Reducing Design Time for Linear Motion Systems

Al Ng, Director, Engineering - Rails, Guides & Components
Thomson Industries, Inc.
540.633.3549
540.639.4162 (fax)
www.thomsonlinear.com
Thomson@thomsonlinear.com

Reducing engineering design time for new linear motion system projects is integral to lower overall costs and faster time to market. This article is intended to help you reduce design time by minimizing non-value added activities, such as re-design, over design, or scope creep. We'll do this by reviewing the basics of thoroughly understanding all of the application criteria, verifying calculations and analysis via parametric testing of components, modules, and full assemblies, and proving out projected performance results with testing.

At the start of a new linear motion system design problem, capture as much of the pertinent application information as possible to avoid having to go back and repeat portions of, if not the entire, design process. Be wary and prepared for scope change. Use theoretical calculations and analyses to determine the best initial designs and then compare them with test measurements of the key performance attributes on actual equipment. Confirm bench test results by performing cycle tests under actual field conditions.

Identifying the requirements

Key Application information data

- Load / Speed (Dynamic and Static)
- Voltage 12, 24, 36, 48 VDC, 110, 220, VAC
- Direction of load
- Stroke length
- Life / Duty Cycle
- Environmental
- End of stroke protection: clutch? Limit switches?
- How will actuator be controlled?
- Feedback
- UL, CSA, CE
- Other…..Consult your Actuator Application engineer for additional design considerations.

Figure 1: Typical design checklist for linear motion systems

The first and very critical step of nearly every engineering process is identifying the application requirements. Each product may have a unique set of criteria that will affect its performance. Using a checklist will help to ensure the consideration of parameters that may otherwise be overlooked. The selection of the correct ball screw assembly for a specific application can require an iterative process to determine the smallest envelope and most cost-effective solution. The design load, linear velocity, and positional accuracy requirements are used to calculate the diameter, lead and load capacity of the suitable ball screw assembly. Individual ball screw components can then be selected based on life, dimensional constraints, mounting configuration and environmental conditions.

A good place to start is by defining the direction and magnitude of the load. The system orientation can be very important. With a horizontal orientation the drive load is equal to the payload weight times the frictional coefficient while with a vertical orientation the drive load is equal to the weight. Loads acting on linear bearings and guides can be vertical loads, horizontal loads or pitch, roll, or yaw moment loads, or any combination thereof. Loads may also vary in their magnitude and direction. The resultant load vectors at each bearing must be established from the proper combination of the various load vectors to which the linear bearing system is subjected, as life expectancy cannot be estimated based on just the overall system load vectors. The load that each linear bearing is subjected to is called the equivalent load for that given bearing. The system is then sized based on the sizing of the most heavily loaded bearing. For more information on computation methods for an equivalent load, refer to the linear bearing and guide suppliers' catalogues.

A ball screw assembly, for example, is intended to carry axial loads, translating rotational motion to axial motion. The ability of the ball screw to resist buckling under compressive loads is called its column strength. The screw carries an axial load that is effectively equal in magnitude and opposite in direction to the load imparted to the ball nut, its complementary part, and is related by the design geometries to the driving motor's torque. In general, the column strength is the limiting design parameter because for longer lengths it can be much lower than the material's actual compressive strength. Since the free length to diameter ratio is intimately related to column bucking, it follows that for a given diameter, the axial load capacity of a ball screw is dependent upon its free length.

The life of the linear motion system can be predicted based on its operational profile. Simply – how many hours per day, days per week and weeks per year the ball screw will be run. For more complex applications or more refined life prediction, one needs to build a detailed comprehensive motion profile breaking down the movements to basically straight segments. Each segment of the motion profile would require information as to the speed at the beginning and endow the segment, the time duration of the segment, and the torque during the segment.

Determine the positional accuracy and repeatability that your application requires. For example, inch ball screws are typically produced in two grades – Precision and Precision Plus. Precision grade ball screws would be used in applications requiring relatively coarse movement or those utilizing linear feedback for positional location. Where as Precision Plus grade ball screws would be used when repeatable positioning within microns is critical and no linear feedback device is used. While Precision grade screws have greater cumulative variation over the useful length of the screw, Precision Plus grade screws limits accumulation of lead error, providing more precise positioning over the screw's entire useful length.

Using application charts for sizing and selection

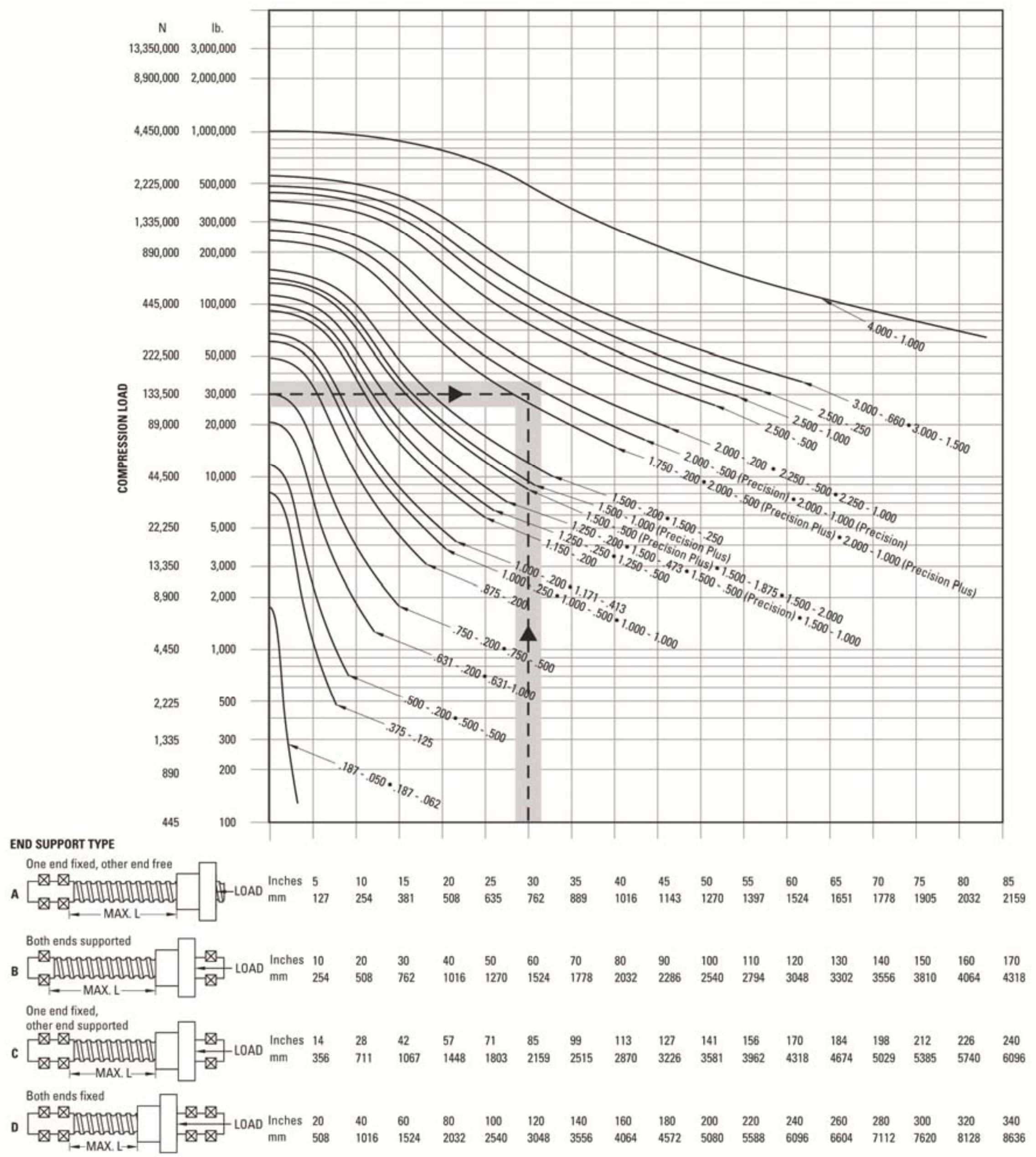

Figure 2: Compression load vs. length

Charts provided by linear motion systems suppliers can be a time saving shortcut to proper sizing and selection of linear motion systems. For example, the chart in Figure 2 simplifies the selection process for choosing a ball screw diameter for a specific compression load. All screws with curves which pass through or above and to the right of the plotted point are suitable for the example. The suitable compression loads shown in this graph are not to exceed the maximum static load capacity as given in the rating table for the individual ball nut assembly. For example, a length of 85 in. (2159mm) yields a maximum system load of 30,000 lb. (133,500 N) with the fixity condition of one end fixed and the other end supported.

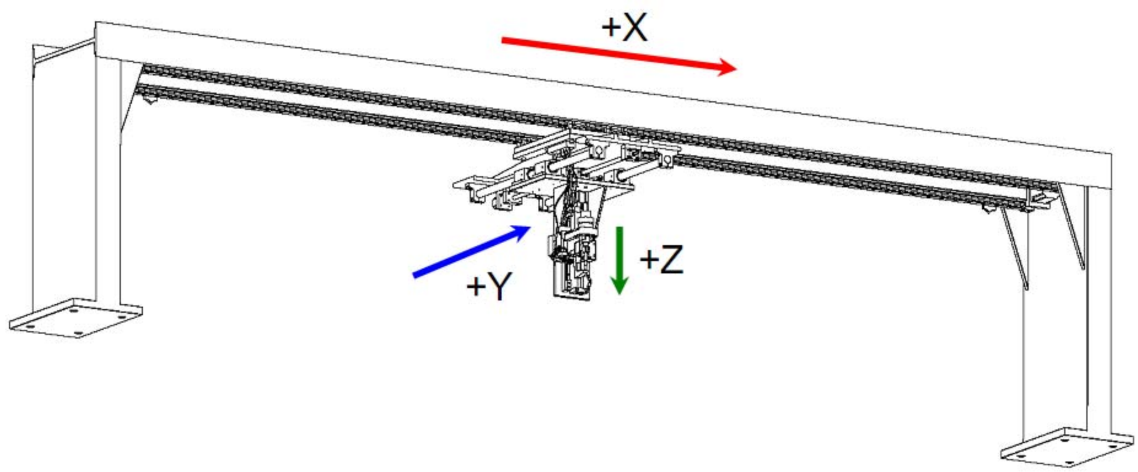

Figure 3: Welding gantry application

Using catalog formulas for sizing and selection

Here is a three-axis welding gantry application as an example to demonstrate how to select and size ball screws using catalog formulas. The ball screw runs the entire length of the x axis and is supported on either ends by bearing supports. For simplicity, we will define the nut mounting as flanged, material as alloy steel, thread direction as right hand and product series as Metric. The system orientation in this application is horizontal with a screw driven design with a length of the x axis is 6 meters and will use fixed ends with a thermally stable flange amount.

A load of 2,668.9 Newtons (600 lbs) is applied by a carriage riding on profile rails. The travel length is 4.5 m (177.165 in) and the unsupported length is 5.818 meters (229.055 in). The required speed is 0.1 meters per second (3.927 in/sec) and an acceleration of plus and minus 2.5 m/s^2 (98.4 in/s^2) is needed. The duty cycle is 8 hours per day, 5 days per week and 50 weeks per year with an average of 10 cycles per hour. The life requirement is 20 years for the ball screw and 5 years for components. An additional requirement is that stepper motor be used due to a preference of the electrical engineering department.

Next, we select the linear bearings for the x axis. The primary requirements of this application are high load capacity and high stiffness. The application has a relatively long travel length of 5.500 meters (18 feet); however the availability of 6 meter length screws eliminates the need for butt joining. Low maintenance is an important requirement of this application. The result was the selection of 500 series ball profile rail linear guides. The Thomson 500 Series Ball Linear Guides provide long life, exceptional rigidity, high dynamic and static load capacities, accommodation for high moment loads, high running accuracy, multiple sealing options and multiple lubrication inlet options.

With this selection made, we now calculate the load on the ball screws.

$F = N \times \mu_r$
where μ_r is the frictional coefficient which is 0.005 for this particular linear guide.
F = 2,698 N X 0.005 = 13.3 N (3.0 lbs)
$F = ma = 2{,}668.9\ N / 9.81\ m/s^2 \times 2.5\ m/s^2 = 680.1\ N$ (153 lbs)
F_{eq} – 303.8 N (68.3 lbs)

Based on this loading, we select the NEFF KGF-D ball nut as the starting point. This ball nut has an integral flange, integral wiper and a DIN 69051 mounting and the ball screw has an accuracy of +/- 50 μm / 300 mm accuracy.

Next we look at compression loading in this application which is determined by the following formula.

$F_c\ [N] = C_s \times 9{,}687 \times 10^4 \times d_r^4 / l^2$
Where:
F_c = Critical bucking force (N)
C_s = End fixity factor based on following table:

End fixity	C_s
One end fixed, one end free	0.25
Both ends supported	1.00
One end fixed, one end supported	2.00
Both ends fixed	4.00

$d_{r=}$ root diameter (mm)
l = unsupported length (mm)

Inputs:
D_r = 56.9
l = 5,818 mm
C_s = 4.00

Outputs
F_c = 119,991.6 N
$F_s = F_c \times S$ (Safety factor of 0.8)
F_s = 95,993 N

Verification
680.1 N < 95,993.3 N – Pass!

Now, check the life expectancy requirement. Life is typically rated at L_{10}, which represents the time after which 90% of ball screws will still perform.

L_{10} [revolutions] = $(C_{am} / F_{eq})^3 \times 10^6$

In this application life expectancy is 1,035,752.6 years. The reason life is so high is that we selected the ball screw based on critical speed rather than life.

Finally, we check the life expectancy of the bearing supports. A typical fixed bearing support is the WBK Series. The life expectancy of a bearing support can be determined using this formula.

L_{10} [hours] = $(C_{am}/P_r)^3 \times (1 \times 10^6 / 60 \times n)$
$P_r = (0.35 \times F_r) + (0.57 \times F_a)$

C_{am} = 51.5 kN (11,577.7 lbs)
F_a = 68.3 lbs / 2 = 34.15 lbs
F_r = 0.0 lbs
P_r = 19.47 lbs
L_{10} = 22.1 years
22.1 > 5 – Pass!

Testing the proposed design

Once you have selected your design based on the calculations, you need to test, to make sure your premises are correct. The testing is designed to validate that what was proposed was actually delivered and, if that was not the case, to guide any corrective actions that may be required. Validation testing should be designed to answer questions such as the following:

- Does the finished product meet the design specification?
- Is the performance consistent or not, within experimental limits, with the theoretical calculations and if not, by how much and why?
- Does the product provide the required level of reliability?
- What are the potential modes and points of failure for the product?
- How does the current solution compare to alternatives?

For large systems and machines you may wish to begin with component testing before moving on to bench testing of subassemblies and then finally to testing of the complete assembly. At each phase of testing, the test results should be reviewed and compared to the theoretical calculations to make sure that the design is on the right track or consider reasonable opportunities for improvement. Testing is intended to reveal to us what we might have missed in our calculations and modeling.

Configured linear motion systems

It is also important, all along the process, to consider whether it might make more sense to purchase a configured linear motion system rather than to design and assemble your own. In this case, you would provide the requirements of the application to a linear motion integrator such as the mounting configuration, positioning requirements, environmental conditions, loading conditions, move requirements, and any special considerations. The integrator would then typically utilize a web-based sizing and selection system (see sidebar) to design and configure a custom linear motion system based on your input. The integrator can often provide a quote and CAD file of the proposed design within 24 hours of your request. The cost of such a system will be less than the cost of the individual components in most cases. This approach can typically reduce engineering time and assembly cost by 90% or more and can often provide a savings in material cost of 20% to 30%. Most important, by reducing the time spent on designing linear motion systems, your engineers will spend less time on working in an area outside of their core competencies, and more time focusing on what they do best, overall system integration.

In summary, take advantage of all useful resources to save resources and design time. Don't overlook the ability of linear motion vendors to provide configured linear motion assemblies that can help you reduce engineering and assembly costs. Evaluate the alternatives of purchasing components vs. modules vs. complete systems in terms of their impact on design and assembly time. Use, to your advantage, all available design tools such as charts, formulae, online selection systems, and as well, 3D models. Finally, engage technical support to leverage their product expertise in standard, modified standard and specialty solutions. Be sure to confirm that the vendor has design verification/testing/analysis data to back design claims and design positions. This approach can reduce design time to a minimum while ensuring that linear motion systems meet performance and durability requirements.

Linear Motion. **Optimized.**

SIDEBAR: **How to Size and Select Linear Motion Systems in Minutes rather than Hours**
Economical and proven standard components meet the vast majority of linear motion requirements. In these applications, web-based sizing and selection tools can literally cut system sizing and selection time from hours to minutes.

Leveraging web-based sizing and selection tools, such as Linear MOTIONEERING® (www.linearmotioneering.com) from Thomson, the user enters the key parameters of the application. These requirements are filtered through a comprehensive set of calculations. The application then presents a listing of products that meet the application requirements ranked by cost. Outputs include 3D models, pricing, delivery times and ordering information.

Step 1 – Establish the system orientation
The user picks the application's orientation: inverted, vertical, horizontal side or horizontal. Then the user selects the mounting configuration – fully supported, end supported or intermittently supported.

Step 2 - Enter the positioning requirements and the stroke length, defined from hard stop to hard stop
The user selects whether the positioning requirement will be defined in terms of accuracy, repeatability or maximum allowable backlash. The user then selects a value for the choice that was selected.

Step 3 - Define the environmental conditions that are critical in determining the correct material selection, cover strategy and lubrication scheme
The user selects a condition from the following choices: clean, water/chemical spray/fog, impact/press application/vibration, moderate to heavy dust particulate count, high pressure/temperature washdown, water/chemical splash and clean room. Based on the environment selection, the application will recommend linear slide options such as chrome plated ball guide, stainless steel ball guide, Raydent surface ball guide, CR linear bearings, polymer plain bearings, etc. The user can change these options.

Step 4 - Enter the load and applied force
The load is the weight that the carrier or saddle supports, including the payload, fixturing and tooling. The user locates the center of gravity of the load with respect to the center of the carriage/saddle by entering x, y and z values. The user enters the applied or external force. This process related force is assumed to be exerted at the center of gravity of the load.

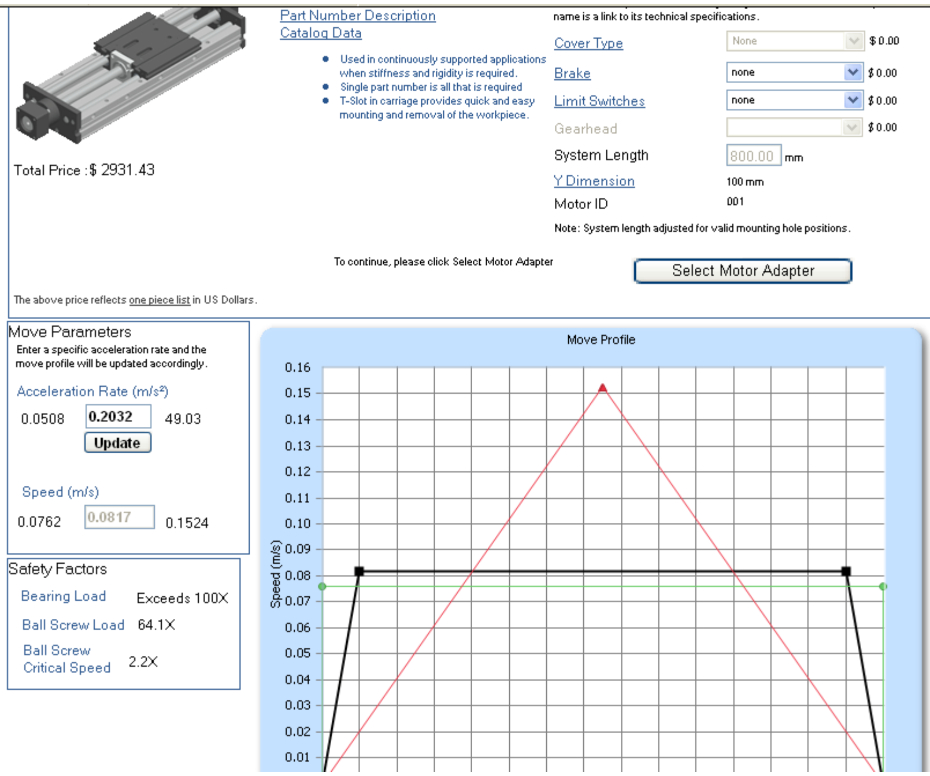

Figure 4: Application calculates minimum acceleration move profile (green), recommended move profile (black) and maximum acceleration move profile (red). Screen shot from Linear MOTIONEERING (www.linearmotioneering.com) web-based sizing and selection tool.

Step 5 - Enter the move profile requirements

The user enters the move distance, move time and dwell time. The program determines the appropriate acceleration rates for each individual system that meets the requirements of the applications. The user then selects one of the systems in the solution set. The application presents several move profiles. The green move profile is based on maximum acceleration and the red move profile is based on minimum acceleration. The user determines a recommended move profile between the maximum and minimum and provides the desired acceleration rate.

Based on the recommended move profile, the application calculates the bearing and drive loads, and ball screw critical speed. The user can also enter his own acceleration rate. When the user does so and presses the update button, the application presents the user's selected move profile and updates the safety factors based on the new move profile.

Lastly, users can select options such as motor mounts, cover type, brake, limit switches and gearhead. The application presents the total price of the system, and dimensions. The user can download a 3D CAD model of the solution in the native format of 20+ major CAD software packages or a neutral file format. The user views and prints the specifications, saves the application or requests a quote.

This approach dramatically reduces the time and cost involved in designing and sourcing a linear system. It provides the opportunity for a company to focus its scarce engineering resources on its core competencies while taking advantage of the linear systems supplier's extensive experience.

The popularity of such design tools is driving manufacturers to develop additional resources to help machine builders save time and optimize performance. As an example, Thomson has available a number of additional tools to help simplify and speed the design process, including:

- Linear MOTIONEERING® for Linear Guides - www.thomsonlinear.com/linear_motioneering_screws
- Linear MOTIONEERING® for Ball and Lead Screws - www.linearmotioneering.com/screws
- Micron MOTIONEERING® for Micron TRUE™ Planetary Gearheads - www.micronmotioneering.com
- Linear MOTIONEERING® for 60 Case® LinearRace Shafting - www.linearmotioneering/shafting

About Thomson

With more than 60 years of motion control innovation and quality, Thomson is the industry's premier producer of Linear Ball Bushing® Bearings and Profile Rail Bearings, 60 Case™ Shafting, ground and rolled Ball Screws, Linear Actuators, Gearheads, Clutches, Brakes, Linear Systems, and related accessories. Thomson invented the Linear Ball Bushing Bearing in 1945, and has set the standard ever since with an unsurpassed set of mechanical motion control solutions serving global commercial and aerospace & defense markets. Thomson Industries, Inc. has facilities in North America, Europe and Asia with over 2000 distributor locations around the world.

Thomson, 1500 Mittel Boulevard, Wood Dale, IL 60191-1073; 1-540-633-3549; 1-540-633-0294 (fax); Thomson@thomsonlinear.com; www.thomsonlinear.com.