Chapter 6

Integrating Motors and Systems

Features

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Introduction

In the career of nearly every mechanical or electrical engineer, at least one situation arises when a motor must be *fit* or sized to a mechanical system. My first "real world" experience came in 1972. There were lots of considerations:

- product type
- transport type
- transport angle
- screw pitch
- inertias
- efficiencies
- gearing, belting
- and others

After adding in several dozen other factors, a motor requirement emerged. At that point, calculations were needed to optimize the motor selection.

Over the years and after countless repetitions of the calculations involved, I was forced to develop a computer program to do these calculations. The program saved me many hours and eliminated the errors normally associated with any long hand calculation routine. After developing the program, I realized that there are quite a few designers that overlook, by design or by circumstance, many subtle sizing requirements. This may be due primarily to the complexity of the calculation method, the number of variables, and the repetition of calculations involved.

This chapter is intended to provide an overview of the **basics** for integrating a motor to a system and to provide you with the foundation to:

- Properly determine the **type** of system you employ,
- Properly **select** the type of control method you need,
- Properly **size** your motor requirement,
- **Develop** the motor parameter specifications, and
- **Verify** the motor profile you have selected.

I will begin my discussion by defining terms used throughout this chapter. Understanding these terms will promote an understanding of other discussions in this handbook.

System and Control Term Definitions

The major terms and/or components of a system that we are concerned with in this chapter are:

Axis –	Any movable part of the machine that requires controlled motion.
Load –	The end-product to be manipulated or worked.
Load Driver –	The machine part (i.e., roller, wheel, leadscrew) which directly moves the end product (load).
Size the System (motor) –	To find the torque, voltage, current, and/or speed requirements.
Table (Carrier) –	The surface or device that supports the load.

Load Driving Methods

Inline

Figure 6.1 shows an *Inline* system consisting of a load moving in an axial direction with respect to the load driver.

An example of an Inline system is a leadscrew that is directly attached to the load by a screw follower. For instance, a ballscrew and ballnut or an acme screw and nut comprise an Inline system. The load in this system type is transported in-line to the axial direction of the leadscrew (load driver) as the leadscrew rotates.

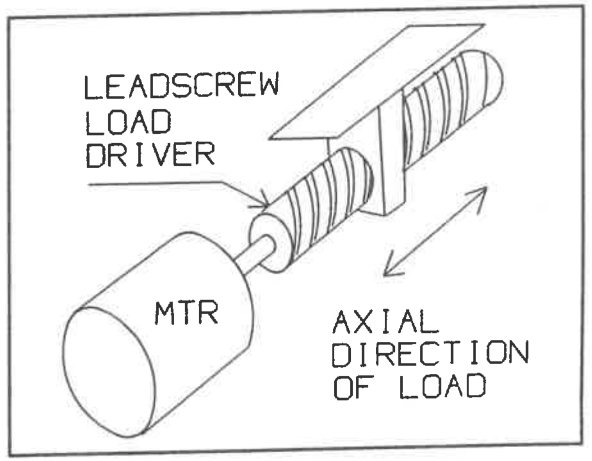

Figure 6.1 Inline driving method.

Rotary

The *Rotary* system in Figure 6.2 consists of a load that rotates in a radial path around its center. It is not required that the load be *balanced* or that it move in a path around the load driving device; it is only required that the load move in a radial fashion. Do not confuse this with the circular motion developed by multiple inline axes called *Circular Interpolation* (discussed later in this handbook). A Rotary system defines rotation affected by only one axis.

An example of a Rotary system is a rotating spindle, which either rotates the work (such as a lathe), or rotates the tools that come into contact with work that is moving inline (such as a milling machine).

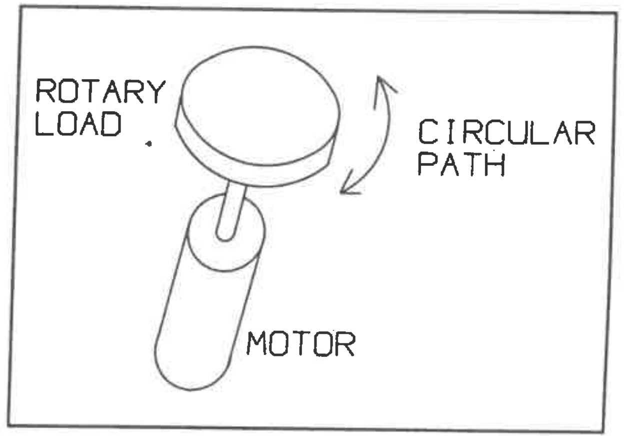

Figure 6.2 Rotary driving method.

Tangential

A *Tangential* system is one in which the load is moving in a direction perpendicular to the axial direction of the load driver (Figure 6.3).

An example of a tangentially-loaded system is a simple conveyor. The conveyor belt motion is perpendicular to the axial direction of the drive roller.

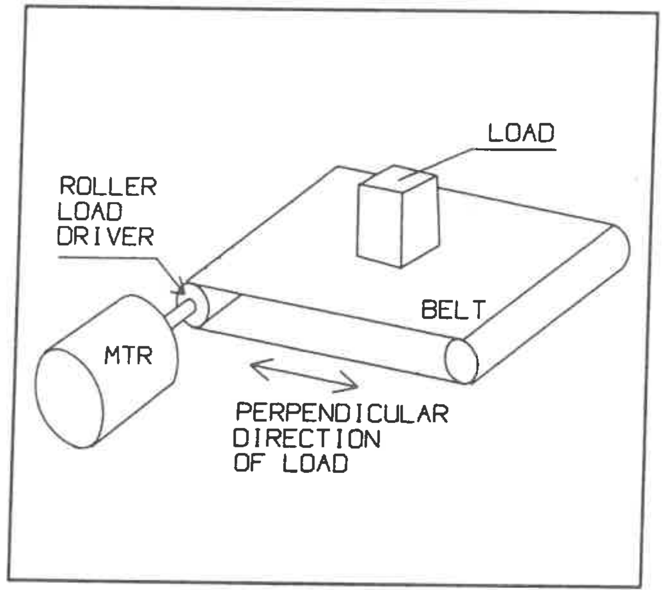

Figure 6.3 Tangential driving method.

The mechanism actually driving the load will fit only one of the three driving methods described above. However, it is not uncommon for a combination of the above driving methods to be used to transmit the power from the motor to the actual load driver.

In all of the described system types, if more than one axis of motion is involved because of the mechanical design, it is extremely important to coordinate the calculations of each axis. Small load changes in a given axis can have a substantial dynamic effect in other axes. The calculations are not difficult once the system is defined. However, defining your system can be most challenging.

Control

There are three types of control methods. Your control method selection is based on your system performance requirements, overall machine specifications, budget requirements, and qualified tradeoffs[1].

Position Control

This control method moves the load from one known fixed **position** to another known fixed position. The feedback loop(s) involved may be any combination of the types listed in Chapter 9 or others not mentioned. However, the emphasis is on the term *feedback*. As long as we can control the motion, and can determine its position in space, we can position the load as required.

Velocity Control

Velocity control moves the load either continuously for a certain time interval or from one place to another at a prescribed **velocity**. It is not required to know the load position, and its stopping point is satisfactory within the boundary of the system deceleration profile.

Torque Control

Do not confuse **torque** control with **current** control. Torque control simply means applying a known current to a motion device such as a motor or a solenoid that has a known torque coefficient (Kt) in order to develop a known constant torque.

The formula for Torque produced is:

$$T = (I)\,(Kt)$$

where:

T = torque produced
I = current in Amperes
Kt = constant given by torque/Amperes

Torque control can be used to maintain tension on materials, for clamping machine parts, or to limit the available torque to a system that could be damaged if the motion mechanism is allowed to achieve its rated current.

The following explanation should eliminate confusion about torque and current modes:

Torque mode – No velocity or position feedback loop is employed. Applying a setpoint voltage to the motor amplifier's signal input produces a constant motor current. As the motor loading increases, the motor will slow down (begin to stall). Throughout the stalling process and when the motor finally halts (stalls) it will exert a constant pull or tension on the load not exceeding [(I) (Kt)].

Current mode – A feedback loop is used. Applying a setpoint voltage to the motor amplifier's signal input will set the initial motor *velocity* requirement. As motor loading increases and the motor slows down, speed decrease is sensed by the motion controller via the feedback device. The controller will then correct for the change in speed by altering the *setpoint* voltage. The motion controller in this mode will attempt to maintain the original operating velocity.

Current mode for motion control should NOT be confused with current control for the motor amplifier. Motor amplifiers have several operating modes that have nothing directly to do with the type of motion control employed. Two of the motor amplifier modes available are velocity control mode and current control mode.

Velocity control mode uses either the motor's back-EMF or a tachometer to feedback a velocity signal to the motor drive amplifier. If the velocity detected is greater than or less than the requested velocity signal output, the drive amplifier by itself will correct for the deviation. This is sometimes called an inside velocity loop. The benefits of this type of operation are discussed in Chapter 8.

Current control mode, as associated strictly with the motor drive amplifier, simply monitors the motor *driving current* and tries to maintain it at the value requested by the signal input voltage in Amps-per-Volt. No self-adjustment is made for deviations in velocity if the motor is brought to a halt.

Specifying the Motion Device Requirements

This section discusses how to analyze the motion to develop the appropriate calculation requirements. To maintain the highest degree of performance and reliability, the same principles apply, whether the machine is in the design stage or completed.

Rule 1: Design from the product back to the control.

Have you ever met a motion control designer who has not assumed at least once that the mechanical engineer had taken all of the product handling requirements into consideration? Similarly, have you ever been in a situation where a mechanical designer had reciprocated and simply dismissed certain mechanical operations, depending instead on your control or software to handle the requirements that could have been handled mechanically?

Many designers work strictly from the information they are provided . . . "not questions asked.". This practice generally results in trouble. Often, mechanical engineers assume that if a machine is computer controlled, the computer can do some of the tasks generally relegated to mechanics.

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[1] Gains in one area offsetting reductions in another.

This is flawed reasoning. By independently communicating with the other project designers, you will ensure a successful outcome. ***Assume nothing!***

Designing from the product back to the controller ensures that *you* will determine the restrictions of the product and the mechanics first hand. This gives *you*, the control designer, a better grasp of the machine's functional requirement. You also preserve the opportunity to question the mechanical designer about potential control or software weaknesses. Designing in this fashion will produce success through teamwork! There are questions you must ask . . . *ask them!* Asking questions is the only way to improve your knowledge of the product, and the system required to handle it.

Rule 2: Determine the product restrictions for each axis in the system.

Questions you might ask about a product include:

- **Allowable acceleration/deceleration**—How much and what types of stress can the product handle?
- **Velocity limits**—How fast can the product be moved without loss of control?
- **Associated pressures**—How much force can be applied to hold, manipulate the product, or both?
- **Product weight**—How much *worst case* weight must the machine deal with?
- **Dimensions**—What does the product look like?
- **Structural limitations**—How sturdy is the product? How strong is the machine?
- **Light wavelength**—Will the product be destroyed if exposed to certain types of light, or will it be invisible to sensors at certain light wavelengths?
- **Product color(s)**—Is color a factor in the handling, sensing, or development of the product?
- **Electromagnetic Fields**—Are there any restrictions regarding product exposure to electrical or magnetic fields?
- **Work to be accomplished**—What is it that the machine does with the product (conveyor, index, mold, spray, tension)?
- **Product cutting/forming limitations**—How fast can the product be worked?
- **Temperature limitations**—Hot and cold limitations?

This information may only be **part** of what you must know to insure safe, reliable, precise, and **predictable** product handling.

Not all axes necessarily touch the product. A paint spraying axis may apply the paint to the product but will not physically contact it. The paint spraying axis load, therefore, is the paint. Now you will need to learn details about the paint. For example, spraying speed, spraying distance, weight of the paint, paint pressure, and so on. Each axis may present itself as a totally different problem for any given machine. Do not assume all forces will be the same for all problems.

Rule 3: Determine the type of load carrier used to support the load.

Not all system loads require a moving supporting structure. An example might be a board product resting on two parallel, non-movable, one-inch diameter rails. The board is transported by pawl pushers (or fingers) evenly spaced behind the board. The pawls drive the board through the machine by chains, belts, or other means that never touch the board.

Rule 4: Determine what type of load driver is set up for each axis on the machine.

Once you understand what the load is and have discovered what the restrictions are in dealing with it (system specifications, weight, dimensions, temperature, light, accel./decel., speed,. . .), and you have concluded what type of load carrier and driver to use, you can begin **sizing** the system.

To this point, you should know the following:

For an ***Inline*** system:

- Load weight
- Load slide friction (if no load carrier is used)
- Table (or load carrier) weight (if used)
- Table slide friction (if used)
- Maximum axis velocity
- Acceleration time from 0 to maximum velocity
- General load handling restrictions.

For a ***Rotary*** system:

- Load weight, or load width and diameter
- Rotary table (if used) weight, or width and diameter
- Rotary table friction (if used)
- The percent efficiency between rotary load and the load driver if the load is driven directly, or between the rotary table and load driver.
- Maximum axis velocity
- Acceleration time from zero to maximum velocity
- General load handling restrictions.

For a ***Tangential*** system:

- Load weight
- Load slide friction (if no load carrier is used)
- Table or load carrier weight (if used)
- Table slide friction (if used)
- Type of load moving device (chain, belt, cable, etc.)
- Dimensions and weight of the load moving device.
- The percent efficiency between the load and the load driver
- The percent efficiency between the load carrier and the load driver (if used)
- Load driver width and diameter
- Maximum axis velocity
- Acceleration time from zero to maximum velocity
- General load handling restrictions.

In using any of the above systems, note that in the case of liquid dispensing, you must consider the weight of the liquid, the dispensing nozzle, the hoses, and so on. To arrive at a more accurate sizing result, figure out the pressure required to move the liquid through the tubing and out of the dispensing nozzle at a required volume to get the imposed vector force and direction that will be applied to the supporting structure. An example would be a garden hose that flails out of control when streaming out water at high pressure. Counteractive forces are necessary to stabilize the hose.

It is important to understand that the scope of this handbook is not to provide a course on material handling, but to invoke thought processes out of which design methods will emerge. Your design skills will produce the requirements.

Calculating System Torque Requirements

Determine Required System Motion Performance

Before any system of calculations, set up a system/axis timing diagram similar to that described in Chapter 4, and determine the required move profiles for all system axes. You will use the diagrams to develop acceleration and deceleration profiles along with the required profile time of a given axis. I^2R losses and other pertinent information can also be figured out from these diagrams.

Calculation #1 – Determining Load Acceleration

Throughout the remaining discussion, a motor will be considered as the motion device.

Torque is a measure of the force required to move the load over a distance. From the perspective of the motor, we will need to first calculate the load acceleration rate.

Inline Torque:

$$RPM = (IPM)(MR)$$

$$AR = \frac{2\pi(RPM)}{60(AT)} \; \frac{rad}{sec^2}$$

$$AD = \frac{(AR)(AT)^2}{2\pi(2)(MR)} \; DU$$

where:

IPM = maximum axis linear velocity
LP = linear pitch or motor revolutions per inch of linear travel
RPM = required motor revolutions per minute
AT = acceleration time in seconds from rest to maximum RPM
AR = acceleration rate
AD = acceleration distance

To meet the acceleration distance (AD) requirement, vary the acceleration time (AT) and recalculate accordingly.

Rotary Torque:

$$AR = \frac{2\pi\,(RPM)}{60\,(AT)} \; \frac{rad}{sec^2}$$

$$AD = \frac{(AR)\,(AT)^2}{2\pi\,(2)}$$

where:

RV = rotational velocity
RPM = RV with no gearing
AT = acceleration time in seconds from rest to maximum RPM
AR = acceleration
AD = acceleration distance

To meet the acceleration distance (AD) requirement, vary the acceleration time (AT) and recalculate accordingly.

Tangential Torque:

$$RPM = \frac{(TV)}{\pi\,(LDD)}\ \frac{DU}{\text{min.}}$$

$$AR = \frac{2\pi\,(RPM)}{60\,(AT)}\ \frac{rad}{\sec^2}$$

$$AD = \frac{(AR)\,(AT)^2}{2\pi\,(2)\,(MR)}\ DU$$

where:
TV = tangential load velocity
LDD = load driver diameter
MR = motor revolutions per DU of linear travel
RPM = motor rpm
AT = acceleration time in seconds from rest to maximum rpm
AR = acceleration
AD = acceleration distance

To meet the acceleration distance (AD) requirement, vary the acceleration time (AT), and recalculate accordingly.

Next, the load torques are found by multiplying the acceleration rate (AR) by the determined inertias (using load weight) as follows . . .

Calculation #2 - Determine Load Torque (using weights)

Inline Load Torque: (assumed American units)

LW	= Lbs.	Load weight
TW	= Lbs.	Table weight
SR	= In.	Screw radius
SL	= In.	Screw length
SD	= Lbs./In.^{3}	Screw density
P	= 1 / Lead	Screw pitch
SPL	= Lbs.	Screw pre-load force (if applicable)
CBW	= Lbs.	Counter balance weight (vertical systems)
WF	= Lbs.	Opposing force applied to work the load
LSF		Load slide friction (if applicable)
TSF		Table slide friction (if applicable)
GFP	= Lbs.	Table gib force pre-load
J_L	= In.Lb.Sec^2	Load inertia
J_T	= In.Lb.Sec^2	Table inertia
J_S	= In.Lb.Sec^2	Screw inertia

Then, using the assumed American units:

$$J_L = \frac{(LW + CBW)\,(0.000179)\,(144)}{386}$$

$$J_T = \frac{(TW)\,(0.000179)\,(144)}{386}$$

$$J_S = \pi\,(SR)^2\,(SD)\left(\frac{(SR)^2}{(24)\,(32.16)}\right)$$

$$SIT = \left(\frac{J_L + J_T}{P^2} + J_S\right)(AR)\ \ inch\ \ pounds$$

Rotary Load Torque:

RLD	= Lbs./In.^{3}	Rotary load density
RLR	= Inches	Rotary load radius
RLW	= Inches	Rotary load width
RTD	= Lbs./In.^{3}	Rotary table density
RTR	= Inches	Rotary table radius
RTW	= Inches	Rotary table width
RLF		Load friction (if applicable)
RTF		Table friction (if applicable)
Jrl	= In. Lb.Sec^2	Rotary load inertia
Jtl	= In.Lb.Sec^2	Rotary table inertia

Then, using the assumed American units:

$$Jrl = \frac{\pi\,(RLR)^2\,(RLW)\,(RLD)\,(RLR)^2}{(32.16)\,(24)}\ \ inch\ \ pound\ \ \sec^2$$

$$Jrt = \frac{\pi\,(RTR)^2\,(RTW)\,(RTD)\,(RTR)^2}{(32.16)\,(24)}\ \ inch\ \ pound\ \ \sec^2$$

System Torque (ST):

$$SIT = (Jrl + Jrt)\,(AR)$$

$$system\ \ torque = SIT + (force\ A + force\ B + \ldots + force\ N)\,(AR)$$

Where: forceA through force N represent the forces such as friction, pre-load or other forces exerted at the radius arm in inches.

When calculating rotary static friction force for balanced loads and carriers, use:

$$RSF = (total\ \ weight)\ (friction)\ (RLP)\ \ inch\ pounds$$

Apply the system loading (load+load table+ . . .) at a distance from the rotational center where you feel the loading exists, usually 1/2 of the rotational load (or rotary carrier) radius. You can position the loading point anywhere on the radial arm you feel the loading is *actually* located (RLP in inches).

$$RSF1 = (RSF)\left(\frac{RLP}{RTD}\right)\ \ inch\ pounds$$

The loading transfer takes place at a distance from the center of the rotary load (rotary transfer distance RTD). This distance forms the ratio used in the transfer of the rotary loading to the load driving device.

$$RSF2 = \frac{RSF1}{GR}$$

Where GR is the gear ratio back to the motor.

The reflected rotational static friction is then divided by the overall gear ratio to determine the *static torque* reflected back to the motor shaft.

Determining the load driving ratio in this manner also allows the designer to calculate the reflected inertia loading as well. The inertia position on the rotary devices radial arm will dictate the ratio scenario. Therefore, the more accurate the effective position of rotary loading, the more accurate the calculations.

Tangential Load Torque: (assumed American units)

LW	= Lbs.	Load weight
TW	= Lbs.	Table weight
CBW	= Lbs.	Counter balance weight (vertical systems)
WF	= Lbs.	Opposing force applied to work the load
LSF		Load slide friction
TSF		Table slide friction (if applicable)
GFP	= Lbs.	Table gib force preload
LDR	= In.	Load driver radius
LDW	= In.	Load driver width
LDD	= Lbs./In.^{3}	Load driver density

J_L	= In.Lb.Sec^2	Load inertia
J_T	= In.Lb.Sec^2	Table inertia
J_{LD}	= In.Lb.Sec^2	Load driver inertia

Then, using the assumed American units:

$$J_L = \frac{(LW + CBW)\ (0.000179)\ (144)}{386}$$

$$J_T = \frac{(TW)\ (0.000179)\ (144)}{386}$$

$$J_{LD} = \pi\ (LDR)^2\ (LDW)\ (LDD)\left(\frac{(LDR)^2}{(24)\ (32.16)}\right)$$

System Load Torque (ST):

$$SIT = (J_L + J_T)\ (AR)\ (LDR + J_{LD})\ (AR)$$

The above calculations are used to solve for the amount of torque in inch-pounds required to directly handle the load if the motor shaft is directly connected to the load driver. The next step is to determine if a motor can be fitted to the torque load without exceeding size and budget requirements.

If a selected motor/amplifier package is too large or too costly, gearing can be worked into the equation to minimize the size, and/or cost. This is the point at which we consider performance/cost trade-offs. For example, it might be more economical to use a high-speed, low-torque motor with gearing rather than a low-speed, high-torque motor without gearing.

The size, weight, cost, and other factors of the motor, amplifier, and gearing package must be realistic with respect to the total machine size, weight, cost, . . . (*do not forget product through-put*), or the design will fail. Failure to optimize cost, performance, and reliability parameters is simply incomplete work.

Based on the above discussion, you must weigh the advantages against the disadvantages when you begin designing a system. For example, an advantage of an *Inline* style system using a screw is the fact that the screw amplifies motor torque automatically, but a disadvantage is that it reduces system speed. The *Tangential* system, on the other hand, is a motor torque reducer and a motor speed amplifier. The motor/amplifier calculations for each of the three system styles, are not similar and must be dealt with carefully.

Using *calculations #3* and *#4* we will work up the remaining miscellaneous system torques and the overall system performance profile.

Something to consider in a *vertical* system is use of a counterbalance. If a counterbalance does not exist, or is not possible to install on the axis, then the torque-loading on the motor can be severely different when the system is moving **up** versus moving **down**. This is due to the effect of Gravity assisting the motor, when the motor is moving the load in the *Down* direction, and fighting the motor when the motor is moving the load in the *Up* direction. A counterbalance will increase the torque-loading on the motor (usually by a factor of two), but will present a reasonably equal torque-loading on the motor regardless if the load is being moved **up** or **down**. If a counterbalance is not to be part of the system/axis design, the next best approach is to use *S* curve acceleration (see chapters 10 and 12). Using an *S* update time configured to the required profile, weight, and gain structure to be used, the *S* curve can help maintain a lower torque-loading on the system while accelerating and/or decelerating.

Calculation #3 - Determine Miscellaneous System Requirements

Gearing

Each gear inertia is calculated as follows:

GR = In. Gear radius
GW = In. Gear width
GD = Lbs./In.^{3} Gear density

Jg = In.Lb.Sec^2 Gear inertia

$$Jg = \pi\,(GR)^2\,(GW)\,(GD)\left(\frac{(GR)^2}{(24)\,(32.16)}\right)$$

After you have calculated all of the individual gear inertias, calculate the overall gear train inertia (including the load) as follows:

1) Add together the inertia of gears locked on the same shaft or those locked together (1:1 ratio).

2) If gear shafting is significant to the inertia loading of the gear train calculate the shaft inertias using the gear formulas, then add the result to the gear(s) it supports. Consider the overall result as the inertia belonging to the gear(s) it supports.

3) Working from the load end of the gear train toward the motor, take the last gear inertia value (total of *#1* and *#2* above), add it to the load inertia and divide that result by the square of the gear ratio between it and the next gear in line. Divide the result again by the percent efficiency between the gears (or other prime movers), and add that result to the inertia of the next gear in line.

4) Continue this process with each gear in line (without using the load inertia) until you have reached the motor end of the gear train. This value reflects the inertia of the load plus the gear train at the motor shaft, J_{ref}.

5) The gear train and load acceleration torque produced is represented by:

$$T_{ref} = (J_{ref})\ (AR)\ \textit{torque units}$$

6) If you do not include the load in the previous work-up, the result will be torque-loading of only the gear train. A good rule of thumb to follow (if the static torque-loading is not available) is to use no more than 5 percent of the calculated torque value (T_{ref}) for the static friction torque-loading transmitted from the gearing to the motor. This rule works in the vast majority of applications, but you must qualify that assumption on your system. Do not forget that the inertia torque-loading increases as a square function of the acceleration time change; therefore, the torque value can be significantly different for small changes in acceleration/deceleration times.

Selecting a Motor to Fit the System Torque Requirement

At this point, select a motor to fit the speed/torque requirements of the system you have just developed. If you are dealing with a high speed index system, you may want to consider a high RMS torque motor to more efficiently handle the head being produced (see the next calculation). Remember, that although a higher torque-per-Ampere rating will allow a cooler running motor, these motors are generally more expensive. By becoming familiar with the motor types available and the torque/voltage/current/cost relationships of each motor style, you will be able to select the proper motor quickly and with less effort.

Finally, working the equations in calculation #4, determine if the system will act within the desired specification(s).

Calculation #4 - Determining Total System Performance

$$SAT = (Jm + J_{ref})\,(AR) + Tr + Tm$$

Where:
SAT = System acceleration torque
J_{ref} = reflected inertia at the motor shaft
Jm = motor inertia
Tr = reflected static torque at motor shaft
Tm = motor static torque

System deceleration torque:

$$(AR)\,(Jm + Jr) - Tr - Tm$$

Drive Voltage required:

$$\left(\frac{SAT}{Kt}\right)(\Omega_{MOTOR}) + Kv\left(\frac{RPM}{1000}\right) + 2$$

Drive Peak Current required:

$$\frac{SAT}{Kt}$$

Where Kt is a motor torque constant (Torque per Amp.)

Drive RMS Current required:

$$\frac{Tr + Tm}{Kt}$$

The system mechanical time constant (SMT) is given as:

$$SMT = \frac{(J_{sys})(\Omega_{MOTOR})}{(K_e)(K_t)}$$

Where:

Ke = motor voltage constant in volts/krpm
[Nm/Amp = (InLbs/Amp)(112985)]

Kt = motor torque constant in nm/A

Ω_{MOTOR} = DC resistance of motor

Jsys = system inertia in kgm^2
[kgm^2 = (InLbs^2)(1129.85/10000)]

The **breakaway frequency** of a system is noted as the frequency where the system fails to follow the input signal with full amplitude and phase accuracy (Figure 6.4).

The **breakaway frequency** (BF) is simply the reciprocal of the mechanical time constant.

$$BF = \frac{1}{10\,(SMT)}$$

The factor of 10 should be added to guarantee that the motor will track tightly to the move profile. Five time constants (SMT) are required for the system to achieve stability during an acceleration and five time constants (SMT) for a deceleration.

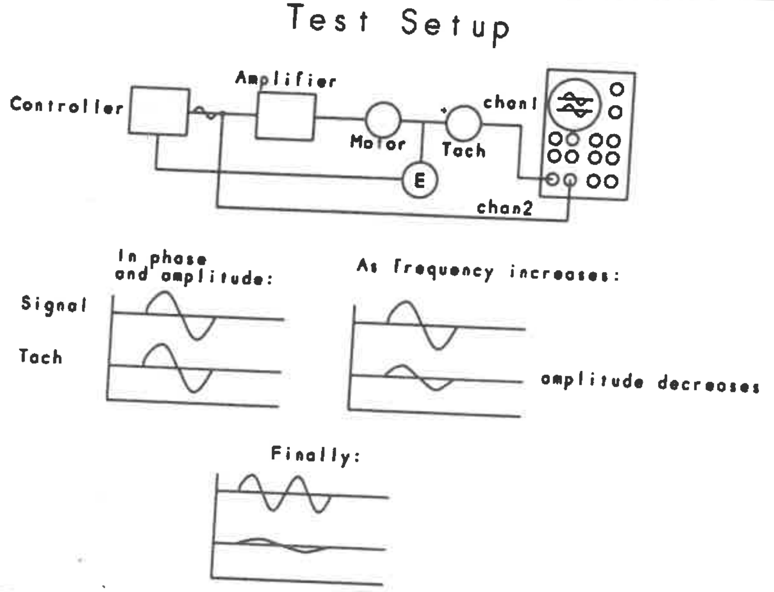

Figure 6.4 Breakaway frequency of a system.

RMS torque is generated by the required move as:

$$RMS,torque = \sqrt{\frac{(SAT)^2(Ta) + (SST)^2(Tr) + (SDT)^2(Td) + (Soff)^2(Toff)}{Ta + Tr + Td + Toff}}\ (torque\ units)$$

Where:

Ta = Accel. time to velocity
Tr = Running time at velocity
Td = Decel. time from velocity to zero
SAT = Sys. Accel. Torque
SST = Sys. Static Torque
SDT = Sys. Decel. Torque
Soff = System torque generated at standstill
Toff = Time spent at standstill

Note that the calculations described above are only a small part of a complete calculation package to use when sizing systems. It is important to take the time to develop your own sizing methodology, or use a sizing package developed by others that will allow you to flex your requirements with solutions you can trust.

A rule of thumb is that if the motor inertia is 30 to 70 percent of the reflected system inertia value, the motor could be the proper one to use. Do a performance calculation to see if there is a *fit*, if its cost is within budget. Something I once read in a motor manufacturer's guide book about motor selection stated "*. . . the motor inertia should equal the load inertia . . .* " for optimum motor performance and cost. If the motor inertia is too small, the overbearing system inertia will require longer acceleration and deceleration times to reduce the motor torque-loading and prevent the motor from *over-currenting* or position overshooting. In turn, if the motor inertia is too great, the motor/drive amplifier package will probably not be the most economical for the job.

However, the main reason for the philosophy of matching the reflected load to motor inertias is the power surging that goes on during the commutation periods within the motor. As the commutation occurs, the motor may allow a slow down of the load as the motor currents shift within the motor windings (think about SCR type drives). The motor inertia allows a "carry through" of the implied motor power via a "fly wheel" effect. In todays technology, this requirement can be changed due to the higher bandwidth motors available, which reduces the commutation power surging.

If you work out a <u>profile</u> versus <u>performance</u> calculation and then perform a motor/system torque check, you can usually select a motor smaller than most motor manufacturers will suggest. The money saved can then be directed into the system control and/or the never ending *creeping feature-isms*.

Things to watch for are:

- System mechanical response (bandwidth),
- Motor RMS and Peak voltage/current needs,
- Drive amplifier RMS and Peak voltage/current capability and
- RMS heating of the motor.

It makes little sense to size a system and then select a motor drive amplifier with a 100VDC bus when your work-up showed the profile required 150VDC. You won't achieve the desired performance.

Conclusion

Although this chapter deals mainly with DC servos, selecting a stepper motor, AC motor or any other type of motion generator for a given application will still require system load sizing. The real difference lies in how the other style of motion generator is chosen from its rating specifications. If you consider all the **necessary** system parameters, the sizing operation discussed above will not only be accurate, but it will be reasonably easy to achieve.

Phasing Motors to Control Systems

With and Without Velocity Loops

As an applications engineer, I speak with hundreds of people each month; although, not all my contacts concern applications problems. One of the most often asked questions that I field concerns proper motor velocity and position loop phasing.

Here, I use the term *phasing* to describe the relationship of motor motion with the system command. Motor phasing is perhaps the greatest nightmare a newcomer to the field can experience. When phasing multiple control loops, sometimes even the most experienced engineers encounter problems. This chapter is devoted to outlining simple phasing techniques. The intent is to save the many man-hours of frustration and perhaps even the unforeseen catastrophes that can emerge as a result of improperly phased systems.

Defining Motor Control Phasing

First, let's define *phasing*. Simply stated, correct phasing means: the motor <u>direction</u> and <u>RPM</u> are coordinated with the velocity and/or position control loops.

In other words, if the control system commands the motor to remain stationary and it does not, the control loops are not functioning properly; hence, they are *out of phase*. Just imagine all of the hard-wired out-of-phase possibilities and all of the symptoms that naturally follow them. There is too much at stake for you to be in error. You can damage the motor, the drive, or the machine. Worse yet, you may damage yourself or someone close to you. A possible secondary effect is to become discouraged with the manufacturer of a given device. All of this can result simply because you were not familiar with the basic principles and techniques of phasing.

In certain systems, it is possible to test motor phasing while the motor is disconnected from the machine, but this is not always the case. Linear scale systems or split systems with tachometer and encoders on opposing sides of the machine make it difficult or impossible to disconnect the motor. Consider further, startup systems with a computer reading the position feedback from an encoder board and then transferring the results to an analog driver board.

Good practice habits dictate that the first-time startup of any motor control system should be direct and to the point. It should <u>not</u> be mired in problem symptoms, troubleshooting bugs, or any other frustrating experience. Every day phasing situations vary widely, but the good news is, by following several basic steps your system can be properly phased in a relatively short period of time.

Basic Phasing Rules

Rule #1: Whenever possible, phase the system with the motor shaft disconnected from the mechanical load. In the event of a motor runaway, no damage to the system will occur.

Rule #2: Always maintain immediate access to a motor kill switch and ***man it***. In the event of a runaway, the motor can be promptly shut down.

Rule #3: Connect and phase the lowest level control loop first, then propagate outwardly, connecting and phasing each successively higher level control loop in order.

This rule is no different than solving:

$$[(2)(2) + 3[(2)(5)] + (4)(4)] = ?$$

You simply solve the groups within the lower level parenthesis first, then accumulate the total solution outwardly:

$$(4 + [(3)(10)] + 16) = 4 + 30 + 16 = 50$$

Note, that I talk about *loops*. It is irrelevant whether there is one, two, or ten control loops involved with the motor motion control. If each loop is connected and phased at its proper time, the system phasing can be done quickly.

Rule #4: Remember that outer loops should respond slower than inner loops to ensure good motion stability.

Rule #5: Always secure the proper tools. This includes at least the device schematics or interface pinout tables (available from all manufacturers), a multimeter, perhaps an oscilloscope, and the system wiring diagram.

Rule #6: Be patient! You will complete the task much more quickly if you do it right the first time.

Motor Control Phasing

System Style #1: Single Position Loop, No Velocity Loop System

The worst thing designers can do when they encounter this type of system is to hook it all up, then turn on the power. This amounts to nothing more than guessing and has less than a 50-50 chance of functioning when power is applied.

Phasing in this manner is asking for trouble. You may not think so if you have succeeded with flea-power motors at your workstation. However, try it sometime with motors ranging from 20 Hp to 40 Hp, those that you cannot hold in a vise or with a piece of tape. If the phasing is wrong, I guarantee that the motor can do some real damage, if not to you, then to something around you when it leaps off your workstation in reaction to the impulse torque of the armature.

Remember Isaac Newton . . . action and reaction?

Procedure #1: Testing Voltage Direction

With the motor disconnected:

1) Connect a voltmeter across the motor armature leads [(+) lead to (+) motor, and (-) lead to (-) motor].

2) Rotate the motor armature clockwise, by hand, looking at the motor shaft end of the motor.

3) Rotate the motor fast enough to obtain a voltage deflection on the meter (it can be small, since we are only interested in the direction rather than the value).

4) Record whether the voltage swings positive (+) or negative (-) with respect to the motor armature rotation.

5) Mark the motor armature wire connected to the voltmeter (+) lead: ARMATURE (+), and to the armature wire connected to the voltmeter (-) lead, mark it: ARMATURE (-).

Now, connect ARMATURE (+) to the motor drive amplifier (+) output, and do likewise for ARMATURE (-). Apply a DC signal to the motor drive amplifier's signal input that is the same polarity as is generated by the rotated armature. This will cause the motor to rotate in the previously determined direction. If you want the motor to rotate in the opposite direction, simply swap the (+) and (-) motor leads. Motor drive amplifiers are assumed to be non-inverting. That is, a (+) signal input yields a (+) voltage output from the (+) armature output connection, and likewise, the same is the case for a (-) signal input.

The proper method for phasing a *Single-Position Loop, No-Velocity Loop System* is:

1) Disconnect power to the motor, drive, and control systems.

2) Do the test outlined in *Procedure #1*.

3) Connect the motor armature to the motor drive amplifier as specified in *Procedure #1* above.

4) Connect the feedback device channels A, B, and I, to the position control feedback inputs. Connect /A, /B, and /I if using the differential channels.

5) Connect the position loop DAC[2] signal wires to the motor drive amplifier signal input connections.

6) Power-ON the <u>position</u> controller (motion CPU) system only.

7) When the position control loop initializes, it will send a correction DAC voltage to the motor drive amplifier to maintain null position (no movement).

8) Place a voltmeter across the position control system DAC (+) output to SIG and (-) to COMMON on the amplifier.[3]

9) Slowly rotate the motor shaft in what you consider to be the (+) direction as determined in Procedure #1 above. A (-) voltage should appear from the DAC (+) signal lead with respect to the signal return lead.

If the voltage direction reading is positive (+):

a) Power-OFF the position control loop.
b) <u>Swap</u> encoder channel A with /A or channel B with /B, **<u>but not both.</u>**
c) Proceed with *Step #6* above.

NOTE: In the case of single-ended feedback devices, swap channel A with B.

10) Power-OFF the position loop.

11) Power-ON the position loop and reestablish system position

12) Power-ON the motor drive amplifier. The position control loop should now be holding the motor.

13) Command the position loop to **<u>slowly</u>** move the motor in what **<u>you</u>** consider the forward (+) direction.

14) If the motor turns in the correct direction, proceed to *Step #15*. If the motor is turning backwards:

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[2] Digital to Analog Converter.

[3] On some amplifiers these two connections may be labeled ±REF.

a) Power-OFF both the position control system and the motor drive amplifier.
b) Swap encoder channel A with /A or channel B with /B, **<u>but not both</u>**.
c) Swap the (+) and (-) armature wires at either the motor or motor drive amplifier, whichever is easier.
d) Proceed with *Step #11* above.

15) With the motor now properly phased, the next step is to verify the *index marker phasing*. First check to find out whether your control system requires a *level-triggered* or *edge-triggered* index signal.

Edge-Triggered and Simple Level Trigger Control

If the control triggers on an index edge or simply on an index level, verify whether the I and /I feedback inputs are correct. If they need to be reversed, simply swap the I and /I wires, or follow the directions supplied by the position control manufacturer.

Complex Level-Triggered Control

If the control triggers on an index level relative to a corresponding level on one or both of the main axis feedback channels (A or B) and you have found that the index level is incorrect, simply swap the index I and /I wires. If the Index level is correct, but is out of phase with channels A, and/or B then:

a) Swap channel A with /A if required.
b) Swap channel B with /B if required.
c) Swap A with /A and B with /B only if a) or b) above were done.
d) Proceed to *Step #6*.

16) This completes the phasing of the *position loop only* system style.

<u>System Style #2:</u> Single Velocity Loop, No Position Loop System

Procedure #2: Tachometer Voltage Direction

1) Do the test described in *Procedure #1*.

2) Connect the voltmeter across the tachometer wires. As you rotate the motor in the same direction as described above for *Procedure #1*, read the voltage on the voltmeter.

3) Record the (+) or (-) tachometer voltage direction.

With the motor armature connected as described in *Procedure #1*, the tachometer should be connected to the motor drive amplifier so that its voltage is **<u>opposite</u>** to that of the signal input requirement. This will produce the feedback required to maintain motor stability.

The proper method for phasing a *single-velocity loop, no position loop* is:

1) Power-OFF the motor, drive, and control systems.

2) Do the test in *Procedure #1*.

3) Connect the motor armature to the motor drive amplifier accordingly.

4) Connect the tachometer wires to the motor drive amplifier tachometer input connections as in *Procedure #2*.

5) With the control DAC disconnected from the motor drive amplifier, place a jumper wire across the motor drive amplifier signal input connections SIG to COM.

> **CAUTION:** The motor may move when power is applied due to improper balance or other drive conditions. Proceed with care.

6) Power-ON the motor drive amplifier.

7) If the motor slowly rotates, adjust the balance potentiometer to stop motor movements.

   If the motor runs fast:

   a) Power-OFF the motor drive amplifier.
   b) Reverse the tachometer signal wires at the motor amplifier.
   c) Proceed to *Step #6*.

> **NOTE:** If the motor still can not be stabilized to zero motion, contact the motor drive amplifier manufacturer.

8) Power-OFF the motor drive amplifier.

9) Remove the jumper applied in *Step #5* above.

10) Apply a control voltage to the motor drive amplifier signal input.

11) Power-ON the motor drive amplifier.

12) Increase the control voltage to slowly rotate the motor in the direction you consider forward (+).

    a) If the motor rotates in the opposite direction, power-OFF the control and motor drive amplifier systems.
    b) Swap the tachometer (+) and (-) signal wires.
    c) Swap the motor armature (+) and (-) leads.
    d) Proceed to *Step #11*.

13) This completes the phasing of the *velocity loop only* system.

System Style #3: Dual Loop, Position and Velocity System

I use this style system whenever I require high system response, low speed stability or high index rates. Typical systems include registration, step and repeat indexing (4 to 25 shots per second), match-speed-and-cut type flying cutters (25 feet per minute plus). Phasing of this type system is simply a combination of the preceding two systems with additional steps for reversing phase faults.

The proper method for phasing a *dual-loop system* is:

1) Power-OFF the motor, drive, and control systems.

2) Disconnect the position loop from the system control.

3) Perform the test in *Procedure #1*.

4) Connect the motor armature to the motor drive amplifier accordingly.

5) Connect the tachometer to the motor amplifier tachometer input as in *Procedure #2*.

6) With the control DAC disconnected, place a jumper wire across the motor drive amplifier signal input connections SIG to COM (or +REF. to - REF.).

> **CAUTION:** The motor may move when power is applied due to improper balance or other drive conditions. Proceed with care.

7) Power-ON the motor drive amplifier.

8) Use the Balance potentiometer to stop motor movement, if the motor is slowly rotating.

If the motor is running at high speed:

a) Power-OFF the motor drive amplifier.
b) Reverse the tachometer signal wires at the motor drive amplifier.
c) Proceed to *Step #7*.

NOTE: If the motor still can not be stabilized to zero motion, contact the motor drive amplifier manufacturer.

9) Power-OFF the motor drive amplifier.

10) Remove the jumper placed in *Step #6* above.

11) Apply a control voltage to the motor drive amplifier signal input.

12) Power-ON the motor drive amplifier.

13) Increase the control voltage in the (+) direction to slowly rotate the motor in what you consider the forward direction to verify the velocity loop stability. If the motor is unstable, execute the manufacturers recommended drive setup. If the motor rotates in the opposite direction:

a) Power-OFF the control and motor drive amplifier systems.
b) Swap the tachometer (+) and (-) signal wires.
c) Swap the motor armature (+) and (-) leads.
d) Proceed to *Step #11*.

14) Power-OFF the motor drive amplifier system.

15) Connect the position loop feedback device channels A, /A, B, /B, I, /I to the position control feedback inputs.

16) Connect the position loop DAC signal wires to the motor drive amplifier signal input connections.

17) Power-ON the position control system only.

18) When the position control loop device initializes, it will send a correction DAC voltage to the motor drive amplifier to maintain null position (no movement).

19) Place a voltmeter across the position control system DAC (+) output to SIG and (-) to COM.[4]

20) Slowly rotate the motor shaft in the same direction as previously described to obtain a voltage direction with respect to the rotation in *Procedure #1*.

21) Since the position loop is trying to maintain zero movement of the motor, a (-) voltage should appear on the DAC (+) output line with respect to the DAC (-) line.

If the voltage reading direction is (+):

a) Power-OFF the position control loop.
b) Swap channel A with /A or channel B with /B position feedback wires—**but not both.**
c) Proceed with *Step #17* above.

NOTE: In the case of single ended feedback devices, swap channel A with channel B.

22) Power-OFF the position loop.

23) Power-ON the position loop to reestablish its position.

24) Power-ON the motor drive amplifier. Position holding should now be in control.

25) Command the position loop to **slowly** move the motor in what **you** consider to be the forward (+) direction.

26) If the motor turns correctly, go to *Step #27*. If the motor turns backwards:

a) Power-OFF both the position control system and the motor drive amplifier.
b) Swap channel A with /A or channel B with /B—**but not both** feedback wires.
c) Swap the (+) and (-) armature wires.

NOTE: In the case of single ended feedback devices, swap channel A with B.

d) Swap the (+) and (-) tachometer signal wires.

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[4] On some amplifiers these are ±REF.

e) Proceed with *Step #23* above.

27) With the motor now properly phased, the next step is to verify the index marker phasing. First, find out if your control system requires a level-triggered, or an edge-triggered *Index* signal.

Edge-Triggered and Simple Level Trigger

If the control triggers on an index edge or simply on an index level, verify if the I and /I feedback inputs are correct. If they need to be reversed, simply swap the I, and /I wires, or follow the directions supplied by the position control manufacturer.

Complex Level trigger

If the control triggers on an index level relative to a corresponding level on one or both of the main axis feedback channels (A or B), and you have determined that the index level is incorrect, *simply swap the index I and /I wires.*

If the Index level is correct, but is out of phase with channels A, and/or B:

a) Swap channel A and /A if required.
b) Swap channel B and /B if required.
c) Swap A and /A with B and /B only if a) or b) above were done.
d) Proceed to *Step #17*.

28) This completes the phasing of the *dual loop only* system style.

Conclusion

The above three control loop types are used in 99 percent of all system applications. Additional control loops should be phased as required using combinations of the above methods. If re-phasing of lower loops is necessary, it should be done following the guidelines just discussed. Clearly, the more loops you incorporate, the more carefully you must plan your approach. This will prevent you from creating an out-of-control mess.

Do not omit steps, and do not be intimidated by first-timer's worries. The steps work, and they will become second nature when you have followed them a few times.

Notes: