6

Fault diagnosis of pumps

Pumps are basic components in most technical processes, like in power and chemical industries, mineral and mining, manufacturing, heating, air conditioning and cooling of engines. They are mostly driven by electrical motors or by combustion engines and consume a high percentage of electrical energy. One distinguishes mainly centrifugal pumps for high deliveries with lower pressures and hydrostatic or positive displacement (reciprocating) pumps for high pressures and small deliveries. They transport pure liquids, or mixtures of liquids and solids and herewith increase the pressure to compensate, e.g. for resistance losses or enabling thermodynamic cycles.

In the past, circular pumps were mostly driven with constant speed and the flow rate of liquids was manipulated by valves with corresponding throttling losses. Due to the availability of cheaper speed-controlled induction motors also circular pumps with lower power are now used for controlling the flow rate in order to save energy.

The overall reliability and safety of many plants depends on the health of pumps. Therefore, the supervision and fault diagnosis of pumps is of relatively high importance. In this chapter the results of several case studies will be treated for centrifugal pumps and reciprocating pumps.

6.1 Centrifugal pumps

6.1.1 State of the art in pump supervision and fault detection

Damage to centrifugal pumps occurs either in the hydraulic parts or the mechanical parts. An inquiry by the German Fachgemeinschaft Pumpen, VDMA [6.29], mainly among chemical industry and water treatment plants has shown the following result: 59% of pumps operate continuously, 19% daily and 22% for a short time. Inspection intervals are three months on average. Unplanned repairs because of defects happened within a mean of nine months.

Table 6.1 shows the faulty components as causes of damages to centrifugal pumps.

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The most frequent faulty components are therefore the sliding ring seals and the ball bearings, see Figure 6.1. Causes for faults which lead at least to interruptions of operation or maintenance are shown in Table 6.2. Cavitation, dry run, increased wear and deposits are especially important for fault detection.

Table 6.1. Faulty components as cause for damages to centrifugal pumps, [6.29]

Faulty components	**Reported frequency** [%]	**Faulty component**	**Reported frequency** [%]
sliding ring seal	31	sliding bearings	8
rolling bearing	22	clutch	4
leakage	10	split pipe	3
driving motor	10	casing	3
rotor	9		

Table 6.2. Malfunctions of centrifugal pumps and their explanation

Faults	**Explanation and consequences**
cavitation	development of vapor bubbles inside the fluid if static pressure falls below vapor pressure. Bubbles collapse abruptly leading to damage at the blade wheels and generate crackling sound
gas in fluid	A pressure drop leads to appearance of solved gas in the transported liquid. A separation of gas and liquid and lower head may result
dry run	missing liquid leads to lack of cooling and overheating of bearing. Important for starting phase
wear	*erosion*: mechanical damage to walls because of hard particles or cavitation *corrosion*: by aggressive fluids *bearings*: mechanical damage through fatigue and metal friction, generation of pittings and rents *plugging of relief bore holes*: leads to overloading of axial bearings and their damage *plugging of sliding ring seals*: leads to higher friction and smaller efficiency *increase of split seals*: leads to less efficiency
deposits	deposits of organic material or through chemical reactions at the rotor entrance or outlet lead to less efficiency, higher temperatures until total breakdown of pumping
oscillations	unbalance of the rotor through damage or deposits at the rotor, damage to the bearings

The supervision of pumps depends very much on the applied *instrumentation*. If for example only the outlet pressure is measured for a centrifugal pump with constant known speed only large deviations to the normal operation pressure give hints

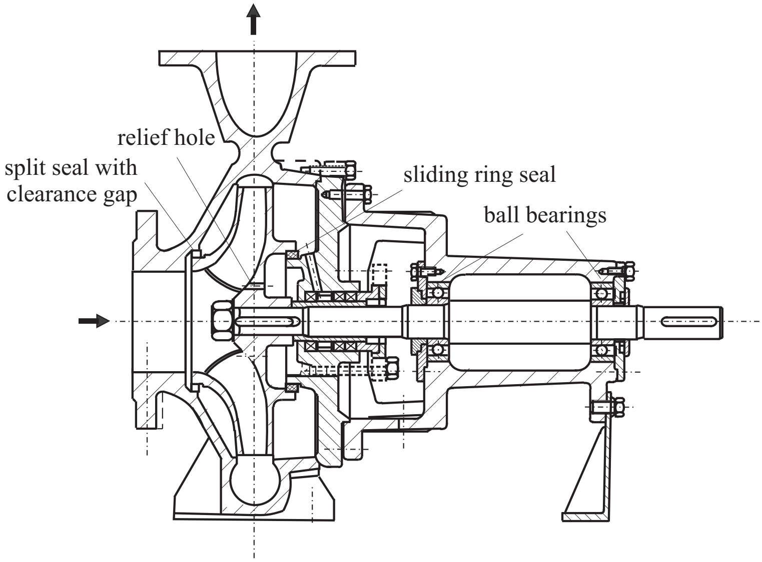

Fig. 6.1. Sectional drawing of a typical centrifugal pump (KSB Etanorm)

that somewhere large faults or failure happened. The addition of volume flow rate measurement improves the situation, as then changes of the head characteristic can be observed, however, without the possibility of fault diagnosis. The measurement of the inlet pressure allows one to observe the NPSH (net positive suction head) with regard to cavitation. All these simple supervision methods generally do not allow an early detection of small faults and do not give information on the causes of faults (diagnosis).

The supervision of *well-instrumented pumps* is usually based on the measurement of inlet and outlet pressure or the head only, the flow rate, speed and temperature of bearing casing and limit checking of these values. For example, if the outlet pressure or flow rate are too low (or too high) compared to the normal or rated values, this may be the result of gas enclosures, dry run, large deposits, strong deposits or bearing or motor defects. These large deviations from normal operation are easily observable by the exceeding of adjusted thresholds. But a fault diagnosis and an early fault detection is in general not possible with this checking of limits.

Various research efforts have given an insight into the pump behavior under the influence of faults. The application of *vibration sensors* and analysis of structure-borne noise is investigated, e.g. by [6.18], [6.10], [6.25], [6.20], [6.17]. The methods require special sensors and pump-specific and signal-specific evaluation methods and allow one to detect vibration-related faults under certain operating conditions, see the discussion in Section 6.1.5.

The simultaneous evaluation of several measurements and development of *model-based fault-detection methods* was performed by [6.6] (pump with variable speed and parameter estimation), [6.22] (pump with constant speed and parameter estimation), [6.5] and [6.30] (pumps with different power and combination of parity equations and parameter estimation). These research projects are the basis for the following sections. Further publications on model-based approaches are [6.8] confirming parameter-estimation-based approaches, and [6.1] applying a state observer and parameter estimation.

6.1.2 Models of centrifugal pumps and pipe systems

a) Pump

The torque M applied to the rotor of a radial centrifugal pump leads to a rotational speed ω and transmits a momentum increase of the liquid from the rotor inlet with smaller radius r_1 to the rotor outlet with larger radius r_2 by guiding the liquid through blade-bounded channels. The theoretical required torque follows from an angular-momentum balance equation, known as Euler's turbine equation. This leads to the theoretical pump head

$$H_{th} = h_{th1}\omega^2 - h_{th2}\omega\dot{V} \tag{6.1.1}$$

where the delivery head is defined as

$$H = \frac{p_2 - p_1}{\rho g} = \frac{\Delta p}{\rho g} \tag{6.1.2}$$

with p_1 the pressure at the inlet and p_2 at the outlet. $\dot{V}$ is the volume flow rate.

Taking into account a finite number of blades, blade and tube friction losses, impact losses due to nontangential flow at the blade entrance, the basic equation for the delivery head of the pump becomes, [6.2], [6.5], [6.26]:

$$H = h_{nn}\omega^2 - h_{nv}\omega\dot{V} - h_{vv}\dot{V}^2 \tag{6.1.3}$$

The coefficients h_i are determined by the basic equations and contain empirically determined parameters.

The corresponding power transmitted to the fluid is

$$P = \rho g H\dot{V} = M\omega \tag{6.1.4}$$

The theoretical pump torque then results with (6.1.2) and (6.1.1):

$$M_{th} = \rho g \frac{\dot{V}}{\omega} H_{th} = \rho g \left(h_{th1}\omega\dot{V} - h_{th2}\dot{V}^2 \right) \tag{6.1.5}$$

Including the flow losses, (6.1.3) has to be inserted in (6.1.4), resulting in the real torque:

$$M_P = \rho g \left(h_{nn}\omega\dot{V} - h_{nv}\dot{V}^2 - h_{vv}\frac{\dot{V}^3}{\omega} \right) \tag{6.1.6}$$

The mechanical part of the pump is modeled by the rotational impulse balance

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