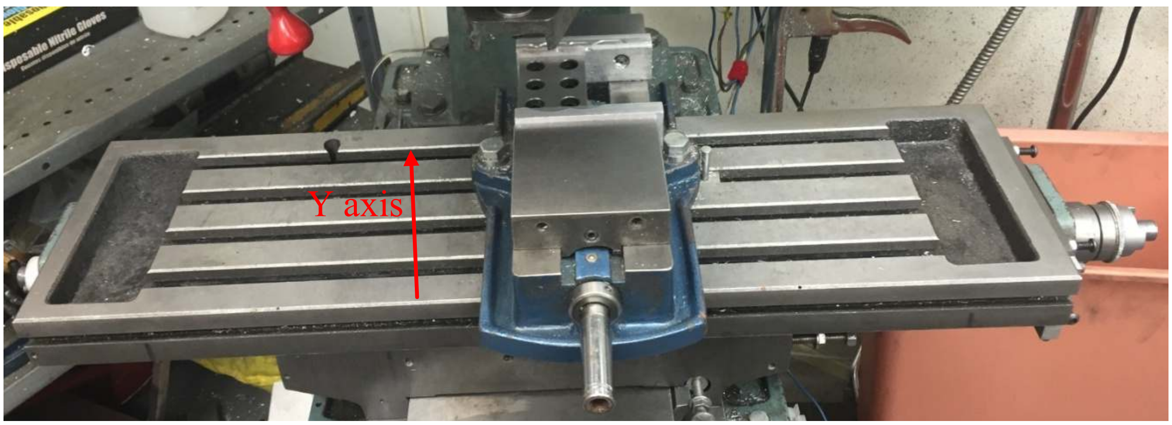
Reducing Y Axis Backlash on a RF-30 Mill/Drill, Version 2.0

By R. G. Sparber



Conclusion

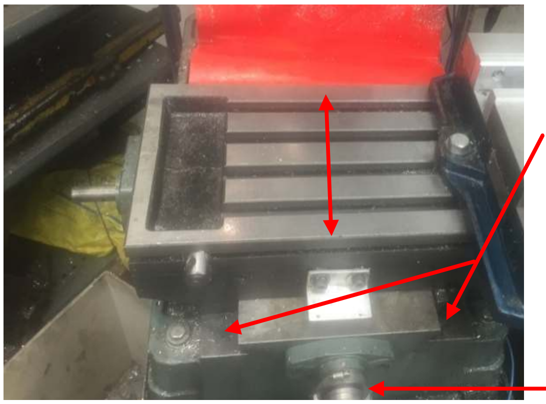
I was able to reduce Y axis backlash from 0.04 to 0.002 inches without binding of the leadscrew. This was accomplished by preloading the bearings, modifying the take up nut, modifying the leadscrew bearings, and aligning the leadscrew.

It is best to deal with the X axis first before addressing backlash on the Y axis. Otherwise, the Y leadscrew will block access to the screws that secure the X take up nut. See http://rick.sparber.org/XAA.pdf for how to align the X axis.

Contents

Why Fuss over Alignment?

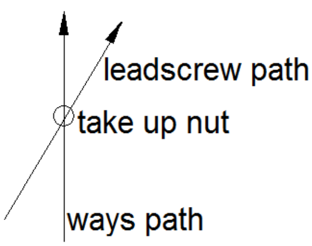
Before we talk about how to precisely align the Y axis leadscrew[2], let's talk about why this is important. After all, can't we just tighten the take up nut until all play is removed?



As the leadscrew turns, it drives the apron in and out. The path taken by the apron is set by its ways.

The leadscrew moves the apron by driving its take up nut. Since the take up nut is bolted to the apron, its path must also follow the ways.

The leadscrew is bolted to the base which also contains the ways. However, this does not automatically mean that the leadscrew is perfectly parallel to the ways.



We have the leadscrew trying to move the take up nut along its major axis while the nut is confined to move along the ways. This conflict causes the nut to bind on the leadscrew while it tries to follow two paths at the same time.

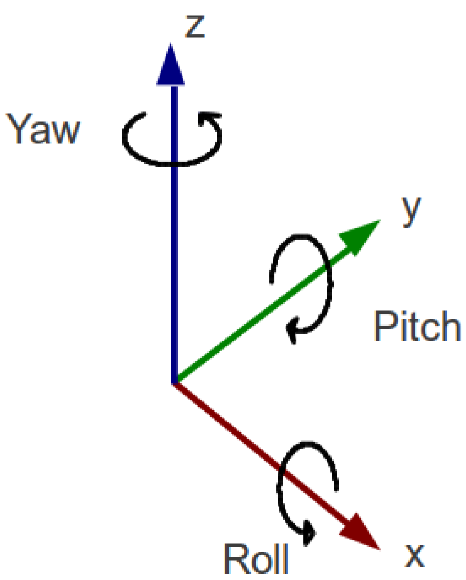
Only when the leadscrew is parallel to the ways will there be no binding.

By allowing play between the leadscrew and its take up nut, we can tolerate limited misalignment between leadscrew and ways. This play is called ***backlash***. Since we want to minimize backlash, we want to align the leadscrew to the ways as close as possible.

[2] Although I am dealing with a leadscrew and take up nut here, alignment is even more critical with a ball screw where backlash is far less.

Terminology

The Y leadscrew can move in six different ways relative to the take up nut.



- Rotation around the Z axis - this is called **yaw**. Zero yaw is when the leadscrew is parallel to the YZ plane.

- Rotation around the X axis - this is called **roll**. Zero roll is when the leadscrew is parallel to the XY plane.

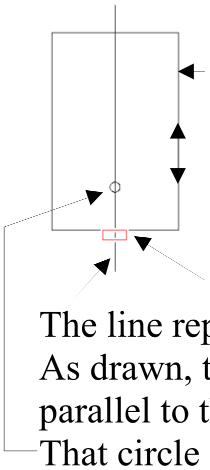
- Rotation around the Y axis - this is called **pitch** and is the normal rotation of the leadscrew.

- Offset along the **X axis** - this is sideways misalignment.

- Offset along the **Z axis** - this is up and down misalignment.

- Movement along the **Y axis** - this is unwanted movement of the leadscrew along its major axis and is caused by bearing play.

Rotation around the Z Axis: Yaw



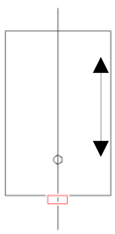
The rectangle represents the Y axis ways.

The apron is constrained to move only along the flanks of this rectangle.

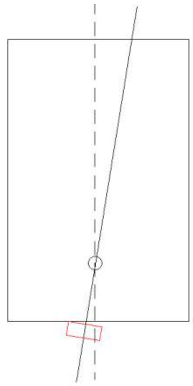
This red rectangle is the bearing block.

The line represents the major axis of the leadscrew. As drawn, the major axis of the leadscrew is exactly parallel to the ways.

That circle on the line represents the center of the take up nut.



As the leadscrew turns, this take up nut moves along the leadscrew. The take up nut is attached to the apron and causes it to move. Since we have perfect alignment between ways and leadscrew, there is no binding of the moving parts.



Consider what happens if the leadscrew is not parallel to the ways (yaw not zero). The take up nut is on the leadscrew so they are aligned. But as the leadscrew turns, the nut is forced to follow a path that is not parallel to the ways. Yet the apron, which is secured to the nut, must follow the ways. It all just binds up.

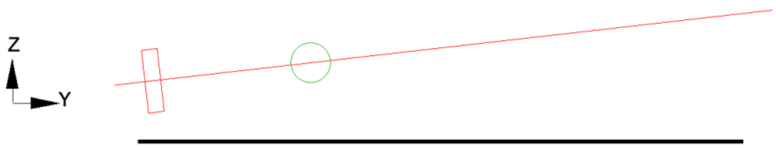
How much movement you get depends on how much play exists between nut and leadscrew. This play is called backlash. The smaller the backlash, the better the needed alignment.

Looking from under the mill, you can see the the bottom of the apron and the take up nut. The Y leadscrew has been removed.

The take up nut is free to slide in the slot. A single bolt locks the take up nut to the apron. In this way, the take up nut is free to pivot until the bolt is tightened.

As manufactured, you can only get access to this bolt by removing the X leadscrew and sliding the table half way off of the apron. I avoided this hassle by drilling a hole in my table. For details, see http://rick.sparber.org/IAYN.pdf

Rotation around the X Axis: Roll

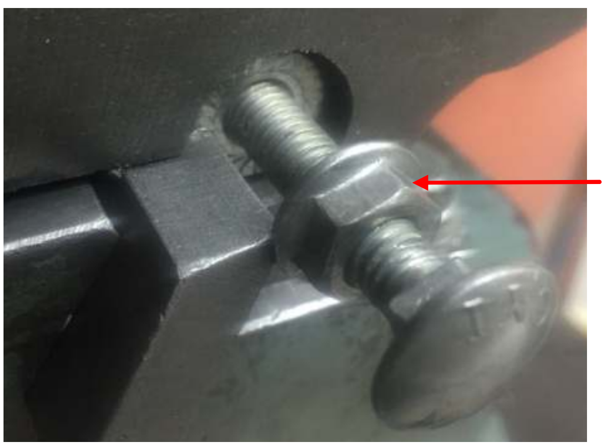


The Y leadscrew alignment argument also applies when you view it from the side.

The thick black line is the Y ways as viewed from the side. The red rectangle is the bearing block and the green circle is the take up nut. This view is of the YZ plane. The leadscrew must be parallel to is ways and not tilt up or down (roll equal to zero).

Rotation around the Y Axis: Pitch

We want the leadscrew to freely turn so it can move the apron. This requires us to minimize drag on the table.



One source of drag is a Y ways gib that is able to slide as the apron moves in and out. I solved this problem with an improved Gib retainer. see http://rick.sparber.org/GR.pdf

X and Z Axis Offset Error

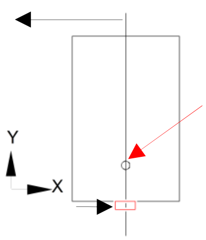
As manufactured, the take up nut tends to push the leadscrew's major axis out of radial alignment with the nut's major axis as backlash is removed. This can be solved by modifying the take up nut. See http://rick.sparber.org/YTUN.pdf for details.

Aligning the leadscrew with the ways on the XY plane must occur while we also are aligned with the nut. The nut is tightened until the leadscrew cannot turn. This ideally gives us the best centering of the leadscrew within the nut.

Unwanted Movement Along Y Axis

Any sliding of the leadscrew along its major axis contributes to backlash. As manufactured, there was about 0.03 inches of play. This was solved by preloading the bearings with an expandable washer. See: http://rick.sparber.org/VTW.pdf

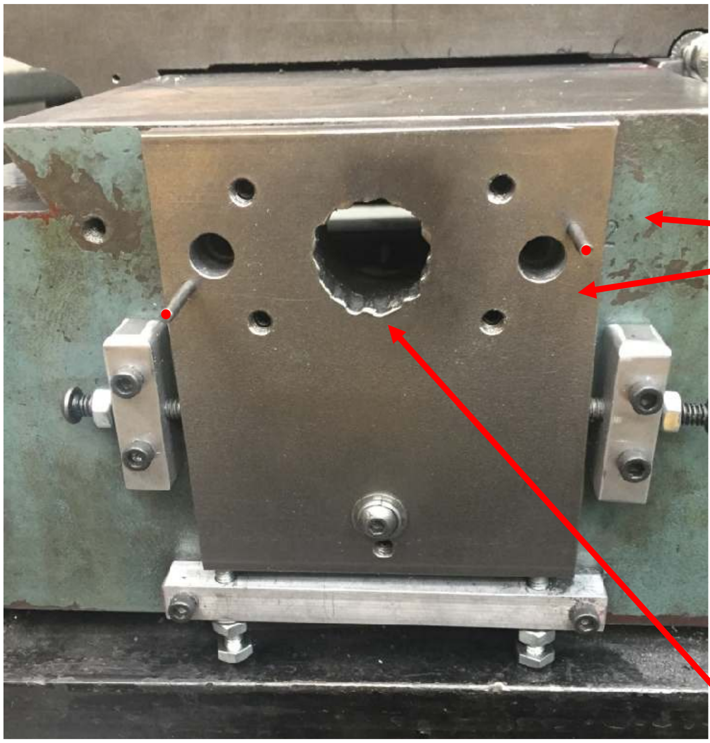
Adjusting Yaw



If we push the bearing block to the right, the leadscrew will pivot counterclockwise
around the nut (the circle). Note that since the nut is close to the bearing block, a very small movement at the bearing block causes a large movement at the other end of the leadscrew.

The nut's retaining bolt must be snug yet permit the nut to rotate.

This pivoting is around the Z axis so is yaw.

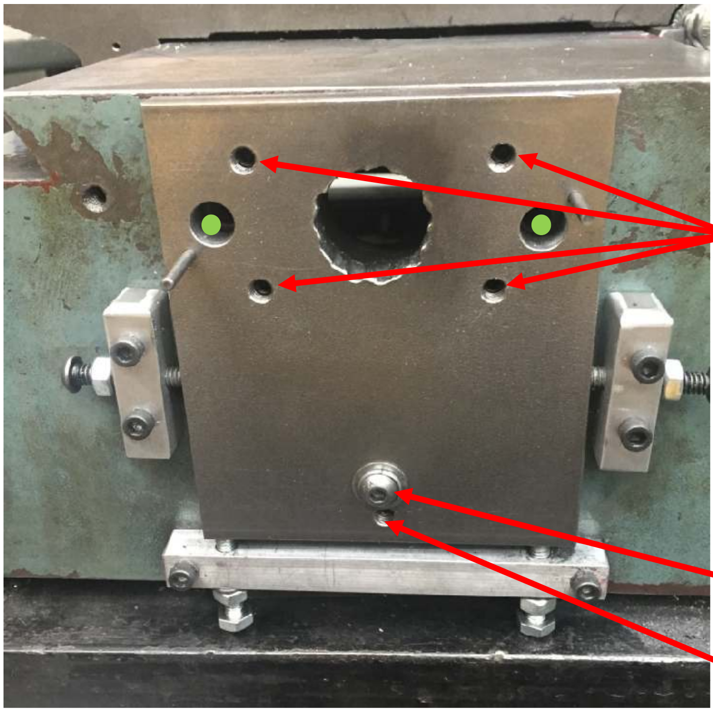


As manufactured, it is impossible to change the alignment of the Y leadscrew. My solution was to create a new mounting support. It can be positioned independent of the base casting.

I used ½ inch thick cold rolled steel so there is minimal deflection of the support as various screws are tightened.

Notice the two pins protruding from the plate (red dots). They are used to align the bearing block to the plate. We then move the plate around to align the leadscrew[3].

I had to chain drill the large hole that passes the leadscrew. At the time my mill was, shall we say, unavailable.

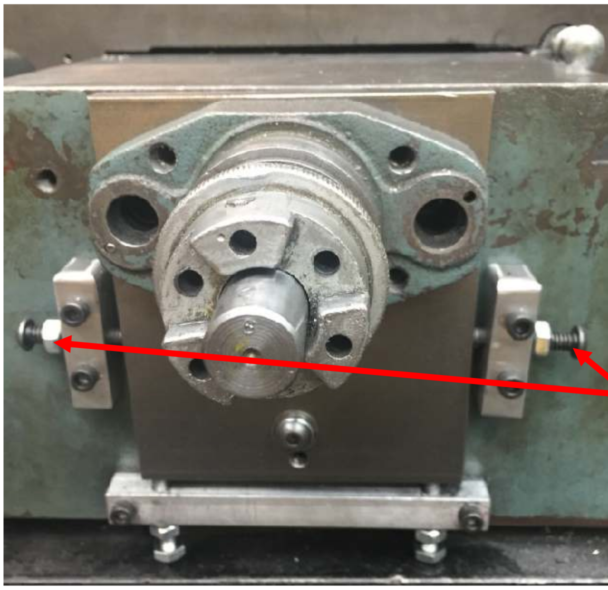


The plate has been drilled and tapped ¼-20 to hold five set screws.

The top four set screws counteract the clamping force of the top two mounting bolts which will pass through oversized clearance holes (marked with green dots). These holes permits the plate to be moved side to side and up and down without binding on the bolts.

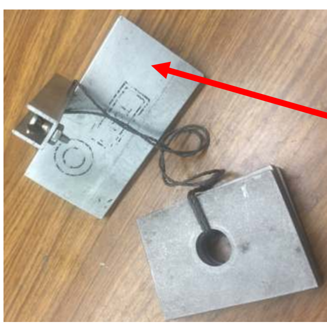
The bottom mounting bolt also feeds through a generous clearance hole. It counteracts the force of the set screw below it. When all set screws and bolts are correctly tightened, the steel plate is locked in position. This in turn locks the Y leadscrew so it can only rotate.

[3] It is essential that the leadscrew have minimal play in its bearings. This is accomplished by using an expandable washer. See http://rick.sparber.org/VTW.pdf for details.

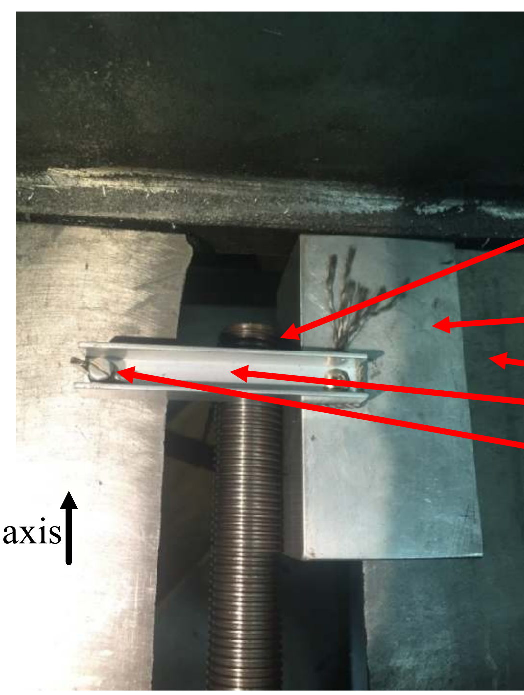


Here you see the bearing block and leadscrew installed on the pins. Bolts will be added later to clamp the bearing block to the plate and to the mill's base. The bearing block must be snug against the plate. To begin with, this is accomplished by turning the leadscrew such that it pulls in. Later bolts are added.

Adjustment of the leadscrew's end for yaw is accomplished with a pair of horizontal jack screws. When this alignment has been achieved, the two jacks are tightened to prevent further movement of the plate along the X axis. Those jam nuts initially locked the screws but later I found that they were not needed.



This odd collection of scrap from my junk drawer is actually half of a precision instrument for measuring yaw. There is a piece of extruded 2 x 2 inch aluminum angle about ¼ inch thick. It attaches to a short piece of U channel that has an adjustable screw on the end. Looped around this channel at the angle end is a string. The string connects to a series of weights.



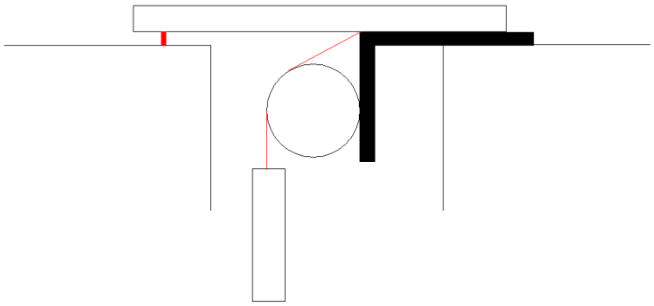
Y axis

With the apron moved forward, a gap is reveled with the Y leadscrew inside.

The angle is placed with its vertical face against the leadscrew.

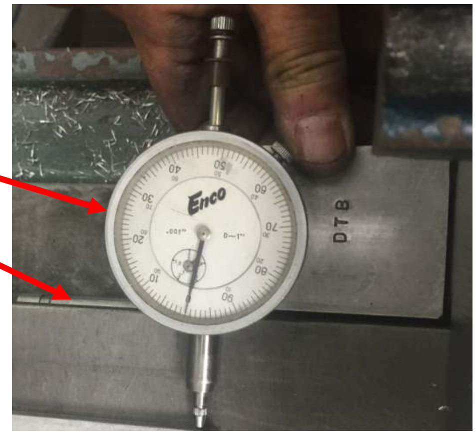
The horizontal face of the angle rests on the right machined top surface.

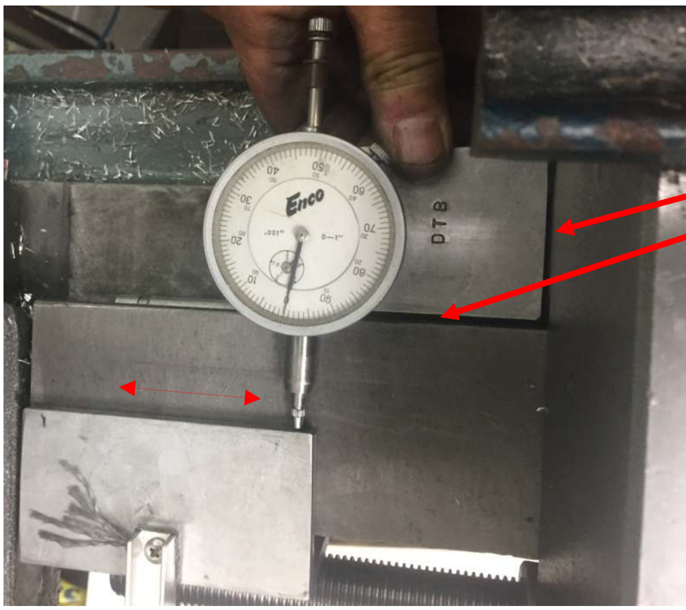
The U channel crosses the gap and the screw at the end of the channel has been adjusted to contact the left top surface when the angle is flat on the right surface.



The string is run over the top of the leadscrew and the weights hang down. The string then pulls the angle tightly against the outside diameter of the leadscrew and also down against the right top surface. The horizontal channel bar prevents the angle from rotating. The screw (shown as a red rectangle) is adjusted so the angle lays flat on the right horizontal reference surface.

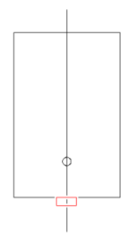
The second half of this instrument consists of a push rod Dial Test Indicator (DTI) which is attached to a block (marked DTB[4]). The vertical edge of the block contacts a rod that rests in the right Y ways dovetail.



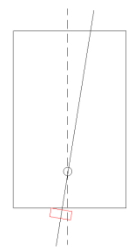


Here is the entire assembly. The DTI contacts the angle's vertical edge nearest the front of the mill. The DTB block contacts the back of the apron. Since the left edge of the DTB block contacts the rod contacting the ways, movement of the block and therefore the DTI is parallel to the ways.

I zero the DTI at this starting point. If the DTI reads zero while I move along the angle, the leadscrew is parallel to the ways and yaw is zero.



If the DTI needle moves, my yaw is not zero. Here you see an error of 0.003 inches. That must be brought down under 0.0005 inches.

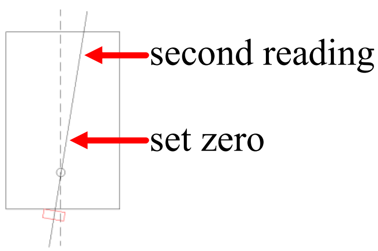


[4] These markings were purely by accident. The block was originally used for another project.

By adjusting the horizontal jack screws I can smoothly swing the leadscrew until the yaw is zero.

Note that the mounting bolts are barely finger tight. There has to be room for the face of the plate to move relative to the base. A gap will form between plate and base that will later be secured.

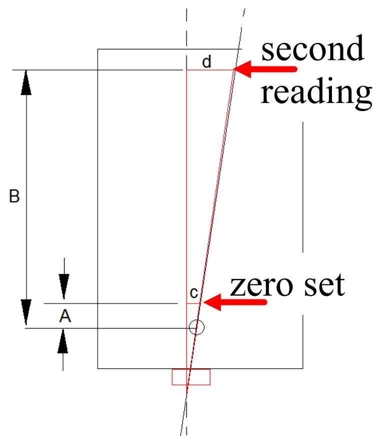
Ah, but there is a little more to this puzzle. My DTI is zeroed at a point some distance from the pivot and my second reading is further away.



The problem is that I don't know what the second reading should be as I adjust the horizontal jacks. If I read 0.005 inches, adjusting until it reads zero is wrong because my set zero point moved too. You can go back and forth between measurement points until it reads zero but there is a better way: use math. A valuable added benefit here is that any movement not predicted by the math indicates that something is binding.

I know that many of you really hate math and will avoid it at all costs. But please give this a try. It will save you a lot of frustration as you align the leadscrew and you only need to deal with the equation once.

In order to minimize your pain, the full derivation of the equations is in the Appendix.



Using a steel ruler, measure the distance from the center of the take up nut's bolt to the zero set point of the DTI. Call this distance "A". Distance "B" is from bolt to the second reading location.

Then calculate the correction value, *k*:

$$k = 1 + \frac{B}{(A - B)} \qquad (8)$$

Record *k* for future reference.

Multiply *k* by my second DTI reading. With the DTI at the second reading location, swing over the leadscrew until it reads zero. Then move the leadscrew an addition distance of *k* times the reading. This will align the leadscrew.

Let's try a set of numbers to show you how this works. I measured "A" and found 1.5 inches. "B" was 4.5 inches. Using (8) I get

$$k = 1 + \frac{B}{(A - B)}$$

$$k = 1 + \frac{4.5}{(1.5 - 4.5)}$$

$$k = -\frac{1}{2}$$

I zeroed my DTI at the zero set point. Say I read 0.005 inches for my second reading point. Call this reading E.

$$g = k\,E \qquad (9)$$

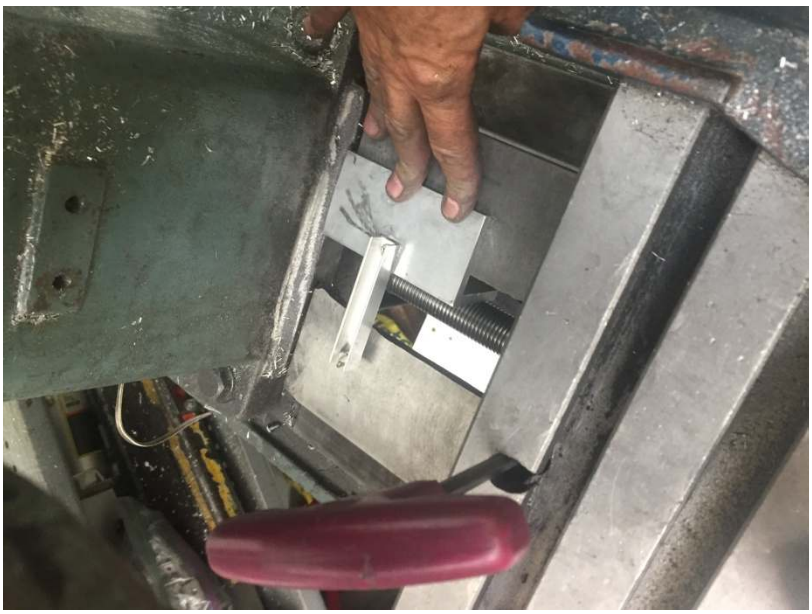
$$g = -\frac{1}{2}E$$

I first move my DTI needle from its present location back to zero. Then the $-\frac{1}{2}E$ says to continue moving until we are at half this distance, $-\frac{1}{2} \times 0.005\ inches = -0.0025\ inches$. The leadscrew should now be aligned.

Do slide the DTI back to the zero set point and verify that the DTI reading is $-0.0025\ inches$. If it is not, something may be binding up.

Recall that this alignment is done by loosening one horizontal jack and tightening the other.

If you can't move the needed distance, something is binding. Check that the two horizontal jack screws are not both snug. That would prevent moving the end of the leadscrew. Also verify that the Y axis take up nut's mounting bolt is just snug and permits rotation of the nut.

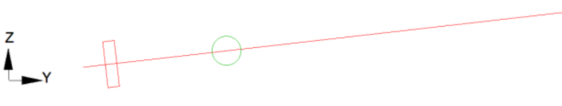


When you are satisfied that the Y leadscrew is aligned correctly as viewed from the top, the final step is to lock its position. This is done by firmly holding the thick angle with one hand and tightening the nut with the other. Do a final check of alignment before moving on.

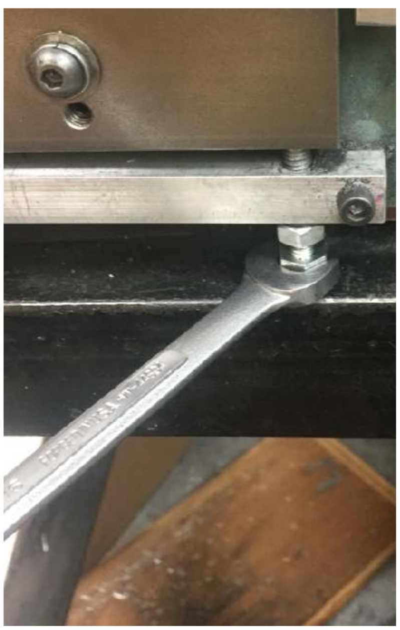
The leadscrew is now aligned side to side. In other words, yaw is very close to zero.

We have so far accomplished two of the three tasks necessary for alignment. The leadscrew is aligned with the take up nut and yaw has been set to near zero. We will be making one more iterations so if you are within 0.001 inches for now it is fine. Next up is setting roll to zero. In other words, we need to set the leadscrew so it is parallel to its ways in the YZ plane which means no vertical tilt.

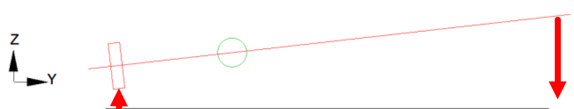
Adjusting Roll



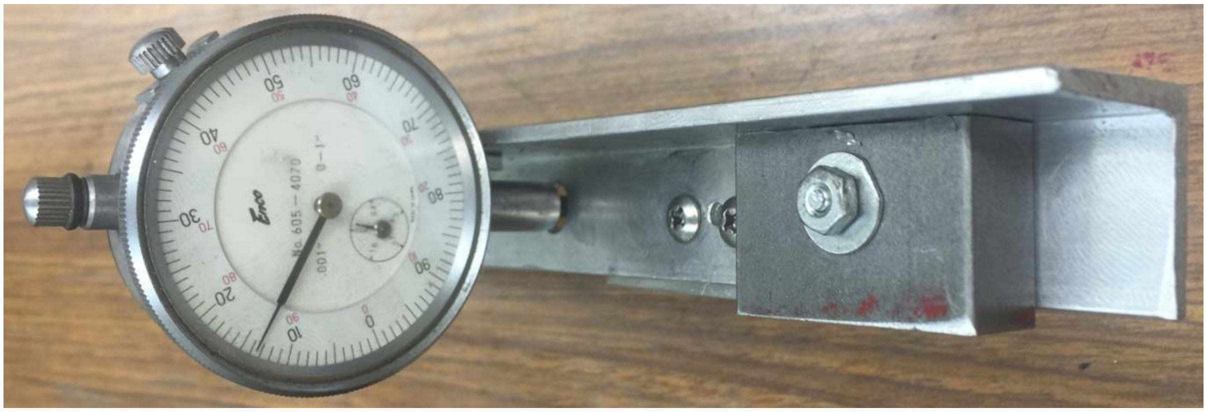
This is a side view of the leadscrew. The thick horizontal line is our ways. The leadscrew is likely tilted up due to the weight of the bearing block (red rectangle) to the left of the nut (green circle).



Using a wrench, the two vertical jack screws raise the plate while the leadscrew tilt is monitored. This monitoring requires another measuring instrument.



force of jack screw pivot of leadscrew

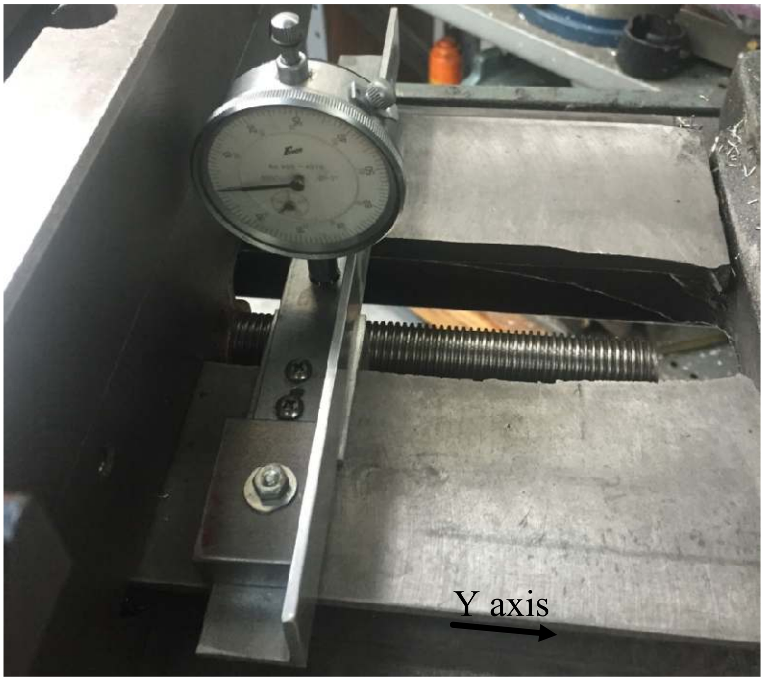


I'm using a second push rod DTI. Since it is necessary to switch between measuring yaw and roll, it is far more convenient to have two DTIs. The block of steel bolted to the angle prevents the instrument from tipping over.

This attached angle contacts the outside of the leadscrew and positions the push rod at a consistent point on the top of the leadscrew. It does not have to be exactly centered on the leadscrew, just consistent. The tip of the pushrod has been replaced with a flat head screw so it don't fall into the threads.

The bottom surface of the angle rests on the surfaces flanking the slot.

Don't be confused by all of the extra holes. Some were left over from past uses of these bits of metal. Others were formed as the instrument was perfected.



The instrument is now in the zero set position. The pushrod of the DTI is about 1 inch from the center of the take up nut's bolt. This distance is our "A" value to be used in equation (8).

We then move to the second reading position which is about 5 inches away. This is our "B". Equation (8) now comes into play:

$$k = 1 + \frac{B}{(A - B)} \qquad (8)$$

$$k = 1 + \frac{5}{(1 - 5)}$$

$$k = -\frac{1}{4}$$

The DTI reads 0.001 inches high. Equation (9) says

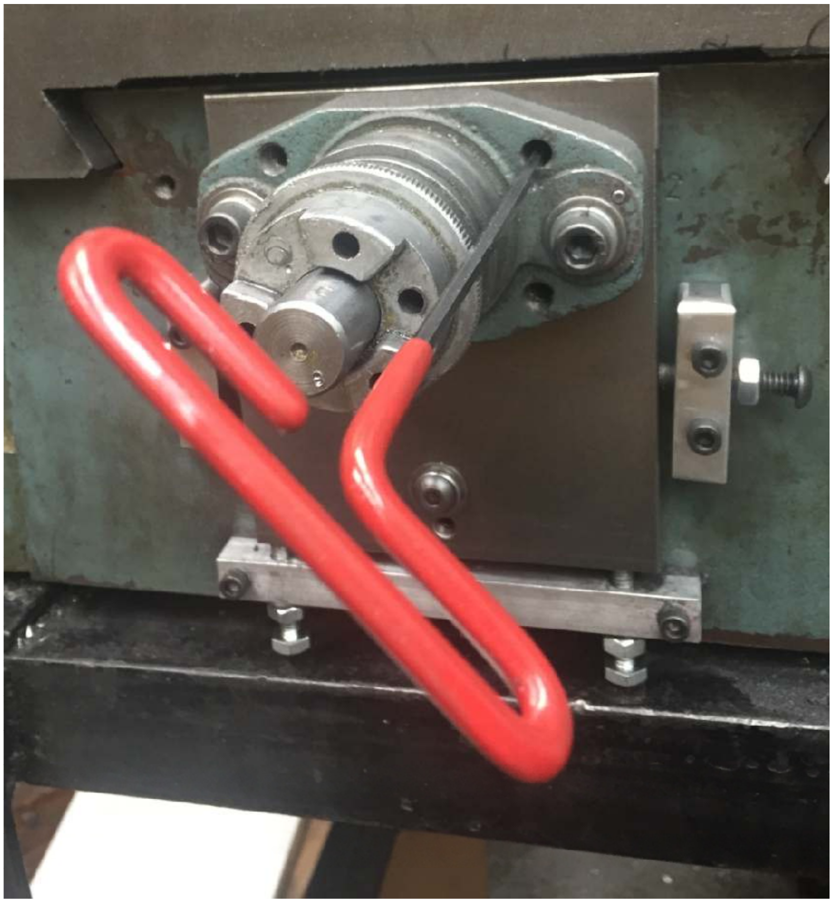
$$g = k\,E \qquad (9)$$

$$g = -\frac{1}{4}E$$

We swing the leadscrew until the DTI reads zero and then move an additional 0.00025 inches.

Once the roll has been set to zero, go back and verify the yaw is still zero. If you must change the yaw, remember to slightly loosen the take up nut's hold down bolt so the leadscrew can pivot. Then tighten it back up.

Note that I'm not actually contacting the ways which are at the bottom of the dovetails, but rather this surface above the ways. Measurements say it is good enough.



With the mounting plate locked in place with the jacks in the X and Z directions, we must stabilize the Y direction. The three mounting screws are barely snug and the bearing block is tight against the mounting plate. The next step is to gently turn in the 5 set screws until they contact the base of the mill. Then the mounting screws are tightened. Verify roll and yaw again to be sure nothing shifted. At this point, small shifts can be corrected by adjusting these set screws. Just be sure you loosen the mounting screws enough to provide room for movement. Now is the time to get roll and yaw error down to below 0.0005 inches.

All of these mounting screws have a washer under the head so they can move around their oversized clearance holes. They also have spring washers to help with adjusting the set screws.

The top 4 set screws take the force generated by the top two mounting screws. They fine tune yaw (the side to side alignment). The single bottom set screw carries the bottom mounting screw's force. They work together to fine tune roll (the vertical tilt of the leadscrew).

With a bit of care and patience, it is possible to set the leadscrew to better than 0.0005 inches in a 4 inch run for both roll and yaw.

The next test is to reduce the Y backlash to a minimum without having any binding. Then measure the change in backlash along the leadscrew. Recall that misalignment of the leadscrew relative to the ways causes binding as backlash is reduced.

Using my finger DTI, I measured a backlash[5] of 0.0015 inches at my vise's fixed jaw.

I then moved the table along the Y axis a distance of 3 inches and did not see any binding. The backlash increased to 0.0020 inches.

About 0.0002 inches of this increase was due to radial error in the leadscrew: Turning the leadscrew shows a cyclic error of about 2 tenths.

The rest is probably due to leadscrew wear and leadscrew misalignment. However, since this satisfies my original goal, I'm happy. I do plan to periodically check the backlash to be sure it does not drift over time.

[5] Mach3 is used to jog the leadscrew precisely 0.001 inches at a time. The mach3 backlash function lets me specify the backlash compensation. When jogging 0.001 inches in either direction causes the DTI to move exactly 0.001 inches, my backlash value stored by Mach3 is my measured result.

I set my CNC software's backlash compensation to the average of these two readings: 0.00175 inches. At my fixed jaw, the compensated backlash will overshoot by about 0.0003 inches. At my 3 inch point, it undershoots by the same amount.

It is important to understand that all of these adjustments are on a static machine. The ultimate test involves machining a series of test coupons of known size. Actual error is the difference between what the g-code specified and the coupons measure.

Acknowledgments

Thanks to John Herrmann for collaborating with me on this project.

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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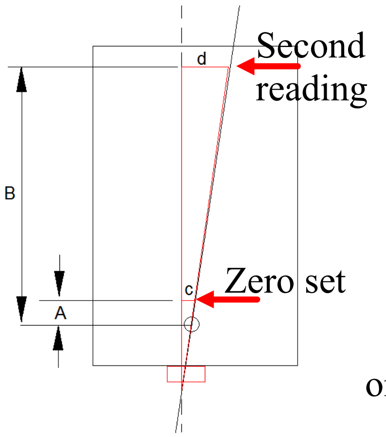
Appendix

Derivation of the equations used to align the leadscrew.



I don't know distance "c" or "d" but the DTI did give me d minus c which I will call "E". Note that right triangle Ac shares the same angle at the nut (circle) as triangle Bd. This means that I can use the rule of similar triangles and say:

$$\frac{c}{A} = \frac{d}{B}$$

or

$$d = \frac{cB}{A} \qquad (2)$$

I defined E = d - c (3)

Combining (2) and (3) I get

$$E = \left(\frac{cB}{A}\right) - c$$

or

$$E = \left(\frac{B}{A} - 1\right)c$$

or

$$c = \frac{E}{\left(\frac{B}{A} - 1\right)} \qquad (4)$$

Plug (4) into (2) and I get

$$d = \frac{E}{\left(\frac{B}{A} - 1\right)} \ \frac{B}{A} \qquad (5)$$

In order to align the leadscrew, I want to move a distance of -d so will multiply (5) by -1 to get

$$f = n\,E \qquad (6)$$

$$\text{Where } n = \frac{B}{(A-B)} \qquad (7)$$

Equations 7 lets me calculate a correction factor, n, that compensates for my zero set position. I then multiply n by my second DTI reading, equation 6, and swing the needle a distance ***opposite*** the initial deflection. This will align the leadscrew.

The magnitude of n is always greater than 1. This means I will always be moving from the measured value back to zero. Then I will move a bit more. For the convenience of the user, I have extracted the 1:

$$\text{Where } k = 1 + \frac{B}{(A-B)} \qquad (8)$$

The user firsts move the DTI from its reading to zero. Then they move an additional distance of

$$g = k\,E \qquad (9)$$