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MODELING ROBUST AND COST EFFECTIVE HYDRAULIC SYSTEMS

1. Background

High power density requires high demands on the hydraulic system and its components. To achieve an optimised utilisation of the system many different factors must be regarded. The fear for a high failure rate can many times motivate a system design with very low pressure, which leads to lower efficiency and bigger components. The life cycle cost, LCC, for the system can be lower anyway as the system will be more robust. Improved oil properties or more efficient filtration of may also result in lower LCC, as the wear rate of key components in the system can be reduced by such actions.

Fluid properties, fluid cleanliness and the working conditions are all important for the hydraulic system LCC. Models that can be used for predicting the costs or cost-savings, can be a great help for the system designers and the users. Additional costs that are deliberately introduced with a preventing purpose would be easier to compare with an estimated cost saving by a more robust and problem free operation.

Solid particles in the hydraulic fluid cause serious wear in many components. The author has earlier developed a model for predicting the wear and optimizing the filtration. This paper is an attempt to describe how the model can be extended for a more general life cycle cost prediction.

Pressure, rotational speed and fluid viscosity are factors that very likely will have an impact on the dirt sensitivity of a pump. An increased pressure will increase the failure rate both due to contaminant wear and material fatigue failures. The same factors will also have an impact on the efficiency of the system. With mathematical models the efficiency can be optimized. Hence, variable displacement pump/motors and oil viscosity/temperature can be controlled in order to minimize the energy losses. However, a design with optimised efficiency is maybe not the best choice if all the costs are regarded.

2. The Model

The total costs for building and running a hydraulic system can be divided into several categories. The objective is to define these and set up general mathematical models for each category. The key to success of such a work is to select the most important factors and not go too deep into less important details. Now it is suggested that every type of cost can be connected to one of four general categories. The sum of these over the life of the system will be the life cycle cost.

$$LCC = K_I + K_E + K_F + K_M$$

where: K_I - the initial cost for building the system, i.e. the investment, K_E - energy costs of the system, K_F - the costs caused by the occurring system failures or loss of productivity, K_M - the costs for preventive maintenance actions, costs for filter consumption etc.

In order to minimise the LCC it is necessary to set up mathematical models for each category. Such a model is necessary to use, as system parameters have an impact on several of the identified categories in different directions. The purpose is to calculate the LCC and check if one or several of these category terms are allowed to increase by a certain system design, as at least one of them can be considerably reduced in the same time.

2.1. Investments

The initial cost is dependent on the different choices in system design. A system design with lower pressure leads to higher flow rate and bigger components, which is equivalent with higher investments. This design is many time preferred in stationary hydraulic systems. While in mobile hydraulics smaller components often are desired at the price of higher failure frequency.

Providing the system with more filters for better contaminant protection will also lead to a higher initial cost. It might be possible to present models for the investments, but it can be difficult to make them general. So no modelling will be provided for this category at this stage. It is easy for the user to sum the initial costs for different system alternatives and add those to the model.

2.2. Energy

The total energy cost for the system is the product of the power consumption, the run time of the system and energy cost factor.

$$K_E = P \cdot t_s \cdot c_E$$

where: P - the power consumption of the system, t_s - the total run time for the system, c_E - the energy cost factor.

The power consumption can be divided into ideal power and power losses. The ideal power needed is given and is not reachable from the design of the hydraulic system. Models for the power losses, on the other hand, are more interesting to consider. Here the cost saving potential can be considerable by an appropriate system design.

The losses are occurring when the energy is transformed from mechanical to hydraulic and vice versa. They are also occurring when the fluid passes restrictions, pipes and hoses. The losses will be more or less dependent of the viscosity, due to the nature of flow. Pressure drops in pipes and hoses can easily be calculated, as necessary data are available in most cases. The ambition to include the viscosity in models for pumps and motors is more difficult. The manufacturers usually provide information about efficiency of pumps and motors at different speeds, displacement and pressure. Detailed information about the efficiency at different viscosity is rarely available. Therefor measurements were performed on a hydrostatic transmission in order to get more detailed knowledge about the impact from the oil properties on the efficiency. The results from that investigation can be now used in a model for a more general LCC analysis.

As expected the power losses were found to be strongly dependent on the viscosity. Empirical models were fitted to the power loss data for two different types of fluids. For a mineral oil at constant rotational speed the best fit was achieved with the following model:

$$P_f = a_0 p^2 + a_1 \mu^2 + \frac{a_2}{\mu^3} + a_3 \frac{p^2}{\mu} + a_4$$

where: P_f - the power loss, a_0, a_1, a_2, a_3, a_4 - fitted coefficients for the system, p - the system pressure, μ - the oil viscosity.

A suitable viscosity can be selected by a temperature control and by an appropriate viscosity grade of the oil. The system pressure will be the result from the system design and the prevailing loads.

2.3. Occurring failures and repairing maintenance

System failures can be the result from an unlimited number of reasons. Here only the hydraulic failures and repairing will be regarded even if other type of failures can be even so usual. Failures in the hydraulic system can be divided into three main groups:

- over load break downs,
- material fatigue failures,
- wear & friction.

The two first categories are strongly dependent on the system pressure, while effects from contaminants in the fluid can probably be neglected in general even if there can be connections in some cases. The last category (wear & friction) is strongly dependent of solid particles in the hydraulic fluid. The costs due to failures can be described according to the following simplification:

$$K_F = c_p\,(k_{p0} + k_{px}\,N_x)\,t_s$$

where: c_p - the mean cost for a system failure, N_x - the mean particle concentration in the system for particles greater than x, k_{p0}, k_{px} - the system failure sensitivity coefficients.

Coefficient k_{p0} is strongly dependent on the system pressure and k_{px} is probably dependent on pressure as well and even hydraulic fluid properties, rotational speed etc. If all the contaminant effects are transferred to one particle size the modelling will be much simpler.

Models based on theoretical analysis of the particle concentration in a filtrated system were developed many years ago. These are based on particle generation rate, filtration flow rate and filter efficiency. Most difficult to assess in practice is the particle generation rate for a system. Very little data from field or laboratory experiments are available today.

2.4. Preventive maintenance actions

The major cost from the preventive maintenance actions is probably due to filtration. Filters are blocked by the captured contaminants and have to be replaced. A filter has a certain dirt holding capacity, which can be expressed as a number of particles greater than a certain size x. When this occur the pressure drop increase to a undesired limit. Above that limit a proper function of the filter may not be maintained. The total cost due to filter consumption can be expressed according to the following model:

$$K_M = c_f \frac{R_x}{\kappa_x} t_s$$

where: R_x - the number of generated particles per unit time to the system, κ_x - the maximum number of particles the filters can capture, c_f - the mean cost connected to a filter cartridge replacement.

In general a fine filter will be blocked earlier compared with a coarser at the same size/price. This means that for the best choice it must be a compromise between contaminant-related failures and the filter rating. It should be a good balance between costs from contaminant-related failures and actions in order to decrease the particle concentration. The higher the particle generation rate is the higher will the filter cost be. The particle concentration in the system will also increase, hence the failures will increase as well. So it is important from all aspects to keep the contaminants out from the hydraulic systems.

3. Conclusions

There can be much to gain if different cost sources for hydraulic drives are identified, analysed and compared. This work has not the ambition to be complete and cover all kind of systems and effects. However, if the most important effects can be covered in the model that is sufficient. Then the possibility to make hydraulic systems more reliable, robust, cost effective and competitive is obvious.