Energy & Petroleum Regulatory Authority

VOLUME THREE

Liquid Pumping Systems Energy Auditing Guidebook

1. Introduction

Water use is essential for the provision of goods and services in commercial, industrial, agricultural and domestic setups. Pumping systems play a vital role in the delivery of water. These systems are commonly powered by petrol or diesel engines and electric motors, and in the process consume substantial amount of energy. Energy auditors should focus on assisting facilities to use the pumping system energy efficiently. It is, therefore, important for energy auditors to understand the working principle and efficiency of these pumping systems. This guidebook shall focus on pumping systems powered by electric motors because they are the most prevalent.

2. Components of pumping systems

Figure 1 illustrates the components of pumping systems

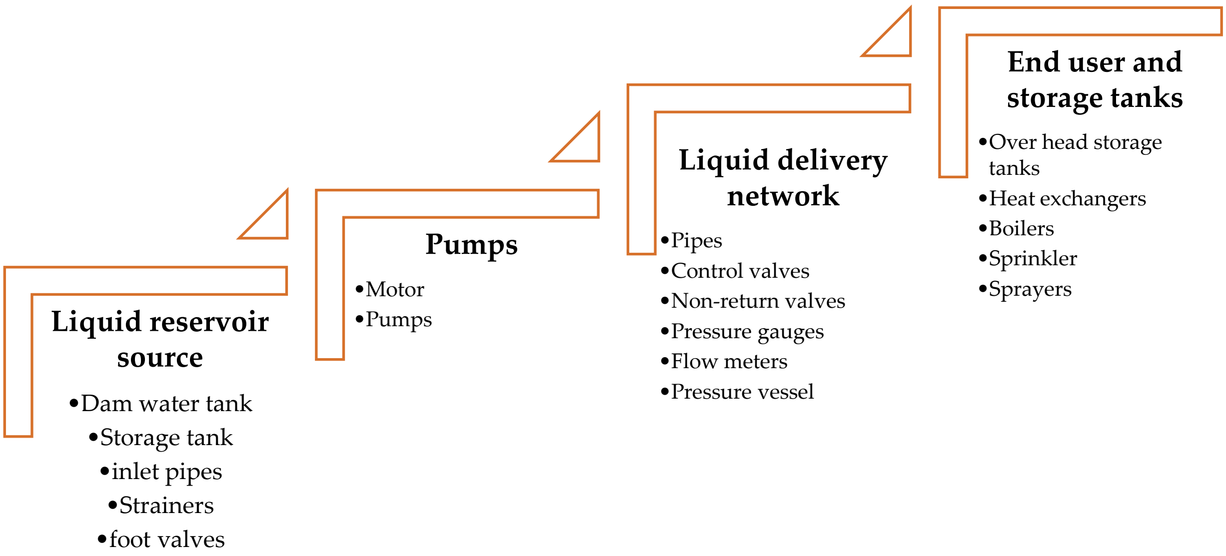


Figure 1:Parts of a pumping system

Figure 1 guides the energy auditor on key components of a pumping system that they should understand prior to initiating the energy audit process. A whole system audit should consider all of the components and processes described therein. The approach used for auditing the system depends on their configuration.

There are two main pumping system configurations: open and closed. In closed systems, the pump draws liquid from the reservoir to the point of use via the delivery network and recirculates it to the reservoir. In an open system, on the other hand, the water liquid is terminally delivered to the point of use. The configuration notwithstanding, the liquid flow can either be constant or variable. Once the auditor has established the configuration, they should sequentially audit the energy use and recommend the energy conservation measures.

3. Steps in auditing pumping systems

Auditing the energy use of a pumping system has three fundamental steps, as illustrated in Figure 2:

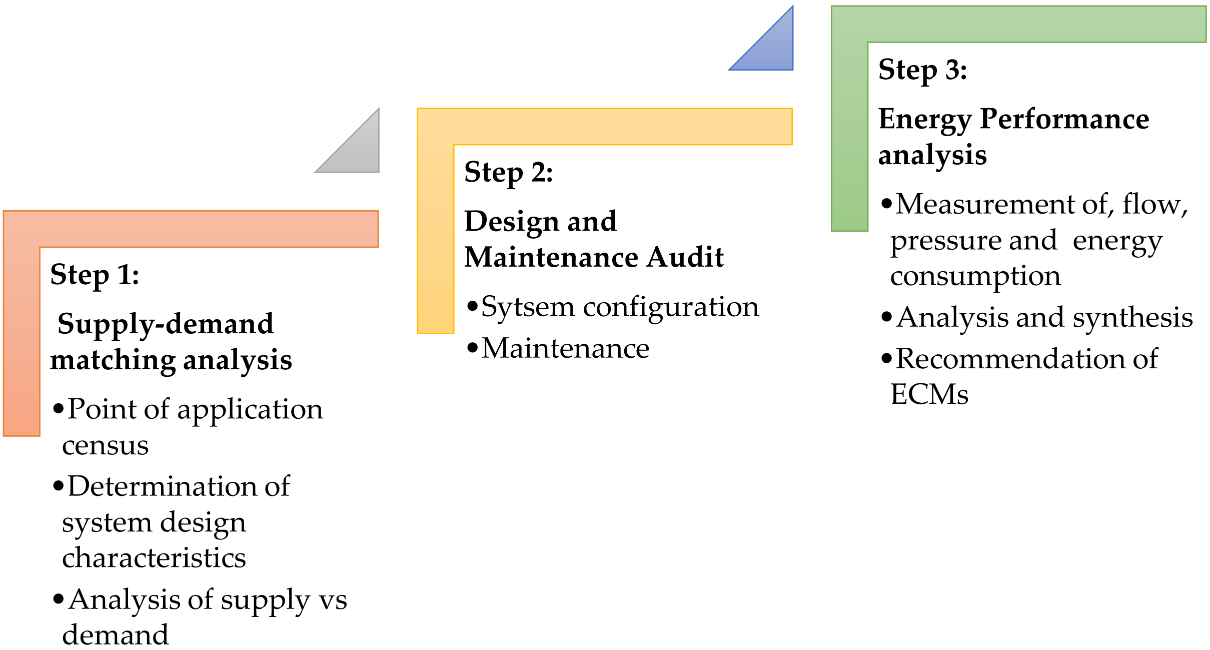


Figure 2: Steps in auditing pumping systems

The processes illustrated in Figure 2 are sequential, with the results from the preceding step informing the analysis of the succeeding step.

Step 1: Supply-demand matching analysis

For efficient operation of pumping systems, the pumping capacity should match the volumetric water requirements at the point of use. Situations where the capacity is either oversized or undersized will always lead to inefficient operations due to:

Poor pump loading factor	The efficiency of a motor has been empirically established to increase with the loading factor up to a certain limit. The recommended factors vary with the motor capacity and can be determined from the motor load efficiency curves.

Friction head losses	In cases where the water demand is less than the designed supply capacity, the operator will be forced to throttle the system, leading to an increase in the velocity in the pipeline. This leads to an increase in friction losses, as explained by the Darcy–Weisbach equation.
Frequent sudden starts and stops	An oversized pump will be subjected to frequent starts and stops as a result of instantaneously meeting demand requirements. Such operating conditions lead to increased cases of inrush currents, which are five to seven times higher running currents, leading to overheating.

Demand-supply matching analysis is conducted in two steps:

i. *Determination of the facility water demand*

Water demand should be established as per specific periods. The periods vary with the application. For example, in a hotel, the demand can be determined using the daily water consumption, while in a cooling or heating system, this will be established using the water demand per cycle. This demand should then be compared with the pumping system's supply capacity.

ii. *Determination of the existing pumping system supply capacity*

To determine the existing supply capacity, the auditor should establish pumping system specifications. The specifications include: the design flow rate; design operating pressure; pump efficiency; motor power rating; motor efficiency; and net positive suction head (NPSH). These specifications can be obtained from the nameplate and the data sheet of the pump. Figure 1 shows an example of a water pump nameplate.

Figure 3: Sample of a pump nameplate

The water supply capacity of the system should be at most 20% above the water demand.

Example 1

Consider a moulding machine that has a chilled water requirement of $5m^3$/hr. The water is supplied by a pump rated at $8m^3$/hr. This means the system capacity is 60% more than the demand requirements. As per the 20% capping requirement, the supply capacity would have been $6m^3$/hr.

This example is a case of system oversizing and should be a starting point for conducting a pumping system energy audit.

However, even if the load and supply match within the acceptable limits, the auditor should still go ahead to undertake the process audit of the pumping system.

Step 2: Design and Maintenance Audit

In addition to loading, the energy performance of pumping systems is also a function of design and operating conditions. The design involves system sizing and configuration while operating conditions are informed by maintenance and settings of the system. An energy auditor should, therefore, be well versed with the design and operating principles of the pumping system being audited.

Figure 4 can be used to guide the auditor on procedural steps of auditing the system design and maintenance.

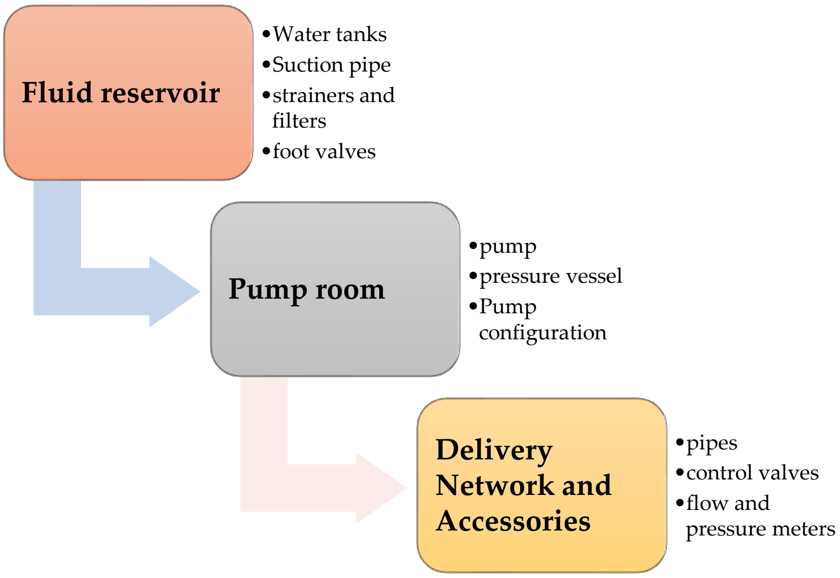


Figure 4: Steps of auditing the system design and maintenance

The following are the design and maintenance considerations for some of the major components.

Reservoir and suction pipe	The reservoir should be designed such that it provides a constant supply of water to the pump. This is achieved by ensuring that the minimum net positive suction head **(NPSH)** is maintained. The filters and strainers should be cleaned regularly to avoid clogging. Operating the pumping system with clogged filters and strainers or NPSH lower minimum than the design value may lead to relatively lower fluid delivery and cavitation.
Pump	Confirm that pump specifications are compatible with the design and pipeline. This can be done by checking the system operating point versus the pump-pipeline characteristics curves. Assess the stability of the pump by checking if there are vibrations. Such vibrations could be a result of loose mounting, belts, coupling, rewound motors and cavitation. Cavitation manifests itself in the form of vibrations and sounds like gravel, marbles, or crackling inside the pump. Vibrations can be measured by use of a vibrometer, while flow rate is measured using a flow meter (energy losses due to vibrations will be discussed in the *analysis section).*

Pressure vessel	A pressure vessel is used in a pumping system to reduce the starts and stops of the pump, therefore reducing the aggregate running time. It must operate at the operating pressure indicated on the nameplate. To test its performance, run the system and check if it attains the required pressure specifications. In cases where the pressure is not attained, this indicates that the pump will lead to more operation cycles, leading to increased aggregate running time. This situation can be as a result of: malfunctioning pressure switch; damage on the pressure vessel; pressure vessel design mismatch with the pump.
Pump configuration	In some instances, a pumping system can have more than one pump. The configuration of the pumps can be to deliver the desired pressure or flow rate. If the aim is to increase pressure, pumps are configured in series. On the other hand, if the objective is to increase the flow rate, the pumps are configured in parallel. For a parallel connection, caution should be taken to ensure that the pumps are operating at the same pressure. Even in cases where the pumps have the same design pressure, it can be a challenge to synchronize them. It is therefore recommended that a bigger pump is used, in order to increase the flow rate. On the other hand, to increase the pressure, it is recommended to use booster pumps that is pumps in series.
End use and storage tanks	Some of the end uses in a pumping system are to supply water to: i. Storage tank ii. Heat exchanger iii. Sprinklers in irrigation system iv. Cleaning nozzles v. Water taps The auditor should establish whether the end use is compatible with the pumping system and is in good working condition.

Accessories	The pumping system accessories such as valves, pressure gauges and meters should be at the correct positioning and in good working conditions.

It is worth noting that a poorly designed or maintained pumping system not only leads to energy losses and poor service delivery but is also an operational hazard.

A whole system audit is essential for optimal realization of energy savings. This implies that the analysis of energy performance should go beyond the pump output. The fluid delivery networks design and maintenance contribute to the overall energy performance of the system.

Step 3: Energy Performance Analysis

Once an auditor carries out the supply-demand load matching, as well as the design and maintenance assessment, they should undertake primary data collection. Measurement and data collection should be undertaken within the operation cycle of the facility. The information obtained will be used in energy performance analysis. The analysis will inform the energy conservation measures (ECMs) that can be implemented by the facility. This section covers energy performance analysis using examples.

Example 2.

Consider a chiller system in a data centre with a water-cooled condenser with a designed water supply of 1,500 m^3/h (about 0.42 m^3/s) at a pressure of 4.0 bars (about 41.0 m). The pump efficiency was 88%. During an audit, it was established that the system was operating at 750 m^3/h (about 0.21 m^3/s) and 4.7 bars (48.0m). The motor nameplate rating is 300 kW with an efficiency of 92%. In this case, the auditor may deduce the following:

i. There may be a case of underperformance of the chiller due to undercooling on the condenser side. The undercooling is due to the reduction of heat load evacuated from the transport fluid.
ii. The slow cooling rate inferred in (i) above will lead to longer running hours of the chiller before it attains the desired conditions.
iii. The increased pressure observed in this case may lead to bursting of the pipes and tubes
iv. Low pump efficiency. This is because the pump will be operating outside the best operating zone. This concept is illustrated by Figure 5.

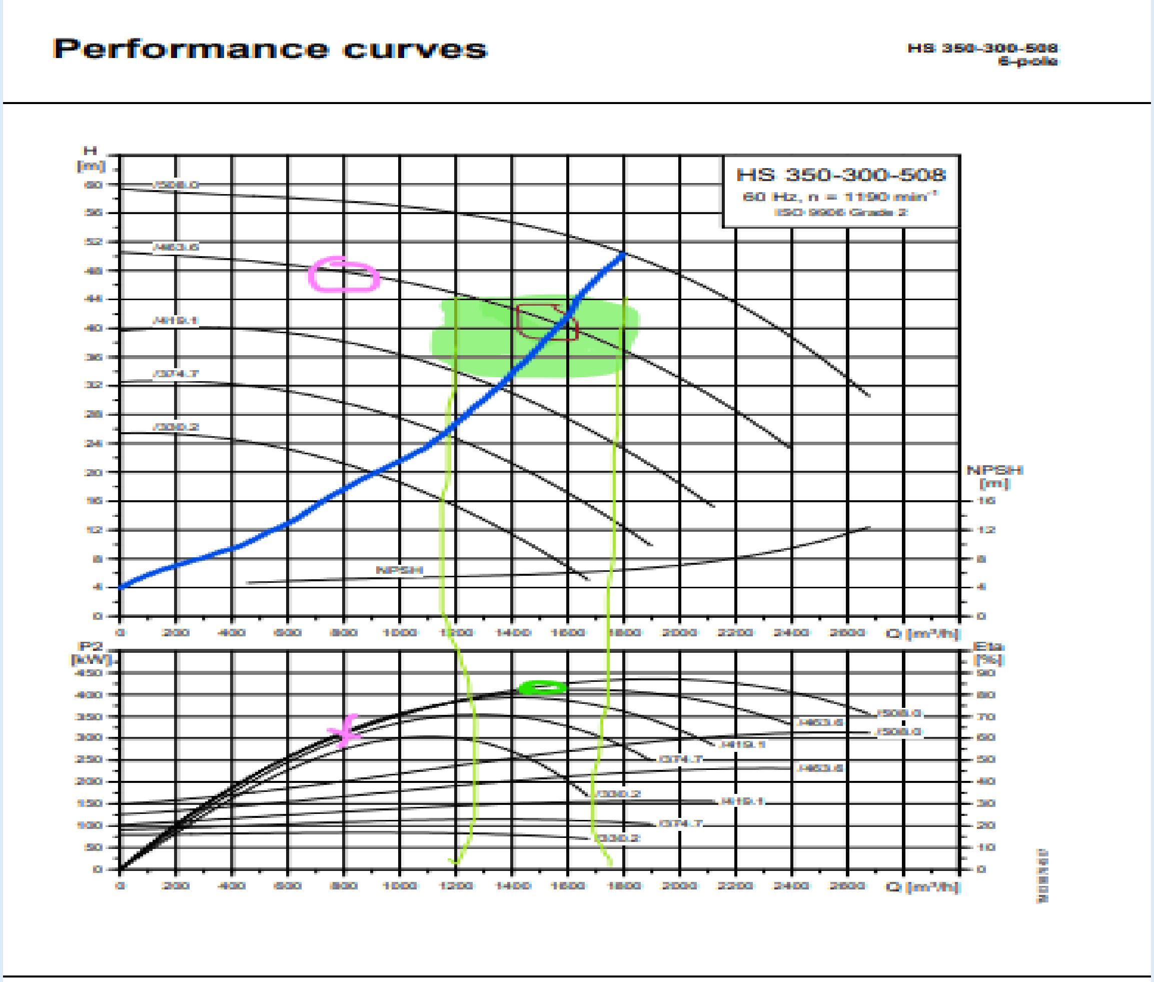


Figure 5: The pumping system operating points.

As illustrated in Figure 5, the prevailing conditions have shifted to the left of the best operating point (BEP) by increasing the pressure and decreasing the flow rate. When a pump operates outside the BEP, it compromises its efficiency. The superimposition of the system curve with the efficiency curve demonstrates the shift in efficiency by 20%, that is, from 80% to 60%. To reduce the flow, the pump operator might have throttled the system. This reduces the capacity factor to 59% as demonstrated in the following computation:

$$Capacity\ Factor\ (\%) = \frac{4.7\ bars\ \times\ 0.21 m^3/s}{4\ bars \times 0.42\ m^3/s} \times 100 = 59\%$$

The reduction in the capacity factor has resulted in the reduction of the pumping efficiency from 80% to 60%.

In case the auditor establishes that the prevailing operating condition is sufficiently meeting the chiller requirements, they need to recommend resizing of the system. To resize the system, the following steps should be used:

Step 1:

Determination of the fluid power P_f using equation

$$P_f = \frac{H \times \rho \times g \times Q}{1000} kW$$

where

H	Total head in metres
Q	Flow rate in m^3/s
ρ	Water density in kg/m^3
g	Gravitational acceleration at $9.81 m/s^2$

The fluid power will therefore be

$$P_f = \frac{60 \times 1000 \times 9.81 \times 750}{1000} kW$$

$$P_f = 122.40\ kW$$

To get the motor power rating Ps (shaft power) to deliver this fluid power, the following equation will be used

$$P_s = \frac{P_f}{\eta_p} kW$$

In this case η_p the pump efficiency, can be assumed to be 0.88; therefore, the shaft power will be:

$$P_s = \frac{122.4}{0.88} kW$$

$$P_s = 139.1\ kW$$

A motor size of 139.1kW is, however, not available in the market. The auditor needs to select the next available motor. According to sales manuals, the nearest available motor is sized at 150kW.

Sticky point: *The shaft power is the power normally indicated on the nameplate of the motor. There may be a tendency for some auditors to confuse this power to be the electrical power drawn from the* grid.

The auditor needs to make a comparison between the newly sized motor with the originally designed one, to determine the power savings. To compute the power drawn from the grid, the shaft power is multiplied by the loading factor and divided by the motor efficiency. Using this example, the power savings will be

$$Power\ savings = \frac{300 \times 0.8}{0.92} - \frac{150 \times 0.93}{0.95}$$

$$= 114.027 kW$$

Points to note;

i) The efficiency of the new motor has been taken to be 0.95 (a few points higher than the old motor) because of the assumption that newer motors in the market have increased efficiency.

ii) The loading factor for the new motor has also been assumed to be higher (at 0.93) because the reduction in the supply capacity means that the supply will nearly match the demand.

iii) With the power savings, the energy savings can be calculated using the total running hours of the pump for the year.

Let us now consider a case where a pumping system has vibration problems using the following example.

Example 3

Consider a pump with the following information.

i. Type of Pump: centrifugal pump

ii. Rated flow was 126 m^3/hour

iii. Rated Head was 55 metres of water

iv. Rated Motor power was 30 kW

v. Pumping efficiency =67.465%

vi. Motor efficiency = 92%

The auditor established and recorded the following information:

i. The density of water was 988 kg/m^3

ii. The operation cycle is 11 hours

Measured energy during the cycle **231.55 kWh**

From the information given, vibration measurements were done and the results are presented in Table 1.

Table 1: Vibration displacement verse time

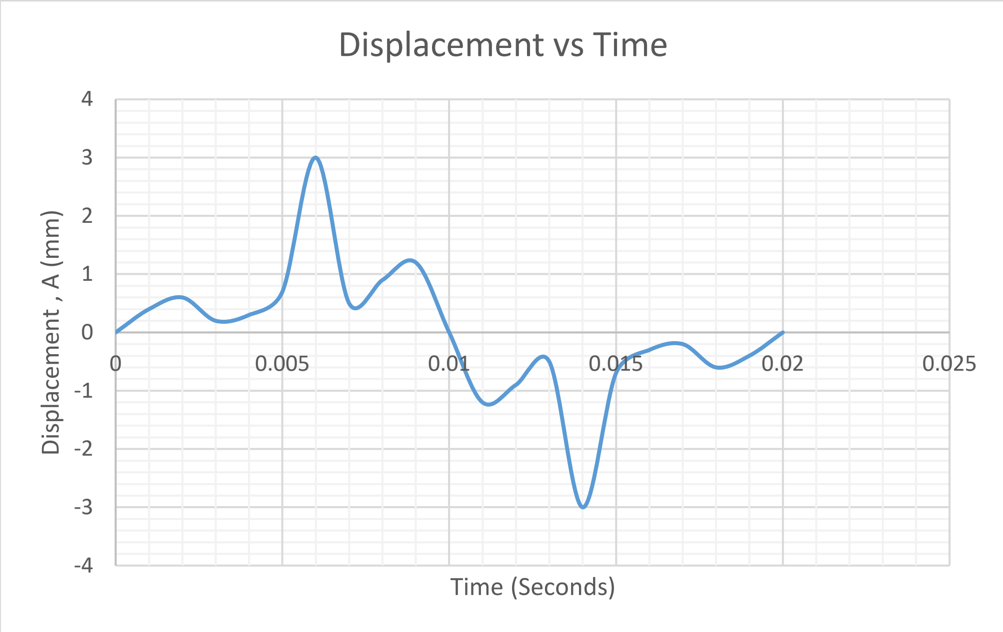
Time (s)	0	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.01	0.011	0.012	0.013	0.014	0.015	0.016	0.017	0.018	0.019	0.02
Amplitude (A)	0	0.4	0.6	0.2	0.3	0.7	3	0.5	0.9	1.2	0	-1.2	-0.9	-0.5	-3	-0.7	-0.3	-0.2	-0.6	-0.4	0

Time (s)	0.021	0.022	0.023	0.024	0.025	0.026	0.027	0.028	0.029	0.03	0.031	0.032	0.033	0.034	0.035	0.036	0.037	0.038	0.039	0.04
Amplitude (A)	0.4	0.6	0.2	0.3	0.7	3	0.5	0.9	1.2	0	-1.2	-0.9	-0.5	-3	-0.7	-0.3	-0.2	-0.6	-0.4	0

Time (s)	0.041	0.042	0.043	0.044	0.045	0.046	0.047	0.048	0.049	0.05	0.051	0.052	0.053	0.054	0.055	0.056	0.057	0.058	0.059	0.06

Amplitude (A)	0.4	0.6	0.2	0.3	0.7	3	0.5	0.9	1.2	0	-1.2	-0.9	-0.5	-3	-0.7	-0.3	-0.2	-0.6	-0.4	0

Time (s)	0.061	0.062	0.063	0.064	0.065	0.066	0.067	0.068	0.069	0.07	0.071	0.072	0.073	0.074	0.075	0.076	0.077	0.078	0.079	0.08
Amplitude (A)	0.4	0.6	0.2	0.3	0.7	3	0.5	0.9	1.2	0	-1.2	-0.9	-0.5	-3	-0.7	-0.3	-0.2	-0.6	-0.4	0



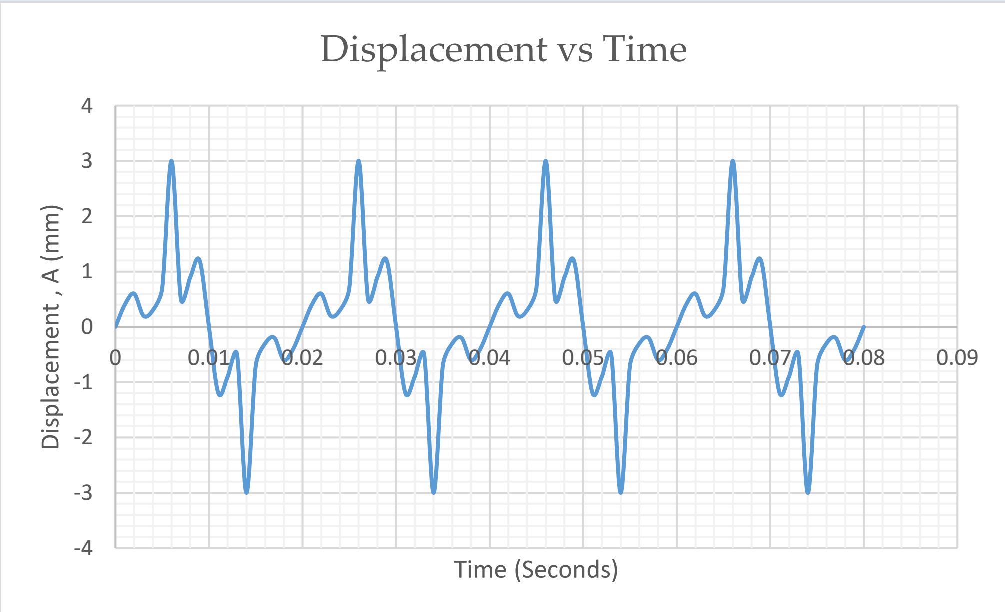


Figure 6: Vibration displacement verse time

Vibration period is 0.02 seconds.

Vibrations often lead to loss of energy. An energy auditor can quantify this loss using the following equation:

$$VE = 2\pi^2 m f^2 A_{rms}^2 \qquad (10)$$

Where

VE	Vibrations energy (joules)
m	Mass of the vibrating system (kg)
f	Vibrational frequency
A_{rms}	root mean square of the Amplitude of Vibration

A_{rms} is calculated using equation

$$A_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} A_i^2} \qquad ()$$

Where A is obtained from measurements as presented in the table in this example (note that there are 21 amplitudes in the cycle).

$$A_{rms} = \sqrt{\frac{1}{21}\sum_{i=1}^{21} A_i^2} = 1.097\ mm$$

Vibration Energy (VE) wasted in one cycle

$$VE = \frac{2 \times \pi^2 \times 736 \times 50^2 \times 0.000001097_{rms}^2}{1000} = 4.36 \times 10^{-8} kW$$

Note: The vibration energy is mechanical and should be converted to electrical power using the motor efficiency. Assuming a motor efficiency of 0.92, the electrical energy lost for operation of 11 hours per day is:

Electrical power lost

$$Electrical\ energy\ lost = \frac{VE}{\eta}$$

$$= \frac{4.36 \times 10^{-8} kW}{0.02 \times 0.92} 3600 \times 11$$

$$= 0.0865 kWh$$

Energy wasted in 11 hours is 0.0865 kWh. Assuming the pump runs for 300 days per year, the total energy wasted per year is 25.9 kWh. Auditors should advise facilities to reduce vibrations by ensuring the adjustment of loose joints and mountings, and avoidance of cavitation and rewinding. Annual energy losses of 25.9kWh per year may seem small, but note that cavitation can cause vibrations to a range of up to 10,000 Hz. For pumps less than 50 kW, this is dangerous and means that the pump will not function normally. These pumps can operate at vibrations

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of 1000Hz without operators noticing. This means the pump will be losing about 11,267.62 kWh of energy annually.