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High-Precision Internal Diameter Measurements Using Eddy Current Arrays

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Abstract

Tubular components subjected to extreme pressure and intense wear, requiring high-precision internal-diameter measurements, were investigated. Such measurements are currently carried out using slow mechanical devices and/or costly laboratory equipment.

This paper describes the development process of a new measurement tool, capable of +/- 0.015mm diameter evaluation, using state-of-the-art eddy current array technology. In addition to high precision sizing, the test method provides traceability, 360deg coverage and robust probes adapted to most harsh environments.

Many aspects of the development are presented in this paper: eddy current coil design, mechanical probe design and implementation on commercially available Eddy Current Array NDT equipment. The various steps to obtain an operational system will be discussed: first prototypes and basic concepts, experimental results and challenges, probe improvements and evaluation of the final probe precision.

Keywords: Diameter, measurements, eddy current arrays

1. Background

Barrels (such as mortars tubes) have traditionally been inspected using mechanical gauges. These gauges do have a lot of limitations: inspection is time consuming, accuracy is operator dependent, measurement of the tube over 360 deg is not possible and traceability is limited.

Some products have been developed to improve the inspection accuracy, but these solutions are not adapted to field conditions. An advanced demonstration model has been built to encompass all requirements including field conditions:

- High Precision diameter measurement
- Robust / portable equipment for field use
- Mapping of the tube wear over 360degrees
- Possibility of storing data for further analysis
- Possibility of detecting surface defects would be an asset

For this application, Eddy Current has been selected over other possible solutions (UT testing, Optical measurement, etc) because it can lead to a very robust system (thus adaptable to the field conditions). The drawback to eddy current is that diameter measurement isn't as straightforward as for other methods. This paper will describe the various design steps we have been through to obtain reliable eddy current diameter measurements.

2. Design choices and basic concepts

To satisfy the requirements on tube wear mapping, Eddy Current Array has been preferred over conventional Eddy Current. Eddy Current Array also provides the capability to map the tubes for defects.

Early in the design process, we had to consider how to accurately convert a sensing coil for tube wall distance into a precise diameter measurement. While this may seem very straightforward at first, that very basic condition had a huge impact on the probe design.

We soon established that the target accuracy, plus the need for a very robust solution, would make it very difficult to build a probe covering a range of diameters. It was then decided to build a probe that would scan a specific diameter (for example, the 81mm probe will only be used for the 81mm tube).

Another problem is probe centering. Keeping the probe in the tube centerline would require very precise and rather complex mechanics if we require this probe to measure the tube radius on 360deg (see figure 1). On the other hand, it is quite simple to maintain the probe centered in the tube's diameter such that the probe center will always be in the center of the tube (see figure 2). Such an inspection allows diameter measurement over 360deg, but will not generate radius measurement. To maintain a robust design, and because the diameter (not the radius) is the important parameter to measure, this last solution has been selected.

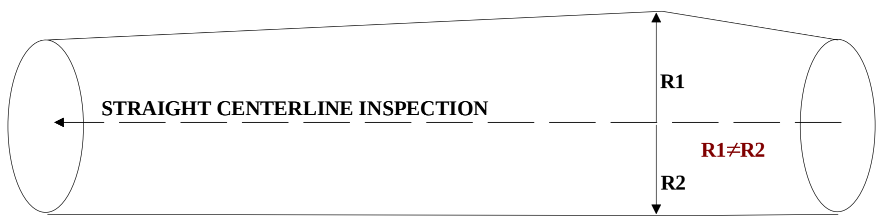

Figure 1. Straight centerline probe scan configuration

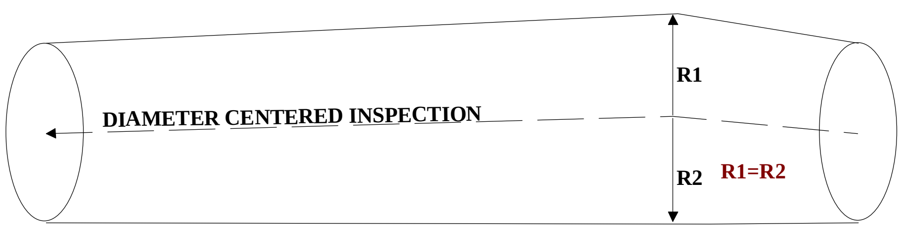

Figure 2. Diameter centered inspection.

Figure 3 shows the prototype probe mechanical design. Two sets of centering wheels take care of probe centering. Two separate probe rings have been built to evaluate the best possible coil location. Early results with the probe have shown a more stable response using coil ring#1; this coil location was thus selected.

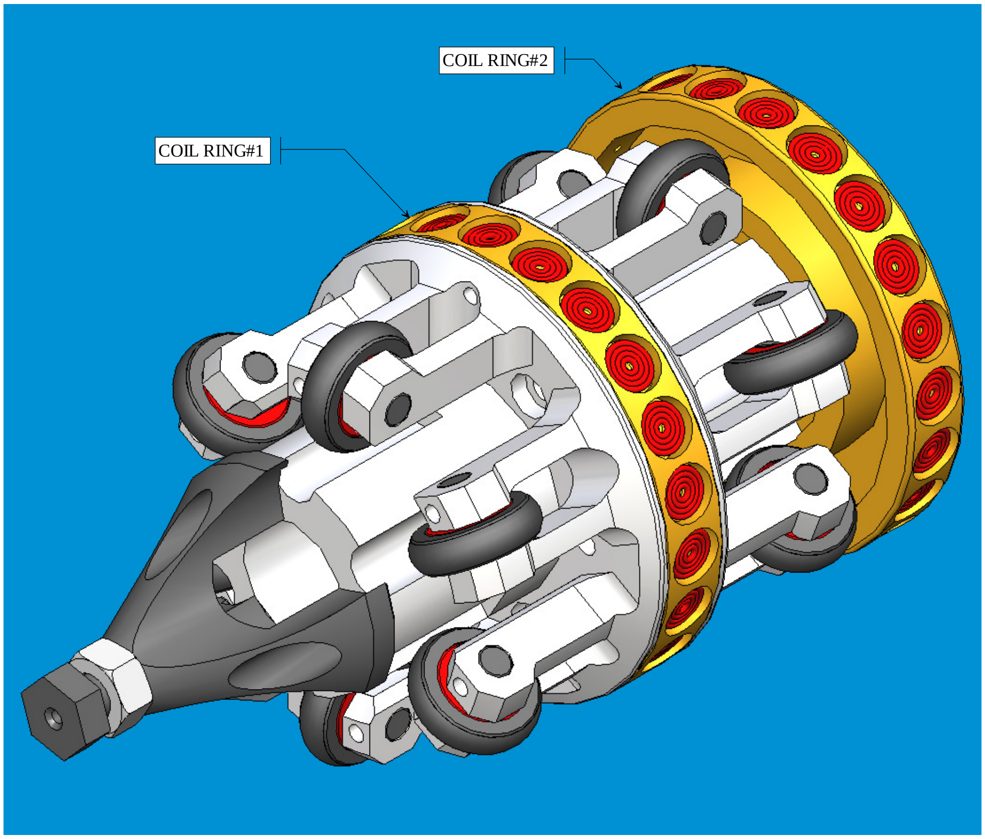

Figure 3 : Prototype probe schematics

An interesting side effect of the selected diameter measurement method is vibration and centering error noise removal. By adding measurement from opposite eddy current sensors, the exact position of the probe in the tube is not so important. To illustrate this, consider the array probe cross section shown on figure 4 where three sets of coils have been detailed. The tube diameter for each set of coils is given by equation 1, which is independant of probe position in the tube.

Tube diameter = probe diameter + coil#1 reading + coil#2 reading
Reading is the coil to tube wall distance measurement
Equation 1. Tube diameter measurement from coil readings

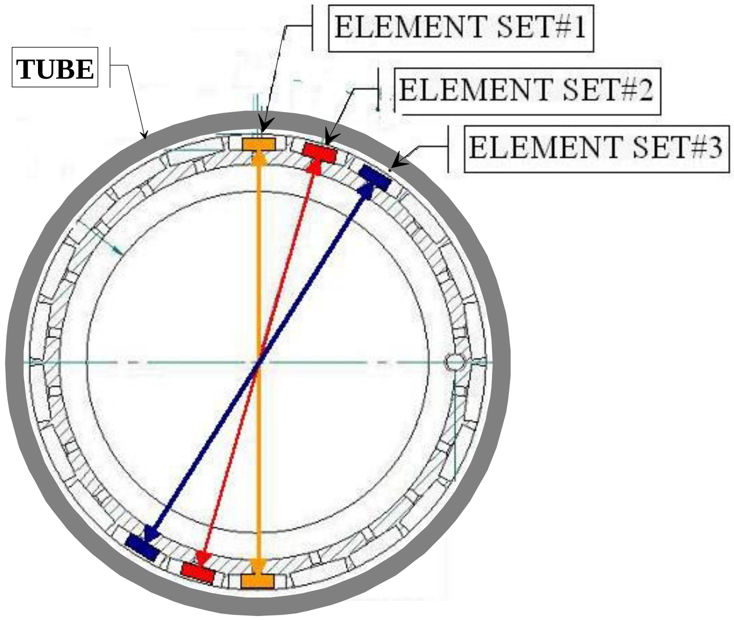

Figure 4. Set of opposite coils reading tube diameter

This “noise reduction” phenomenon has been demonstrated experimentally by directly adding the eddy current readings of opposite eddy current coils. The picture below illustrates the results:

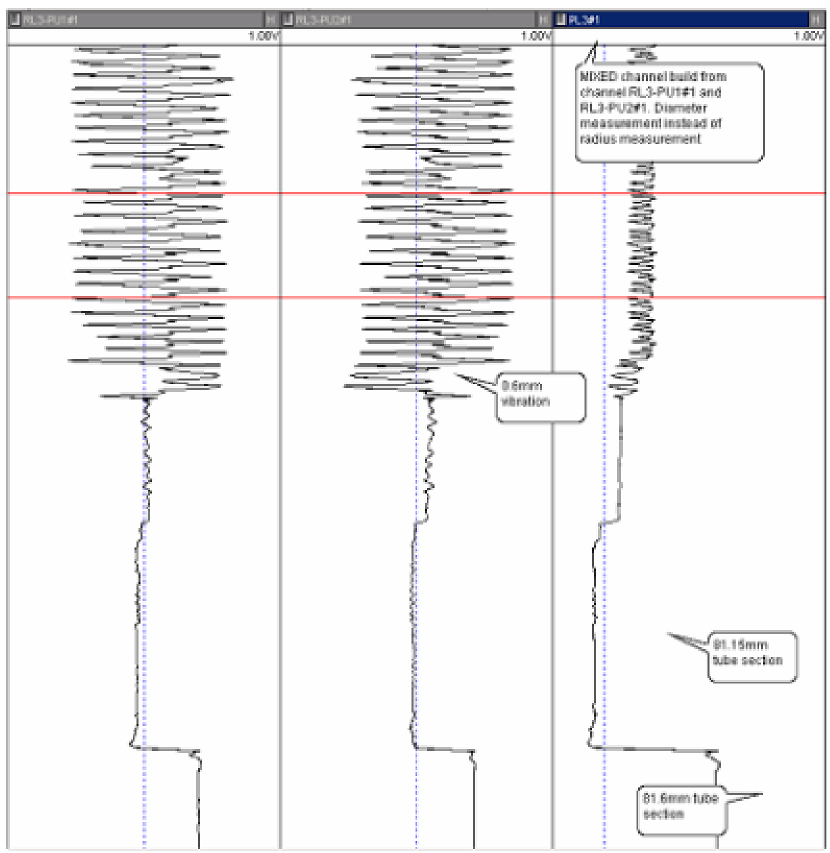

Figure 5. Noise reduction example; right strip chart is obtained by adding coil readings

Vibration noise is reduced by 16dB, diameter measurement signal is increased by 6dB.

3. Coil design

The coils have been designed to increase the influence of lift off variation versus other parameters such as temperature and metallurgical changes.

To reduce the influence of temperature, a transmit–receive configuration has been selected [1]. The use of opposite coil mixing also helps to further reduce the temperature drifts.

To improve the coil response on lift-off, coils have been integrated in a ferromagnetic housing. The test part being ferromagnetic as well, a lift off variation will directly change the magnetic coupling between the probe and the tube leading to a strong response.

To reduce the impact of metallurgical variation on reading, we have tested 3 different coils for alloy sensitivity. Take note that for each of those readings, the gains have been set to have the same lift off sensitivity.

- Coil#1 optimized for 1 kHz
- Coil#2 optimized for 400 kHz
- Coil#3 optimized for 1000 kHz

We have measured the operation points on 3 different alloys, the results are shown in figure 6 for each of them. Green is steel alloy#1; red is steel alloy#2(cold rolled); blue is steel alloy#3(hot rolled).

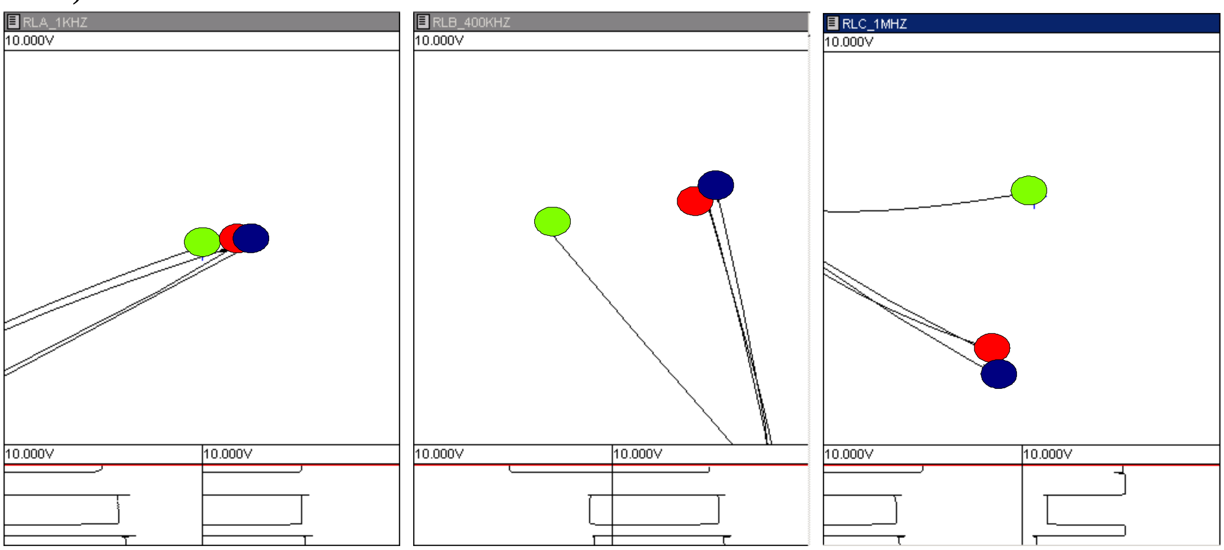

Figure 6 : Operation points with 3 different alloys on coil#1 (1kHz); coil#2 (400kHz) ; coil#3 (1MHz)

The reduction of the variation due to alloy type will prevent the system to be sensitive to the metallurgical composition of the tubes. So, we are searching for the smallest difference between the measurements on these three sample parts.

We can easily conclude from these results that coil#1 is less sensitive to the steel alloy and cold work (similar to wear) than coil#2 and coil#3. This coil has been selected.

To ensure a precise measurement on the complete probe array, each coil of the array needs to be set to the exact same level of sensitivity (so that a specific Volt reading converts to the same mm reading for all coils of the array). This is achieved by automatically setting the gain and phase angle of the coil on a precisely machined test piece. The probe's coils are first balanced on the 81.15mm section; the 81.15mm -> 81.6mm transition is then set to 0.45V @ 0 degrees on the impedance plane.

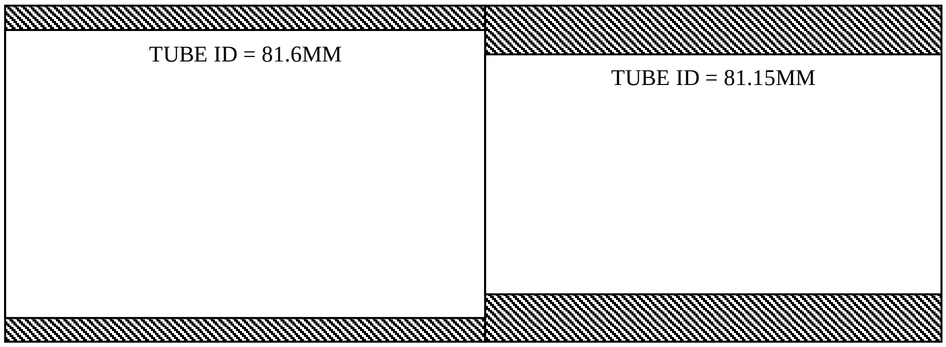

Figure 7 : Calibration tube

To convert the probe's reading from Volts to mm, a conversion chart has been established (horizontal amplitude in volt to diameter reading in mm).

4. Experimental results on test tubes

Five test tubes with various level of wear have been tested with the prototype probe to measure the accuracy of the test method. The readings have been compared to the measurements from existing lab equipment. The lab equipment is not capable of 360 deg inspection so only the measurements at the same angles were analyzed (referred as Vertical and Horizontal on the graphs). Figures 8 and 9 are examples of the results obtained.

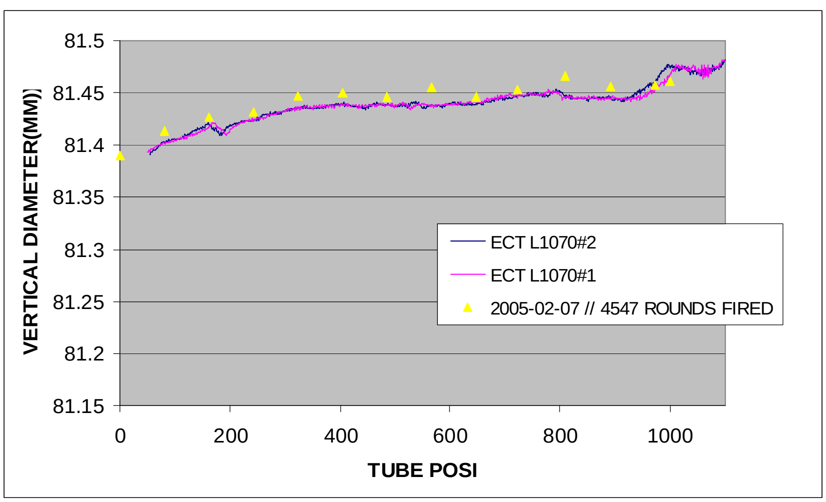

Figure 8 : Field test on real tube, Vertical measurement

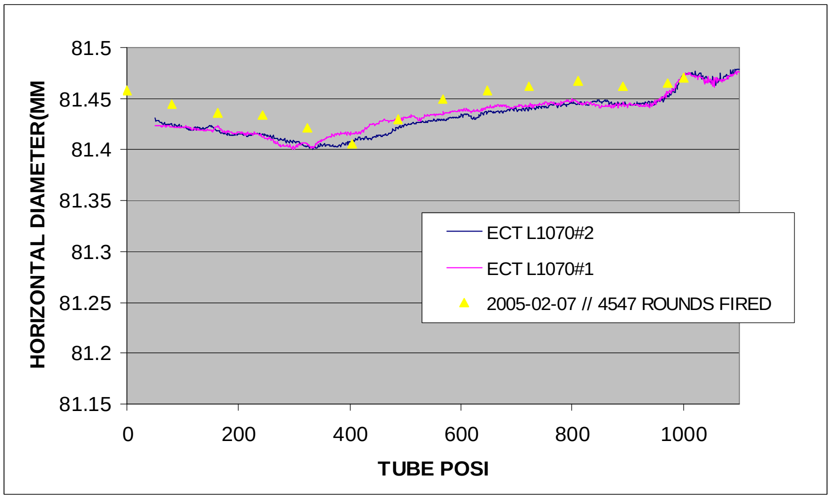

Figure 9 : Field test on real tube, Horizontal measurement

Analysis of the data from the five tubes, compared to both the horizontal and vertical readings from the lab measurement device, lead us to approximate the probe's precision to +/- 0.015mm

5. Conclusions

The feasibility of a precise, robust, portable and fast tube ID measurement device has been demonstrated during this project. The prototype probe uses Eddy Current Array technology to map the tube's wear over 360deg with a +/-0.015mm precision. Eddy current technology should also make possible the detection of some surface defects. Data traceability should be no problem with modern Eddy Current Array electronics such as the Olympus NDT OmniScan ECA. In addition, there is the possibility of detecting surface defects.

References

[1] National standard of Canada, Advanced Manual For: Eddy Current Test Method, CAN/CGSB-48.14-M86, Canadian General Standard Board, p. 41