

The Electric Fan as a Cooling Package Air Flow Meter

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ABSTRACT

A D.C. permanent magnet motor powered fan can serve as a cooling package air flow meter. This allows for continuous air flow monitoring during vehicle operation with applications to more precise air flow control schemes. In the freewheel mode, the air flow is a linear function of the open circuit voltage of the motor. In the powered mode, the motor voltage and current can be used with a motor and fan model to predict fan air flow. The model is explained and verifying test results are presented. Comparison of the accuracy and complexity vs. that of arrays of precision anemometers is provided.

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INTRODUCTION

We consider how to determine the actual air flow through the front end cooling package in a vehicle on the road. The common practice has been to calibrate banks of special propeller anemometers in the lab and carry them on the road. This technique has been used for projects to study the maldistribution of air flows through radiators, improving air flows by front end geometry changes and the like. See for example Williams [1]. Such anemometer banks are expensive and not suitable for continuous use in a production vehicle. So there has been no practical way to monitor front end air flow continuously for every produced vehicle.

The use of a permanent magnet (PM) D.C. motor driven fan offers the possibility of real time measurement of the front end air flow. This is because the motor is a linear D.C. generator in the unpowered (freewheel) mode and the current/voltage relation under powered conditions allows one to know the motor speed and torque. These relationships along with the fan power coefficient were discussed in the prior paper by Scott [2].

The ability to monitor front end air flows in real time opens up options for cooling system control that were previously not available. The air flow rate, combined with other measureables like air and coolant temperatures, can tell us if the radiator is performing correctly. More importantly, it provides a feedback signal valuable for active cooling system control schemes. We know that such control schemes are

becoming more important as means for improving fuel economy. See, for example, Cho[3]

MODEL OVERVIEW

In the freewheel or "ram" air operating mode, the fan motor acts as a D.C. generator. The terminal voltage of the motor is then a linear function of the motor speed. The speed is a linear function of the air volume flow rate. This relation is independent of the air density as we shall show. Thus the fan motor becomes an air flow meter under these conditions.

In the powered operating mode, the motor speed and shaft torque are functions of the voltage and current. The air temperature effect on this relation is linear as we shall show.

Knowing the motor shaft torque and speed, we may calculate the fan power coefficient. This dimensionless parameter is a function of the fan flow coefficient alone. Knowing the flow coefficient, we know the air volume flow rate.

Thus the fan becomes an air flow meter whose characteristics are those of the fan/motor combination. This means that the addition of different heat exchangers, grille shutters, etc. does not change the flow meter feature.

The needed coefficients for the fan can be determined in a laboratory test facility as described below.

In what follows we review the motor and fan equations and demonstrate the idea with test results for several configurations over a range of air temperatures.

The limiting constraints on this air flow meter are the uncertainties in our ability to determine the various coefficients. We will give an indication of how accurately one can determine the air flow as a result.

TEST FACILITY

Figure (1) is a schematic of the test facilities used to verify the proposed model. The supply air temperature is adjustable between 5 and 55°C. The air flow can be varied between 0 and 200,000 liters/min. The fan box is a 1.25m cube. The inlet chamber is approximately 3×3×4 meters. Flow rate is measured with ASME long radius nozzles. Flow rate is controlled by large valves downstream of the nozzles.

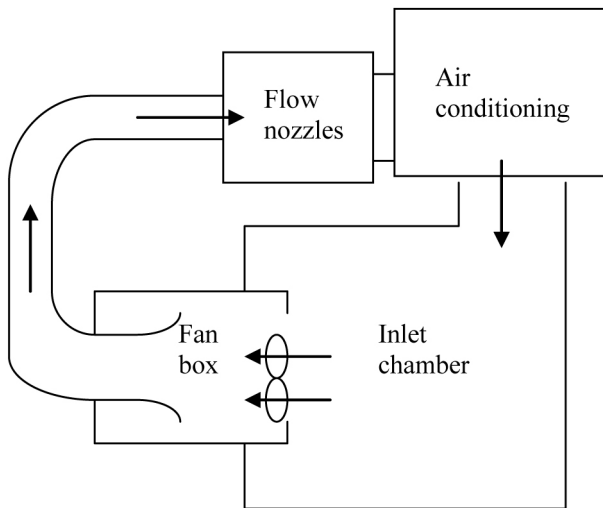


FIG. 1. Fan Test Rig Arrangement

The fan can be tested alone or with heat exchangers and other elements mounted with it to simulate the arrangements in the vehicle.

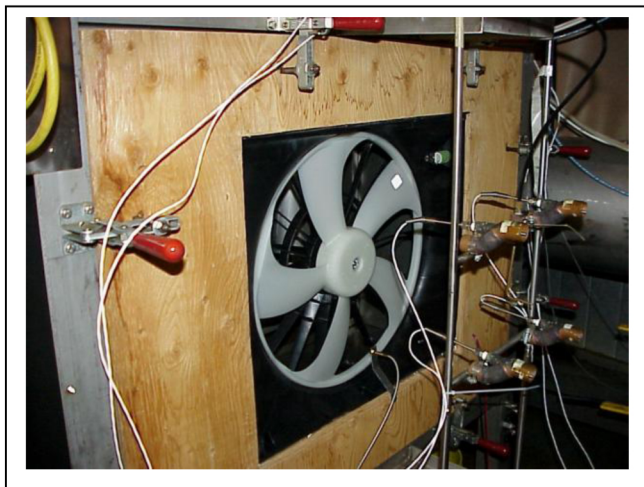


FIG. 2. Fan Mounted in Test Box

The fan used for this study is a basic PM motor axial design with a hub diameter of 152mm and an outer diameter of 546 mm. The fan mounted in the fan box is shown in Figure (2)

ELECTRIC MOTOR MODEL FOR POWERED OPERATION

The voltage/current model for a D.C. PM motor is:

$$E = K_m \omega + R_a I \quad (1)$$

where K_m is the magnetic constant and R_a is the armature resistance.

K_m and R_a are linear functions of the air temperature.

In the unpowered condition, with no current drawn from the motor (now acting as a generator), equation (1) shows that the voltage (back EMF) is a linear function of the speed. To wit:

$$E = K_m \omega \quad (2)$$

To calibrate the fan motor, one may take current and speed data during a test of the fan. Writing equation (1) as:

$$\frac{E}{\omega} = K_m + R_a \frac{I}{\omega} \quad (3)$$

a plot of E/ω vs. I/ω should be a straight line.

Figure (3) shows how well the model fits the performance of the sample fan. This is the data for 9, 11.5, and 14 volts at 30°C air. The magnetic constant is 0.0405 and the armature resistance is 0.2205

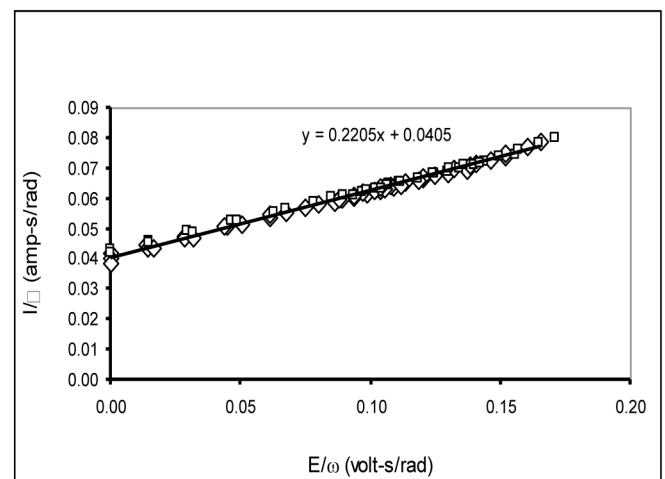


FIG. 3. Fan Motor Behavior, 30°C for 9, 11.5, and 14V

The same unit tested at two other temperatures yielded two sets of k_m and R_a values. The temperature dependence is linear as shown in Figure (4).

Thus for this motor, the model for powered operation is:

$$\omega = \frac{E}{K_m} - \frac{R_a}{K_m} I \quad (4)$$

and the temperature dependence of K_m and R_a is fit with:

$$K_m = 0.04402 - 6.344 \times 10^{-5} T \quad (5)$$

$$R_a = 0.199 + 3.92 \times 10^{-4} T \quad (6)$$

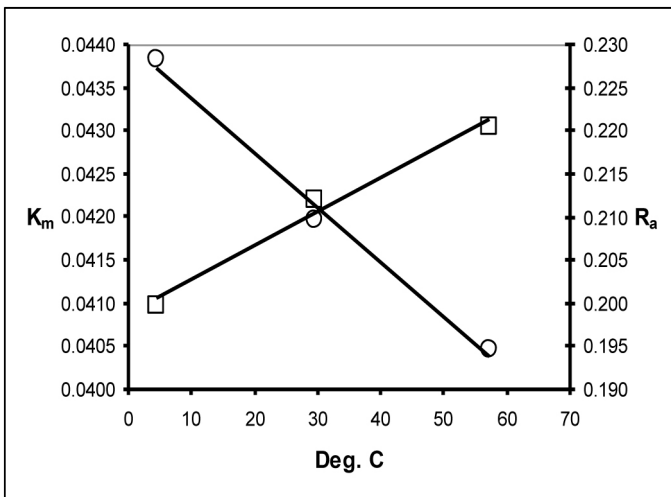


FIG. 4. Motor Constants Showing Linear Relation with Temperature

The model equation predicts the actual speed with an average error of 2.9%

The linear motor model also provides the torque as the magnetic constant times the current. This is the torque generated by the motor. Some torque is required to overcome friction which is mostly drag from the magnet. Thus a realistic model for the motor output shaft torque is:

$$\tau = K_m [I - I_0] \quad (7)$$

where I_0 accounts for the magnet drag torque.

ELECTRIC MOTOR MODEL FOR UNPOWERED OPERATION

When the motor is not powered (freewheel operation), the fan is a free spinning turbine. Here the speed depends only on the air volume flow rate. In this case the terminal voltage will be directly proportional to the speed. The data for the tested fan is shown in Figure (5)

If we use the magnetic constant values from equation (5) to predict these motor speeds from the measured voltage using $\omega = E/K_m$, we get agreement within an average error of 4%. Figure (6) shows the comparison.

If we use the actual freewheel data to determine a better K_m value, the uncertainty only decreases by about 0.2%. Thus, for example, at 30°C, equation (5) gives $K_m = 0.042$ while using the freewheel volts vs. speed data we get $K_m = 0.043$. So if one does not have actual freewheel voltage values, the error in using the powered fan K_m value is insignificant.

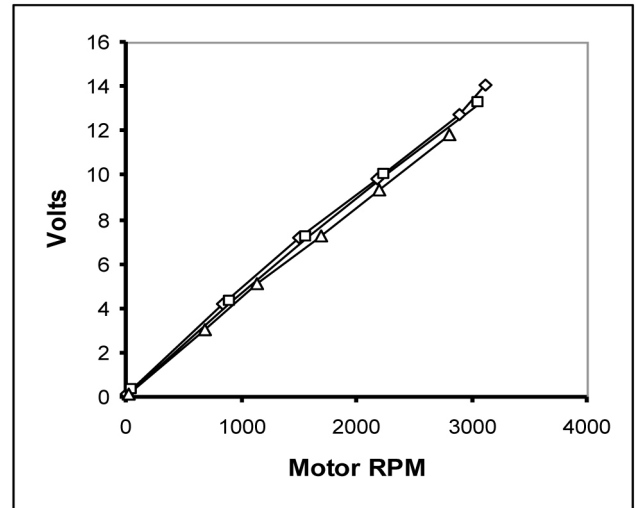


FIG. 5. Freewheel Motor Volts for 5, 30, and 55°C

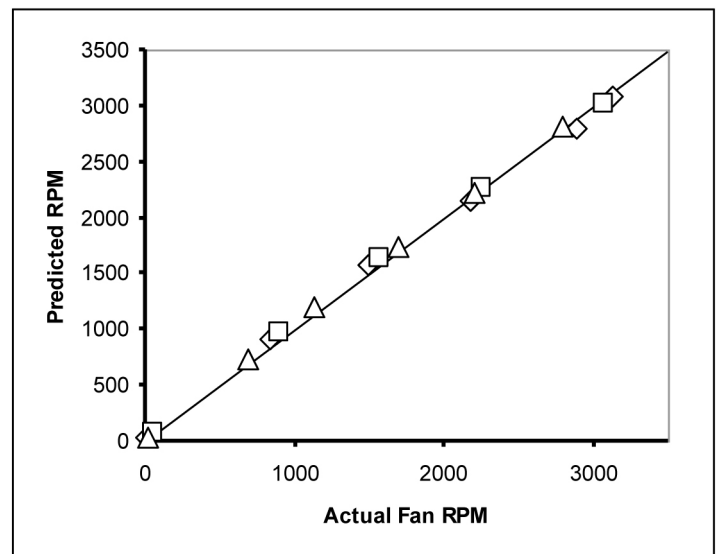


FIG. 6. Actual vs. Predicted Fan Freewheel Speed