

Reducing Quill Backlash and Setting Z Axis Gain on a RF-30 Mill/Drill, version 1.3

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Conclusion

I was able to achieve an accuracy of better than ± 2 thousandths of an inch from zero to 0.4000 inches.

The Journey



Have you ever seen a pig so dressed up? I have to smile when I see how far my RF-30 and I have gone in the last 25 years. We have done a lot together, learned much, and found more yet to be done.

Today's adventure involved

1. reducing the backlash in the quill and
2. correctly setting the Z Axis Gain (having the quill moves the commanded distance).

These are essential parts of adding Computer Numerical Control (CNC).

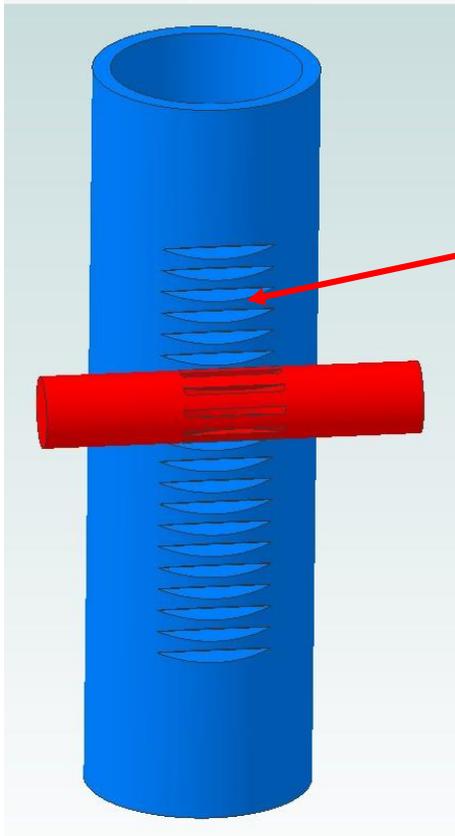
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Quill backlash

Quill backlash can be partially compensated with the software so the rest is up to me.

Only with the help of many people was I able to sort this one out. But the effort was well worth it. For about \$25 I believe have reduced my quill backlash to less than ± 0.001 inch. I'm hesitant to declare victory until I start to make real parts under a variety of situations.

What is Quill Backlash?

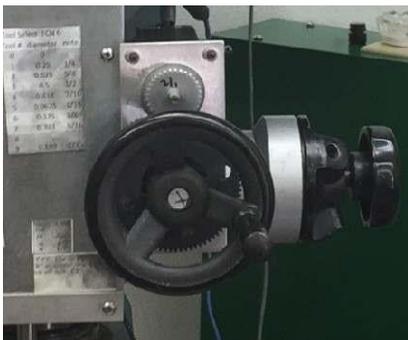


If you looked inside the head of the mill with your back to the column, you would see something like this view. The blue cylinder is the quill. The spindle fits inside along with its bearings. Cut into the quill is a rack.

The rack engages with a cylinder that also has teeth cut into it. I call this cylinder the pinion gear shaft and the teeth are my pinion gear.

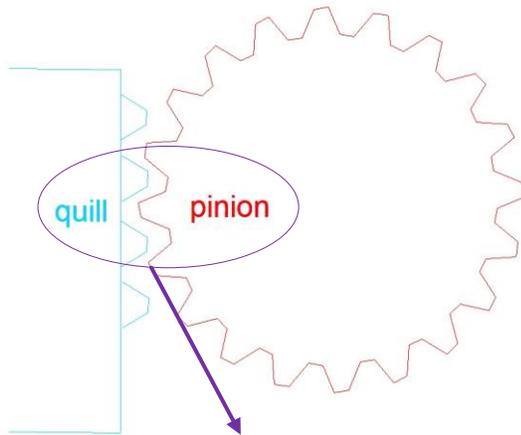
As the pinion gear turns, the quill moves up or down.

The pinion gear shaft connects to a coiled flat spring at one end. The spring tries to rotate the pinion gear so the quill will rise.

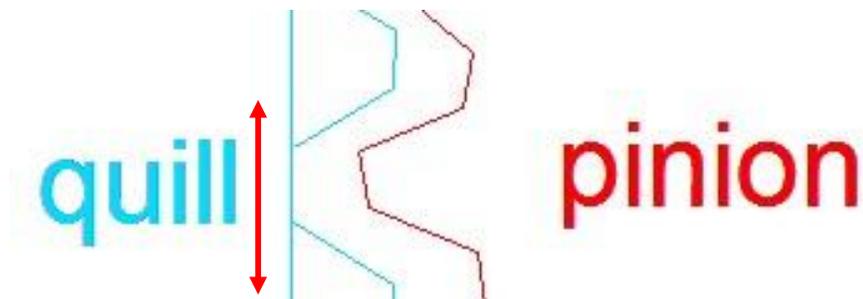


At the other end of the pinion gear shaft is the fine feed gears. By turning the fine feed hand wheel, the pinion gear turns at a reduced rate causing the quill to move. In my case, the hand wheel connects to the Z axis drive gear box which in turn connects to the fine feed.

If the pinion gear shaft is held stationary, we can rotate the hand wheel a small amount. This is the fine feed backlash and can be compensated by my Mach3 CNC software. When I change the direction of feed, Mach3 first rotates an amount equal to this backlash. Then it starts to count distance.

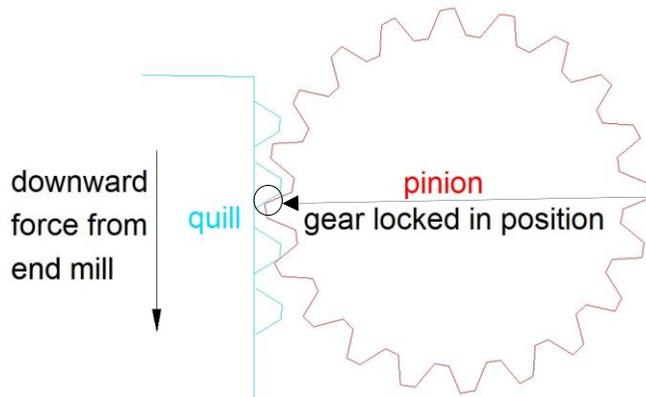


There is a second source of backlash that is not as obvious. With the pinion gear shaft held stationary, I can move the quill up and down. This is because the rack and pinion do not perfectly fit together.

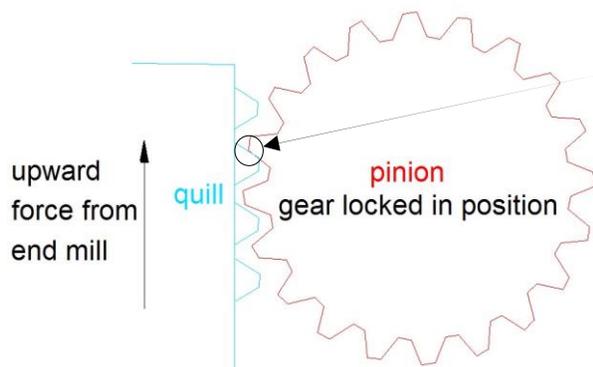




I can directly measure this backlash by using a finger Dial Test Indicator (DTI). The DTI is supported on the table and the finger is resting on the underside of the quill. Using just finger pressure, I can raise the quill a few thousandths of an inch.



When I plunge cut with an end mill, there is a downward force as the flutes try to screw themselves into the metal. The rack pulls down on the engaged tooth of the pinion gear.



When I side mill, there is an upward force so the rack rises and lifts up on the adjacent tooth in the pinion gear.

Backlash as a function of cutting action is not nice.

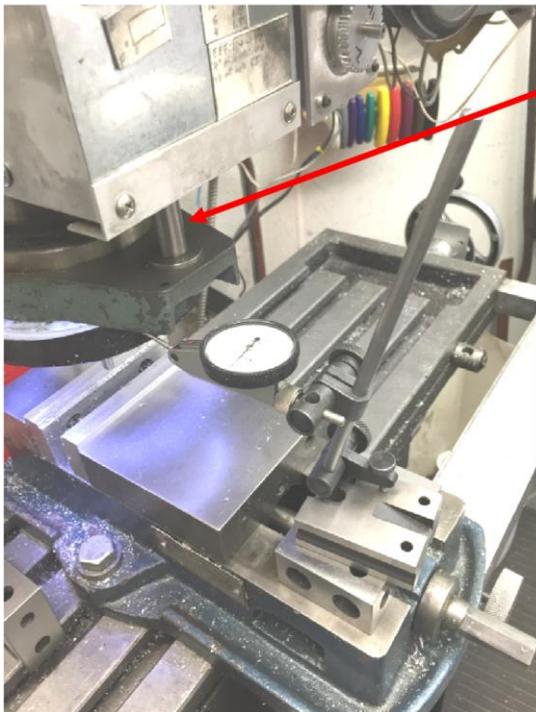
Dealing With Z Axis Rack and Pinion Backlash

A few solutions exist for this problem. Some people have moved the pinion gear closer to the rack so the backlash is reduced. Can't move it too close or they will bind.

I tried fishing a piece of stainless steel shim stock between rack and pinion. This had the effect of reducing the backlash but was surprisingly unpredictable. Lots of random error was measured.

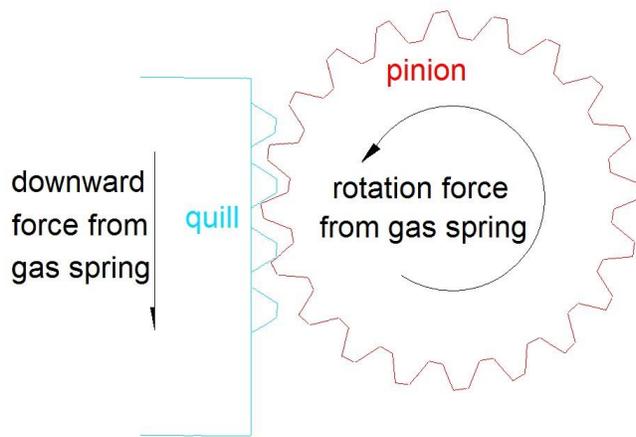
A more direct solution is to remove the pinion gear and put a ball screw flanking the quill. Turning the ball screw raises and lowers the quill with little to no backlash. It is clear to me that this is the most foolproof but also the most expensive solution.

Is there a lower cost and good enough method? I posed the question on the mach1mach2cnc and mill_drill Yahoo groups. Lots of valuable bits and pieces of ideas came back. One guy said he used an air cylinder to push the quill down. This biases the quill downward regardless of cutting force. Great idea but I don't have a ready source of compressed air in my shop. I did have a spring so tested the idea with it.



I put the spring around this rod which is attached to the quill's lower bearing support. The spring wasn't very long but it was stiff. Over the small range of this spring, I noticed a large reduction in backlash.

Feeding this discovery to a friend, he suggested using a gas spring. This idea has turned out to work rather well.

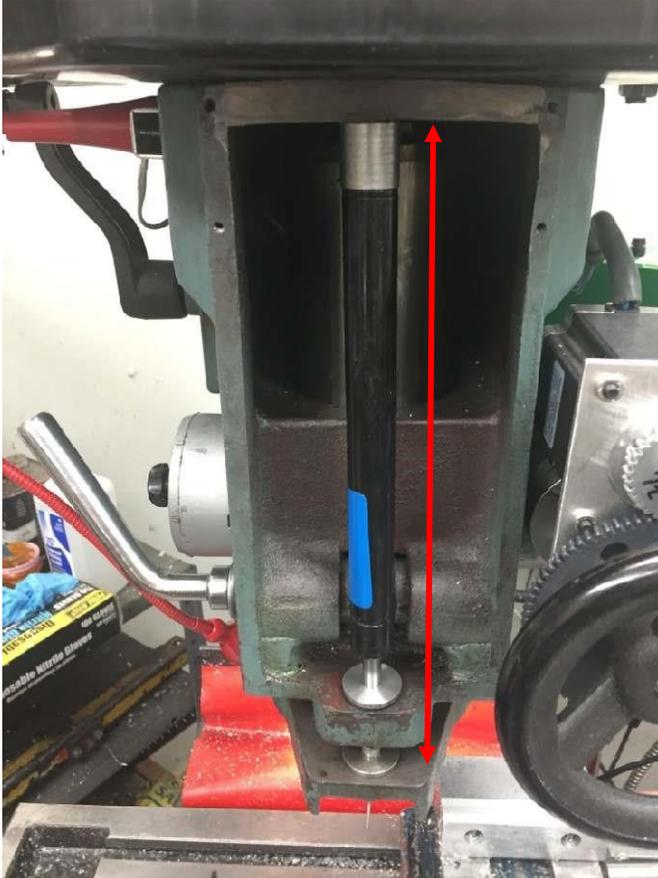


Let's take a moment to look at what the quill's gas spring get us. The gas spring is pushing down on the quill forcing the bottom surface of rack teeth to contact the top surface of pinion teeth.

At first, I tightened the flat spring attached to the pinion gear shaft until it balanced the downward force of the gas spring. But later discovered that

my random error was less if I disconnecting the flat spring from the pinion shaft. This was done by unhooking the flat spring and removing a screw fitted to the pinion shaft. I had to leave the spring case and end screw attached to prevent sideways movement of the pinion gear shaft.

Without the flat spring attached, the downward force of the quill is transmitted through the pinion gear and the fine feed gears into the stepper motor gears. This gives me a single backlash rather than two independent backlashes.



How did I choose the gas spring?

With the cover removed from my mill head, I raised the quill up as far as it would go. Then I measured the distance between the top support and the top of the quill spindle bearing support. This is the compressed length of the gas spring.

Then I lowered the quill down as far as it would go and measured this distance again. I found that an uncompressed gas spring 15 inches long and compressed of 8 inches long would work.

I then went to AutoZone® and was able to buy the correct size gas spring for \$25 including tax. The hard part was explaining to the people at AutoZone that I wanted this part but it was to go on a mill and not a car. Fortunately, they quickly adapted to my odd request and I had the right part in no time.

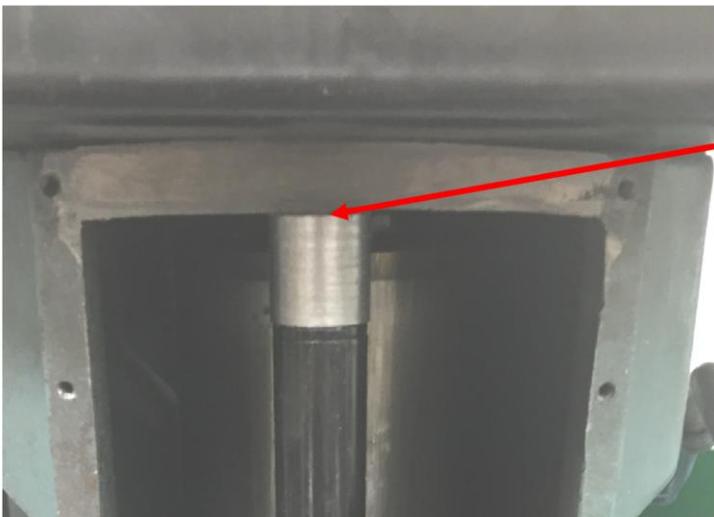
The correct name for the gas spring is a "Gas-Charged Lift Support". They come in a variety of lengths and compression forces. I bought the Mighty Lift! model E 95091:



I have unscrewed the plastic part from the piston. The other end's plastic parts comes off the same way.



I drilled out a $\frac{3}{4}$ " length of CRS using a #1 drill. It was then possible to screw the metric stud on securely.



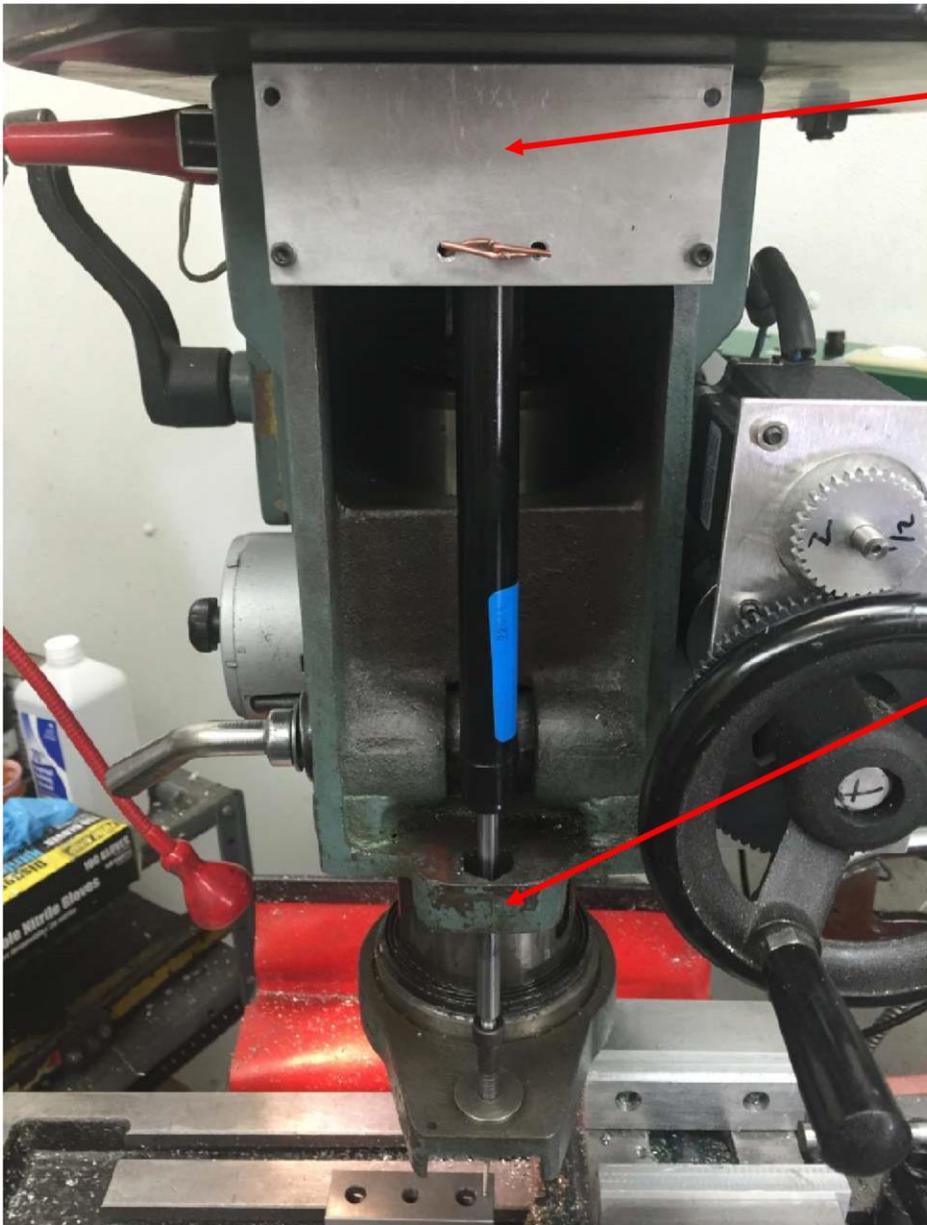
This cylinder presses against the top of the opening.



The piston's end sits in the top of a Socket Head Cap Screw 5/16-18 bolt which is threaded into a piece of cold rolled steel.



The lip prevents the cylinder from falling through the hole. Otherwise, nothing is a close fit here.

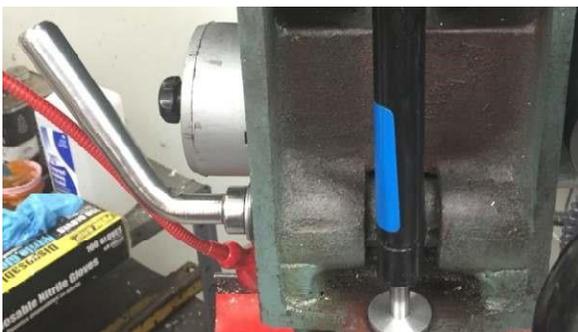


I happened to have an aluminum plate left over from a previous project. I used it and a length of copper wire to gently secure the top of the gas spring so it would not move off of the top support surface.

It is essential that the gas spring is only supported at the top and bottom.

Originally I had a guide sleeve that fit into this hole in the head casting. It caused binding of the gas spring which manifest itself as random Z axis error.

Quill Lock



The rules for manual machining do not necessarily apply to CNC. Quill lock is such a rule.

When I manual machined, I would lock the quill except when I needed to move it. With CNC I cannot jump in to adjust this lock while running. No surprise there.

It is also common with manual machining to leave the quill lock partially applied.

This drag helps to reduce random error caused by the quill moving within its bore. With CNC, at least on my machine, I found that any application of the quill lock caused random small jumps in quill position while the drive motor was running.

Completely removing the quill lock including the two locking cylinders that contacted the quill gave more consistent results.

Backlash Test Results

I found that a value of 0.00125 gave me "symmetric error". By this I mean that about half the time I was over and half the time I was under. When the error is not symmetric, I know I don't have the best value.

My "static" backlash test consisted of stepping 0.001" at a time. By static I mean that the machine is not running.

I would step up ("Page Up" on my keyboard) twice, zero my DTI and then step down ("Page Down" on my keyboard). Ideally I would read 0.001". If the reading was less than 0.001", then my backlash was too small. If larger than 0.001", the backlash was too big. A second test took two steps down, zeroed the DTI, and then took one step up. I have used ↑ here to mean Page Up which jogs the quill up and ↓ to mean Page Down which jogs the quill down.

↑↑zero↓ gave me the following values over 10 tries. Values are in thousandths of an inch:

-0.2, -0.4, -0.3, -0.3, -0.5, -0.5, -0.5, 0, 0, 0.

↓↓zero↑ gave me

0.1, 0, 0.1, 0, -0.5, 0, 0, 0.2, 0, 0.

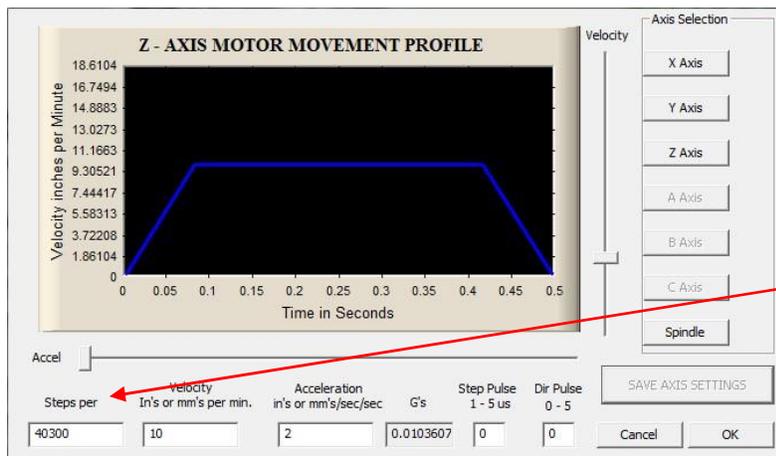
It is useful to run this static test because if this error is excessive, it will only get worse during cutting.

Average error was -0.14 thousandths of an inch. This is small enough to ignore given other errors in the system.

Z Axis Gain

With backlash out of the way, we can more clearly see how much the quill actually moves under Mach3 control.

"Steps per" Theory



"Steps per" is part of the Motor Tuning page in Mach3. This initially confused me because I read "Steps per" and a number. What does "Steps per 40300" mean? Then I realized the software developer had left off the units of distance *before* the number. Furthermore, this

distance is what the DRO thinks has moved, not the actual movement. So now I call it **Steps per [DRO inch]²**. This is the **Digital Read Out** on the screen. Mach3 is told to move a specific distance so outputs a specific number of steps. This may or may not turn out to be the actual distance.

Let me define a few terms in order to clarify the following section:

- DRO inch - the distance as displayed on the **Digital Read Out** of Mach3
- Steps per [DRO inch] - the number of steps sent from Mach3 to the stepper motor driver when the DRO shows a change of 1 inch
- Actual inch - the actual distance moved as measured using independent means (like my finger DTI and spacer blocks or a micrometer)
- Gain - the ratio of DRO inch to Actual inch

Ideally gain equals 1 which means that when Mach3 is commanded to move 1.000 inches, that is what we get.

I have set up the Z axis motor tuning so "S" steps are generated for each DRO inch.

² The argument is equally valid with Steps per DRO mm.



When I put down a spacer block "B" inches thick, I read a thickness of "A" DRO inches.

I can then assemble these measurements such that the **DRO inch** units cancel:

$$\frac{h}{h} = \frac{\text{DRO inches}}{\text{DRO inches}} = 1$$

$$\frac{0.7070 \text{ DRO inches}}{0.7000 \text{ DRO inches}} = 1.010$$

$$\frac{0.7070}{0.7000} \times \text{DRO inches} = \text{DRO inches} \quad (2)$$

My goal is to have a gain, \$

equal to 1 which means I can modify (2)

$$\frac{0.7070}{0.7000} \times \text{DRO inches} = \text{DRO inches} \quad (3)$$

I take my present Steps per [DRO inch] value, multiply it by the gain, and it gives me a new Steps per [DRO inch].

Example: I currently have 40300 set as my Steps per [DRO inch]. I take a 0.7000 inch³ spacer block, my "B", and measure it using the DRO, my "A". The result is a reading of 0.7070 DRO inches⁴.

$$= \frac{40300 \text{ Steps per [DRO inch]} \times 1.010}{1} = 40803 \text{ Steps per [DRO inch]} \quad (1)$$

From (3) I get

³ These spacer blocks have a tolerance of ± 0.0001 inches.

⁴ The DRO in Mach3 is set up to display to the nearest 0.0001 inches.

$$\frac{(\times .) / (0.1010 \times 40300) /}{\frac{1}{h}} = \frac{1}{h} = 40703$$

In an ideal world, changing the Steps per [DRO inch] value in Mach3 from 40,300 to 40,703 will cause the DRO indicated movement to equal the actual movement.

In other words, the gain will equal $\frac{\text{DRO inch}}{\text{Actual inch}} = 1$.

In a non-ideal world, many data points are taken and the results averaged to give an average Gain. It is standard Metrology practice to ignore the maximum and minimum values. This filters out random error so you are left looking at just the Gain component.

Time to start using this equation in my shop.

"Steps per" Shop Experience - Static Test

I found that extending the quill more than 2.5 inches caused excessive error so limited the range to an extension of 0 to 2.5 inches.

Testing every 0.500 inches was sufficient when the gas spring was in place. Before using the gas spring, I had to test every 0.100 inches and then average out the random error.

I am using my finger DTI showing zero as my precision touchdown indicator.

Here is how the last two static accuracy tests ran:



I started at 40,406 steps per [inch] and measured my stack of spacer blocks every 0.500 inch. With the DTI's finger contacting my reference surface, I zeroed the DTI and Mach3. Then I raised the quill via Mach3 above 0.500 inches, slid over my 0.500 inch spacer block, and lower the quill via mach3 until the DTI read zero. I used the shift key and "Page Down" to lower the quill quickly. When close, I tapped the Page Down key which dropped me in steps of 0.0001 inch. When the DTI read zero, Mach3 told me the DRO distances as shown below:

0 (set on DTI and Mach3)
 0.4975
 0.9993
 1.4990
 1.9970
 2.5013

By dividing each of these Mach3 DRO numbers by the spacer value, I get the gain. For example, $\frac{0.4975}{0.500} = 0.9950$. Averaging these gain values gave me 0.9985.

Using (3):

$$\frac{40347}{40406} = 0.9985 \quad (3)$$

Therefore 40,347 is the number I plugged into Mach3's Z axis motor tuning field. I ran the test again:

0 (set on DTI and Mach3)
 0.4988
 1.0011
 1.5019
 2.0002
 2.5051

This time the average gain was 1.0004. I took a break for lunch and when I came back, repeated the test. This time the average gain was 1.0005.

If I wanted to go another cycle, I would change the Steps per [DRO inch] to

$$40347 \quad \times 1.0005 = 40367$$

But I'm going to call it good and move on. There comes a point where I am chasing noise and going another cycle would be just that. This decision is based on past experience playing with Mach3 on this mill/drill. If dynamic tests show an error bias towards excessive gain, I will make another tiny adjustment to Steps per [DRO inch].

"Steps per" Shop Experience - Dynamic Tests



My dynamic test consisted of milling a series of progressively deeper holes in a block of 6061 aluminum. The first hole was approximately 0.01 inches deep. It was my reference depth. I zero my mic in this hole. The second hole was cut 0.1000 DRO inches deeper than my reference. The third hole was cut 0.2000 DRO inches deeper than my reference. The fourth hole was 0.3000 DRO inches deeper than my reference.

A second column of holes followed the same pattern. In this way I am able to test repeatability and accuracy.



Each set of 10 holes represents one test cycle and produces one data point.

All data was entered into an Excel® spreadsheet for analysis.

For all test cycles, I calculate the gain for each hole and its error except for the primary reference hole (ref) and the secondary reference hole which has a DRO value of 0.0000. I tossed the worst case reading if it was far from the rest.

The first goal was to determine if my Steps per [DRO inch] was set correctly. I didn't want outlier data points influencing the result. The second goal was to use the corrected value to determine expected

accuracy.

cycle 1			
this time I cut without WD40			
no vac			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0		
-0.1000	-0.10095	0.9906	0.95
-0.2000	-0.17465		-25.35
-0.3000	-0.3032	0.9894	3.2
-0.4000	-0.40225	0.9944	2.25
0.0000	0.0004		-0.4
-0.1000	-0.1012	0.9881	1.2
-0.2000	-0.2021	0.9896	2.1
-0.3000	-0.30345	0.9886	3.45
-0.4000	-0.40215	0.9947	2.15
	sum	6.9355	
	average gain	0.9908	

On this run I had one hole that was way off. Rather than having a depth of -0.2000 inches it was -0.17465 inches. I did not include this data point in my calculation but certainly want to figure out what caused it.

cycle 2			
no change in steps per			
this time I cut with WD40			
no vac			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0		
-0.1000	-0.1002	0.9980	0.2
-0.2000	-0.20135	0.9933	1.35
-0.3000	-0.30235	0.9922	2.35
-0.4000	-0.40135	0.9966	1.35
0.0000	-0.0005		0.5
-0.1000	-0.1002	0.9980	0.2
-0.2000	-0.20185	0.9908	1.85
-0.3000	-0.30265	0.9912	2.65
-0.4000	-0.4012	0.9970	1.2
	sum	7.9573	
	average gain	0.9947	

This test cycle was run with cutting fluid but still no shop vac removing chips. None of the data points were way off so I used them all.

cycle 3			
no change in steps per			
this time I cut with WD40 and used vac on last 2 holes			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0.00000		
-0.1000	-0.10085	0.9916	0.85
-0.2000	-0.20230	0.9886	2.3
-0.3000	-0.30300	0.9901	3
-0.4000	-0.40165	0.9959	1.65
0.0000	-0.00070		0.7
-0.1000	-0.10095	0.9906	0.95
-0.2000	-0.20240	0.9881	2.4
-0.3000	-0.30340	0.9888	3.4
-0.4000	-0.40175	0.9956	1.75
	sum	7.9294	
	average gain	0.9912	

I started to use the shop vac this time but only on the last two holes. That makes it even more interesting that my worst data point was the second to last hole.

cycle 4			
no change in steps per			
this time I cut with WD40 and used vac on all holes			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0		
-0.1000	-0.10045	0.9955	0.45
-0.2000	-0.20125	0.9938	1.25
-0.3000	-0.30225	0.9926	2.25
-0.4000	-0.3994	1.0015	-0.6
0.0000	-0.00085		0.85
-0.1000	-0.1004	0.9960	0.4
-0.2000	-0.2016	0.9921	1.6
-0.3000	-0.30255	0.9916	2.55
-0.4000	-0.4007	0.9983	0.7
	sum	7.9613	
	average gain	0.9952	

This time I used cutting fluid and ran my shop vac on all holes.

Looking over these first four test cycles, I can calculate the average gain using 28 data points. To do this I first added up all valid gain points across the four cycles. Then I divided by 28. The result was an average gain of 0.9930.

Using (3): 0'

$$\times) \frac{\quad}{!''} \quad (3)$$

$$\begin{matrix} (@.BBA@ \\ D@HA@ \end{matrix} \times \frac{\quad}{!''} = 40445 \frac{\quad}{!''} \quad (3)$$

So in theory, if I use 40,445 Steps per [DRO inch], my average gain should be 1.0000.

Before we try it, look back to my static test. If I had gone one more cycle, I would have used 40,367 which is 0.19% smaller than 40,445. That may not sound like a big difference but for a 2.500 inch movement, this means 4.8 thousandths of an inch.

cycle 5			
change in steps per to		40445	
this time I cut with WD40 and used vac on all holes			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0		
-0.1000	-0.0998	1.0020	-0.2
-0.2000	-0.1998	1.0010	-0.2
-0.3000	-0.3007	0.9977	0.7
-0.4000	-0.3999	1.0003	-0.1
0.0000			0
-0.1000	-0.09985	1.0015	-0.15
-0.2000	-0.2002	0.9990	0.2
-0.3000	-0.3007	0.9977	0.7
-0.4000	-0.3996	1.0010	-0.4
	sum	8.0001	
average gain		1.0000	

Using my new Steps per [DRO inch] value, I calculated an average gain of 1.000.

Now, before thinking this was rigged or jumping up to celebrate, understand that this is just one data point and by itself, means nothing. When I saw it, my first reaction was just that Murphy⁵ was having a bit of fun with me.

⁵ Look up Murphy's Law if you are confused.

cycle 6			
4/16/2015 wet, full vac, no change in gain			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0		
-0.1000	-0.09945	1.0055	-0.55
-0.2000	-0.20025	0.9988	0.25
-0.3000	-0.3002	0.9993	0.2
-0.4000	-0.3988	1.0030	-1.2
0.0000	0.0001		-0.1
-0.1000	-0.09975	1.0025	-0.25
-0.2000	-0.1887		-11.3
-0.3000	-0.30025	0.9992	0.25
-0.4000	-0.39855	1.0036	-1.45
	sum	7.0119	
average gain		1.0017	

This is far more consistent with the torment that Murphy likes to inflict. I had one major outlier which I had to remove.

cycle 7			
4/16/2015 wet, full vac, no change in gain			
DRO	actual	gain (DRO/actual)	error (DRO- actual) in thou
ref	0		
-0.1000	-0.10005	0.9995	0.05
-0.2000	-0.2007	0.9965	0.7
-0.3000	-0.301	0.9967	1
-0.4000	-0.3996	1.0010	-0.4
0.0000	-0.00065		0.65
-0.1000	-0.1007	0.9930	0.7
-0.2000	-0.20025	0.9988	0.25
-0.3000	-0.3013	0.9957	1.3
-0.4000	-0.3997	1.0008	-0.3
	sum	7.9819	
average gain		0.9977	

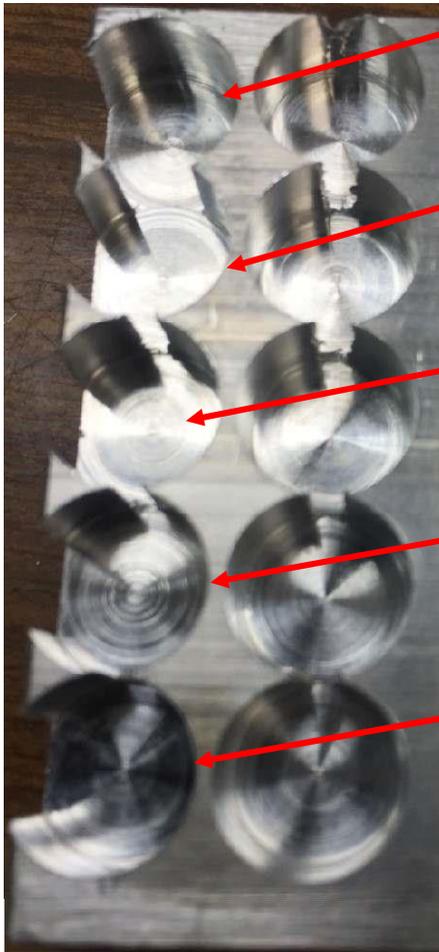
This time all data points were almost too well behaved.

Calculating the average gain over these last three cycles gave me 0.9997. More importantly, the worst case error range, not including the one outlier, was

+1.3 -1.45 thousandths of an inch.

Rounding to the nearest thousandths of an inch we have ± 1 . But this great news must be tempered by the fact that random large errors have been ignored. In this final series of tests we had one data point way off out of 24. Clearly this is not acceptable.

It is certainly interesting that both outliers were at -0.2000 inches. I wrote a program that just drilled 0.2000 inch deep holes. Here is my first test cycle.



The upper left hole was defined as my reference. Note that there is a round feature at its center.

This round feature does not exist in the hole directly below it. This hole is 0.00025 inches deeper than my reference.

The hole below it has a single circular gouge in it. This hole is 0.00005 inches shallower than my reference.

Next comes the mother lode. The bottom of this hole is very rough. It is 0.03170 inches shallower than my reference hole.

The last hole in this column is 0.00020 inches shallower than my reference hole. The bottom is smooth.

The second column of holes has some scoring but nothing like the worst of the first column.

This test cycle tells me that my outliers were due to cutter problems. Since most holes were fine, I doubt my cutter is dull. More likely I had an accumulation of chips stuck to the bottom of the end mill which prevented the cutting edge from contacting the workpiece. This would cause shallow holes.

I can now ignore those outlier data points with a clear conscience.

Ben Crettenden sent me the following -

I used what cylinder was in stock at my local auto place which was a bit shorter than what I was hoping but it won't limit what I can do. I made a solid spacer on top that fits in the space nice. On the spindle end I cut the hex off a 12mm bolt & tapped 6mm to suit the end of the gas cylinder. Locked into spindle with 2x lock nuts each side of the bracket.



It provides about 100mm of stroke on the spindle under the cylinder pressure. Honestly I had no confidence using a slot drill/ uni mill before but with this mod it has completely changed. I have done one small job & a fairly large job last couple of days and it seems to have done the trick.

I got a mate that is good with drafting to draw up what we could measure - spindle & spline, between centres mounting dimensions etc. Long term I am going to make a custom spindle with tight tolerance on the spline. Aiming for 0.1mm backlash. I will let you how that goes. I just need a few more jobs to be able to purchase a rotary table!

Ben

Acknowledgments

The guy that told me about using a compressed air cylinder was on one of the Yahoo groups but I can't find his name. Hopefully he will identify himself so I can properly acknowledge his contribution. Thanks to John Herrmann for suggesting the gas spring. Thanks to all that commented on my question. Even if I didn't follow their suggested path, it did help me better understand the problem and possible options. Thanks to Paul Thompson for reviewing this article and suggesting experiments. Thanks to Ben Crettenden for sending pictures and text of his work. Nicely done!

I welcome your comments and questions.

If you wish to be contacted each time I publish an article, email me with just "Article Alias" in the subject line.

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