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Motor Sizing Application Note

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Introduction

Linear motor sizing is relatively straightforward when the proper mathematical relationships are used. Given a moving mass and motion profile, the equations of motion and a few motor parameters can be used to calculate a motor's temperature rise. In the first step, the RMS force required by the moving mass and motion profile is calculated. In the next step, a model of the motor's thermal performance is used to calculate the final temperature of the motor windings. The peak and continuous current and power and the peak voltage required can also be calculated for sizing the amplifier and power supply

Parker-Trilogy's WebTIPS sizing software uses this approach to calculate motor temperature rises that have been verified by experimental results and thousands of applications over many years. This Application Note will give a simplified overview of the equations and algorithms used by the software and provide an example spreadsheet to use when the software package is not applicable.

Motion Profile

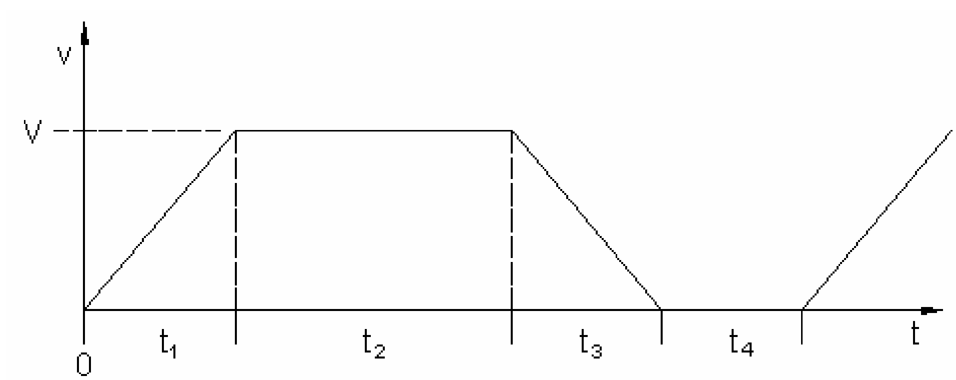

Figure1. Typical Motion Profile

Motor sizing usually begins by defining the motion profile and total moving mass, M. It is important to include the masses of the motor, user payload, and all other moving items in M. A typical motion profile is shown in Figure 1. The force required for each portion of the motion profile can be calculated as follows,

(1)
$$F_1 = M \times a + fric$$
$$F_2 = fric$$
$$F_3 = M \times (-a) + fric$$
$$F_4 = 0$$

where a is the acceleration rate (V / t_1) and fric is the force required to overcome friction. The peak and RMS forces for the profile are given by

(2)
$$F_{peak} = Max(F_1, F_2, F_3, F_4)$$
$$F_{RMS} = \sqrt{\frac{F_1^2 \times t_1 + F_2^2 \times t_2 + F_3^2 \times t_3 + F_4^2 \times t_4}{t_1 + t_2 + t_3 + t_4}}$$

The motion profile shown in Figure 1 is just an example. More complicated profiles will require different approaches to calculate the peak and continuous forces required. Unusual motion profiles, such as cam-followers or exponential accelerations, can almost always be described by equations or tabular data. Basic calculus and physics can be used to determine acceleration vs. time from this data. The relationship for force vs. time can then be determined by using F=ma and incorporating frictional forces, external forces, gravitational forces, etc. An RMS calculation can be performed on this data to determine the continuous force required.

The peak and continuous currents for a given motor can be calculated by using the motor's force constant, K_f. The force constant is the amount of force that will be generated by the motor at a given current level.

(3)
$$K_f = F / I$$

This can be rearranged to calculate the currents required,

(4)
$$I_{peak} = F_{peak} / K_f$$
$$I_{RMS} = F_{RMS} / K_f$$

Power Calculations

Once the current required is known, the thermal power that is generated in the motor can be calculated by using

(5)
$$P_g = \frac{3}{4} R \times I_{RMS}^2$$

where R is the motor's resistance. However, resistance is a function of temperature so the value of P_g will increase as the motor heats up during use and its resistance increases. Since the motor's resistance is usually given at a specific temperature, its value at the final temperature must be determined. The resistance of copper increases 0.393% per degree C of temperature rise. The following equation can be used to calculate hot resistance values,

(6)
$$R_{hot} = \left(1 + \frac{0.393(T_{hot} - T_{amb})}{100}\right) R_{amb}$$

The motor will continue to heat up until the amount of power generated in the windings equals the amount of power being dissipated by the surroundings. The following equation describes the power being dissipated by the motor's surroundings,

(7)
$$P_D = T_c (T_{hot} - T_{amb})$$

where T_c is the system's thermal dissipation constant in Watts/deg C, T_{hot} is the motor temperature, and T_{amb} is the ambient temperature of the surroundings. The system's thermal dissipation constant is an experimentally measured value. It is also the reciprocal of the motor's thermal resistance, T_R, usually given in deg C/Watt.

Final Temperature Calculations

Since power-in must equal power-out at steady-state, setting P_g equal to P_D and simplifying will yield the equation for the motor's steady-state hot temperature,

$$P_D = P_g$$

$$T_c(T_{hot} - T_{amb}) = \frac{3}{4} R_{hot} \times I_{RMS}^2$$

$$T_c(T_{hot} - T_{amb}) = \frac{3}{4}\left(1 + \frac{0.393(T_{hot} - T_{amb})}{100}\right) R_{amb} \left(\frac{F_{RMS}}{K_f}\right)^2$$

(8) $$T_{hot} = \frac{\frac{3}{4} R_{amb} \left(\frac{F_{RMS}}{K_f}\right)^2}{T_c - \frac{3}{4} R_{amb} \left(\frac{F_{RMS}}{K_f}\right)^2 \frac{0.393}{100}} + T_{amb}$$

This shows that given a motor's force constant, ambient resistance, and thermal dissipation constant, the steady-state hot temperature of the windings can be calculated for a given force output. Once T_{hot} is known, R_{hot} can be determined using (6). The actual thermal power generated by the motor windings can be calculated by using the motor's final resistance value and (5),

$$P_{RMS} = \frac{3}{4} R_{hot} \times I_{RMS}^2$$

$$P_{peak} = \frac{3}{4} R_{hot} \times I_{peak}^2$$

Since (8) is complex, it is probably best to build it into a spreadsheet or software package to minimize errors due to hand calculation. An example of such a spreadsheet is shown in Table 1. The parameters used are for a Parker-Trilogy 310-2S coil. The F_{rms} input value can be changed to determine the effect on T_{hot}, R_{hot}, and P_{RMS}.

Ramb (Ohms)	8.6
Kf (N/A)	27.3
Tc(W/deg C)	1.26
Tamb (deg C)	25
Frms (N)	57
Thot (deg C)	49.5
Rhot (Ohms)	9.4
Irms (A)	2.1
Prms (W)	31

Table 1. Sizing Spreadsheet Example using 310-2S Motor

Amplifier Sizing

The voltage required for each step of the motion profile can be calculated by using the motor's BEMF constant, K_e, and Ohm's law,

(9)

$$V_1 = K_e \times V + \frac{F_1}{K_f} \times R_{hot}$$

$$V_2 = K_e \times V + \frac{F_2}{K_f} \times R_{hot}$$

$$V_3 = K_e \times V + \frac{F_3}{K_f} \times R_{hot}$$

$$V_4 = 0$$

The maximum voltage required will be the largest of these values,

(10) $$V_{\max} = Max(V_1, V_2, V_3, V_4)$$

Now all the critical parameters for motor and amplifier sizing are known. The final motor temperature will verify the suitability of a given motor for a specified motion profile and payload. The peak and continuous currents and maximum voltage required will determine the power required from the amplifier and power supply and the suitability of the given motor winding.

The current calculations used in the model assume ideal motion while the current requirements in a servo system are almost always higher than ideal because of outside disturbances, vibrations, etc. It is a good idea to select an amplifier that will provide adequate current margin. An additional 10-20% is usually safe. The voltage calculations are fairly precise so additional margin is not usually required for voltage.

The thermal model only considers thermal power. Mechanical power is accounted for by the maximum voltage calculation. As long as the selected amplifier and power supply can supply the required current at the maximum voltage, the mechanical power requirements will be met. However, during deceleration this mechanical power is converted back into electrical power and must be re-absorbed by the amplifier and power supply. This is known as regeneration. For high loads and high speeds, this effect can be significant and external regeneration resistors might be needed by the amplifier. Most amplifier manufacturers give the specifications and relationships needed to perform regeneration calculations for their equipment and it is a good idea to check these requirements for high load, high speed applications.

Duty Cycle Considerations

It is possible to model a motion profile that requires large peak currents and relatively low continuous currents if long dwells are considered. Since the thermal calculations are based on RMS forces and currents, care must be taken to evaluate the peak requirements of the motion profile against the peak ratings of the recommended motor. If the required peaks are larger than the motor's ratings, a larger motor must be used!

Additional WebTIPS Features

The calculation engine for WebTIPS uses the approach detailed so far, but it also incorporates the following features,

- The ability to model more complex motion profiles, such as sinusoidal motion and S-curve acceleration.
- Canned motion profile generators to simplify data entry.
- The ability to incorporate loads due to vertical operation and/or external forces acting on the motor.
- Simplified data entry for multi-axis system sizing.
- Advanced algorithms for current calculations using non-linear force constants for iron-core motors.
- An empirical database of thermal dissipation constants to ensure accurate results.
- The ability to repeat the calculations so many different motors and systems can be considered at once.
- Stored motor and actuator masses for more accurate results when more than one possibility is considered.
- Advanced models for frictional forces.
- The ability to work in SI or Imperial units and to switch back-and-forth at will.
- Graphical representations of Force, Acceleration, Velocity, and Position vs. Time to verify accuracy of the motion profile.
- Automatic checking of peak profile requirements against peak motor specifications to ensure suitability.
- Advanced reporting features to customize the output.
- The ability to store and retrieve profiles to maintain historical records.

Summary

Anytime linear motors move a mass or exert force, current flows through their windings and heat is generated. How quickly this heat can be removed and the maximum temperature the windings can withstand are what limits motor performance. If a particular motor is applied in a manner that exceeds its design capabilities, permanent failure will result. Therefore it is important to be able to know accurately the temperature rise of a particular motor in a given application.

The following relationship can be used to determine a motor's steady-state temperature based on a required force output and three basic motor parameters,

(8) $$T_{hot} = \frac{\frac{3}{4} R_{amb} \left(\frac{F_{RMS}}{K_f} \right)^2}{T_c - \frac{3}{4} R_{amb} \left(\frac{F_{RMS}}{K_f} \right)^2 \frac{0.393}{100}} + T_{amb}$$

This algorithm can be built into a spreadsheet for simplified results. An example of such a spreadsheet is given in Table 1.

Ramb (Ohms)	8.6
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Table 1. Sizing Spreadsheet Example using 310-2S Motor

Pre-packaged software that incorporates additional features such as simplified motion profile modeling, amplifier and power supply sizing, and stored databases of motor parameters can be created. Parker-Trilogy's WebTIPS is one such software package.