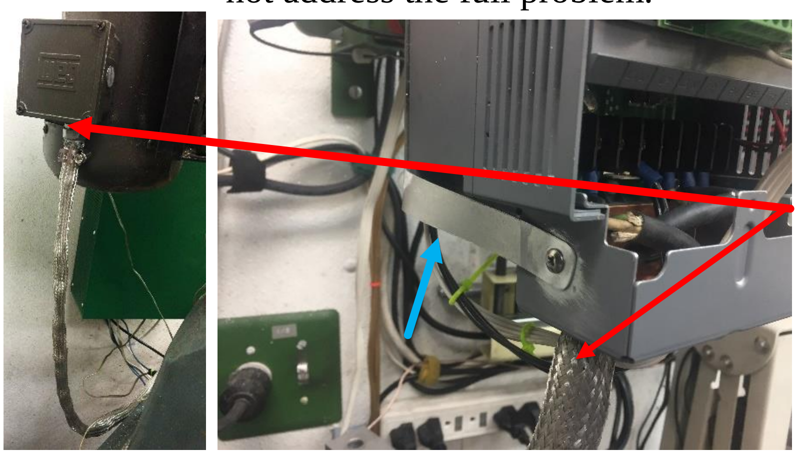
Variable Frequency Drive Noise Reduction, Version 2.1

By R. G. Sparber

Protected by Creative Commons.[1]

Conclusion

My Variable Frequency Drive (VFD) plus its spindle motor generated enough noise to destabilize my Computer Numerical Control (CNC) system. This noise was reduced to a benign level by adding a grounding strap between the VFD and the frame of the motor. Although this worked, it does not address the full problem.



A more complete remedy was to enclose the cable running between VFD and motor enclosure. This was done with copper braid carefully terminated at each end.

Additionally, I discovered that the VFD support arm was floating. A strap was added (blue arrow).

The fact that the VFD to motor grounding strap worked implies that most of my problem was due to the motor and the attached mill acting as a transmitting antenna rather than the motor cables inducing noise current into the CNC system. However, the braided tubing should reduce both modes of coupling. Unfortunately, my only measure of success is the lack of error messages reported by the CNC's PC (CNCPC). This does not tell me how close I am to having a problem.

Background

What could be simpler? We have a transmitter and we have one or more receivers. If the transmitter is your local radio station and your receiver is the radio in your home, that is simple to understand. The transmitter sends a signal and your radio receives it.

But what if the receiver is one or more computers driving your CNC system and the transmitter is probably related to the spindle motor? Well, it does it some of the time but not instantly. Not so simple to figure out. And you can't just leave the spindle motor off.

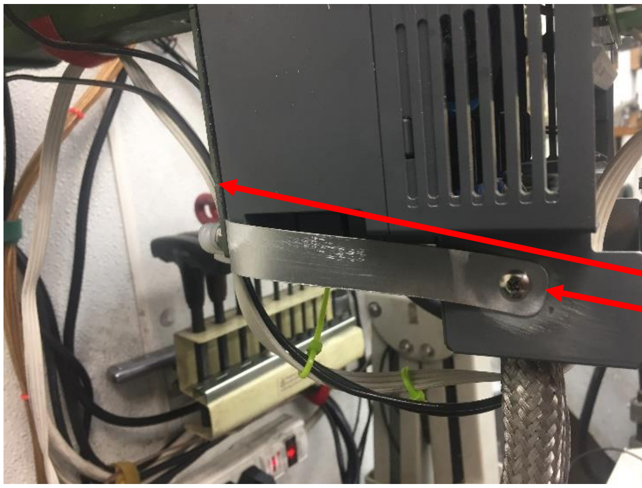
A Summary of Experimental Fixes

Here is my quick and dirty temporary fix. I ran a strip of sheet metal between the VFD and a mounting bolt on the motor. Without the strip, an error would halt program execution within 30 seconds. Preceding this failure was a continuous stream of corrupted data between the CNCPC and the Acorn (Thanks to Marty for showing me these messages). With this connection, There was no corrupted data reported.

I then experimented with ribbon cable. Picture very fine wires encased in insulation all running along parallel paths. At the ends, these fine wires were soldered together. This too eliminated program execution errors.

The long term fix was to use copper braided tubing[2]. The wires that run from VFD to motor are inside. One end was terminated in the VFD ground and the other end terminated at the motor enclosure.

[2] I bought 10 feet of this tubing on eBay for $30 from "acdcwireandsupply". When it is installed, I will verify that the system is stable.



The VFD support arm was not connected to VFD ground. This can cause the arm to pick up radiated noise from the VFD and reradiate it into the CNC control complex.

I installed a strap between the support arm plate and VFD ground.

This strap cut the failure rate by half.

Testing Methodology

With the spindle running, I ran a simple test program that moved all 3 axes.

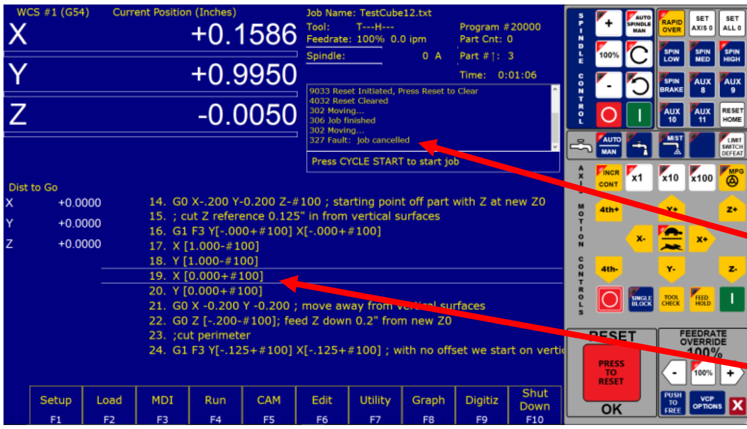
When the system experienced a fault, I recorded details. For each configuration I ran sets of 5 cycles. It was common to find 3 or 4 failures within those 5 cycles. Adding just the VFD ground to VFD support strap cut this down to 1 to 2 failures per 5 cycles. With all fixes in place, I ran 10 cycles with no failures.

These tests are necessary but not sufficient. Are we teetering on the cliff or well back from the edge of failures? Only by monitoring the receiving nodes in the CNC control complex and knowing their thresholds can we calculate the noise margin.

This monitoring would require soldering onto the Acorn board and possibly the CNCPC. At this time, I feel the potential benefits do not outweigh the risk of doing damage.

Theory

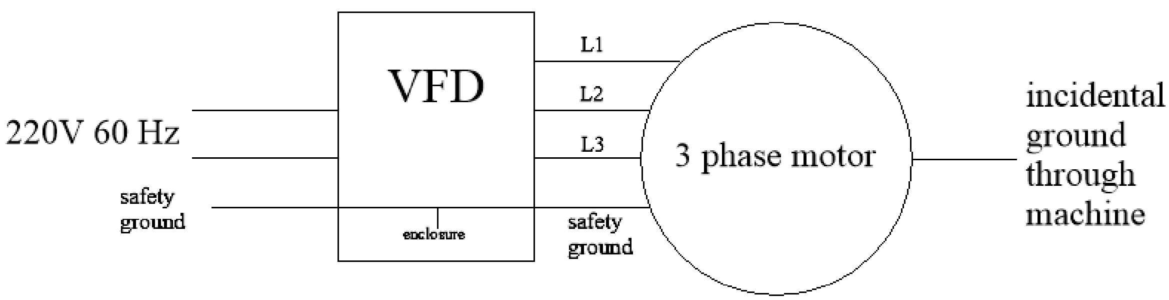
I have owned my TECO VFD for many years. When I was running the CNC program Mach3, all would be fine for many days. Then something would go wrong. Never did figure that out but there were so many software bugs, it wasn't practical to debug.



Then I upgraded to Centroid's CNC12 with Acorn. Rock solid software. All went well during set up. But when I powered up my spindle and put it under even light load[3], I would get a "327 Fault" that shut down program execution. It happened randomly so I knew it wasn't a G-code programming error.

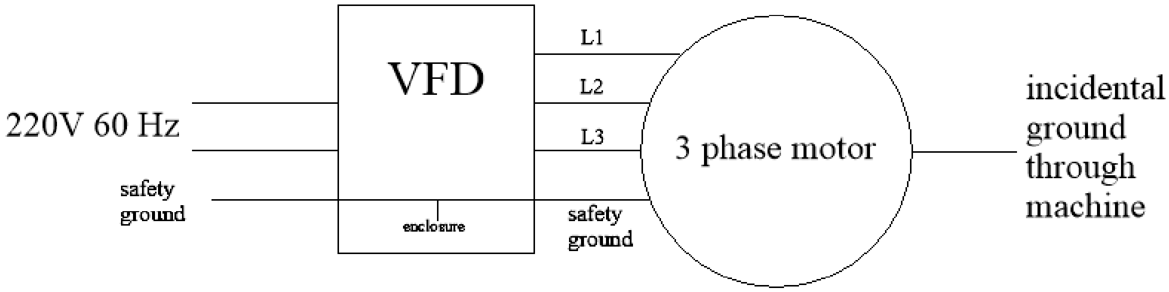
According to Centroid, a "327 Fault" is an unexpected input while running a job. The errors logged[4] before I hit the 327 Fault show problems with the data path between CNCPC and Acorn. That is consistent with one or more cables picking up a noise spike like a radio receiver and/or induced current.

Since the problem only occurs when the spindle is running, it is very likely the VFD and/or motor is our noise source. Time to take a closer look at them.



Starting on the far left, I have 220 volts at 60 Hz feeding my VFD. There is also a safety ground. If a fault developed inside the VFD that caused the housing to connect to 220V, the safety ground would save me. Rather than have the housing rise to a dangerous voltage, the safety ground would channel current back to the breaker box long enough for the breaker to trip. Note that the safety ground

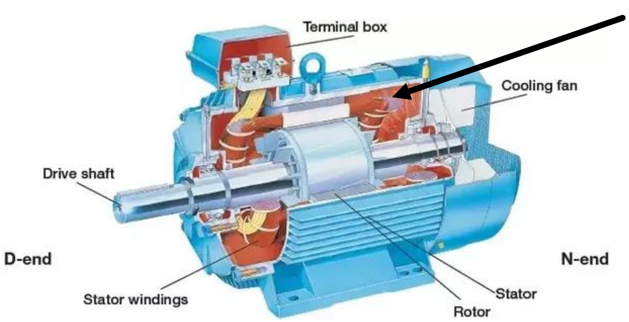
[3] In this case, the program ran fine until I rested my finger on the spinning spindle.
[4] The error log can be found by generating a report. Open the report, then open urf, and finally, open msg_log.



continues on to the motor which is bolted to my mill. There is also a safety ground bonded to my machine. Since the motor is bolted to the machine, it picks up this second ground.

These safety grounds are absolutely essential to protecting me from power faults. However, they do not do much to stop the transmission of high frequency electrical noise.

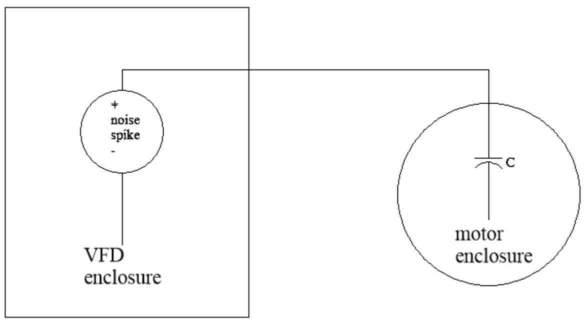
The VFD takes in the 220VAC, chops it up, and outputs voltages on L1, L2, and L3. It is close enough to a sinewave that the motor is happy. There are high frequency spikes mixed in with these output voltages but the motor only reacts to the extent that its temperature rises a little.



Inside the motor, a coil of wire connects between L1 and L2. It is electrically isolated from the metal case. When a voltage is applied between L1 and L2, this coil generates a magnetic field which rotates the drive shaft 120°. Similarly, the coil connected between L2 and L3 is energized and the drive shaft turns another 120°. The coil between L3 and L1 brings us around that last 120°.

There is another way to look at this motor. Recall that spikes exist on L1, L2, and L3. These spikes are with respect to safety ground.

The coils inside the motor are in close proximity to its metal case. This means there is a small capacitance between the coil and the motor's enclosure.



Look at this arrangement as a circuit with a noise spike voltage source inside the VFD. One end is connected to the VFD's enclosure. The other end is connect to the lines that connect to the motor's coils. These coils, in turn, have a capacitance to the motor's enclosure and mill[5]. All of that metal acts as an antenna and radiate to the rest of the system. Not good.

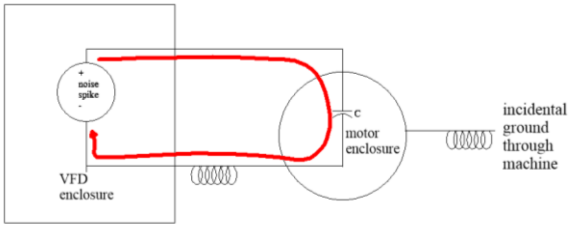
A second noise injection mode involves induced current. The amount of noise induced into the rest of the system is a function of

1. the distance between the offending wires and the signal paths being corrupted
2. the efficiency of the radiating wires: The larger the area defined by the current path through these wires, the more noise is induced.
3. the magnitude of the noise current

With proper "cable management", power cables are routed away from signal cables. So item 1 is usually easy to solve.

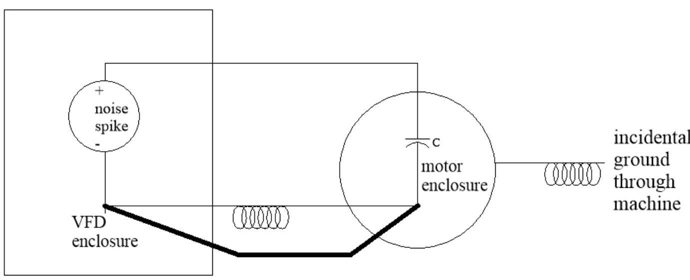
Item 3 is tricky. We can reduce the noise current by adding inductance but this runs the risk of letting the motor enclosure's voltage increase. Then we are back to having a big antenna. It is better to deal with item 2, the area defined by the wires, than trying to reduce the magnitude of the noise current. Time for a closer look.

[5] Since the motor is bolted to the mill, both have the same voltage on them.

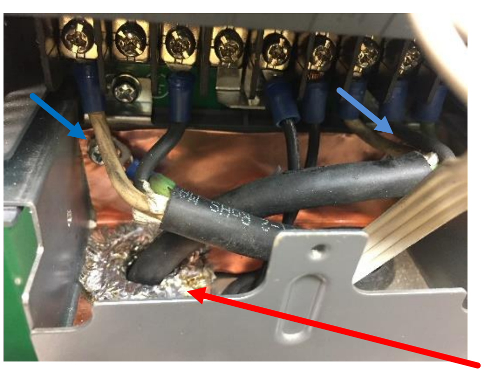


The VFD enclosure is connected to the motor enclosure and mill via the safety ground in the same cable that holds L1, L2, and L3.

The incidental ground through the machine involves eStop and home sensor circuits. It is reasonable to assume that the inductance of this safety ground wire is less than the inductance of the incidental ground path. This means that most of the noise current flows in the path marked by the red arrow. We are on the right track here because all of these wires do run in the same cable. However, that inductance means the safety ground wire doesn't carry much high frequency current so the motor enclosure and mill end up acting as an antenna. If we can reduce that inductance, we will be able to reduce both the antenna and induced current problems.



The thick black line is a low inductance conductor. It must run along the cable holding L1, L2, and L3. This diverts most of the noise current away from the two inductances and reduces the area enclosed by the current's path. It also reduces the noise voltage on the motor enclosure and mill relative to VFD ground.



I used braided copper tubing for the conductor. It is made from many fine wires woven into a flexible, low inductance[6], cable.

Here you see how I terminated the tubing at the VFD end to minimize inductance. The end is flared out and soldered to a sheet of thin copper foil. The foil is then bolted to the two available ground terminals (blue arrows) in the box. Once cool, the cable and the safety ground were fed through the tubing.

[6] If oil or some other insulating material coats the fine strands, they won't be able to contact each other. This will increase inductance.

At the motor end, I was able to use a standard conduit coupler and a short length of conduit. The tubing slid over the conduit and was secured with a hose clamp. Ah, but there is more to this story.

My motor was designed to be sealed. This was done with a rubber gasket between access door and box plus between box and the body of the motor. Great for keeping out contaminants. Awful for high frequency noise suppression.

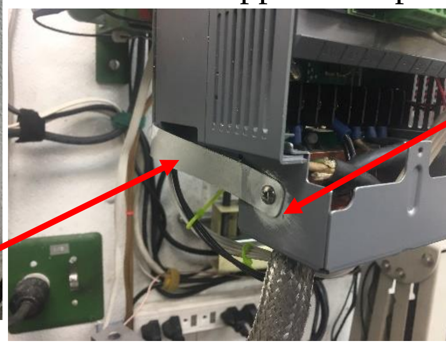
Here is the box to motor body seal. It had to go because I need to have a full metal on metal connection. I also removed the gasket between cover and box.

I ground off the paint under the box.

With the box now in direct contact with the motor housing, my braided copper tubing has a low inductance connection.

Any piece of metal not tied to ground have the potential to pick up radiation from the VFD and reradiate it into the CNC control complex. Using an ohmmeter with one probe touching VFD ground, I touched various parts of the system looking for continuity (Thanks “agsweeney1972”).

It didn’t take long to discover that the VFD support arm was not connected to ground. Sure there were 4 bolts passing through the VFD mounting ears and into the support arm plate, but the VFD case is plastic.



I first drilled a hole in the ground cover of the VFD. Then all paint was removed around the hole. I also verified that there was no paint around the bottom left mounting hole.

The strap was run from this mounting hole to the VFD ground cover.

Testing

I took some strips of sheet metal about 5/8” wide and ran them from the VFD to the motor. The motor’s cable is nearby but not close enough for optimal induced noise suppression.

The strips of metal have far less inductance[7] than the safety ground which is good. But notice the distance between the cable and my metal strips. I have reduced the voltage on the motor housing with respect to the VFD’s safety ground but increased the area defined by the current path. It might have helped or hurt the system’s stability.

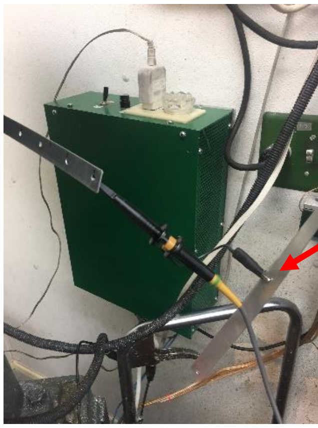
Well, it turned out to help. No more error that halts my program. However, we do not know how much margin exists. Clearly, we are not done yet.

This arrangement can tell us a bit about what is going on. For starters, it implies that radiated noise is the major component of what upsets the CNCPC. The strap lowers the voltage on the motor and mill which acts as a transmitting antenna. That strap does little to reduce induced current because it is not placed on the VFD to motor cable.

Using a digital oscilloscope, we can catch the peaks of spikes that cause trouble.

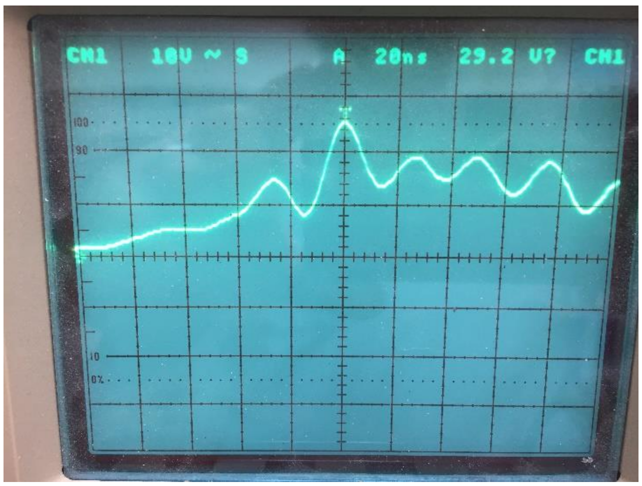
---

[7] At high frequencies, most of the current flows on the surface of a conductor. If you took a piece of solid copper 10 gage wire, it would have a lot of inductance. By flattening it to a 0.001” thick foil, the inductance would be dramatically lower because the surface would be so much bigger. Search for “Skin Effect” for more information.



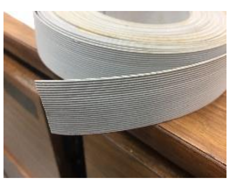
With the strap unbolted, I connected my oscilloscope probe's input to the strap going to one of the motor's mounting bolt.

The probe ground connected to the VFD's safety ground. This arrangement lets me see the voltage on the motor's enclosure and mill with respect to the VFD's ground.



The 'scope caught a positive spike of 25 volts. Realize that this is the voltage across 6 feet of 12 gage wire. If you were to measure the voltage drop at 60 Hz, it would be almost 0.

With the strap ends bolted together, the voltage between VFD ground and motor is essentially 0.

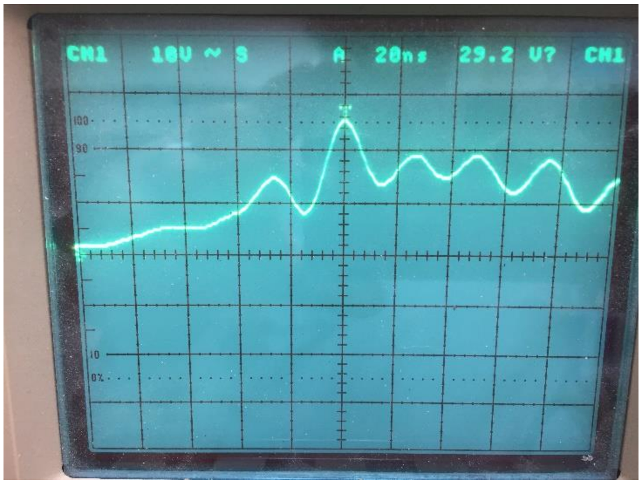


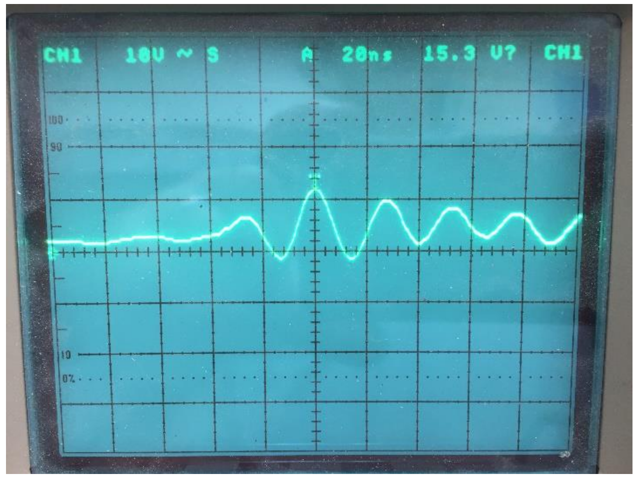
Next I took some very fine gage wire ribbon and soldered the ends to pieces of copper. The idea is that the ribbon will form Litz Wire[8] which has low inductance. Besides, at the moment I had this ribbon and don't have any copper braid.

The ribbon was clamped to VFD ground and dressed along the motor cable.

At the motor end I clamped the ribbon to a mounting bolt.

[8] See https://en.wikipedia.org/wiki/Litz_wire for details.





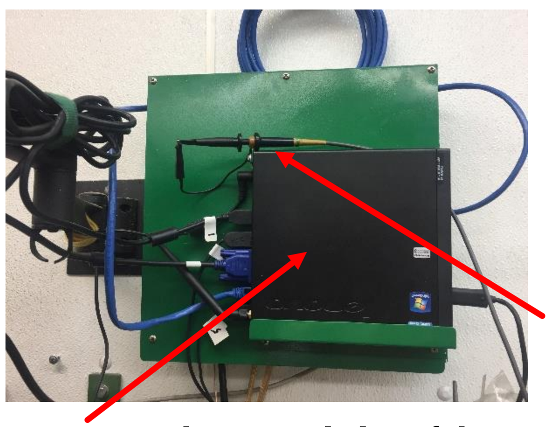
Without the ribbon: 25 volts.

With the ribbon: 12 volts.

So the ribbon reduced the radiated spike by half. I ran the program a few times without any problems. It should greatly reduce induced noise but I had no reliable way to measure it. No errors were recorded in the log.

This test demonstrates that adding a lower inductance connection between VFD and motor does reduce noise. It does not tell us how close we are to failure.

Testing the woven copper tubing turned out to be inconclusive. Sure, the CNC system was stable, but I found no way to measure how close we were from a failure.

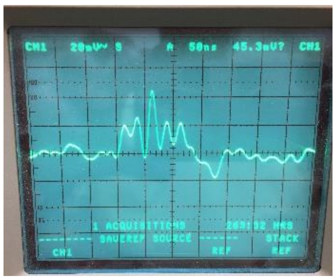


One attempt at measuring radiation at the CNC control complex was to place an oscilloscope probe on top of the CNCPC. The ground clip of the probe connected to the tip. This formed a loop antenna.

I then ran 4 cases:

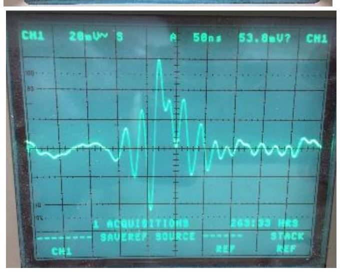
Just tubing grounded at both ends.

Peak is 40 mV.



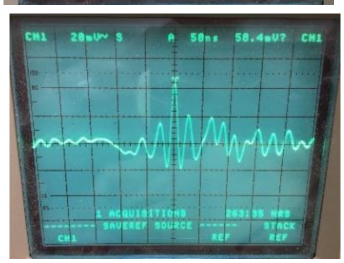
Tubing grounded at both ends plus strap.

Peak is 40 mV.



Tubing tied at VFD end only plus with strap.

Peak is 60 mV.



Tubing tied at VFD end only and no strap.

Peak is 50 mV.

I see no significant difference in peak voltage. Having just the tubing (first picture), gave the widest pulse which implies a lower peak frequency content (Thanks “eng199”). With one end of the tubing disconnected and no strap (last picture) gave the smallest pulse width which implies a higher peak frequency content.

In general, the higher the frequency, the more disruption is possible. However, I don’t see any dramatic results here.

Acknowledgements
Thanks to all on the Centroid forum for helping me figure this out.

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.

Rick Sparber
Rgsparber.ha@gmail.com
Rick.Sparber.org