MAIN ROTOR BLADE BALANCING – BLADE ALIGNMENT (See Comments on Page-11)

29 March, 2012 – Recently I decided to chrome the bare steel bits and pieces on the main rotor due to corrosion. That meant that I would have to rebalance from scratch when the lead/lag links came back. The static balance is covered very well in the construction DVDs but I'll go over the steps I took here since they differed slightly. Before I sent the parts off I carefully measured the length of each link from the outer edge of each ball joint:

	Master Blade	Slave Blade
Before Chroming	6.667 in.	6.496 in
After 3-Pound "Wiggle Test"	6.667 in.	6.490 in

Once they came back I reassembled the links and installed them on the two blades. Then I disconnected the pitch rod on the master blade and hung a 3-pound weight on the pitch arm and wiggled the rotor head to allow the blade to seek its natural position. The adjustment of the lead/lag link's length is extremely sensitive. I measured the angle of the blade grip using my Mitutoyo Pro 3600 digital protractor, and once I got below 0.3 degrees I called that good enough and tightened the lock nuts on the link. Then I pulled the link off and measured it. It was <u>exactly</u> the same as before the parts went to the chrome shop. That was reassuring!

Once the master blade is done the VDV calls for you to adjust the slave blade by running a string from tip to tip and adjusting the slave link to make the line pass directly over the center of the top bolt, but as a test I decided to do the same 3-pound wiggle test on the slave blade to see what I would end up with. After repeating that process I ran a fishing line across the two blades and attached a lead weight to each end. The next step was to support the two blades so the string would pass across the top of the bolt head without too much friction and then line up the string at each end so it came off the end of the tip precisely at the junction between the extrusion and the sheet metal.

Here's what my initial setup looked like – More reassurance that I'm on the right track…

I should mention that the small center hole on that bolt head is not in the center of the head. I chucked the bolt shank up in my lathe to make that center hole and was surprised to see that the head was not exactly centered on the shank. It was slightly off, so the hole is centered on the bolt shank but not the head. Anyway, this is awfully close but I decided to tweak the slave link to center the line.
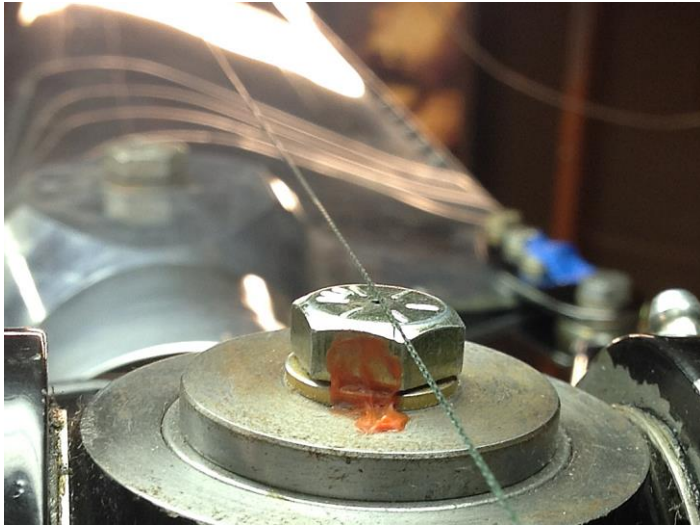
After a final tweak of the slave lead/lag link's length the line passed directly over the hole. So now the two blades are perpendicular to each other. After pulling the link off and measuring it I ended up with a difference of 0.006 inches.

Doug went through all this when he checked out the ship and when I repeated the process on the master blade I ended up exactly where it was before (and after Doug's checkout.) He then did the dynamic balance using a weight on the side of the rotor head. As you'll see, I elected to remove his weight and dial out the vibration by adjusting the slave link. This probably accounts for the 0.006 inch delta from where it was after my dynamic balance and where it is now after doing another static balance.

The next fifteen pages or so will detail my earlier dynamic balance. I had to redo it again after the chrome pieces came back, but the process was exactly the same. This second time I ended up with a final reading of 0.10 ips. When you get that close you're down to small fractions of a gram of tip weight and fractions of a thousandth of an inch on the lead/lag link's length. At that point it's time to stop.
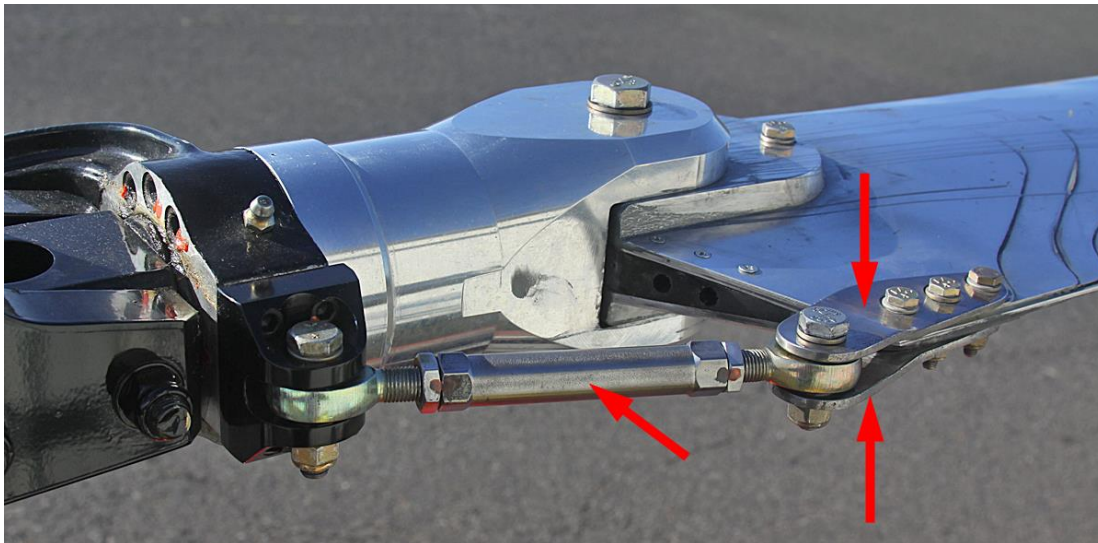
The red arrows show the parts that I had chromed.

And now back to my previous write-up…

STATIC BALANCE

After aligning the blades on the hub so that they're exactly perpendicular to each other the blades must first be statically balanced. As the word 'static' implies, this balance is done with the blades at rest in an area with no air movement. The idea is to adjust the tip weights to make the two blade tips exactly the same distance from the floor. I used a water level made from a 25-foot piece of plastic tubing for the job. Some people use a bubble level or digital protractor placed on the hub. The static balance is only the first step and does not guarantee that the blades will not cause vibrations when in motion. For that we need to do a dynamic balance.

DYNAMIC BALANCE

The first step necessary to do a dynamic balance is to acquire access to a vibration analyzer designed for the purpose. The analyzer will provide two pieces of essential information – the magnitude of the imbalance, measured in inches per second, or 'ips' and a phase angle measured in degrees. This information will be plotted on a polar chart. The direction of the imbalance is shown in a counter clockwise direction from 0 to 360 degrees, and the magnitude is depicted by the concentric rings from 0 to 1.0 ips (Figure 1.)
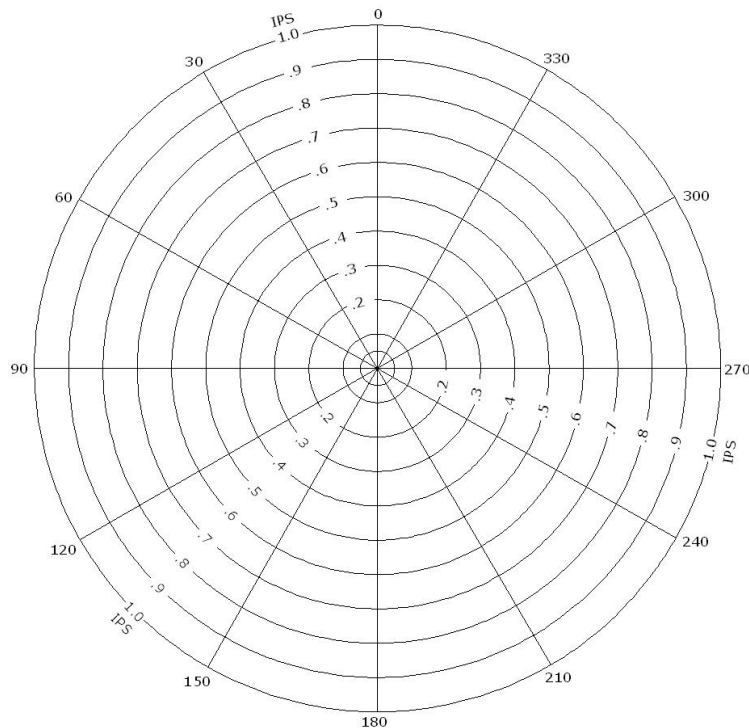

The purpose of the polar chart (Figure 1) is to first determine where the center of mass is in relation to the center of rotation - the middle of the chart, and then allow us to adjust the main rotor to bring the two together. In the Helicycle this is accomplished by adjusting tip weights and either adding a weight to one side of the rotor hub, or adjusting the slave blade's lead/lag link's length.

Before this chart can be of use we need to develop the chart for the particular vibration analyzer and mounting arrangement to be used. I'm using a Pro-Drive which is no longer manufactured. Other units should be very similar.

Figure 1— Blank Polar Chart

The two sensors that are required to measure dynamic balance are shown in Figure 2. They consist of an accelerometer to measure the amplitude of the vibration (#2), and a sensor to determine the phase angle. With the Pro-Drive this is done using an optical sensor (#1) which projects a beam of light and detects the reflection off of a piece of reflective tape (arrow head.)

These two sensors are connected by cables to the processor and display unit that determines the phase angle and amplitude of the vibration which it displays on an LCD screen.

Since the exact placement of these two sensors affects the configuration of the polar chart I'll take a moment to go over them. The phase angle value that the vibration analyzer displays is based on where the processor is triggered by that reflective tape, and is not related to the orientation of the helicopter. It's an arbitrary value. In my case the zero phase angle of the blades should be more or less aligned with the long axis of the helicopter since the optical sensor is mounted in the center of the rear side of the bonnet. As you will see, it looks like the zero axis is actually about 30 degrees offset. This would suggest that the analyzer is triggered when the reflective tape moves out of the beam and not when it moves into it. It doesn't matter, but I like to understand how my equipment functions.

Figure 2─ Vibration Analyzer Sensors

For the accelerometer mount I milled a short rectangular piece that I attached to the rotor mast upper bearing mounting location (Figure 2, #2.) I tapped the end, installed a screw with Loctite, cut the head off and then deburred the end. The accelerometer screws on to the screw. To insure a flat mounting surface I used an end mill to finish the surface before removing the piece from my mill vice. The orientation of the accelerometer is parallel to the plane of rotation and at right angles to the long axis of the ship. My thinking was that the frame is fairly free to vibrate sideways but quite stiff fore and aft. This mounting may make the accelerometer more sensitive to rotor imbalance.

For the optical sensor I made a bracket that extends aft far enough to give it a clear shot at the blade grip. The sensor is six and one half inches from the center of the main shaft and requires a pulse at least 3 milliseconds long to function properly.

Doing the math:
- Radius = 6.5 inches (from center of shaft to sensor)
- Circumference = Ω x D or 40.84 inches
- RPM = 619 or 10.32 revolutions per second
- That yields a velocity of 421.5 inches per second 6.5 inches from the shaft center
- I've got a 2-inch piece of tape on the blade grip which will give me a pulse duration of 4.7 ms which satisfies the 3 milliseconds minimum pulse width for the optical sensor. This will work.

I'm leaving all of the mounting hardware for both the tail rotor and the main rotor permanently attached when not in use. It's not in the way and makes retesting much quicker to set up.

OK, now that the vibration analyzer sensors are mounted and the blank polar chart is ready to go, it's time to gather data. Before we can start making adjustments it would be nice to know ahead of time what affect they will have. Some folks skip this step and dispense with the polar chart entirely, but I find it painful to watch.
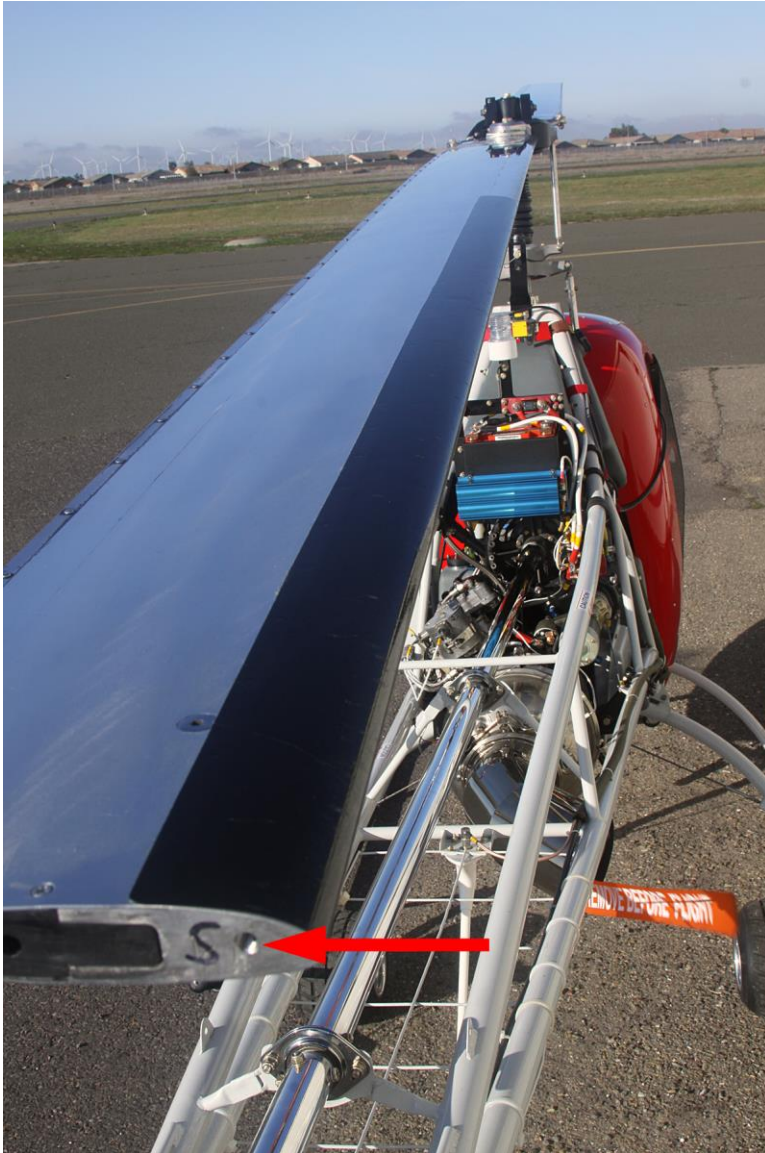
Figure 3 ─ Leading Edge Tape and Tip Weight Location

Since my main rotor blades were initially balanced I've made a few changes. I also installed black abrasion tape on the leading edges. Dust had been eating my blades up at a prodigious rate. This tape is made by 3M and it's specifically designed for jet aircraft and helicopter blades. It must be properly applied of course, and that's an entire story in itself.

Since a lot of changes had been made to the main rotor I decided to start fresh so I removed all the weights.

One last thing – I drilled and tapped ¼-20 threads in each tip (Figure 3, red arrow) and that's where my tip weight set screws go.
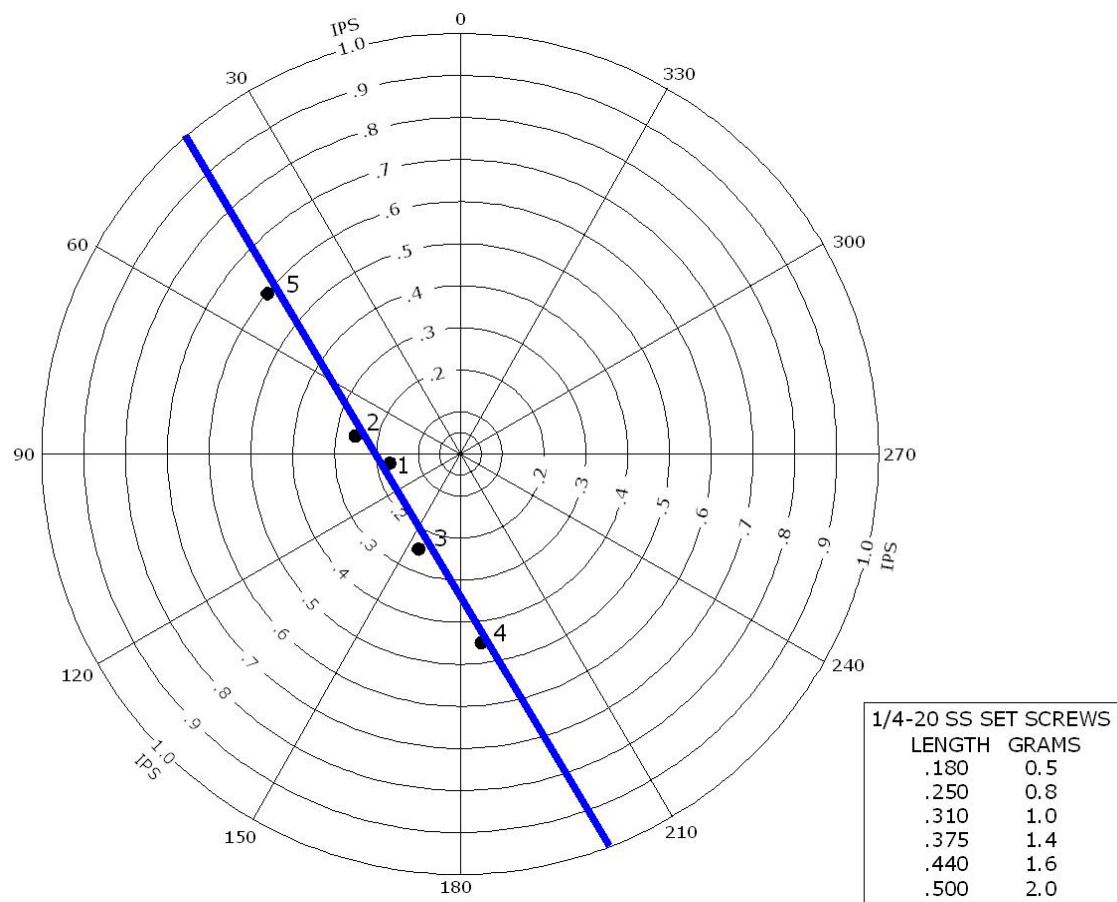
Figure 4 ─ Tip Weight Reference Run

The main rotor rotates counterclockwise so I show rotation in that direction on the polar chart. Here's how I started -- With no weights I ran the rotor up to flight speed and took a reading (#1.) I measured 0.16 ips @ 94º. By some miracle the main rotor was almost perfect which wasn't going to help me understand this process at all, so I installed a 0.180-inch set screw (0.5 gram) in the master blade tip, ran the rotor back up to speed, took another reading (#2), shut everything down, and then moved it to the slave tip and repeated the process (#3.) The plots were encouraging since points 1,2 and 3 looked like they line up fairly well. To be sure I removed that screw and installed a 0.5-inch screw (2.0 grams) in the slave blade (#4) and then moved it to the master side (#5.) The blue line passes nicely through all of the points which gave me a lot of confidence in the data.

1/4-20 SS SET SCREWS	
LENGTH	GRAMS
.180	0.5
.250	0.8
.310	1.0
.375	1.4
.440	1.6
.500	2.0

Now that I've collected the tip weight data I can add it to my chart and move that blue line off to the side and out of the plot (Figure 5.) That's now my tip weight move line. Any time I change a tip weight the center of mass will move along that 30º - 210º axis[1]. The center of mass could be anywhere on that chart, but the underline direction of movement will be along that axis when changing a tip weight. I can also scale the movement in grams based on my reference run.

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[1] The 30º - 210º axis is determined by the placement of the optical sensor and the reflective tape.
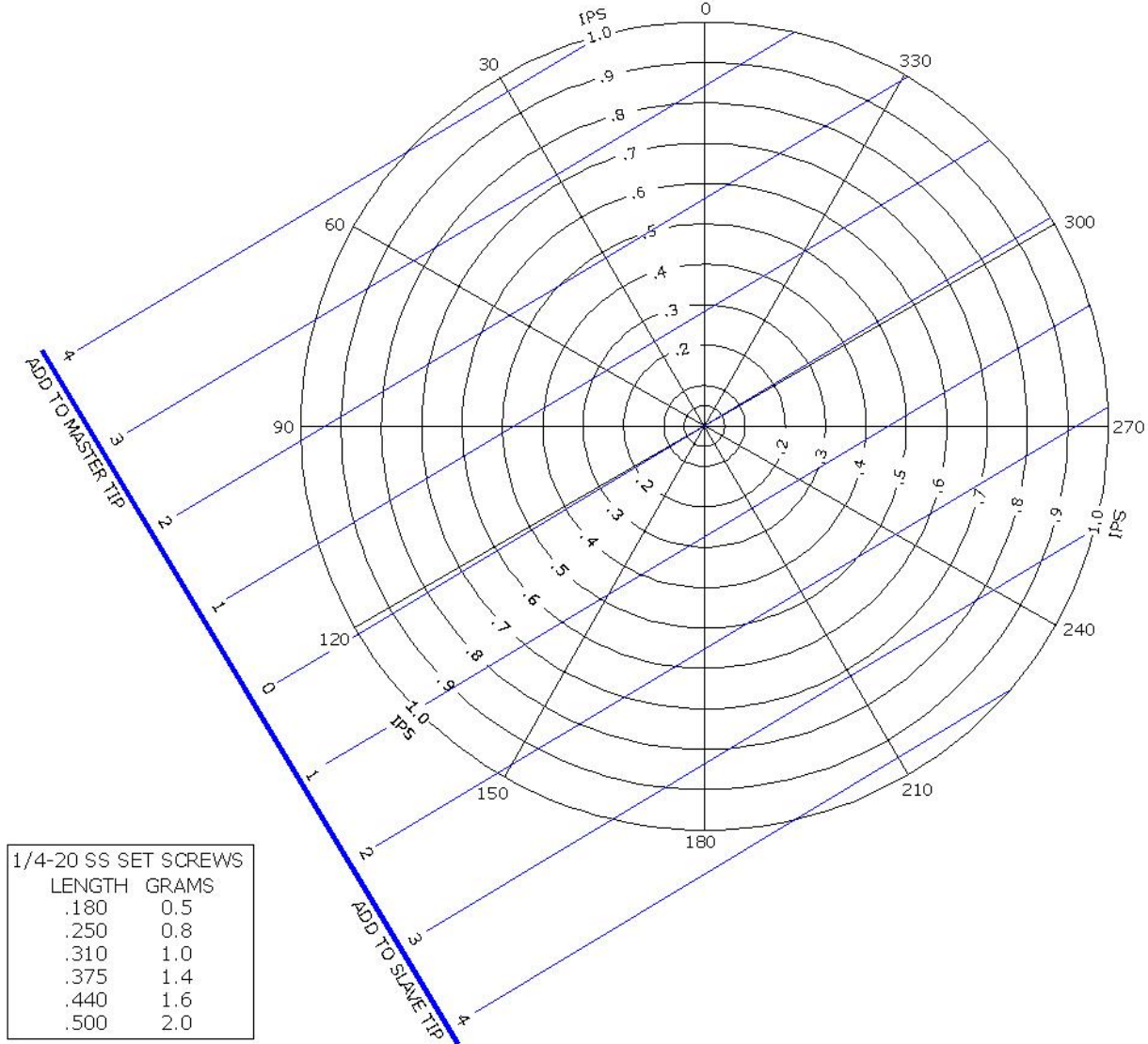
Based on the data collected to generate Figure 4, I can now make the move line for the tip weights and offset it out of the way (Figure 5.) This line makes sense. The trigger point must be the trailing edge of that pulse when the reflective tape has passed out of the beam and disappears. Otherwise the move line would be closer to a 0º - 180º orientation.

1/4-20 SS SET SCREWS	
LENGTH	GRAMS
.180	0.5
.250	0.8
.310	1.0
.375	1.4
.440	1.6
.500	2.0

Figure 5 ─ Tip Weight Move Line

Figure 6 ─ 0.5 Gram Weight

By the way, here's a .5 gram set screw sitting on a dime. When you consider that the main rotor system weighs about fifty pounds, this isn't much! Sitting in the seat, you can actually feel the difference in the balance when moving this little weight from one tip to the other.

The next order of business is to find out what moving a weight from one side of the rotor hub to the other side does (red arrow in Figure 7), and then find out what effect changing the length of the lead/lag link does to the center of mass. I would expect both methods to move the center of mass in an entirely different direction than the tip weights.

Figure 7 ─ Location of Rotor Hub Weights

I would also expect both of those choices to do the same thing and here's why – replacing that bolt and washer (red arrow) with a big weight would move the center of mass towards that side. But look at the blade on the right. You can see that the blade pivots on the large bolt whose nut you can see at the bottom of the blade grip. Shortening the length of that lead/lag link is going to pull that blade towards the camera and also move the center of mass in the same direction. Maybe they will have slightly different affects but I'll bet they're close. I'll have to take more data and plot it to see exactly what happens…

Figure 8 — Hub Weight Move Line
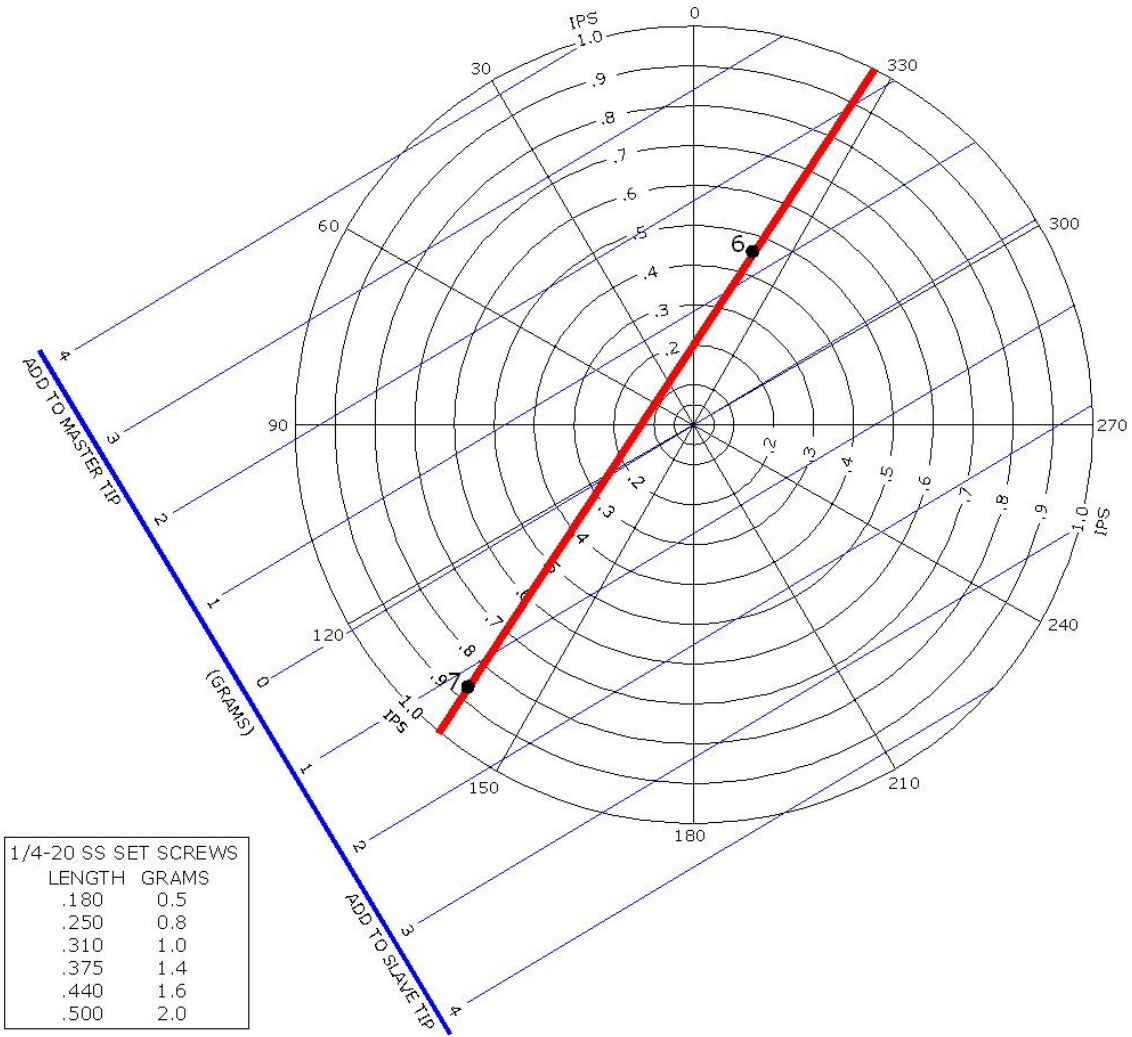
Next I removed the tip weights and mounted a 130 gram hub weight on the side of the hub with the master lead/lag link and took a measurement (Figure 8, #6) and then moved the weight to the other side and took another measurement (#7.) The red line intersects those two points and shows the move line created by moving hub weights. This also told me that I needed to add some weight on the master link side to get the vibration down towards zero (I started on Figure 4 at point 1.)

1/4-20 SS SET SCREWS	
LENGTH	GRAMS
.180	0.5
.250	0.8
.310	1.0
.375	1.4
.440	1.6
.500	2.0

June 9, 2018 – On the next page I suggest adjusting the lead/lag link's length. I now think this is a dangerous idea and should not be attempted without giving it a lot of serious thought.

By doing this you are changing the relationship between the feathering axis of the blade and the center of lift. I think this could have dire consequences and lead to blade instability.
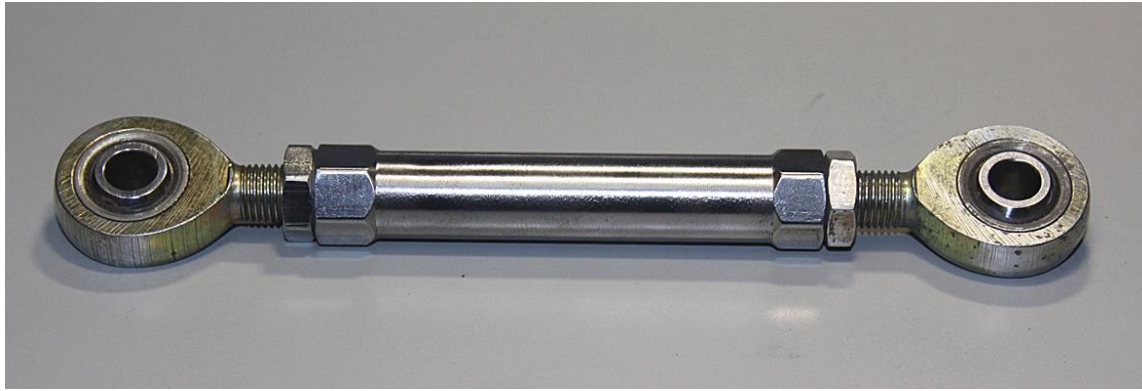
Earlier I mentioned that I could move along the hub move line by either adding weight to one side of the hub **or slightly changing the length of the slave lead/lag link**, and when I say 'slightly' I mean a few thousandths of an inch. This isn't going to be easy. Since this is going to be my preferred method I'll hold off scaling my hub weight move line until I play with the slave lead/lag link and get more data. Then it will turn into a lead/lag link move line instead of hub weight move line.

Figure 9 ─ Lead/Lag Link

The lead/lag link is shown in Figure 9. It's really just a precision turnbuckle. The threads on the two Heim joints are opposite each other so

when you loosen the lock nuts and turn the center piece it will draw in both ends, or push them both out. But you can see that the threads are quite course, so to change the length by 0.002 inches would only require the center piece to be rotated a few degrees, and then everything would change when the lock nuts were retightened. An added complication is that the flat sides of the two Heim joints need to be parallel to each other. Dealing with this level or precision would be impossible without a jig to hold everything steady, and a way to precisely measure the length, so I made myself a jig with a dial indicator to measure relative length (Figure 10.)
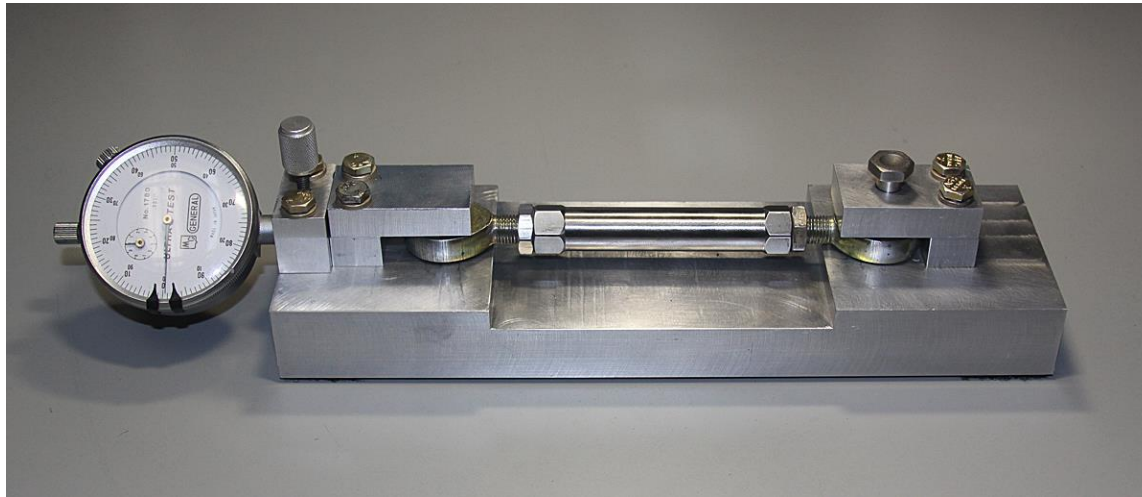
Figure 10 ─ Lead/Lag Adjustment Jig

The jig was fabricated from 6061 T6 aluminum on my mill. All the bolt holes are reamed and the bolts are all press-fits with no slop. The two gaps where the Heim joints go have about 0.002 inches of clearance to keep the joint faces parallel with each other. The pin at the right side is fashioned from a precision bolt and that hole was also reamed. The dial indicator's probe protrudes into the fixture and pushes against the end of the joint on the left side. Overall I have less than 0.001 inches of slop end to end which I can eliminate by always pulling the assembly towards or away from the dial indicator.

Armed with my adjustment jig I am now ready to gather some data by adjusting the lead/lag link. (Never fool with the master blade!)

Remember from Figure 4 that I started out at point 1 with no weight. Now that I've determined my two move lines I can formulate a plan. If I add a 0.5 gram screw to the master blade tip that should return me to my previous point 3, and from there I can travel up the red move line (Figure 11) and right into the axis of rotation. There's only one small detail – I haven't calibrated the lead/lag link so I don't know how much of a change I need to get to the end of that red line. I'll just have to try something and see what I get.
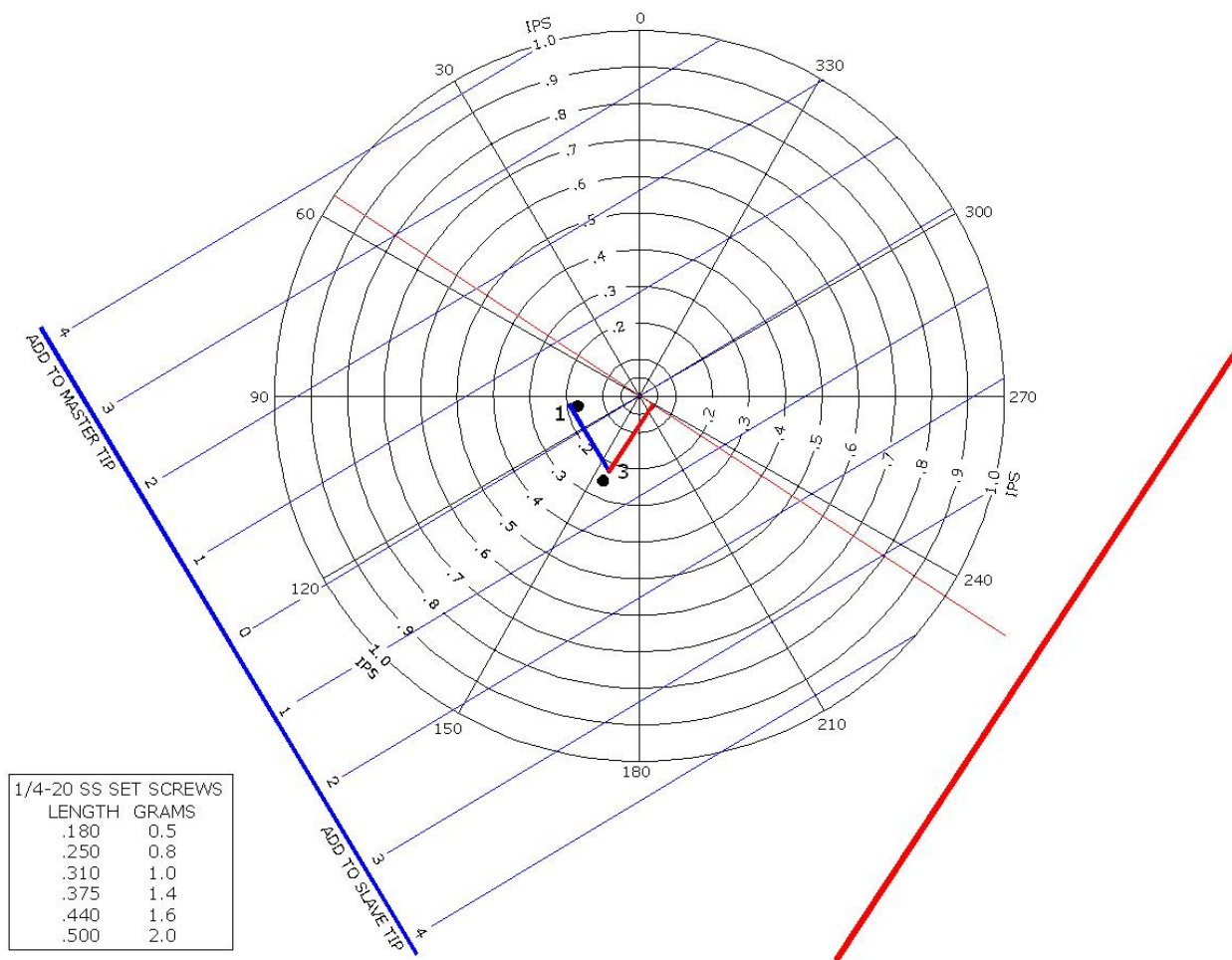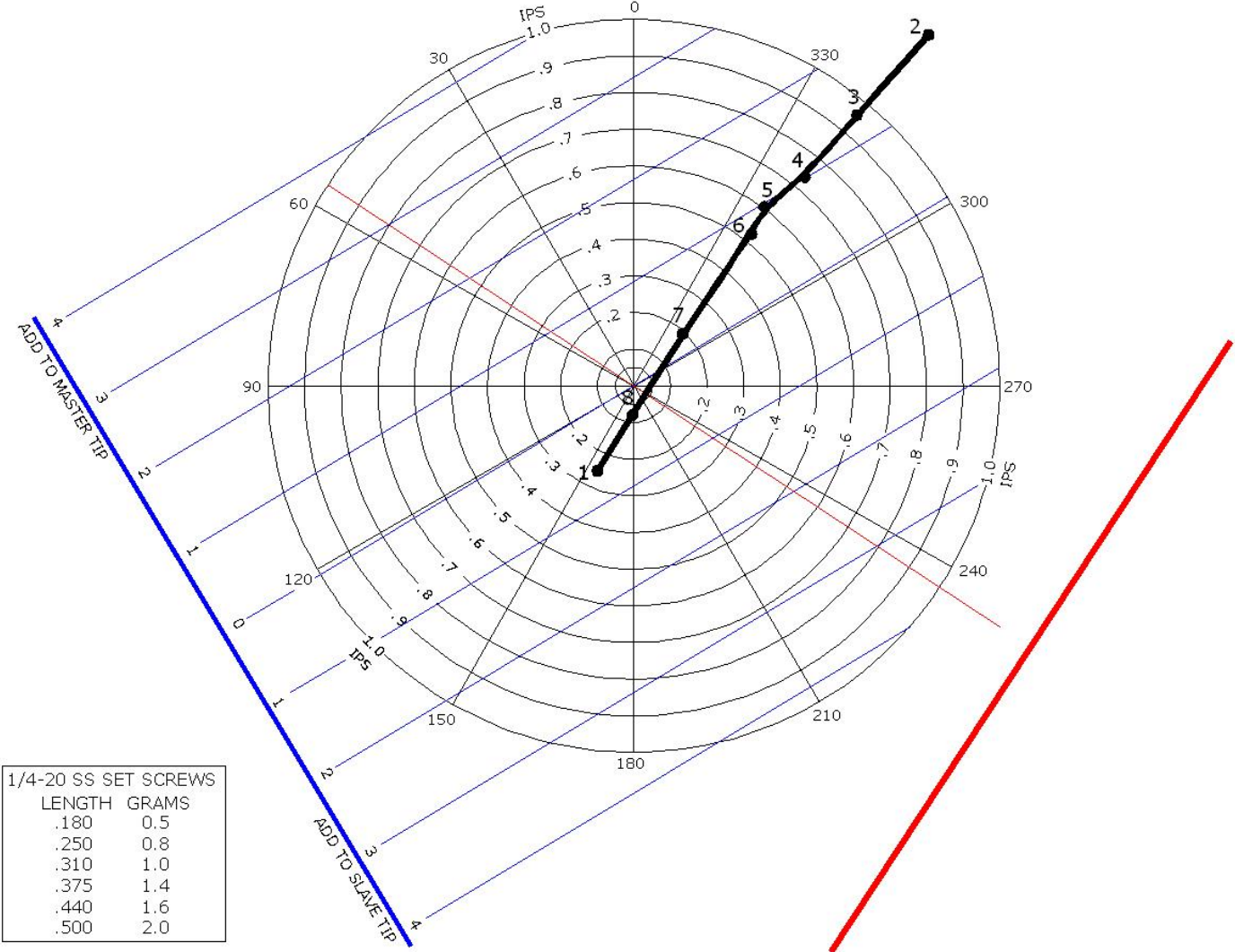

Figure 11 — Dynamic Balance Plan

I removed the slave lead/lag link, installed it in my jig, set the dial indicator to read 0.000 at the peak point of the Heim joint and then loosened the lock nuts and tweaked the link just a tad until the dial indicator read -0.004, and retightened the lock nuts. Once the lock nuts were tightened the length was nowhere near my goal. After about ten tries I started to get the feel for this but unfortunately that's when the knurled locking screw came loose and my dial indicator slipped. That left me with no idea where I was, so I had no choice but to lock the nuts down and try it. The lesson here is to measure the absolute length of the assembly with an 8-inch dial caliper. Too bad I didn't own one. (I do now!)

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1/4-20 SS SET SCREWS	
LENGTH	GRAMS
.180	0.5
.250	0.8
.310	1.0
.375	1.4
.440	1.6
.500	2.0

Figure 12 — Lead/Lag Link Adjustments

In Figure 12 I made the old point 3 from Figure 4 the new starting point as Point 1. The results of that first test were impressive. It felt like the rotor was going to tear itself off the helicopter and I ended up completely off the chart at point 2. The good news was that I was parallel with the red move line, so my theory was sound – moving the hub weight has the same affect as changing the lead/lag link's length.

Since I had no idea how much I had shortened the link I decided to increase the length by only 0.001 inches and ended up at point 3. Another 0.002 increase took me to point 4. I'm not able to really change the length by a thousandth with any degree of confidence since there is slop in the jig and also in the rotor attachment points, but this is what I measured. From then on it was simply a matter of trying not to get carried away and take it slowly.

Here's the raw data:

No.	IPS	Deg.	Total Change	Comments
1	.33	151	N/A	0.5 gram in slave tip – no hub weights
2	1.28	322	0.000	Increased slave lead/lag length. Length unknown
3	.99	324	0.001	Reduced slave lead/lag length 0.001
4	.77	325	0.003	Reduced slave lead/lag length 0.002
5	.64	329	0.004	Reduced slave lead/lag length 0.001
6	.56	328	0.006	Reduced slave lead/lag length 0.002
7	.23	331	0.009	Reduced slave lead/lag length 0.003
8	.04	148	0.011	Reduced slave lead/lag length 0.002

Table 1 ─ Lead/Lag Link Adjustments

Based on Table 1 I think I shortened that link about fifteen thousandths at first, when I only needed to move it about two thousandth. I'll do better next time.

From points 3 to 8 was a total change of eleven thousandths of an inch. Now I can scale that axis and add it to my graph for next time.

From this you can see that the original 0.5 gram weight that I added to the slave tip moved me over so that I slid that previous red line over to intersect the center of the circle. I think the wiggles in the black line can be attributed to interaction with the frame sitting on the ground, gusts of wind, the exact setting of the collective, and how I set the elastomeric bearings when running the rotor up to operating speed. Given all the variables and the complexity of the rotor system I think this worked out nicely. The final polar chart is shown on the next page. Feel free to copy it.

1/4-20 SS SET SCREWS	
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.180	0.5
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