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Modelling and measurement of wear particle flow in a dual oil filter system for condition monitoring

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ABSTRACT

Wear debris is an indicator of the health of machinery, and the availability of accurate methods for characterising debris is important. In this work, a dual filter model for a gear oil system is used in conjunction with operational data to indicate three different system operating states. The quantity of wear particles in gear oil is analysed with respect to system running conditions. It is shown that the model fits the data in terms of startup "particle burst" phenomenon, quasi-stationary conditions during operation, and clean-up filtration when placed out of operation.

In order to establish boundary condition for particle burst phenomenon, the release of wear particles from a pleated mesh filter is measured in a test rig and included in the model. The findings show that a dual filter model, with startup phenomenon included, can describe trends in the wear particle flow observed in the gear oil. Using this model it is possible to draw conclusions on the filtration system performance and wear generation in the gears. Limitations of the proposed model are the lack of ability to describe noise and random burst spikes attributed to measurement error distributions. Trending of gear wear particle generation is made possible by model parameter estimation and identification of an unintended lack of filter change. The model may also be used to optimise system and filtration performance, and to enable continuous condition monitoring.

1. Introduction

Estimation of wear debris generation from oil lubricated machinery and models of contamination present in lubricating oil can be used to assess the systems' condition and follow trends towards machinery breakdown as described for instance by [1–4].

Prior work by Anderson, Driver, Kjer and Szymczyk [5–7] introduced equations for run-in, equilibrium conditions and break-down based on wear generation rate equations. The system differential equation for wear particle concentration rate in machinery with a single oil filter is

$$\frac{dC}{dt}=\frac{1}{V}\left\{\frac{dM_I}{dt}+\frac{dM}{dt}+\frac{dM_F}{dt}-\frac{dM_R}{dt}\right\}, \tag{1}$$

where C is the wear particle concentration (g/m^3), V is the oil volume (m^3), M_I is the initial wear particle mass during run-in (g), M is the wear generation particle mass (g), M_F is the final particle mass (g) generated during break-down and M_R is the removed particle mass (g) from filtration, settling and comminution.

Introduction of stochastic variations to the wear generation rate equations, due to surface asperities, was described by Yan et al. [8], and extension to array notation for coupling different wear debris particle size to tribological wear modes was shown by Henneberg et al. [9].

In this paper we present a dual oil filter model, as seen in Fig. 1, valid only for the quasi-stationary state, as depicted in Fig. 2. This adds a way of simulating wear particle concentration of the gear oil system according to specific run conditions. Quasi-stationary means that the run-in and break-down phase of Eq. (1) is neglected in the model.

We relate the proposed model to run condition data from a ship thruster gear, and compare the estimated wear particle concentration to data from a particle sensor measuring in the gear oil.

Reference, cited measurements and equations in [5–8] are based on direct reading ferrography, and therefore on one-dimensional arrays, which enable segmentation of particles smaller or larger than 5 μm. Current techniques have progressed towards inline measurements with an optical blocking sensor, see

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Nomenclature

Greek symbols

β_{if}	particle retention capability, inline filter (5 μm) (–)
$\boldsymbol{\beta}_{\mathbf{if}}$	array of particle retention capability, inline filter (–)
$\boldsymbol{\gamma}_{\mathbf{if}}$	amplitude of particle burst, inline filter (–)
$\boldsymbol{\tau}_{\gamma}$	time constant array of particle burst, inline filter (h)
$\boldsymbol{\tau}_{\mathbf{if}}$	time constant array of particle burst release process, inline filter (h)

Roman symbols

C	particle concentration (g/m^3)
$\mathbf{C}$	concentration array according to different wear particle sizes (g/m^3)
$\mathbf{I}$	identity array (–)
$\mathbf{k_{if}}$	filtration coefficient array, inline filter (–)
$\mathbf{k_{of}}$	filtration coefficient array, offline filter (–)
$\mathbf{m_{if}}$	array of wear generation particle mass retrained by inline filter (g)
M	wear particle mass generation (g)
$\mathbf{M}$	array of wear generation particle mass (g)
M_F	final wear particle mass generation(g)
M_I	initial wear particle mass generation (g)
M_R	removed wear particle mass by filtration, settling and comminution (g)
$\mathbf{M_{Rif}}$	array of removed wear generation particle mass by inline filter (g)
$\mathbf{M_{Rof}}$	array of removed wear generation particle mass by offline filter (g)
$\mathbf{P_0}$	array of constant wear generation particle mass (g/h)
q_{if}	flow, inline filter (m^3/h)
q_{of}	flow, offline filter (m^3/h)
$\mathbf{S_{if}}$	array of wear particle mass burst from inline filter (g/h)
t	time (h)
V	oil volume (m^3)
$\mathbf{W}'(t)$	array of stochastic variations in wear generation particle mass (g/h)

for instance Li and Zhe, Sjödin and Westin [10,11]. Such a technique has the ability of segmenting particle contaminants into size bins for quantity investigation in the size region 4 μm to > 70 μm (upper limit typically around 200 μm as tested in [12]).

Expanding the system differential equation, Eq. (1), for wear particle concentration rate during a quasi-stationary state ($dM_I/dt \to 0$ and $dM_F/dt \to 0$) and introducing array notation from [9] in a dual oil filter system:

$$\frac{d\mathbf{C}}{dt} = \frac{1}{V}\left\{\frac{d\mathbf{M}}{dt} - \frac{d\mathbf{M}_{Rif}}{dt} - \frac{d\mathbf{M}_{Rof}}{dt}\right\} \tag{2}$$

leads to a set of equations for the different running condition states, where the array notation differentiates particles according to different sizes. In Eq. (2), **C** is the concentration array according to the different wear particle sizes, **M** is the array of wear particle mass generated by the machinery, $\mathbf{M}_{Rif}$ and $\mathbf{M}_{Rof}$ are the arrays of wear particle mass removed by inline and offline filters respectively.

In Section 2 we present a numerical state model solution of the system, according to Eq. (2) with different run conditions for the system.

During inline filter startup, a particle burst phenomenon is observed, attributed to the partial release of retained particles. This burst phenomenon, $\mathbf{S_{if}}$, introduced in Section 2, is documented in a scaled laboratory test sequence using a pleated mesh filter, outlined in Section 3, in order to evaluate the quantity released during startup. The results of this measurement serve as the boundary conditions for the model.

In Section 4 the model is compared with measurement data from a ship thruster system. Discussions of the presented model and conclusions are found in Sections 5 and 6 respectively.

2. Methodology

For a system in a quasi-stationary state the run-in term, dM_I/dt, in Eq. (1) is negligible since the run-in has already passed and due to a non-initiated break-down, the term dM_F/dt is also vanishing. The terms in Eq. (1) can be described by introducing the wear rate constant, $\mathbf{P_0}$ (g/h), and stochastic variations, $\mathbf{W}'(t)$ (g/h) from [8], due to surface asperities, as well as the filtration coefficients k_{if}, k_{of} and flow q_{if}, q_{of} (m^3/h) for the inline and offline filters respectively,

$$\frac{d\mathbf{M}}{dt} = \mathbf{P_0} + \mathbf{W}'(t), \tag{3}$$

$$\frac{d\mathbf{M}_{Rif}}{dt} = q_{if}\mathbf{k_{if}}\mathbf{C}, \tag{4}$$

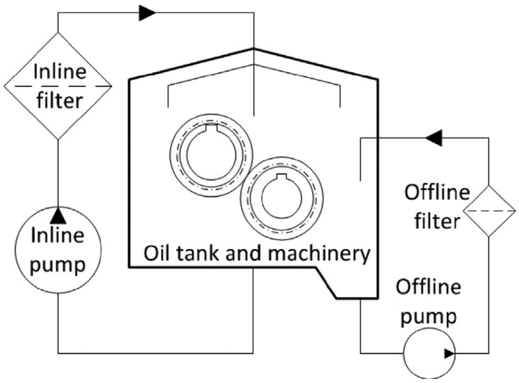

Fig. 1. Sketch of the dual oil filter lubricating system including gear, pumps, inline and offline filters.

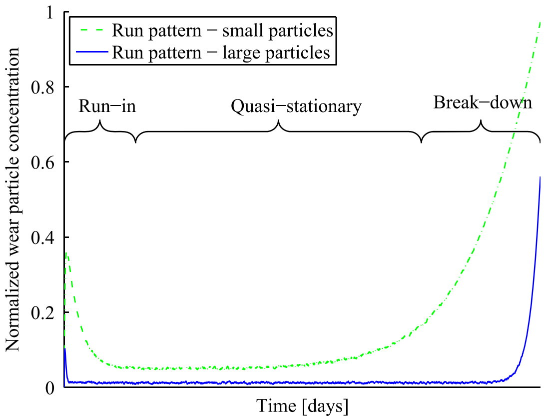

Fig. 2. Run pattern of the equipment life cycle with focus on the quasi-stationary state. Figure reproduced from [9].