

# Measuring thermal losses of water cooled motors using oscillating ultrasonic temperature sensors

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*Abstract – simulations have shown that the evaluation of thermal losses of water cooled electric motors using inexpensive conventional temperature sensors is complicated by the relatively low accuracy of the latter. This accuracy must be below 0.05 K to evaluate motor efficiency with an accuracy of 1%. By experiment, it was shown that oscillating ultrasonic temperature sensors can potentially achieve the required accuracy. It was observed that the output frequency of the oscillating ultrasonic sensor featured substantial hysteresis that would complicate the development of accurate ultrasonic instrumentation.*

## INTRODUCTION

Like all the other mechanisms that transfer energy from one kind into another, electric motors exhibit power losses that heat the motors up. Motors with high power ratings dissipate substantial amounts of heat energy that needs to be removed; an efficient way to achieve this is to employ a water jacket and circulate cooling liquid through it. The difference between the consumed  $P$  and dissipated power  $P_L$  divided by the consumed power determines the motor's efficiency:

$$\eta = \frac{P - P_L}{P} . \quad (1)$$

Motor efficiency can vary from 70% to 96%, even within motors manufactured by the same vendor, depending on the power rating and number of poles of the motor [1]. Manufactured motors are rated by their efficiency (e.g., standard, high and premium efficiency [1]) and priced accordingly, because higher-efficiency motors bring about savings in running cost. Accurately determining a motor's efficiency is not only important for pricing purposes but also for its design optimisation, as even very small

improvements can result in sizable efficiency gains when they are compounded.

Power losses  $P_L$  can be calculated from the measured temperature difference at the inlet and outlet of the water jacket  $\Delta T$ :

$$P_L = cf\Delta T, \quad (2)$$

where  $c$  is the specific heat capacity of water and  $f$  is the water flow rate. In practice, the flow rate is adjusted so that it will not exceed the temperature difference recommended by the manufacturer (e.g., 7–10 K [1]). To accurately determine the motor's efficiency, the temperature sensors' accuracy (and resolution, if the sensors are digital) should be several orders of magnitude below the difference; however, most conventional inexpensive temperature sensors provide an accuracy of only  $\pm 0.25..1$  K.

Oscillating ultrasonic temperature sensors, in contrast, can provide several hundred distinct readings per centigrade [2, 3]. They consist of a pair of ultrasonic transducers immersed into an appropriate liquid, and driving electronics that provide a positive feedback loop. Among several possible implementations of the driving electronics for the sensor, the programmable system on chip (PSoC) realisation was found the most convenient [4]. Fig. 1 shows the experimental arrangement of the chamber, with both the conventional and ultrasonic sensors and driving and data acquisition electronics [5].

This paper reports the simulation results for motor efficiency found from temperature measurements using sensors of various accuracies and experimental results showing

that the required accuracy can be achieved using ultrasonic sensors.

### **I. determining motor efficiency from inaccurate temperature measurements**

An evaluation of a motor's efficiency from temperature measurements was conducted in the following manner:

- For a motor with a known power rating, efficiency and recommended temperature difference of the cooling water at the inlet and outlet, the required flow rate was calculated using (1) and rounded to a 0.1 L/s resolution.
- The resulting temperature difference  $\Delta t_0$  was calculated, and the range of temperature differences measured using two finite accuracy sensors  $\varepsilon_t$  was determined ( $\Delta t = \Delta t_0 \pm 2 \times \varepsilon_t$ ).
- Power loss was calculated for the upper and lower values of the obtained temperature difference range using (2), and the estimated efficiency was found from (1).

Fig. 2 presents the simulation results for 2-pole 75 kW motors of various efficiencies for the initial temperature difference of 10 K. It shows that if the accuracy of the temperature sensors is above 0.5 K, the efficiency class (and the selling price) of the motor can be wrongly determined. Further simulations showed that determining a motor's efficiency with an accuracy of 1% requires the accuracy of the temperature sensors to be below 0.05 K; this is not easy to achieve using conventional means.

### **II. Comparative temperature measurements using conventional and ultrasonic temperature sensors**

Experiments were conducted using the setup presented in Fig. 1 by tens of hours. Data from eight conventional temperature sensors (DS18B20, rated accuracy  $\pm 0.5$  K) were collected, and six of them were selected for the lower standard deviation of their readings (less than 0.05 K). The average value of their readings was later used for the temperature reference. The gain of the electronic driver was selected to ensure the least sensitivity of the output frequency to the gain changes. The centre frequency of the driver's magnitude response was set to 24.4 kHz, and its bandwidth was varied.

Experimental results, presented in Fig. 3, showed a much closer correlation between the

output frequency of ultrasonic sensors and temperature than previously reported [4]. This was achieved using a better reference for the output frequency measurement.

The observed sensitivity of the output frequency to temperature was about 50 Hz/K, making it possible to achieve the equivalent temperature resolution of 0.02 K when measuring output frequency with 1 Hz accuracy.

It is important to note that the relation between the temperature and output frequency of the sensor did not exhibit a one value to one value relationship but rather hysteresis.

### **III. Conclusions**

Thermal losses in water cooled electrical motors (and thus their efficiency) can be estimated by measuring the temperature difference of cooling liquid at the inlet and outlet. Simulations show that the accuracy of the temperature sensors should be considerably higher than that of conventional temperature sensors, closer to 0.05 K. Ultrasonic temperature sensors seem capable of providing the required accuracy, but they actually feature strong hysteresis. We plan to tackle this hysteresis by employing data fusion—processing the output data of conventional and ultrasonic temperature sensors simultaneously, in real time.

### **References**

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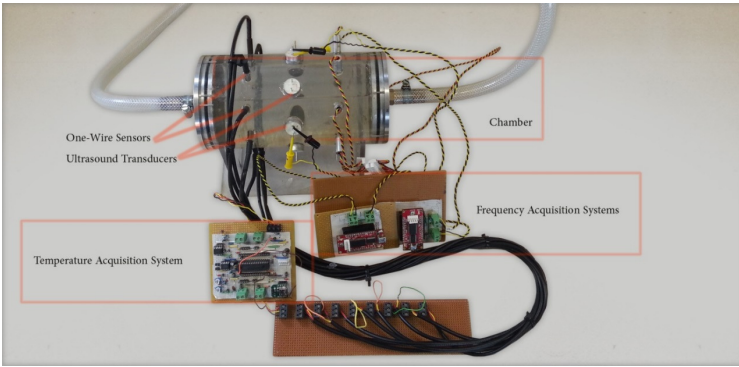


Fig.1 Overview of the experimental setup

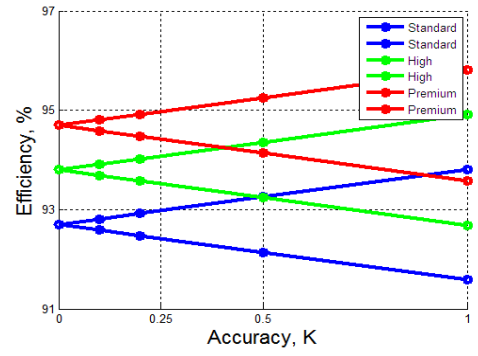
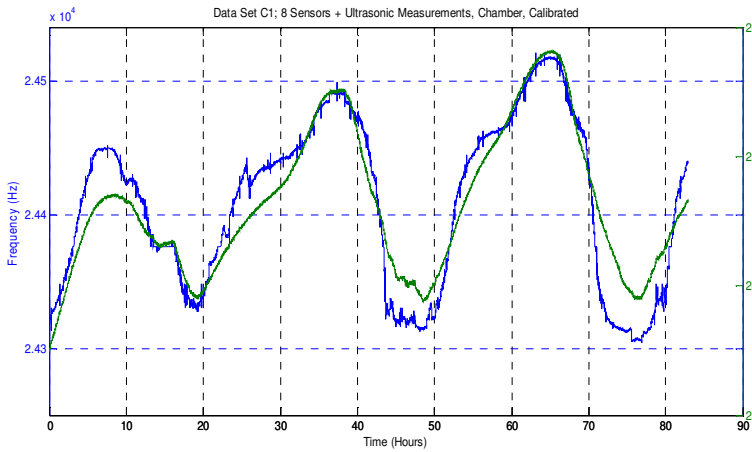
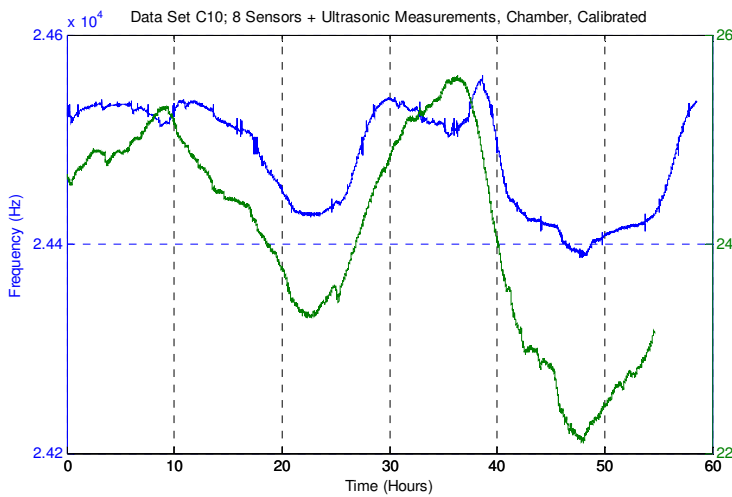
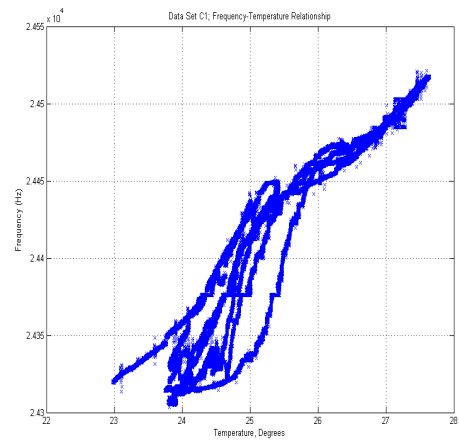


Fig. 2 Simulation results for the estimated efficiency of motors of different types versus the accuracy of temperature sensors



(a)



(b)

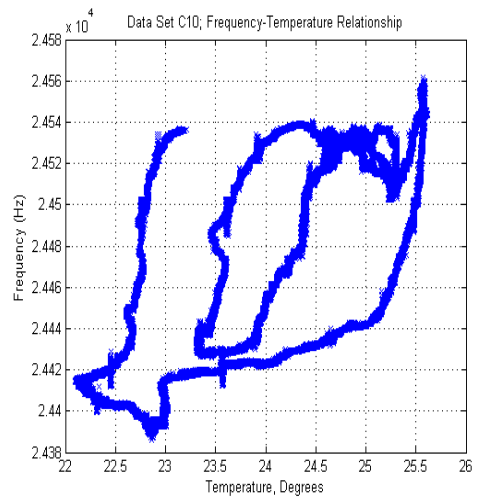


Fig.3 Experimental results for bandwidth of 10 kHz (a) and 7.5 kHz (b)  
 Left: ultrasonic sensor's output frequency (blue line) and temperature (green line) versus time  
 Right: output frequency versus temperature