

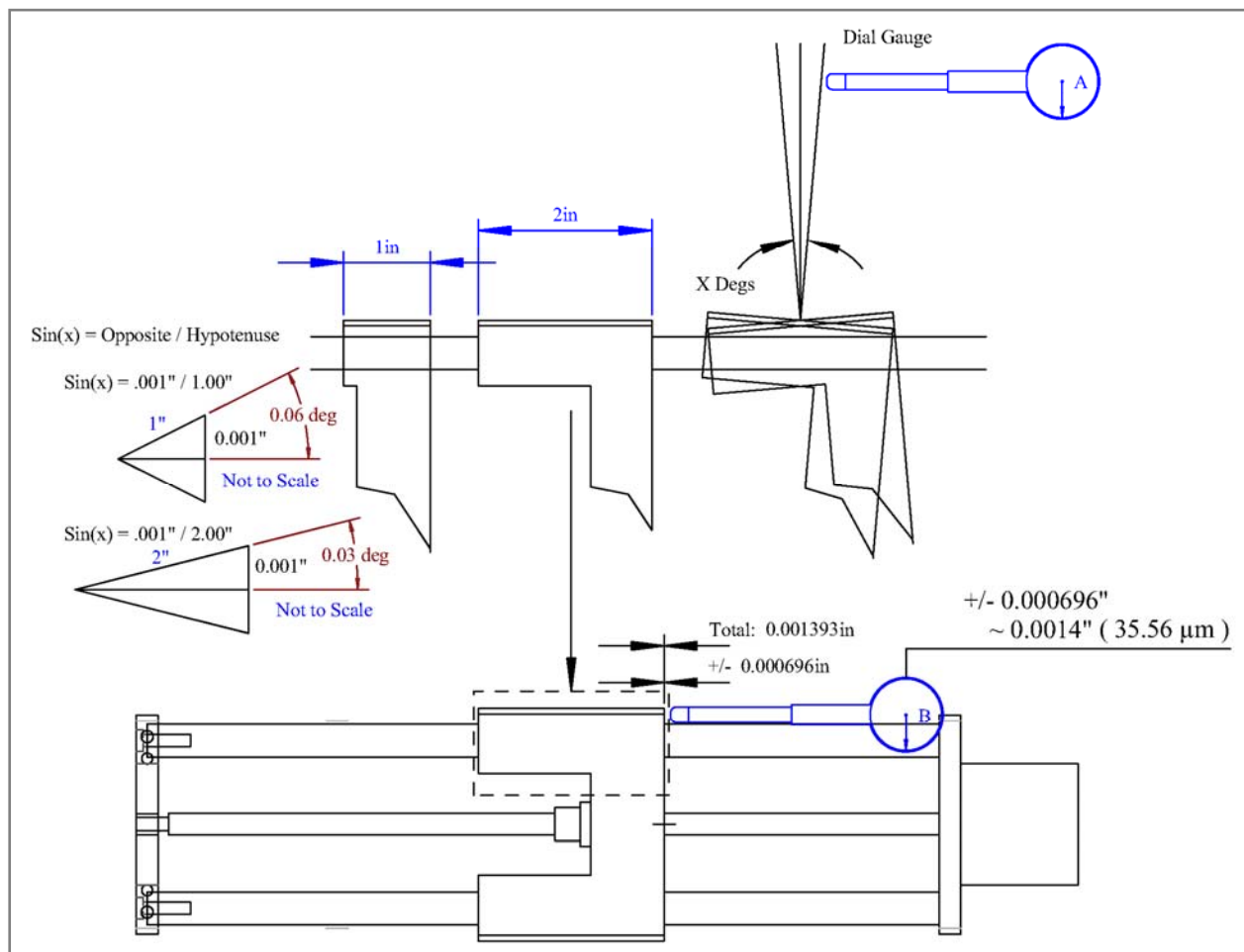
Linear devices and positioning systems have multiple sources of error. The purpose of this paper is to itemize and discuss several key sources of error such that a design team can recognize and either improve or adapt the mechanical design or look at design alternatives. This discussion is relevant to linear actuator based systems (Note 1) as well as conventional rotary to linear systems offered by a myriad of slide and linear bearing manufacturers.

Note 1: Reference: "*Linear Actuator Based Slide Systems*"

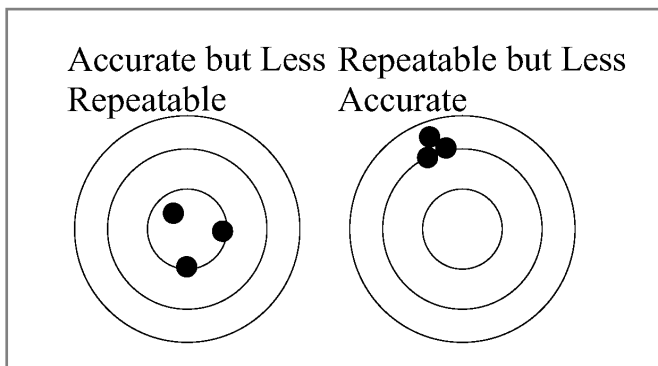
Sources of Error

1. **Lost Steps.** A poorly sized actuator or an inappropriate screw lead, undersized drive, misaligned linear bearing system, load imbalances and improper parameter setups (run current, maximum velocity and accl/decl ramping) have a profound impact on system accuracy. The highest quality linear design can be rendered useless with a single, ill advised and untested parameter setting. The design team must size and test a linear slide with the worse case load and motion profile then add a torque (force) safety factor of 1.25 – 1.35X. Proper sizing and testing address 100% of this design issue.
2. **Carriage Wobble** or pitch, roll and yaw. (NOTE 2) Every linear system exhibits a varying degree of carriage wobble. Several issues are illustrated and discussed below.

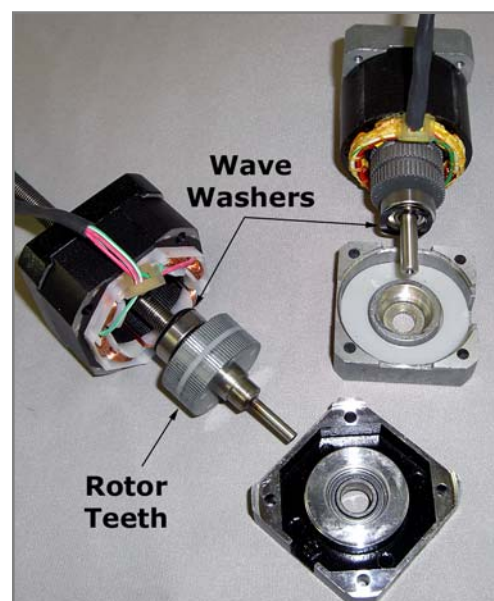
Note 2: Reference: See Page 5



- A. A reasonable estimate of the degree of wobble (pitch, roll or yaw) can be determined with the amount of clearance (play, compensation ...) in the linear bearings. In this plane bearing carriage (on dual round shafts) diagram, the design clearance is a reasonable 0.001" (25.4 μ m).
- B. Wobble is a sinusoidal error that occurs with each revolution of the motor and is aggravated by bent screws. All screws have bends and/or compound bends and these bends work against the nut, carriage and linear bearing system *on each revolution* of the screw.
- View the above diagram and consider a right angle where the length of the carriage (1 or 2 inch length) is the hypotenuse and the bearing clearance, 0.001", is the side opposite.
 - As $\text{Sin}(x) = \text{Opposite}/\text{Hypotenuse}$, note the two angles: The 1" carriage length has a +/- 0.06° wobble and the 2" carriage length has a +/- 0.03° wobble.
 - Two observations:
 - Longer carriages reduce the amount of wobble. In the diagram note the position of dial gauge B and the impact of 0.001" bearing clearance on slide error: Note dial gauge B and the total *potential* wobble error of 0.00142" (~ 36 μ m).
 - From another perspective, this explains how reasonably priced plane bearing systems, with longer carriage lengths, can be designed to meet or exceed more compact, lower clearance bearings that cost 3 – 5 X.
- C. Design note: Note the two dial gauge locations. Position A represents the center of a wafer probe needle mounted 1.5" above the carriage. As suggested in this diagram, **lower profile loads** (closer to the carriage) are desirable. As the working distance, away from the bearing surface increases, the impact on error increases.
3. **Lead Error**. In general, lead accuracy specifications range from 0.0072 in/ft (183 μ m/304.8 mm) for standard screws to 0.0012 in/ft (30.48 μ m/304.8 mm) for precision grade lead screws. For clarity, take a few moments to study the accuracy vs. repeatability diagram shown below. In most applications all that matters is repeatability.



4. **Motor bearing preload error**. The picture on the right illustrates a Size 17 rotary and a Size 17 linear actuator. In both designs, preloading the motor's radial bearing is accomplished with wave washers.
- A. Design note: In linear actuator based slide designs the motor's bearings handle *both* radial



and thrust loading. As the counter bored bearing cavities have standard drill depth error a slide can have up to 0.001" (25.4 μ m) axial play as the thrust loads work with or against the wave washer (s) in bidirectional moves.

Design note: Haydon Size 17, 23 and 34 actuators can be solid shimmed to avoid preload lost motion but smaller Size 8, 11 and 14 actuators use wave washers.

- B. Slides with rotary motors mechanically isolate the motor's bearing system from the lead screw with a flexible coupler. In these applications, the lead or ball screws are bearing supported on both ends. The near bearing, on the screw, handles both radial and thrust loading. In these conventional designs, the lead screw bearing design must address the same preloading and thrust issues discussed above.
5. **Rotor error.** In the same picture, note the machined teeth in the rotor. In the stepper market a generally accepted figure for worse case rotor error (lamination, rotor and permanent magnet design) is 5%. To be clear, 5% of a 1.8° full step or $0.05 * 1.8^\circ = 0.09^\circ$. To gain a better understanding of this error consider two linear designs. The first design uses a screw with a 2.54 mm lead (2.54 mm/rev) and the second uses a screw with a 12.5 mm lead.

Lead	Distance / FS	Linear Error	
2.54 mm	$2.54 / 200 = 0.0127$ mm	$0.0127 * .05 = 0.635$ μ m	Note 1
12.5 mm	$12.5 / 200 = 0.0625$ mm	$0.0625 * .05 = 3.125$ μ m	

Note 1: Whether or not .635 – 3.125 μ m of error is significant depends on the application but however small, it is important to understand and account for all sources of error.

6. **Microstepping Error.** This subject is a difficult one as there are many different factors impacting microstepping error: Motor quality, the winding, drive quality, microstep resolution, application loading, motion profile (Accl/Vm/Decl), run current and system friction. This paper will describe the issue in general terms but leave a more comprehensive explanation to an upcoming paper titled "Microstepping Error".
- A. Given the complexity of the subject and the multivendor and mixed mechanical and electrical engineering components of the issue, customer beware: "You are on your own".
- B. Case A: A full stepping application. Full stepping generates the highest torque as full current is applied to each step.
- C. Case B: With a /16 microstepping setting, there are 16 microsteps between each magnetic pole or 16 microsteps per 1.8 deg FS. The division of current between the two phases is now $1/16^{\text{th}}$. With only $1/16^{\text{th}}$ of the current (torque) working against the load and system friction bad things begin to happen. In higher friction applications, a series of microsteps are commanded but there is no motion until the current (torque) is sufficiently accumulated, with subsequent step pulses, to make the move, then like a spring, the rotor skips forward and catches up. In an open looped stepper application the motion controller commands 32,000 microsteps but the final stopping point, at the "end" of the move is questionable.
- D. In general, /10 thru /16 are acceptable but in some high friction applications, be careful. Where you really "stop" is suspect. Higher microstep resolutions lower vibration and reduce audible noise but small, high resolution move errors can be significant.

Designing With Linear Actuators

Sources of Error ©

E. Recommendations.

- Where possible, use system mechanics to accomplish the desired system resolution. A finer lead is a better design.
- Half step and lower microstep resolutions such as /4 and /8 may have a less desirable degree of vibration but these settings minimize microstepping error.

7. Summary

Error	Design Impact	Notes
Lost Steps	Complete Failure	Size, Test the Worse Cases and Add Safety Margin
Carriage Wobble	A generally overlooked but significant sinusoidal error directly related to linear bearing clearance.	Where possible, maximize carriage length. (Bearing contact)
Lead Error	While lead error is high, in most positioning designs, high repeatability is all that really matters.	Even in high end metrology applications lower cost, repeatable screws can be easily mapped and the error accommodated within the positioning program.
Motor bearing preload Error	Another generally overlooked but significant error in linear actuator based slides. +/- 0.001"	Size 17, 23 and 34 can be hard shimmed. Smaller Size 8 – 14 actuators cannot.
Rotor Error	Minor impact	Be aware of and account for this issue in high resolution applications.
Microstepping Error	Without a high line count, gold standard encoder to view command vs actual microsteps determining the amount of error within a full step is difficult.	In general, half stepping, /4 and /8 microstepping are safer than /10 or higher.

As laser interferometer measurement systems are quite expensive, use high quality analog or digital dial gauges to determine, understand and address the "sum-of-errors" and lost motion. Nothing about a linear design can be assumed. Test and confirm your work.

As error and lost motion are critically important design subjects, *Nycomm Tools for Windows*, (a Nymotion LLC product offered with the [NYT-AP series machine controls](#)) integrates a cycle test and Starrett Wisdom (+/- 1 micron) digital dial gauge interface. Command vs Actual (Starrett feedback) error logging provides a reasonable tool to determine the "sum-of-errors" discussed in this paper. A series of data logged unidirectional and bidirectional moves over the working stroke of a slide helps understand the sum of accumulating (increasing error over distance) and non-accumulating (once per revolution) error as well as bidirectional lost motion due to design clearance between the nut and screw ... as well as "unexpected" mechanical error.

Comments, suggestions and improvements to this working document are greatly appreciated.

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NOTE 2: Error Plot (Live Data: # 65 of 450)

- 800 μm / Rev
- Actuator: 0.9 Deg/FS (400 FS/Rev)
- Half Stepping or 800 HS/Rev
- 350 μm moves is a 0.4375 Rev Move
- Note the absolute error between subsequent moves. Example: Move 3 to 4 swings from and error of -18 μm to + 17 μm or 35 μm
- Wobble Data and Error Analysis: Fedja Mulabdic, Mechanical Engineer and Roy Belak, UBC Intern (2004)

Command	Actual	Error
0.350	0.351	0.001
0.350	0.360	0.010
0.350	0.332	-0.018
0.350	0.367	0.017
0.350	0.332	-0.018
0.350	0.366	0.016
0.350	0.334	-0.016
0.350	0.362	0.012
0.350	0.349	-0.001
0.350	0.345	-0.005
0.350	0.361	0.011
0.350	0.334	-0.016
0.350	0.365	0.015
0.350	0.334	-0.016
0.350	0.362	0.012
0.350	0.337	-0.013
0.350	0.360	0.010
0.350	0.353	0.003
0.350	0.340	-0.010
0.350	0.363	0.013
0.350	0.333	-0.017
0.350	0.365	0.015
0.350	0.332	-0.018
0.350	0.364	0.014
0.350	0.341	-0.009
0.350	0.356	0.006
0.350	0.357	0.007
0.350	0.336	-0.014
0.350	0.365	0.015
0.350	0.330	-0.020

