Eddy Current Inspection of Steel Wire
(An Application Example)

Application Report AP240806

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Introduction and Objective

One of our customers sent us samples of 1.6mm diameter steel wire for evaluation. One sample, approximately 2ft long contained flaws of an unspecified nature (“Bad Wire”). The second sample, approximately 4 ft long was deemed good (“Good Wire”). The objective was to detect the flaws and provide an encircling coil for use in production testing.

I am also using this application as an example for our young application engineers.
One thing to keep in mind is terminology: In the world of “probes” the term “coil” refers to the windings of fine wire that form the internal sensor-coil; in the world of wire/tube/bar the term “coil” refers to a complete “encircling coil” consisting of the sensor-coil, the housing and connector.

Setup

The first step is to determine the frequency to use. Traditionally one uses encircling coils with a frequency range around 40 kHz for production testing of wires, tubes and bar-stock. Sometimes 100 kHz coils are used, depending on the material of the wire and the type of flaw to be detected. Typically, we use encircling coils of type U40-1 for larger diameter products, up to 40mm, or U20-2 coils for diameters up to 20mm. U20 types have smaller housings and are less costly.
For very small wires I have used U5 coils, for up to 5mm wires, and U3 coils for up to 3mm wires.
The U3 variant was created to inspect wire that ends up becoming connector pins. This application required relatively high frequencies, up to 2 MHz, to detect very small flaws.
U3 coils are broad-band and allow for a large frequency range.
Unfortunately, I did not have any U40, U20 or U5 encircling coils available at the diameter needed for the current application. But I did happen to have a U3 coil with an inner diameter of 0.065 inches (U3-060-BD, fig.1). Holder and Guides (fig. 2) are available but were not used in this application.

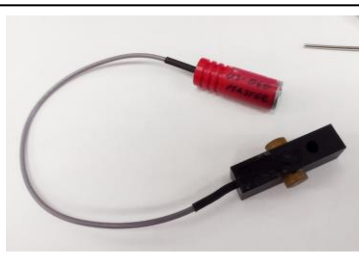

Fig. 1 Encircing coil U3-060-BD

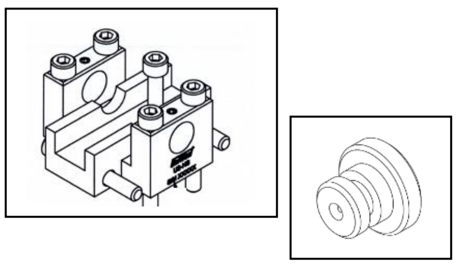

Fig. 2 U3 Coil Holder and Guide

The instrument I used was a UniWest EddyView PRO with cable 94032.

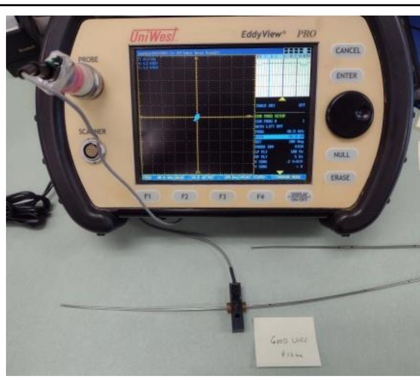

Fig. 3 Equipment Setup

Evaluation

In order to determine a “optimum” frequency I started with the traditional value of 40 kHz. Figures 4 and 5 show the setup and corresponding signal responses for the Good and Bad Wires at 40 kHz.

Why 40 kHz?
Wires often have inclusions such as small “beads” of iron (segregation) which are magnetic and show up as signal-spikes. Wires also can have small pores (rare) or slag (oxides). Slag most often gets stretched out during the drawing process of the wire into long “stringers”, which show up as increased signal noise rather than spikes.

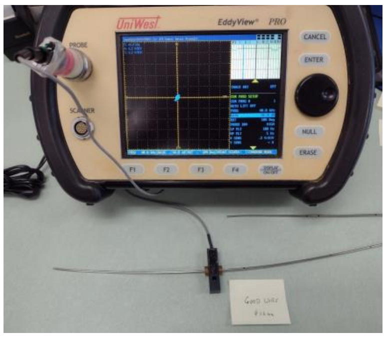

Fig. 4a Good Wire

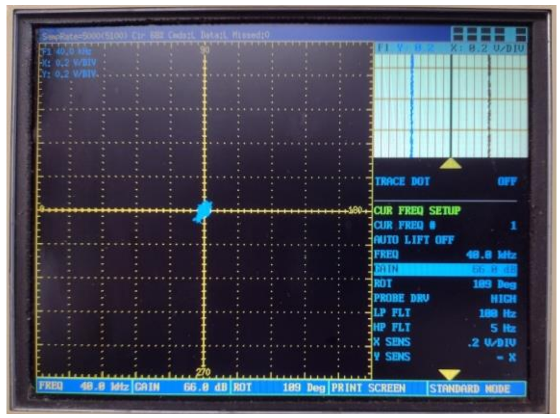

Fig. 4b Signal response at 40 kHz. Good Wire

Fig. 5a Bad Wire

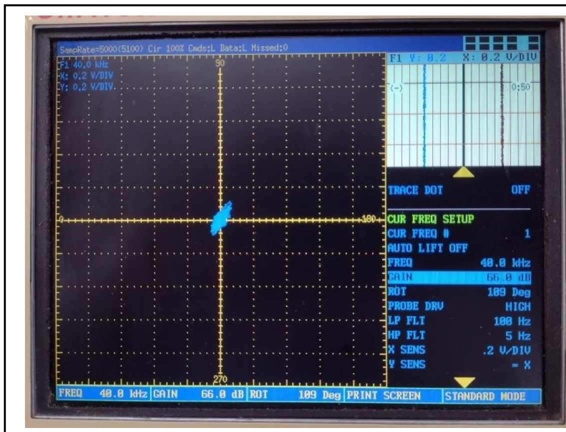

Fig. 5b Signal response at 40 kHz, Bad Wire

There does not seem to be a distinctive difference in the responses at this frequency, which tells me that the flaws are not internal.

I then repeated the test at frequencies 100 kHz, 250 kHz and then 500 kHz, slowly reducing the depth of penetration of the eddy currents to concentrate them more towards the surface of the wire.

Figures 6 and 7 show the setup and corresponding signal responses for the Good and Bad Wire at 500 kHz at different locations along the wire.

Fig. 6a Good Wire

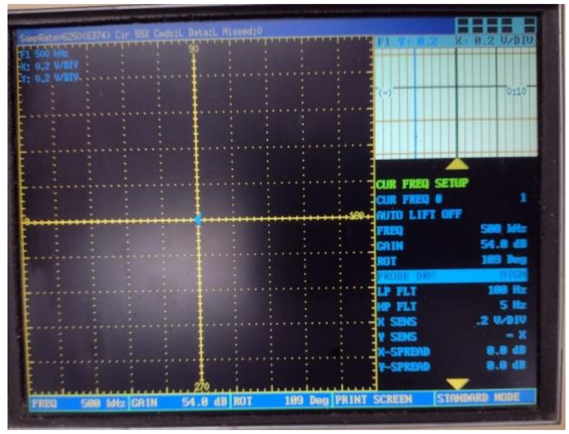

Fig. 6b Signal response at 500 kHz. Good Wire

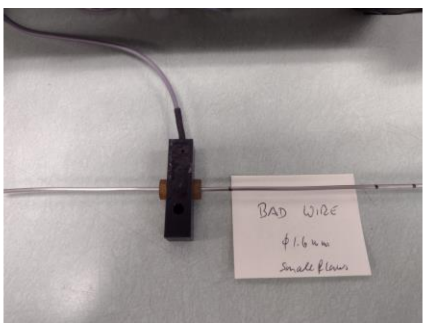

Fig. 7a Bad Wire

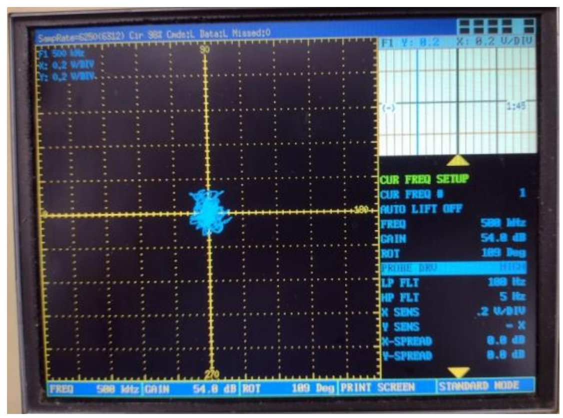

Fig. 7b Signal response at 500 kHz, Bad Wire

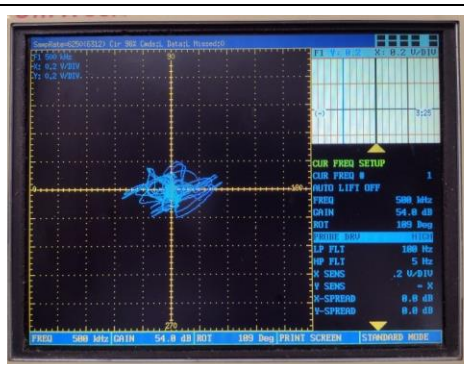

Fig. 7c Signal response at 500 kHz, Bad Wire

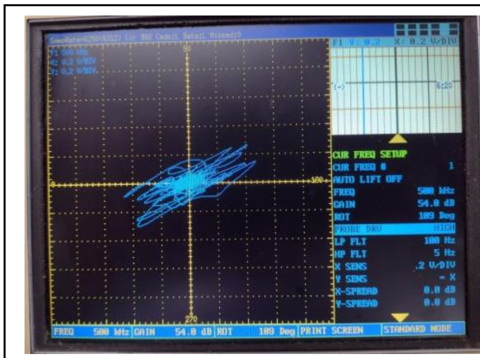

Fig. 7d Signal response at 500 kHz, Bad Wire

As I moved the wire through the encircling coil, I observed several different “indications” (figures 7b to 7d) that must be near or at the surface.

Visual examination showed the presence of many flaws at the surface of the Bad Wire. These are oriented along the length of the wire, circumferentially at the same location. I selected 3 areas, “small flaws”, “medium flaws” and “large flaws” (figures 8, 9 and 10). They appear to be something called “pitting”. There are many causes of pitting, one of which can be a loss of lubrication on a draw-die or pinch-roller when the wire is drawn down in diameter from a larger wire or bar. When that happens, the die can peal material off the surface of the wire. If a die is damaged, the flaws are long, even cuts along the length of the wire. If a pinch-roller is damaged, the flaws occur at fixed distances matching the diameter of the roller. These flaws are not regular and have different diameters and depths.


Fig. 8a Bad Wire, “small flaws”

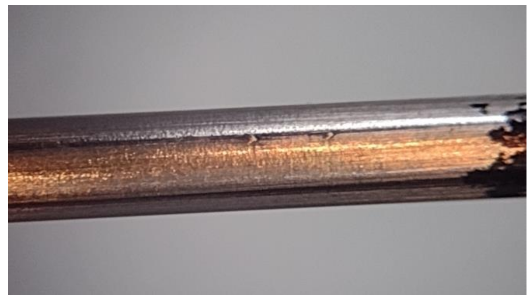
Fig. 8b Bad Wire, “small flaws”, detail

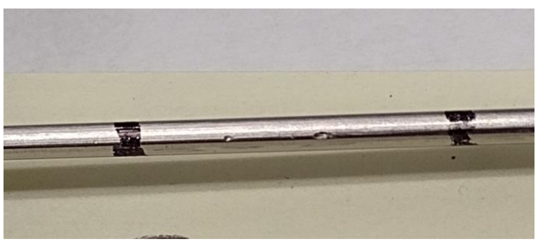
Fig. 9a Bad Wire, “medium flaws”

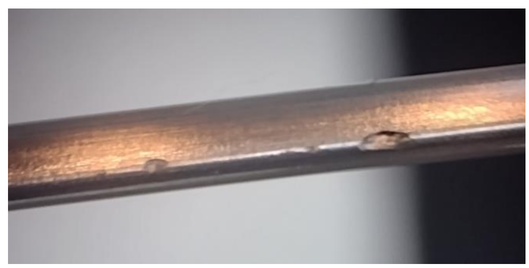
Fig. 9b Bad Wire, “medium flaws”, detail

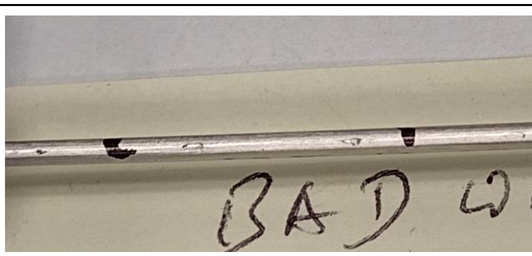

Fig. 10a Bad Wire, “large flaws”


Fig. 10b Bad Wire, “large flaws”, detail

Since the flaws are “near surface” I tried 1 MHz and 2 MHz to see if the signal responses would increase.

Let's look at the responses at 1 MHz in more detail.

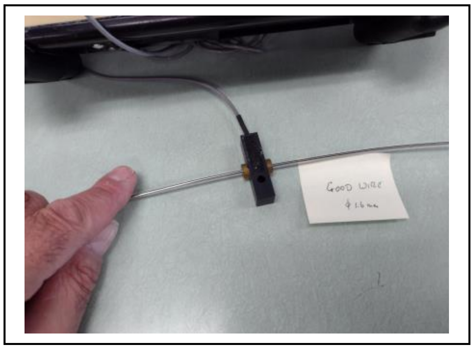

Fig. 11a Good Wire

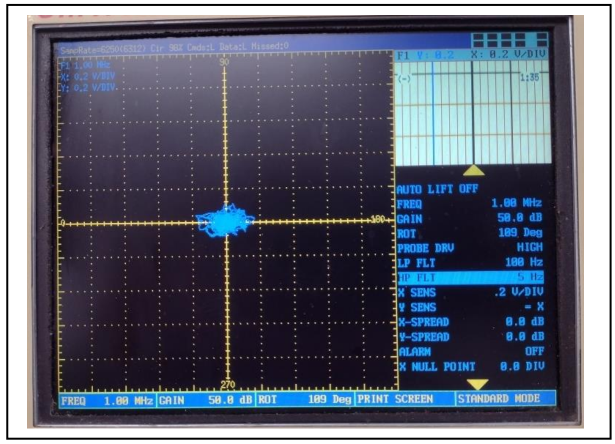

Fig. 11b Signal response at 1 MHz, Good Wire

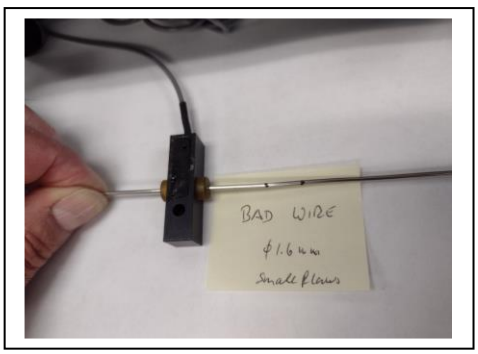

Fig. 12a Bad Wire, small flaws

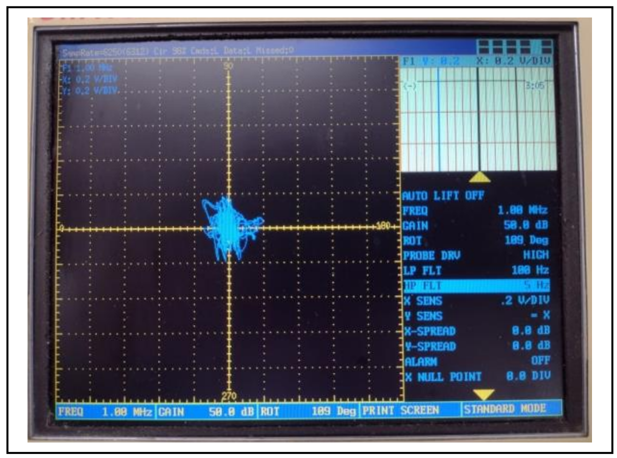

Fig. 12b Signal response at 1 MHz, small flaws

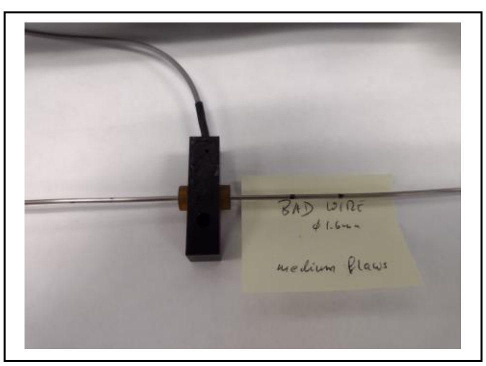

Fig. 13a Bad Wire, medium flaws

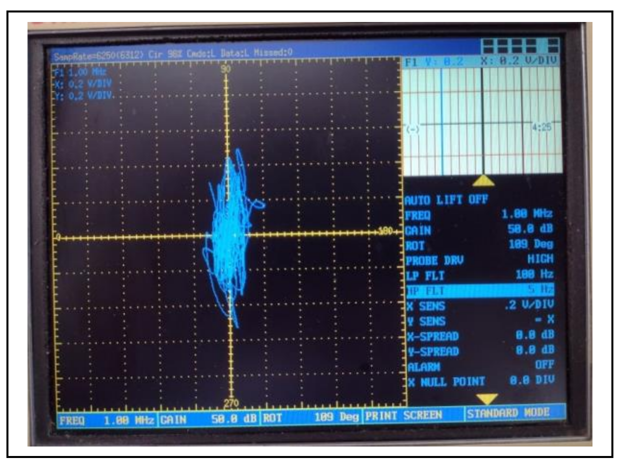

Fig. 13b Signal response at 1 MHz, medium flaws

Fig. 14a Bad Wire, large flaws

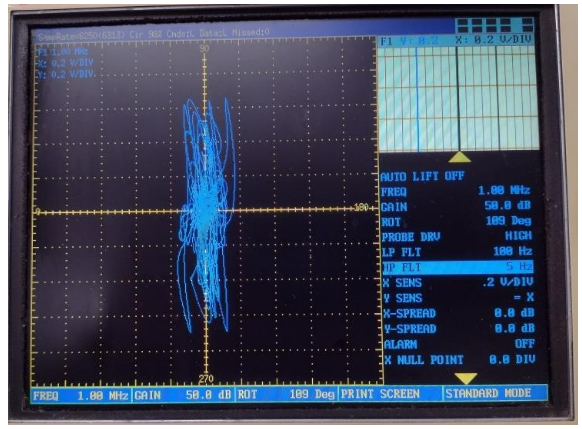

Fig. 14b Signal response at 1 MHz, large flaws

At 1 MHz we can clearly detect the flaws at the surface and see a difference in their size.
Would 2 MHz be more sensitive? The answer is yes (the signal amplitude almost doubles).

But there is a problem we need to consider: Vibration of the wire during production.
As the wire is manufactured, motors pull it down the production line. And spinning motors cause vibration, i.e. a slight shaking of the wire as it passes through the encircling coil.
This produces motion noise. One can simulate this by tapping the wire while in the coil. The signal response is shown in figure 15b.

Fig. 15a Good Wire, vibration

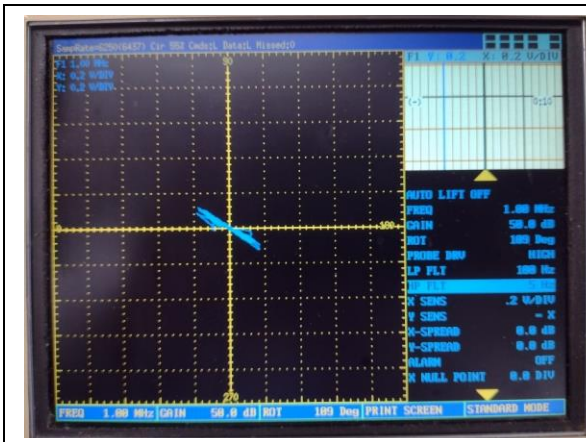

Fig. 15b Signal response at 1 MHz, vibration

Note that there is a difference between the phase angle of the vibration (fig. 15b) and the orientation of the signals from larger flaws (figures 12b and 13b).

Eventually we want to set the instrument to generate an alarm when it encounters flaws. We can set alarm gates in the shape of circles, rectangles, horizontal lines etc. I usually use circle gates or horizontal lines, in this case I'll choose horizontal lines and set vibration noise horizontal so that vibration does not trigger the alarm output. Figure 16 show the vibration signal rotated horizontally.

Fig. 16a Good Wire, vibration

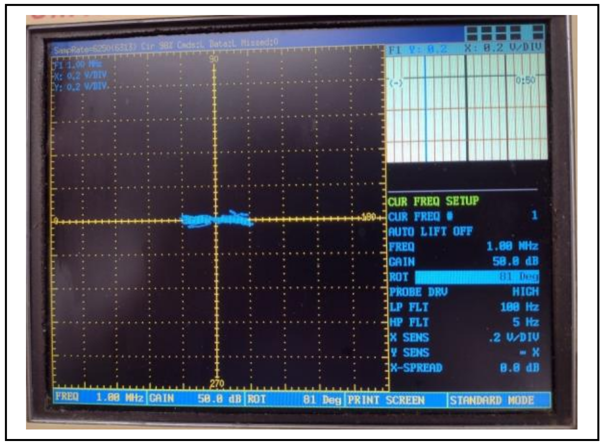

Fig. 16b Signal response from vibration

The next step is to scan the Good Wire and the small flaws in the Bad Wire and set the alarm gates. I will be looking at the strip-chart display to do that (figures 17 and 18). And estimate the threshold to be somewhere around 0.15V

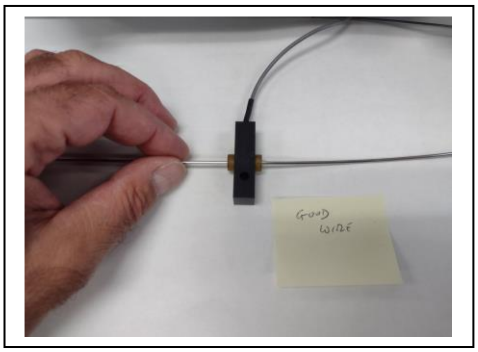

Fig. 17a Good Wire, motion

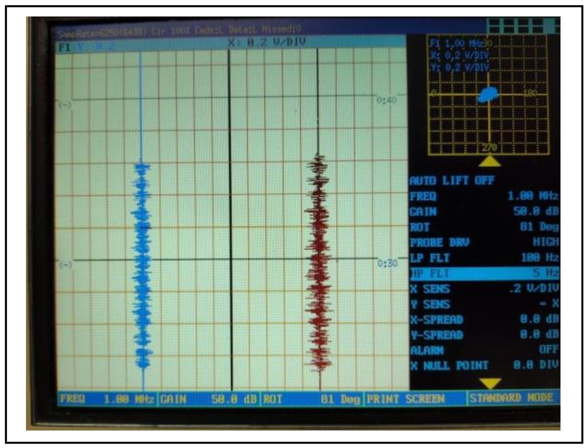

Fig. 17b Signal response from Good Wire

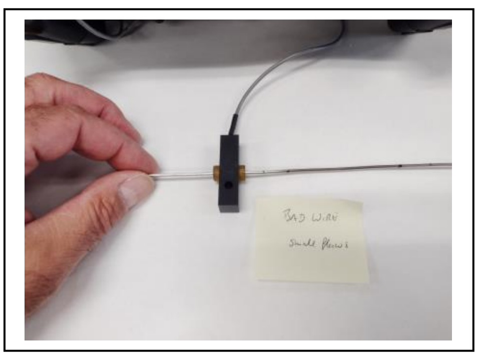

Fig. 18a Bad Wire, small flaws

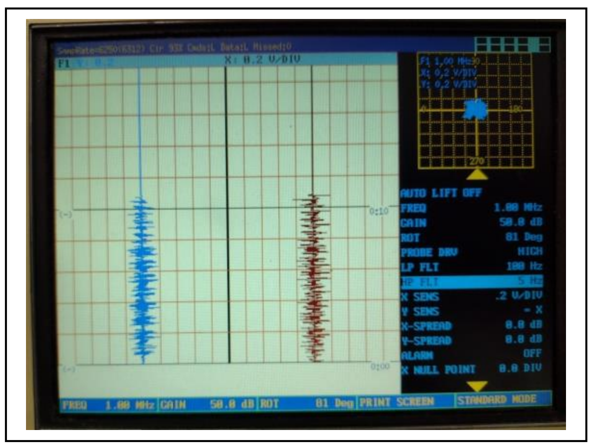

Fig. 18b Signal response small flaws

Enter the alarm setup (fig. 19), set the Alarm type to “Y-only” and adjust the threshold while moving the Good Wire through the coil. Objective: No alarm on Good Wire. Then feed the small flaws through and make sure they trigger the alarm. The check both again (figures 20 and 21).

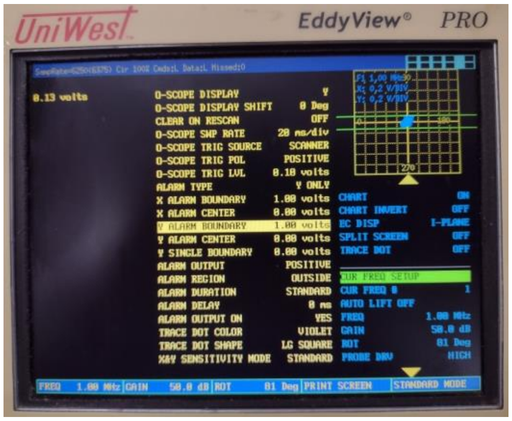

Fig. 19 Setting up the alarm

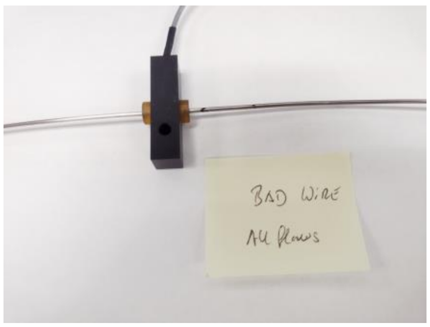

Fig. 20a Bad Wire, all flaws

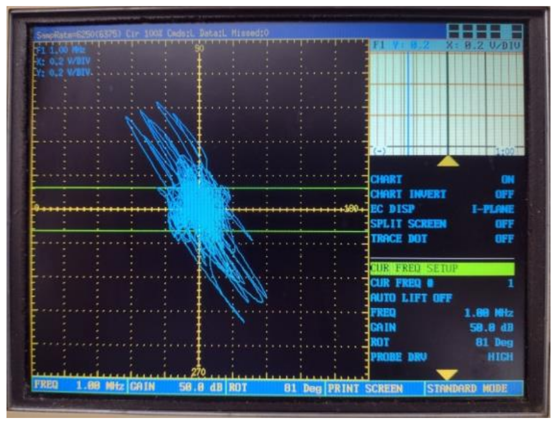

Fig. 20b Signal response Bad Wire with alarm

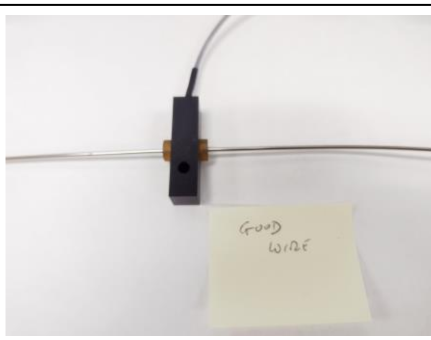

Fig. 21a Good Wire

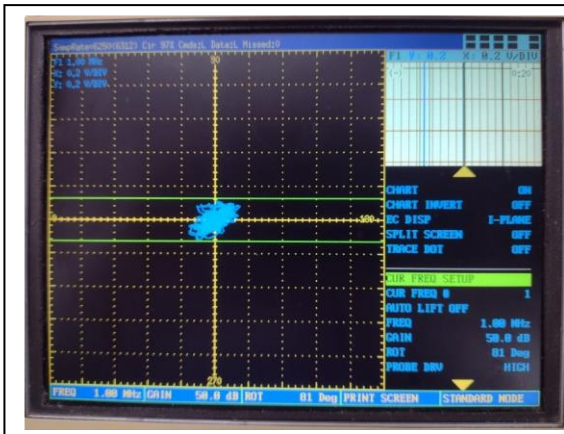

Fig. 21b Signal response Good Wire with no alarm

Results

We can successfully detect the flaws in the Bad Wire".
Why did I not choose 2 MHz since it gives larger flaw responses? Because the vibration noise is significantly larger and can mask flaw indications.

Normally my report would end here, but there is more to the story..
What are the next steps?

The Next Steps

STEP 1

While the above encircling coil was able to detect the flaws, we can not put it into a production line.
The reason is the coil diameter.
An encircling coil with an inner diameter of 0.065 inch (1.65 mm) would not survive very long since flaws of the type above have burrs that will cut the coil. Normally one would like at least 0.020 inch (0.5mm) of space, i.e. an encircling coil with 0.080 to 0.085 inch (2.0 to 2.1 mm) would be the smallest diameter to use.
But we have not accounted for the tolerance of the wire's diameter, nor the accuracy of the centering of the wire in the production line, both of which are "unknowns" at this time. And thus, I have a bit of a dilemma: Use a standard 2.0 mm diameter encircling coil or use the next standard size up, a 2.5 mm coil. If I increase the coil diameter too much, I lose sensitivity (the drop off is approximately exponential). So, let's use a 2.0 mm encircling coil.
The next question is what type of coil configuration (reflection vs bridge), what type of housing and what type of connection. If the customer already has coils of type U20 we might want to consider using the same housing type and build a high-frequency version (200kHz-2MHz) e.g. U20-2HF-2.0. If U40 coils and guides are already in use, we would build a U40 coil version.
Unless the guidance of the wire is very good, I would not recommend a U3 or U5 version since their housings are smaller and not as impact or drag-resistant if the wire starts dragging at the coil.
Let's say we have the type of coil defined and built and are ready to install it. What's next?

STEP 2

The next step would be to make a "wire master".
Take approximately 2 ft (.75m) of Good Wire and place a EDM notch near the center, of the size you will need to detect, for example 0.080 (2mm) inch long and 0.020 inch (0.5mm) deep [rule of thumb: Depth is 30% of diameter of the wire, length is about 4xDepth]. Alternatively, you can drill a small hole 0.020 inch diameter, 0.020 inches deep [holes are easier to detect than EDM notches]. This is not critical since the master will be used as a go/no-go gauge to set the filters in the production line.
Feed the master wire through the coil and make sure the notch or drill-hole triggers the alarm (this is only a test of the alarm-output).

STEP 3

Go to the production line and observe the speed of the wire. The encircling coil with holder should be about 6-10 ft from the last draw-die, and just before the spooler [this is where the wire gets wound onto drums for shipment]. At this point pinch-rollers should be located before and after the encircling coil holder to make sure the wire will be centered in the encircling coil [Holders have guides on either side, but the guides should serve only as "final protection" to prevent damage to the encircling coil].

Note: In some production facilities the eddy current test is not performed in the draw-line because the wire comes out too hot and can melt the encircling coil. Instead, the wire is spooled and once it has cooled it will be moved to a re-spooler for testing.

For the next steps make sure the alarm output to the production line is disconnected [normally the alarm output from the eddy current instrument is connected to a relay or PLC in the production line and goes from there to a paint-marker to mark faulty wire or it shuts down the production line so that faulty wire can be cut out. And you do not want the paint-sprayer to keep dumping paint on everything].

The task on the production line is to set the High-Pass (HP) and Low-Pass filters of the instrument to accommodate the line-speed.
Let’s say the speed is 10 inches/sec which computes to 50 ft/min. We can look at filter-vs-speed charts or do a bit of math and come up with initial settings of HP=10 Hz and LP=250 Hz, almost like the settings I used in the Evaluation Section above.
Set the values on the instrument to HP=10Hz and LP=300 Hz and we’ll fine-tune the settings later.
Feed the master-wire through the encircling coil at about the same speed, observe the signal from the good section of wire to make sure it does not trigger the alarm and make sure the notch or drill-hole triggers the alarm.

Once set up, cut a 2ft section of the wire after the last draw die and run it by hand through the coil. If the wire is “good wire” it should not trigger the alarm. If it does, increase the alarm threshold just a little bit.

Next, start the line. Observe the signal on the instrument as the wires moves through the coil. Good wire should not trigger the alarm output. If it does, increase the HP filter a little bit (in our case at most to HP=15) to reduce the effect of vibration from the production line. If there is a lot of wobble/low-frequency noise, reduce the LP filter a bit.
Observe the signal on the instrument for a while longer. Adjust the alarm threshold to just above the noise-level (assuming the wire going through the coil is “good”)

Now enable the alarm output on the relay or PLC, i.e. activate the paint marker or line-stop.
Common practice is now to stop the line, use a file and create a small cut in the wire several feet before it reaches the coil. Then start the line again and make sure the cut is detected and triggers the alarm which then activates the paint-marker or stops the line so that the file-mark can be cut out.
How deep of a cut is needed? This is a bit arbitrary and takes some practice, but an old rule of thumb was to make it about 0.01 inch (0.2mm) deep.

That’s about it.

Final Remarks

The first thing to keep in mind is that we are using a high-frequency encircling coil. In steel the depth-of-penetration value at 1 MHz is about 0.022 inches (0.54 mm). At this depth the eddy currents have lost about 37% of their intensity. Which means that we are not very sensitive to flaws at the center of our 1.6mm wire.
At the standard 40 kHz we would have a depth-of-penetration of about 0.11 inch (2.7mm), i.e. full coverage of the wire, but lower sensitivity to small flaws. At 120 kHz its about 0.062 inch (1.6mm).
What to do? We probably would need to have two separate coils, one standard and one HF. Or try to run the HF coil at two frequencies if the instrument can sample fast enough for the line-speed.

The second thing to keep in mind is that eddy currents are a bit like magic. There are a lot of factors that affect the eddy currents. Some examples:

- Material of the wire: All factors that affect electrical conductivity, such as alloy composition, hardness, grain-structure and grain-orientation (affect conductivity and contribute to signal response noise). And these can change from production lot to production lot.

- Condition of the wire: Surface condition (affects signal noise), surface geometry (affects effective liftoff and hence sensitivity).
- Eddy current coil: Sensor coil characteristics (absolute vs differential etc.); coil diameter (sensitivity decreases if the coil is too large relative to the diameter of the wire).
- Eddy current instrument: Frequency, high-pass (HP) and low-pass (LP) filter settings, drive-voltage (affects sensitivity), response characteristics of the drive and receiver circuitry.
- The production line: Motion-stability (affects signal noise); drive-motors can generate interference. Guidance and centering of the wire in the line (vibration causes signal noise which can mask flaw indications).
- External frequency generators: High-power factory lights, motors, proximity of other test equipment, radios, TVs, etc. (all can cause noise in the signal responses).

Therefore, we will miss some flaws, and the question will be whether these are detrimental to the product made out of the wire or not.
And we will reject some good wire, but hopefully not too much.

Clearly this discourse has gone beyond the “Evaluation of the 1.6mm Steel Wire”. It summarizes some of my experiences with the wire, tube and bar manufacturing industries.
And I hope it helps current and future NDT technicians that face the task of building coils for wire testing, or are tasked with inspecting wires.

Kennewick WA, USA, 8. August 2024