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Model Based Condition Monitoring of an Air Filter

Condition oriented maintenance can best exploit the wear potential of an assembly group on the one hand, and on the other hand can prevent down times. The challenge is to reliably monitor the assembly-group being maintained, especially if its status cannot directly be derived from one measuring parameter. Using model-based methods could offer a solution for assessing the measured values correctly, depending on the operating conditions. To monitor the condition of an air filter, a model-based method was developed at ILF, implemented as prototype on a tractor and tested in field experiments.

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Keywords

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Self-propelled agricultural machines are highly complex units today. For maintenance, this leads to the following goal conflict: On the one hand, cost reasons require that the wear potential of machinery parts and assemblies is exploited as much as possible before they are exchanged. On the other hand, unforeseen standstill and downtimes of these machines should be kept to a minimum. Here, a condition-oriented maintenance strategy is a promising potential solution. However, this entails the challenge of reliable condition diagnosis of the assembly to be maintained. Therefore, a model-based method was developed at the Institute for Agricultural Machinery and Fluid Power (ILF) which enables the condition of the upstream air filter of a combustion engine to be diagnosed on-line.

State of the art in air-filter monitoring and maintenance

The task of air filters is to prevent the dust contained in the intake air from reaching the engine. In a combine, for example, average dust concentration in the intake air can amount to up to 35 mg/m^3 [1]. In general, a limit switch is used for monitoring, which is activated as soon as a set differential pressure is reached, which is measured at the air filter. An indicator light then informs the driver that the air filter is fully loaded. *Figure 1* shows the conventional system design in the form of a block diagram. Today, the air filter of a combine, for example, is very often cleaned as a precaution during regular maintenance regardless of its actual loading condition, which increases wear on the filter tissue and shortens the total service life of the filter.

Model-based condition monitoring

Since differential pressure strongly depends on the currently aspirated fresh air volume flow and, hence, also the current operating point of the combustion engine, no qualitative conclusion regarding the loading condition of the filter can be drawn based on a differential pressure measurement only. In order to receive on-line information about the loading condition, a model-based method was developed and examined at the Institute for Agricultural Machinery and Fluid Power, which is presented below. *Figure 2* shows the basic design of the system.

An equivalent mathematical model of the air filter assembly is established parallel to the real air filter. In this model, the system behaviour of the air filter is described in the form of mathematical formulas so that the output value X_a can be calculated as a function of the input values X_e. In the considered case, the output value is differential pressure, which is measured at the air filter. The input value is the current operating point of the engine. The latter can be clearly determined, based on engine speed and engine load as two measurement values, which can be read by the CAN bus of the machine in combination with the characteristic curve of maximum engine torque. In addition, the characteristic diagram of the engine-specific combustion air mass flow is required, which determines the combustion air mass flow as a function of the engine operating point. *Figure 3* shows a characteristic diagram of the combustion air mass flow as an example.

For a mathematical description of the system behaviour, the filter was modelled as a throttle valve in the first approach. The so-called throttle equation (1) describes the relationship between the volume flow Q and the pressure difference Δp (according to [2]). Other signs used in the formula are the cross sectional area of the throttle valve A_D, the volume flow rate number α, and the expansion number ε.

$$Q = \alpha \cdot \varepsilon \cdot A_D \sqrt{\frac{2 \cdot \Delta p}{\rho_{Luft}}} \quad \Leftrightarrow \quad \Delta p = \left(\frac{Q}{A_D \cdot \alpha \cdot \varepsilon}\right)^2 \cdot \frac{\rho_{Luft}}{2} \qquad (1)$$

It is assumed that the cross sectional area of the throttle valve A_D becomes smaller as the filter load increases. Based on this equivalent mathematical model, the differential pressure to be expected can now permanently be calculated and compared with the measured value. The difference of the two values provides quantitative information about the loading condition of the filter.

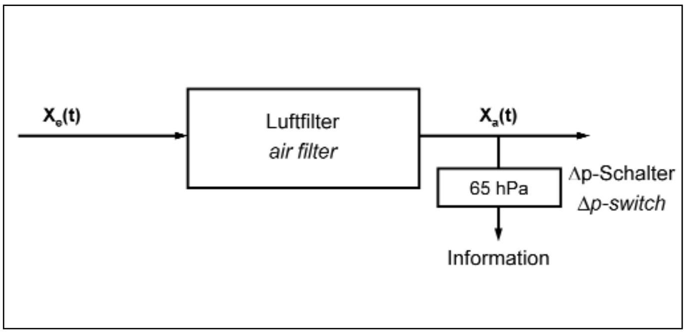

Fig. 1: Block diagram of a common air condition monitoring

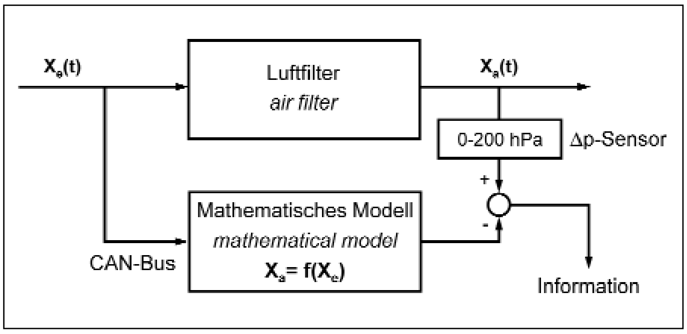

Fig. 2: Block diagram of the model based air filter monitoring

Practical realization

At the Institute for Agricultural Machinery and Fluid Power, the prototype of such an air filter monitoring system was installed on an experimental tractor. A dSPACE-MicroAutoBox hardware in combination with the program package Matlab/Simulink serves as a development platform for this experimental unit. The differential pressure sensor used is a sensor of the type PD23 (0-200 hPa) from the company Keller.

Engine speed and engine load are read from the CAN bus of the tractor, and the current air mass flow of the engine is determined based on the characteristic diagram of the combustion air mass flow, which is part of the model. Dividing by the standard air density provides the volume flow rate Q through the filter.

Before the differential pressure to be expected can be calculated with the aid of the throttle valve equation (1), some unknown values must be set or established.

First, the cross sectional area of the throttle valve is set at 1 m^2 in a new filter. Furthermore, the expansion number ε is joined with the flow rate number α, and functional dependence between α and the volume flow rate Q is assumed. After a reference phase with a new air filter, equation (2) is used to calculate the relationship $\alpha = f(Q)$ with the aid of linear regression based on the measurement values. This relation becomes part of the model.

$$\alpha = f(Q) = \frac{Q}{A_D} \cdot \sqrt{\frac{\rho_{Luft}}{2 \cdot \Delta p}} \qquad (2)$$

As the last missing value, the minimum cross sectional area of the throttle valve $A_{D,min}$ at maximum filter load is determined using equation (3). The switching threshold of the differential pressure switch installed by the factory is assumed to be the maximum permissible differential pressure $\Delta_{pmax,zul}$ at the maximum possible volume flow rate Q_{max}. Now, all missing values for condition monitoring are known.

$$A_{D,min} = \frac{Q_{max}}{\alpha} \cdot \sqrt{\frac{\rho_{Luft}}{2 \cdot \Delta p_{max,zul}}} \qquad (3)$$

During the operating phase of the condition monitoring system, the expected minimum differential pressure Δp_{min} for a new filter (A_D=1 m^2) and the expected maximum differential pressure Δp_{max} for a fully loaded filter ($A_D = A_{D,min}$) are determined mathematically. Finally, the measured real differential pressure ?psensor is correlated with the two calculated values with the aid of equation (4) in order to obtain a filter load value (“Beladung”).

$$\text{Beladung}[\%] = \frac{\Delta p_{Sensor} - \Delta p_{min}}{\Delta p_{max} - \Delta p_{min}} \cdot 100\% \qquad (4)$$

Initial field tests proved the validity of the functional principle of this model-based method of air filter monitoring. However, especially fast variations of the engine operating point still lead to heavy fluctuations in the determined load condition values. This must be attributed to the delays during differential pressure build-up which result from the geometry of the induction pipe and the spatial distance between the filter and the engine.

Summary

Under heavily fluctuating operating conditions, the observation of a directly measurable value for the condition monitoring of an assembly is often insufficiently. Model-based methods take the varying operating conditions into account and thus allow for a quantitative interpretation of the measured values with regard to condition diagnosis. At the Institute for Agricultural Machinery and Fluid Power, a model-based method for the monitoring of the loading condition of the air filter of a tractor was successfully implemented as a prototype and examined. In addition, field trials in a combine during harvesting are planned.

Literature

Books are marked by •

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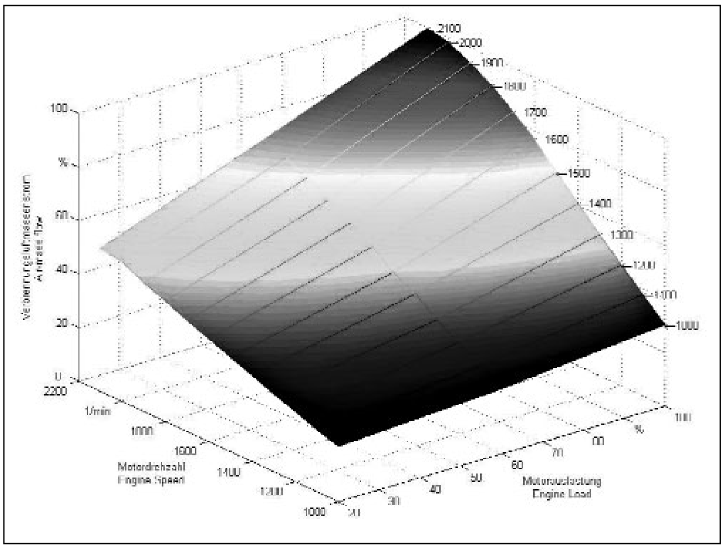

Bild 3: Verbrennungsluftmassenstromkennfeld

Fig. 3: Air-mass flow characteristic diagram