Case Study of Model-Based Estimators for Pump Flow Rate

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ABSTRACT

Flow rate produced by a centrifugal pump is essential information for the control and monitoring of fluid-related processes. As an example, information on the produced flow rate can be used for the optimization of the pump rotational speed based on the resulting specific energy consumption. However, flow rate sensors tend to be costly and prone to failure, which is why pressure measurements and soft sensor approaches are often preferred for determining the produced flow rate.

This paper introduces and studies model-based estimation methods for the pump flow rate, which can be implemented in modern variable-speed drives and in automation systems controlling the drives. Operation and accuracy of the estimators is demonstrated through laboratory test runs. This paper also discusses the possibilities that a modern variable-speed drive can provide with its internal programmable logic controller unit and with the available information on the pumping system operation.

1 INTRODUCTION

Flow rate produced by a centrifugal pump is often essential information for the control and monitoring of fluid-related processes. However, they are also prone to failure and may be simply impractical option for processes, where the fluid level is the primary controlled variable. To this end, soft sensor approach can be viable solution for having information on the produced flow rate without additional hardware or sensors; then the flow rate is determined with the help of a model-based estimator that is tuned with the known characteristics of the pump or the surrounding system /1/.

A feasible unit for employing these estimators is the variable-speed drive (VSD) operating the pumping system. Modern VSDs are versatile devices, providing several application-specific monitoring and control functions for the motor-driven device /2/, /3/. As an example, internal PID controllers and control functions for multi-pump systems are standard features in pump-focused VSDs. Another increasing trend is to have an integrated programmable logic controller (PLC) that allows modification of the VSD, and hence system operation according to specific needs. As these features are nowadays combined with a visually appealing user panel interface, variable-speed drives start to resemble modern PLC systems.

Some variable-speed drives already allow sensorless estimation of the pump flow rate, which can be further used for identification, control and monitoring purposes. This is primarily possible by accurate estimates for the motor rotational speed (n_{est}) and shaft torque (T_{est}), which are commonly available in vector and direct-torque-controlled (DTC) drives. When these estimates are supplied to the model-based estimators, for instance the pump flow rate Q (l/s) and specific energy consumption E_{s} (kWh/m^3) can be determined without additional sensors on the device. These results can be further applied to the monitoring, optimization and fault diagnostic purposes.

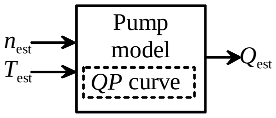


Figure 1. Basic structure of a model-based estimator for the pump flow rate.

However, the practical use of flow rate estimators with variable-speed drives is quite low, since variable-speed drives are rather seen as slave devices for the process automation system than as intelligent monitoring and control units. Main objective of this paper is to introduce available estimators for the pump flow rate and provide information on the possibilities that a modern variable-speed drive can provide with its internal measurements and programmable logic controller unit.

2 INFORMATION PROVIDED BY A MODERN VARIABLE-SPEED DRIVE

Industrial variable-speed drives contain at least phase current measurements for the motor in a pumping system and hence an ability to estimate present rotational speed and shaft torque of the motor. Besides motor control purposes, these measured and calculated values provide usable information for condition and operation monitoring of the pumping system as listed in Table 1. Since the VSD is already connected to the process control system, it may be readily usable as an operation monitoring unit for the pumping system, or it can be separately connected to the plant fieldbus or Ethernet network. The latest variable-speed drives are even able to analyse the driven system operation by themselves and provide information on the system operation with visualized graphs either in the VSD control panel display or in a web-based service portal. The needed analysis functions can be formed to some extent with the internal PLC unit of variable-speed drive: for instance, model-based estimators for the pump flow rate normally operate in the time domain of 10…1000 milliseconds, and they can be well executed with the PLC unit in the variable-speed drive.

Table 1. Measured, calculated and estimated values available in a VSD with their possible applications /4/.

Rotational speed	Flow rate calculation, harmful speed region detection, bearing fault analysis (data for fault frequency calculation).
Power	Flow rate calculation, pump deterioration detection in known circumstances, process change detection, if the speed is constant.
Torque	Detection of failures that may cause the motor overloading. Detection of abnormalities, such as pump cavitation and reversed rotation, which cause additional torque fluctuation.
Operating hours	Timing of maintenance actions, equal use of parallel connected pumps, analysis of pump operation (data for flow duration curve calculation).
Energy consumption	Metering of system energy consumption and efficiency
Motor current	Used by the VSD to estimate the motor operation. Phase loss or earth fault detection, overload detection.

3 MODEL-BASED ESTIMATION METHODS FOR THE PUMP FLOW RATE

3.1 *QP*-curve-based estimation method

Operating characteristics of a centrifugal pump are commonly described by their characteristic curves for the flow rate Q vs. head H and for the flow rate Q vs. shaft power consumption P at the nominal rotational speed n_{nom}. When the latter curve is adjusted to the present rotational speed of the pump (n_{est}) and compared with the present shaft power estimate (P_{est}, i.e. product of n_{est} and T_{est}), a variable-speed drive can determine an estimate for the flow rate (Q_{est}) and further an estimate for the head (H_{est}) as shown in Figure 2a. Typically the adjustment of pump characteristic curves is done with affinity laws ($Q{\sim}n$, $H{\sim}n^2$, $P{\sim}n^3$), which normally assume constant pump efficiency regardless of the change in rotational speed, and result in the following models for the pump operation:

$$H = a_{\mathrm{H2}} \cdot Q^2 + a_{\mathrm{H1}} \cdot \left(\frac{n_{\mathrm{est}}}{n_{\mathrm{nom}}} \right) \cdot Q + a_{\mathrm{H0}} \cdot \left(\frac{n_{\mathrm{est}}}{n_{\mathrm{nom}}} \right)^2 \tag{1}$$

$$P = a_{\mathrm{P2}} \cdot Q^2 + a_{\mathrm{P1}} \cdot \left(\frac{n_{\mathrm{est}}}{n_{\mathrm{nom}}} \right) \cdot Q + a_{\mathrm{P0}} \cdot \left(\frac{n_{\mathrm{est}}}{n_{\mathrm{nom}}} \right)^2 . \tag{2}$$

When P_{est} and Q_{est} are known, also an estimate for the centrifugal pump specific energy consumption $E_{\mathrm{s,est}}$ can be provided for monitoring and control purposes according to

$$E_{\mathrm{s,est}} = \frac{P_{\mathrm{est}}}{Q_{\mathrm{est}}} . \tag{3}$$

Accuracy of this estimation method is primarily affected by the accuracy and shape of the device *QP* curve together with the accuracy of rotational speed and shaft power estimates. Since the estimation method requires a sufficient, non-zero $|\mathrm{d}P/\mathrm{d}Q|$ for the *QP* curve, the method is primarily recommended for radial-flow pumps that transfer clean water. The method is also recommended to be used in a speed range around 20…35% of the nominal pump rotational speed, since the effect of rotational speed change on the pump efficiency is not considered in the affinity laws.

Since the available characteristic curves for the pump may also be inaccurate or even unknown for very low and high rotational speeds, several calibration methods and improvements to this elementary estimation method have been proposed as reviewed in /5/. One of the calibration methods is known as the closed valve test, where the pump is driven with zero flow rate at several rotational speeds to determine the static error in the published and actual *QP* characteristic curve of the pump. One of the improvements is the utilization of system-curve-based estimation for determining the pump flow rate more accurately at lowered rotational speeds /6/.

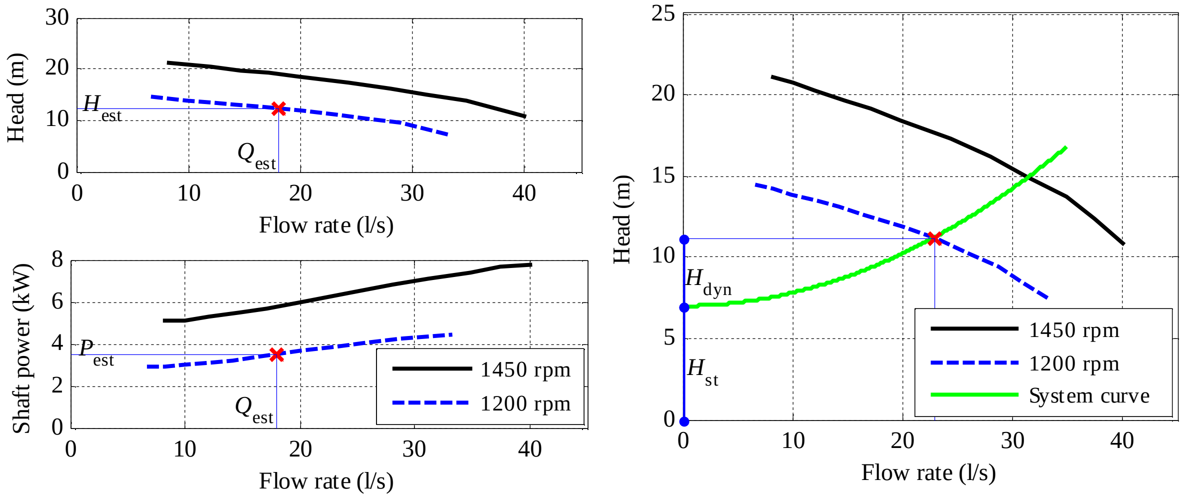
3.2 System-curve-based estimation method

When the pump is operated in a constant process (e.g. in a closed heat transfer loop), the system around the centrifugal pump can be modelled with a constant *QH* curve consisting of a static and dynamic part. The static head H_{st} describes the vertical lift and pressure requirements set for the pumped fluid. The dynamic head H_{dyn} describes the amount of friction losses caused by piping, control valves, and other components of the process. Together their effect on the system head requirement for the pump can be described with

$$H_{sys} = H_{st} + k \cdot Q^2 . \quad (3)$$

Parameters H_{st} and k can be determined according to the process layout, external measurements for the static head and friction losses, or by applying the *QP*-curve-based estimation method as proposed by authors originally in /6/.

Since a centrifugal pump operates in the intersection of the pump and system *QH* curves, (3) provides basic information on the pump operational state as shown in Figure 2b. Then only n_{est} is required from a VSD for the adjustment of (1). After this, the pump flow rate and head can be determined by calculating the intersection location of these two *QH* curves by setting (1) and (3) equal. Compared to the sole use of *QP*-curve-based estimation method, this approach can improve the flow rate estimation especially at lowered rotational speeds of the pump, where also $|dP/dQ|$ gets lower and slight change in change in rotational speed can cause a multiplied change on the pump flow rate.



(*a*) (*b*)

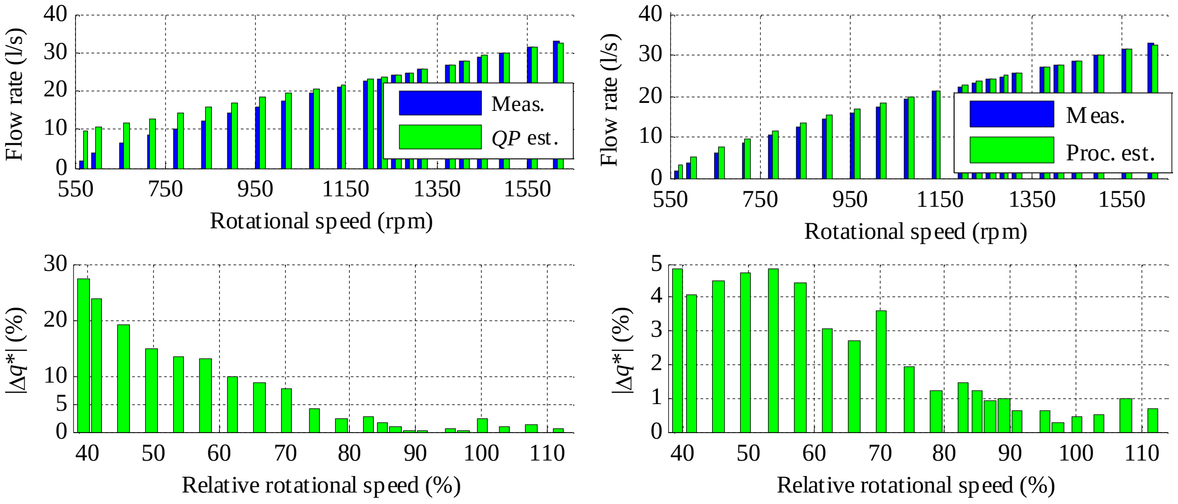
Figure 2. Estimation of flow rate and head with (*a*) *QP*-curve and (*b*) system-curve-based estimation methods.

4 LABORATORY EVALUATION OF THE ESTIMATORS

Operation and accuracy of estimation methods was evaluated through laboratory tests. Laboratory pumping system comprising a radial-flow Sulzer APP22-80 pump (Q_{BEP} = 28 l/s, P_{BEP} = 6.79 kW, n_{nom} = 1450 rpm) was driven with a DTC variable-speed drive at a range of rotational speeds and operating points realized by valves in the surrounding system to alter H_{st} and k. The actual pump operating point location in each case was determined with two Wika S-10 absolute pressure sensors across the pump and an Isoil Industria magnetic flow meter in the surrounding system. The shaft power consumption of the pump was determined using a Dataflex 22/100 measurement sensor and shaft power estimates available from the frequency converter. Laboratory tests were started by measuring the pump QP characteristic curve at 1450 rpm to solve parameters a_{P2}, a_{P1} and a_{P0} for (2).

After this, the pump was driven at 570–1620 rpm (39–112% of 1450 rpm) with a valve setting resulting in H_{st} of 3.4 meters and best-efficiency point (BEP) operating point location for the pump at 1450 rpm. Figure 3a introduces the measured and QP-curve-estimated flow rates at rotational speeds of 570–1620 rpm, and the resulting relative flow rate estimation error ($|\Delta \mathrm{q}^*|$) as a function of relative rotational speed (n/n_{nom}). In this case, the estimation error of the QP curve method increases at rotational speeds below 1100 rpm (76 % of the n_{nom}), which is expectable because of the decreasing $|\mathrm{d}P/\mathrm{d}Q|$. On the other hand, at speeds above 1100 rpm the flow rate estimation error $|\Delta q^*|$ is below 3 %, meaning that in this case the QP method can provide accurate estimation results within the rotational speed region in which the pump efficiency presumably remains unaffected.

Figure 3b illustrates the corresponding results for system-curve-based estimation scheme, when system parameters H_{st} = 3.16 m; k = 0.016 were applied to (3). In this case, the process-curve-based estimation method provides more accurate results than the QP-curve-based method at rotational speeds below 1100 rpm (76 % of the n_{nom}). This supports the suggested capability of the system-curve-based method to improve the accuracy of the pump flow rate estimation with a variable-speed drive. In practice the use of this method requires that the system parameters remain correct during the pumping system operation.



(*a*) (*b*)

Figure 3. Test results for the pump flow rate when (*a*) QP-curve and (*b*) system-curve-based estimation methods were applied.

5 CONCLUSION

Modern variable-speed drives provide new possibilities to the operation and condition monitoring of a pumping system. For instance, information on the pump rotational speed and specific energy consumption can be utilized in the energy-efficiency-based control schemes for pumping systems that can be implemented with internal PLC unit of a variable-speed drive. Although this paper focused on flow rate estimation methods for centrifugal pumps, variable-speed drives are as well usable for estimating the performance of fans, compressors and conveyors.

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