

Laser Flow Sensor for Lubricating Oil

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Abstract – This work describes the development of a laser instrument for measuring the flow speed of oil, for minimum-quantity lubrication. The sensor is the laser diode itself, placed on the oil tube without any lens, acting as a self-mixing interferometer. The dyes inside the oil induce a back scattering of the emitted light, and generate a Doppler signal, measured by the laser monitor photodiode. Through a suitable elaboration of the signal spectrum, it is possible to estimate the oil flow; this measurement is essential for the correct maintainability of machine tools.

I. INTRODUCTION

Typically, the maintenance of machine tools requires lubrication, sometime minimal lubrication, of components and mechanical elements subject to friction. For example, the lubricated elements could be ball bearings of high-speed spindles, for machine tools used in machining centers, or milling machines, boring machines, grinding, drilling, and turning centers of the rolling bearings for supporting rotating axes, as well as the tools in the processes of removal of shavings. A good control of the amount of oil is important for the correct working of the tools.

The standard techniques for controlling the lubrication consists in measuring the oil volume pushed, directly at the pressure pump site. In this work, we propose a novel optical method for measuring the oil flow, based on self-mixing interferometry [1-3]. Thanks to this sensor, it is possible to control the oil flow directly at the site of the lubricated mechanical element, therefore enabling a higher level of detection and diagnostics.

II. OPTICAL SETUP

The proposed optical method for measuring the oil flow is based on self-mixing interferometry. This technique takes advantages of the small disturbances suffered by a laser when subjected to optical back-injection [1]. The main effect consists in a modulation of the emitted power, periodic function of the target distance with period half wavelength $\lambda/2$. An advantage of this technique, with respect to the more standard interferometry, is the optical setup, simple and compact if compared with standard interferometry [4]. A number of applications are described in literature, starting from the contactless measurement of displacement-vibration-speed [5-7], with different approaches for the signal processing

[8-11], also with electrical feedback [12-15]. By modulation of the laser pump current, the self-mixing interferometer can measure also the absolute distance [16-19], and it can be used for estimating some laser parameters [20, 21]. Since the early developments of self-mixing interferometry, a significant application was the flow measurement [22-26], mainly based on the evaluation of the Doppler shift in the signal measured by the laser monitor photodiode. The most studied application is the measurement of blood flow [27-30], but most results are applicable to any liquid containing scattering particles. A recent development consist in eliminating each optics, and placing the laser diode directly on the tube [31]. The Doppler signal appears thanks to the natural divergence of the laser diode. Fig. 1 shows a schematic description of the optical setup.

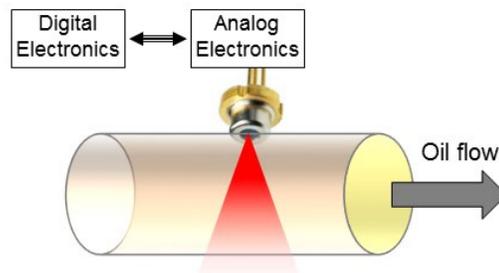


Fig. 1. Sensor scheme.

When the oil flows, the diffused light exhibits a sum of different Doppler shift contributions, depending on the angle α between the laser beam and the movement direction. Each single scattering particle, dragged by the flow at a speed v , induces a Doppler shift equal to

$$f_{\text{Doppler}} = \frac{2}{\lambda} \cdot v \cdot \cos \alpha \quad (1)$$

The self-mixing interferometer integrates all the single scattering contributions, and produces a laser power modulation, measured by the monitor photodiode. For this lensless configuration, the output signal exhibits a broadened spectrum, due to the sum of all the single scattering contributions. In the case of lubricating oil, the scattering particles are mainly the added dyes.

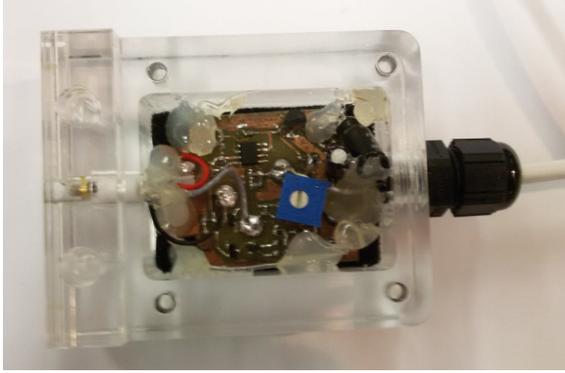


Fig. 2. Sensor photo.

III. SIGNAL PROCESSING

The first sensor prototype is shown in Fig. 2. It includes a laser diode (780 nm, 20 mW), the analog electronics for driving the laser and a trans-impedance amplifier for reading the current of the monitor photodiode. The output signal is sampled by a 12 bit data acquisition card (DAQ), at 50 kSa/s. A PC elaborates the acquired signal and estimates the flow in real-time. Next realizations will include a microcontroller for substituting the DAQ and the PC.

In the time-domain, the signal appears noise-like, but in the frequency-domain it shows a deterministic behavior, depending on the flow speed. For example, Fig. 3 shows the spectrum of the signal acquired in correspondence to an oil flow of 2 drops per second, compared to the noise floor (signal acquired without oil motion).

The optimum signal processing was studied in [31]: in order to find the flow speed, the implemented algorithm is a sort of center of gravity calculation, with nonlinear weight of the spectrum: it is calculated as a weighted average of the difference of the power spectrum $S(f)$, and the noise floor $S_{noise}(f)$ in logarithmic scale.

$$f_0 = \frac{\int_0^{f_{MAX}} \text{Log}(S(f) - S_{noise}(f)) \cdot f \cdot df}{\int_0^{f_{MAX}} \text{Log}(S(f) - S_{noise}(f)) df} \quad (2)$$

The integral is limited to the frequency f_{MAX} , that indicates the first intercept between the signal spectrum and the noise floor. The calculated mean frequency f_0 exhibits a linear dependence with the flow rate [31].

Fig. 4 shows the acquired spectra after subtraction of the noise floor, for three different flow rates: 0.4, 1 and 2 drops/s.

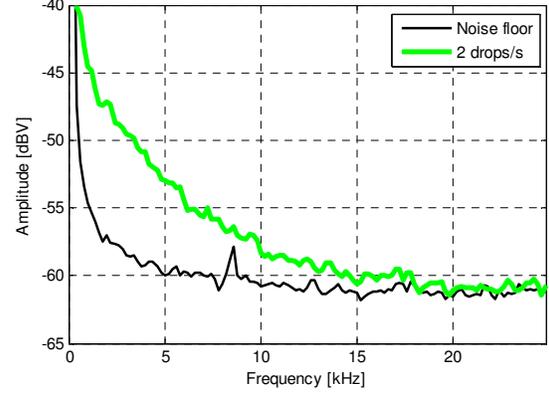


Fig. 3. Spectrum of the acquired signal, in correspondence to a flow of 2 drops/s (thick line), compared to the noise floor (thin line).

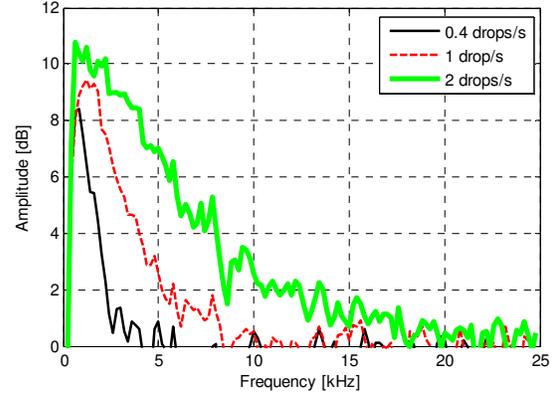


Fig. 4. Signal spectra after the noise-floor subtraction, for different flow rates.

The sensor needs a calibration, because the absolute flow measurement depends on the tube dimension and on the particular laser divergence. A custom-made LabVIEW program calculates the Fast Fourier Transform on 128 samples, implements eq.(2) and shows in real-time the estimated flow-rate. For the particular application of minimal lubrication, the amount of oil-flow is typically indicated in drops/s, therefore we calibrated the sensor by counting the drops fallen in one minute. The sensor can work with a dedicated cuvette, such as in Fig. 2, or directly on a silicon tube. In both cases, the flow is laminar, because of the small speed and high viscosity of the oil.

IV. MEASUREMENT RESULTS

The realized prototype was tested in different conditions: the best results are obtained for small tube (diameter of about 1 mm), because the scattering of the oil is really low (by eye it is impossible to see the flow). Table 1 reports the measurement results for the sensor

working directly on a small tube (internal diameter of 1 mm), calibrated at the rate of 1 drop/s.

Table 1. Sensor characterization.

Real flow-rate [drops/s]	Measured flow-rate [drops/s]
0.3	0.31
0.4	0.39
0.8	0.84
0.9	0.96
1	1.00
2	2.02
3	2.80

The sensor confirms a good linearity for flow-rates up to about 2 drops/s, with a sort of saturation for higher speed, mainly due to the limited sampling frequency. The limit was chosen for the particular application of minimal lubrication, where 2 drops/s is already an high flow-rate. By repeated measurements at different flow-rates, we characterized the sensor: for each flow, we repeated 100 measurements and the evaluated standard deviation is about 1% of the measured value. The real flow-rate was evaluated by counting the number of drops in one minute, and the sensor showed a maximum error always less than 10%. We can conclude that, after a proper sensor calibration, the measurement uncertainty is lower than 5% for the flow range of interest. These performances are well adequate for the monitoring and control of minimal lubrication in industrial applications.

V. CONCLUSIONS

The proposed optical sensor demonstrates qualities well adequate for the application to monitor and diagnosis of minimal lubrication: it is low-cost, because it does not need any optics nor alignment; it is small-size and it can be placed directly on the connection tubes. Its performances, in terms of resolution and accuracy, fit the industrial requirements; therefore, it will be soon ready for commercial applications.

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