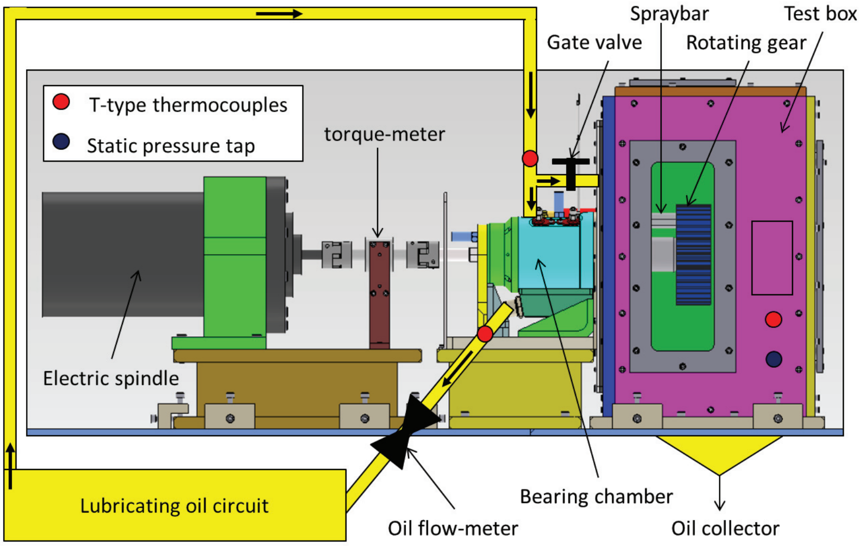

Fig. 1. Test rig layout.

Air and oil temperatures are measured using T-type thermocouples connected to a data acquisition/switch unit (Agilent 34970A) with a measurement accuracy of 0.5 K. The test box is also equipped with three optical accesses in order to perform high speed visualization and particle image velocimetry measurements.

A Phantom Miro M340 camera was used for high speed oil jet visualization, a maximum acquisition frequency of 25 kHz was reached recording 240x320 pixels per frame. A halogen lamp provided the needed light intensity given the low time of the shutter opening. Two optical accesses were used as clearly reported in Fig. 2.

2.1. Test conditions

The oil jet delivered by spray-bar system has to pass through a rotating air flow before impacting on gear teeth. As proposed by Fondelli et al. [5] such phenomenon can be modelled as a liquid jet in high-speed crossflow, where air flow speed is comparable to the pitch line velocity, at least close to the gear teeth (see Fig. 3.a). For such issue, several empirical correlations have been developed by researchers for predicting the liquid column trajectory, namely breakup distance and height, as a function of flow conditions [6], [7]. The main parameters governing the phenomenon are the liquid to gas momentum ratio, Equation 1, and the crossflow Weber number, Equation 2, where

ρ_{air} and ρ_j are the air and oil jet density, D_j is the jet diameter, considered here as the diameter of the hole generating the jet itself, U_p is the air velocity, here taken as the pitch line velocity, U_j is the jet velocity, and σ is the surface tension coefficient. As far as the jet penetration through the crossflow is concerned, it is a growing function of q, while jet's breakup is controlled by We_{cf}.

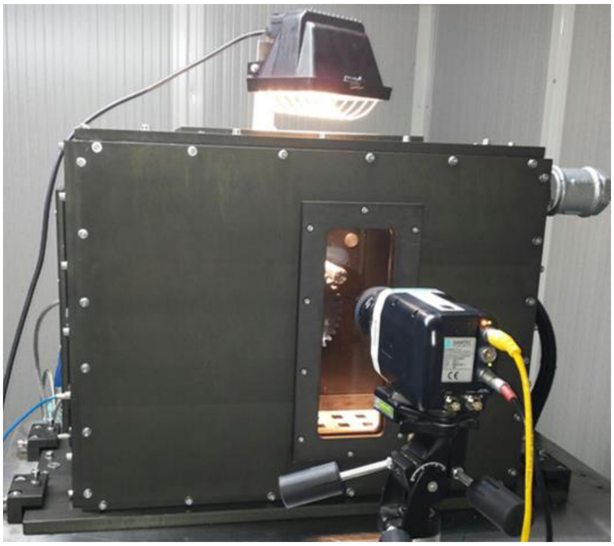

Fig. 2. High speed camera and illuminator setup.

$$q = \frac{\rho_j U_j^2}{\rho_{air} U_p^2} \tag{1}$$

$$We_{cf} = \frac{\rho_{air} D_j U_p^2}{\sigma} \tag{2}$$

As indicated by Sallam et al. [8] for round non turbulent liquid jets in air crossflow, liquid breakup properties are not significantly affected by the liquid to gas momentum ratio, while transitions between various breakup regimes is well described by crossflow Weber number. Four regimes were defined: column breakup, bag breakup, multimode breakup and shear breakup, where transition between the various regimes occurs at We_{cf} equal to 4, 30 and 110. In Fig. 3.b pulsed shadowgraph photographs of bag breakup, left picture, and shear breakup, right picture, of round non turbulent liquid jets in gaseous crossflow performed by Sallam et al. [8] are shown.

Considering the jet impact with the teeth, the quantity of oil interested by the phenomenon, as well as the penetration of the jet into the teeth space, depends on the ratio between the teeth and the oil velocities, defined as:

$$UR = \frac{U_p}{U_j} \tag{3}$$

During the experimental survey discussed in the present work, the pressure within the test box was set at ambient condition and the jet velocity was kept constant, therefore the various working conditions have been changed acting on the wheel rotating speed. Three configurations were tested, by fixing the velocity ratio at 1, 4 and 12, as summarized in Table 1.

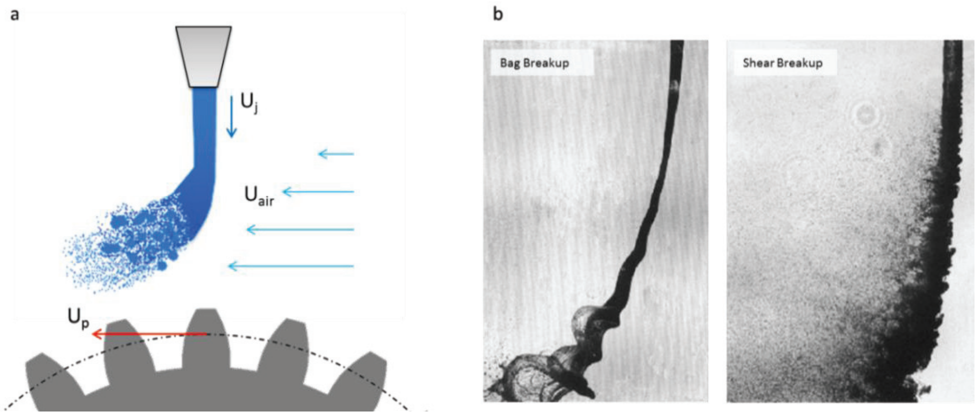

Fig. 3. (a) sketch of liquid jet in the air crossflow; (b) visualization of bag breakup (We = 8) and shear breakup (We = 220) processes of round non turbulent liquid jets in gaseous crossflow performed by Sallam et al. [8].

Table 2Experimental test matrix

Test number	UR	Q	We_{cf}
1	1	875	2
2	4	55	37
3	12	6	366

Referring to Fig. 4, We_{cf} and momentum ratio of the tested condition are indicated by black dots, while color bars have been exploited for highlighting the different breakup regimes defined by Sallam et al. [8]: as can be seen the tested conditions allow to cover the entire range of breakup modes. At the lowest velocity ratio the We_{cf} is close to one thus a notable oil jet deformation and breakup is not expected. On the contrary, for UR fixed to 12 a shear breakup is expected due to a significant enhancement of the air velocity and hence of aerodynamic forces acting on the lubricant flow.

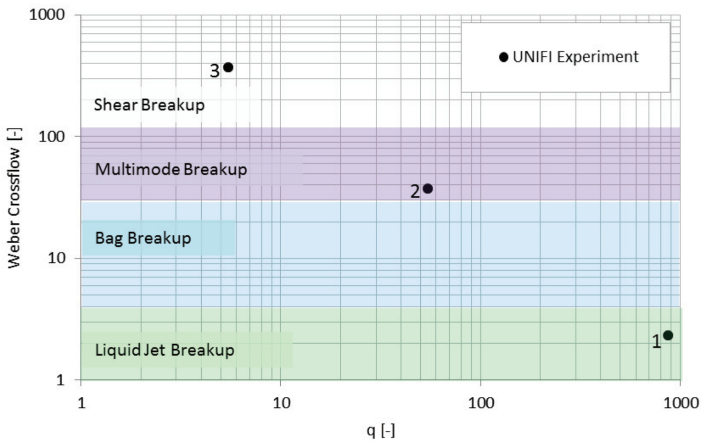

Fig. 4. Experimental test matrix.

3. Experimental results

The videos were acquired with a frequency of 25 kHz, the frame rate was chosen in order to record at least three images for each tooth passage at every velocity. In the next sections every test condition will be represented by three frames reproducing the complete passage of a single tooth through the oil jet. The phenomenon was observed from two different points of view:

- Lateral view, in order to be perfectly orthogonal with the gear, observing the jet penetration within the teeth spacing;
- Isometric view, in order to look at the jet spreading after the hit with the tooth to understand the lubricating capability and its breakup.

3.1. Lateral view

Fig. 5 shows the tests performed from the lateral view, as it is possible to note, the jet is radially directed against the gear. Observing the test at $We_{cf} = 2$ it is evident that the oil jet is slightly influenced by the gear motion until it hits the tooth. After the impact, a portion of oil is thrown away and broken in a series of small particles, while the other enters into the tooth cavity and contributes to the lubrication.

The aerodynamic load acting on the oil jet grow as the wheel speed is increased, as shown clearly in Fig. 5: at $We_{cf} = 366$ in fact the oil jet breakup occurs before the oil reaches the gear tooth, highlighting the strong interaction between the rotating flow field and the jet itself.

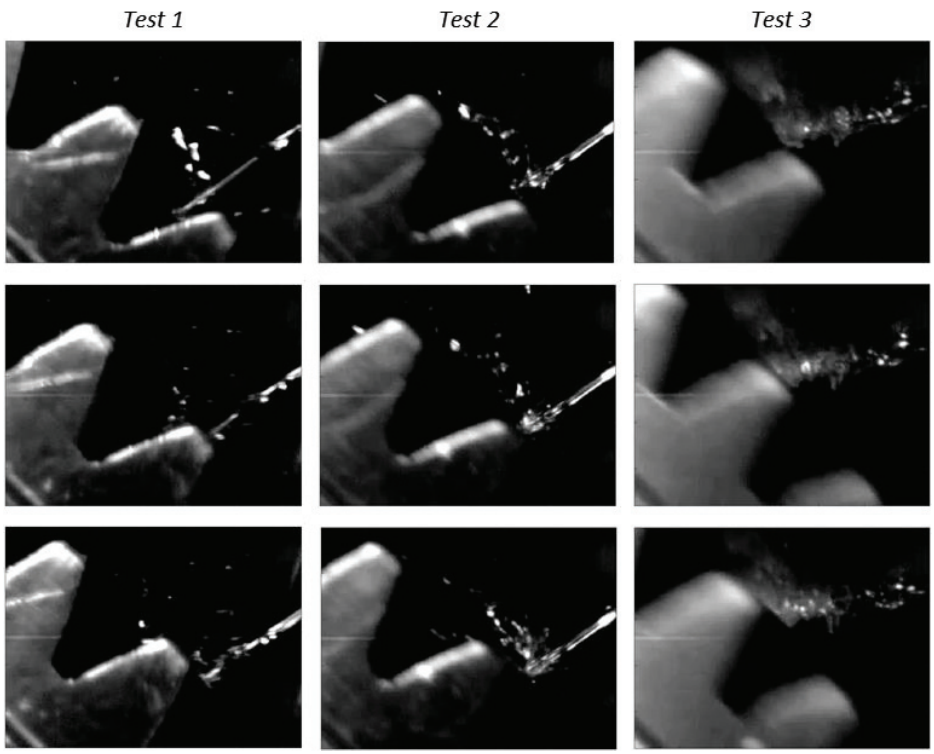

Fig. 5. Lateral view.

The effect of the UR parameter is basically geometrical; this means that the cavity between the two teeth is opened for a certain time so the quantity of the oil that penetrates inside depends only on its velocity. The jet penetration is directly linked with the capacity of lubricating the gear, as can be observed from the isometric view.

3.2. Isometric view

Given the better lighting achieved by the isometric view, it was possible to look inside the teeth spacing, observing the oil spreading within the vane.

The high quality images reported in Fig. 6 reveal that at UR = 1 the oil jet enters into the tooth valley deeply, then hits the tooth flank forming a thin liquid film which expands with high speed both axially and radially toward the tooth root. With increasing the wheel rotational speed, firstly the velocity ratio enhances thus the jet does not have time to enter within the vane before another tooth passage, and secondly increases the crossflow Weber number therefore promoting the oil jet breakup. For these reasons when UR = 4 the amount of oil involved in the gear lubrication process is reduced with respect to the lower velocity ratio, while when UR is fixed to 12 only the gear top land is lubricated.

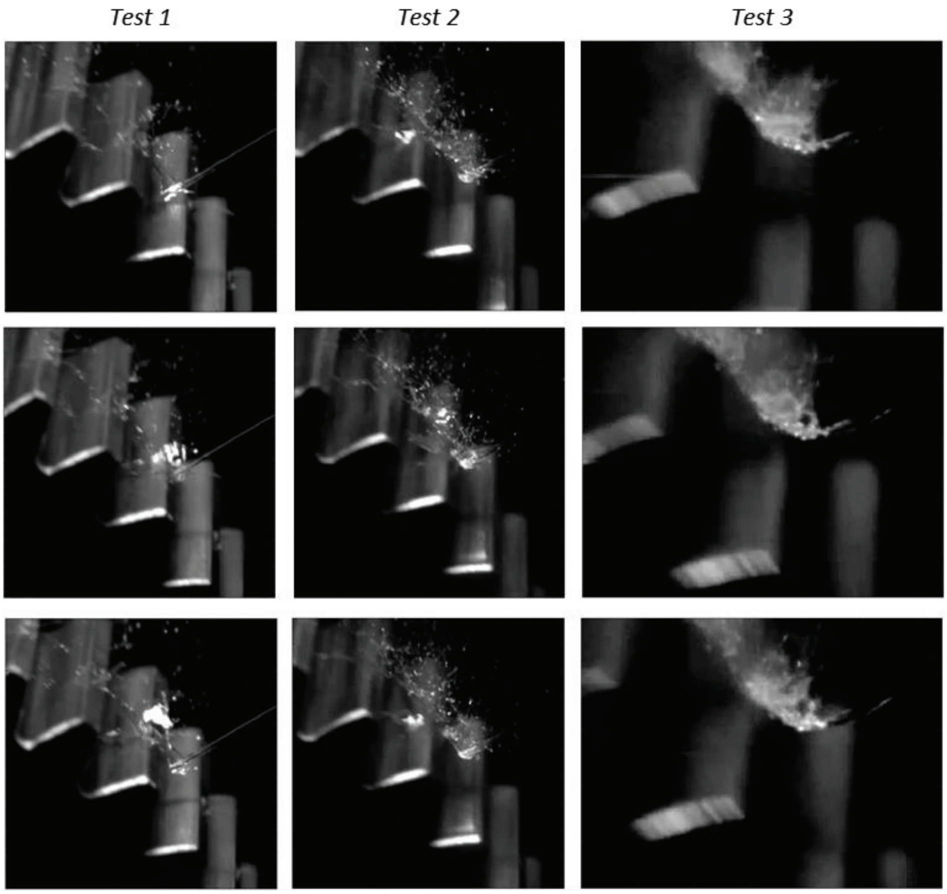

Fig. 6. Isometric view.

4. Conclusions

A new rotating test rig placed at the Department of Industrial Engineering of the University of Florence was exploited for high speed visualization of an oil jet impinging on a rotating gear. Results were showed in terms of sequential frames providing the evolution of a single tooth passing through the oil jet for different rotating velocities. Test conditions were expressed in terms of a jet to pitch line velocity ratio in order to take into account the geometrical conditions at different rotating speeds, and the crossflow Weber number which helps to describe the physical phenomenon of a jet in an air cross-flow. Tests were conducted with constant oil velocity and changing the gear rotational speed.

For low values of velocity ratio, the oil jet enters into the tooth valley where forms a liquid film as the result of the oil-gear interaction. When the rotating velocity is increased the jet penetration is reduced, as well as the amount of liquid involved in the lubrication process, as long as the jet is only able to cover the gear top land when the maximum tested speed is reached. The effect of the air flow field generated by the spur gear rotation was also investigated observing the different breakup of the jet at different Weber conditions: when We_{cf} is low the jet reaches the gear maintaining the same shape, while at higher We_{cf} values the air moved by the gear causes the jet's breakup, thereby creating ligaments and droplets.

These experimental results are only the first step towards the creation of a high reliability test case for CFD validation.

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