Eddy-Current Signal Processing Applied to Aircraft Fuel Tubes Maintenance

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Air Transat Flight TSC 236

- August 24th, 2001, evening.
- North Atlantic Ocean, Azores Islands.
- FL 350, Airbus A330-243.
- FR Toronto (YYZ) TO Lisbon (ZYD).

Air Transat Flight TSC 236

- Actually FR Toronto TO Azores...

Airbus A330 - Engine Number 2

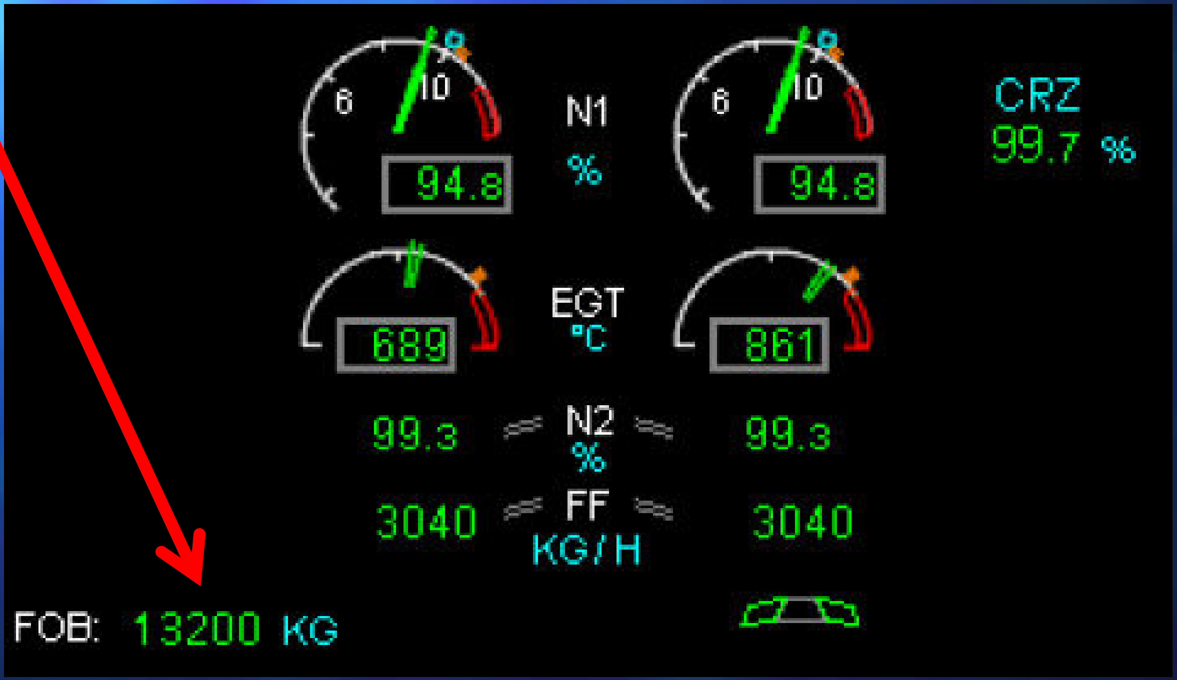
- Intriguing oil parameters:
  - Low oil temperature.
  - High oil pressure.
  - Low volume in the oil reservoir.

	ENGINE Nr 1	ENGINE Nr 2
OIL TEMPERATURE	110^{o}C	65^{o}C
OIL PRESSURE	80 psi	150 psi
OIL QUANTITY	17 liters	14 liters

Rolls Royce RB 211 Trent 772B

Airbus A330 Engines

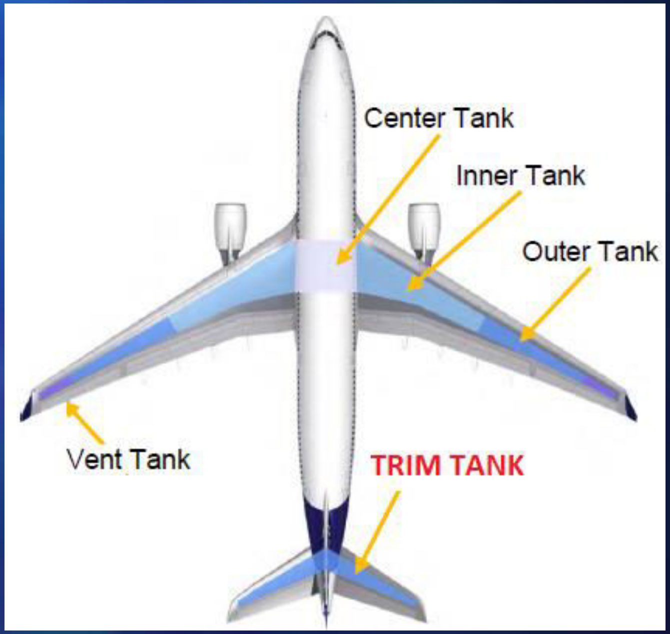
- ✈ Normal engines parameters, but...
- ✈ Inexplicable low FOB (Fuel on Board) quantity readings.



E / WD Screen

- ✈ In addition, the following message illuminate in the E / WD (Engine Warning Display):

- ✈ which means: "Trim Tank Empty"



The Azores Glider

- At 06:13 pm of that day the engine number 2 flamed out.
- 13 minutes later, the left engine flamed out too.
- With no fuel, 65 nautical miles away from Lajes Airport, Terceira Island, Azores and at 34,500 ft altitude, the ~ 160 tons aircraft became an immense glider.

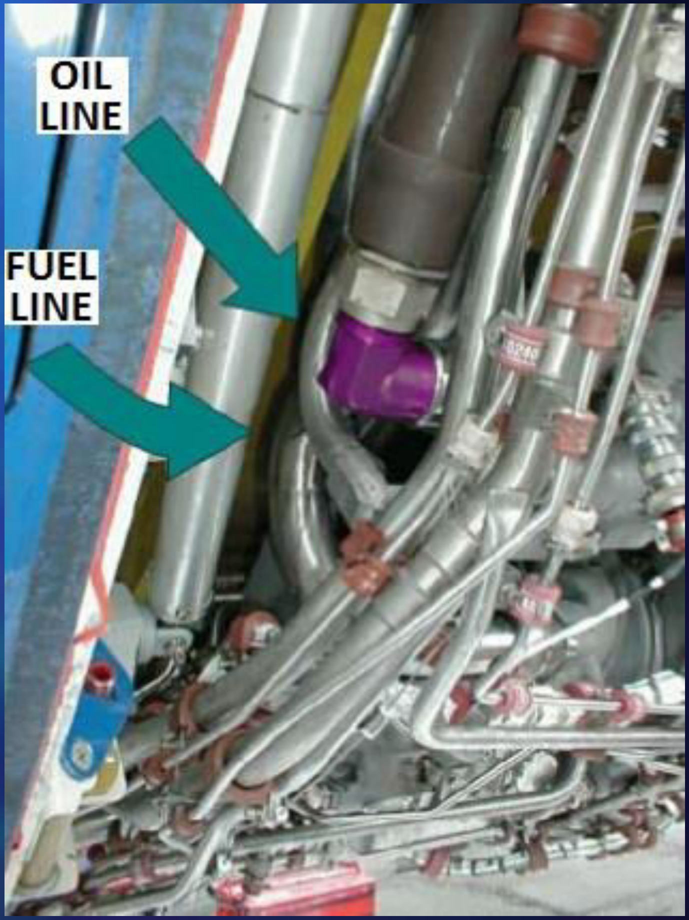
Lajes Airport Approach

Azores Glider Landing

- ✈ Despite small fires in the landing gear and minor structural damage, the emergency landing was ok at RWY 33.
- ✈ However, eighteen people suffered injuries during the emergency evacuation.

Accident Investigation

✈ Investigators found that the strange parameters of engine Nr 2 were caused by a fuel leak through a crack in the fuel line downstream of the fuel-oil heat exchanger.



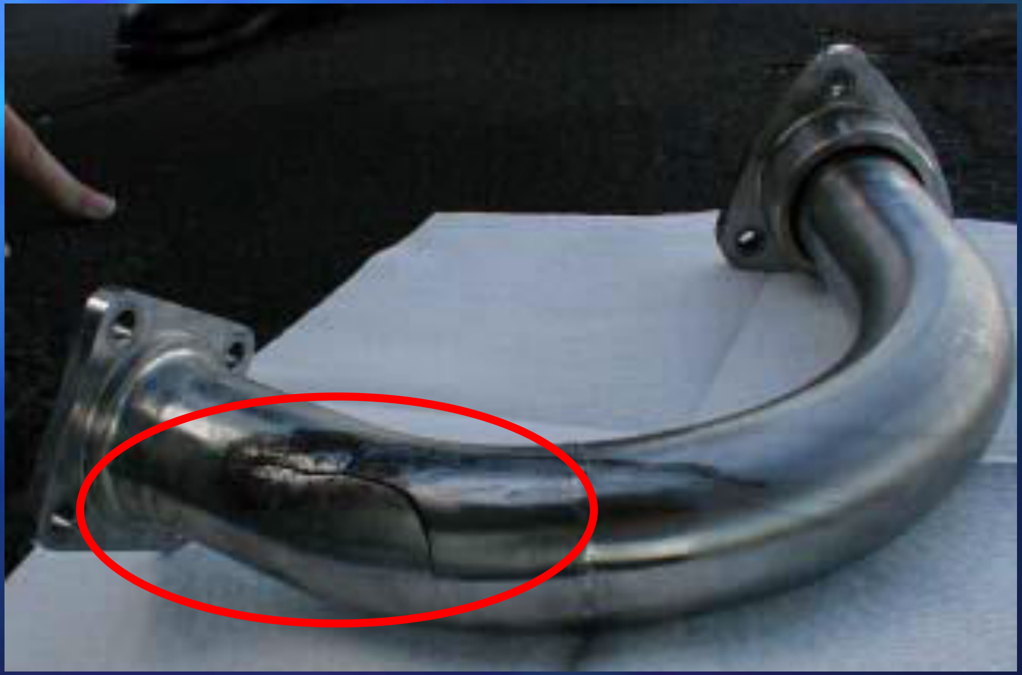
OIL	ENGINE Nr 1	ENGINE Nr 2
TEMP.	110°C	65°C
PRESS.	80 psi	150 psi
VOLUME	17 liters	14 liters

Accident Investigation

- The fuel leak rate reached 13 ton/h.
- That's the reason why the aircraft got no fuel.

Accident Investigation

- The crack was a result of a hard contact between fuel and oil lines due to a non appropriate routine maintenance dozens of flight-hours before.



Why an aircraft get no fuel ?

- In the aviation history, a lot of accidents have been occurred due to lack of fuel.
- The main reasons commonly are:
  - wrong flight range calculations
  - fuel indicators malfunction.
  - bad weather conditions.
  - hard air traffic.
  - navigation errors, etc...

Non Destructive Testing

- The rupture of a fuel tube is a quite rare reason for lack fuel because the tubes are properly inspected.
- The aircraft tubing is inspected through several Non Destructive Testing methods:
  - Liquid Penetrant;
  - Ultra Sound;
  - X-Ray;
  - Eddy-Current.

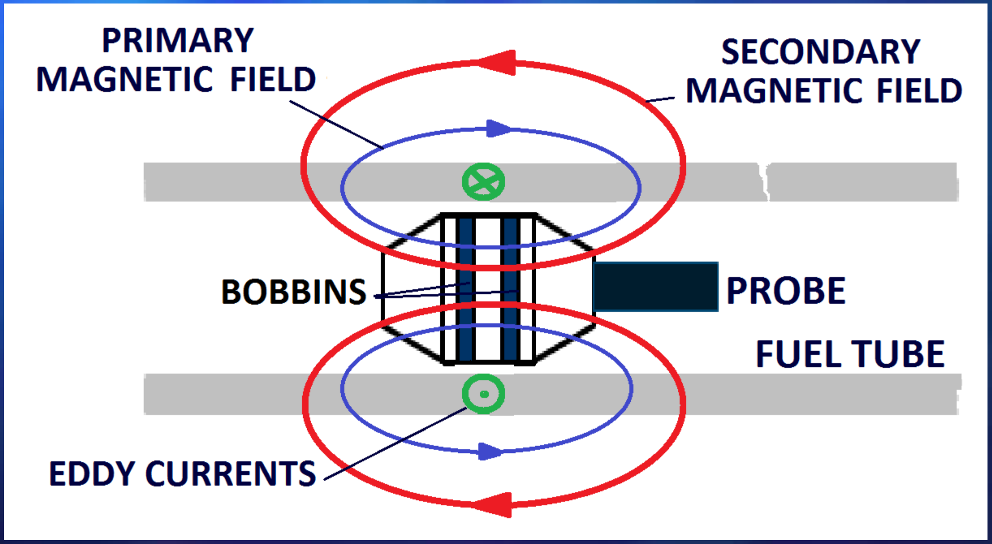
Eddy-Current Testing

- The Eddy-Current Testing (ECT) is an electromagnetic method widely used in aircraft inspection.
- The defects identified through ECT allows important inspection decisions and guarantees the aircrafts safe operations.

Eddy-Current Testing (ECT)

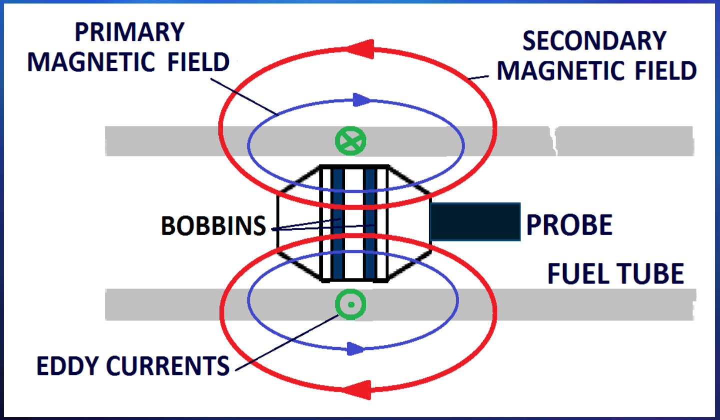
→ The ECT is based on the introduction of an alternate current bobbin coil probe in the fuel tube.

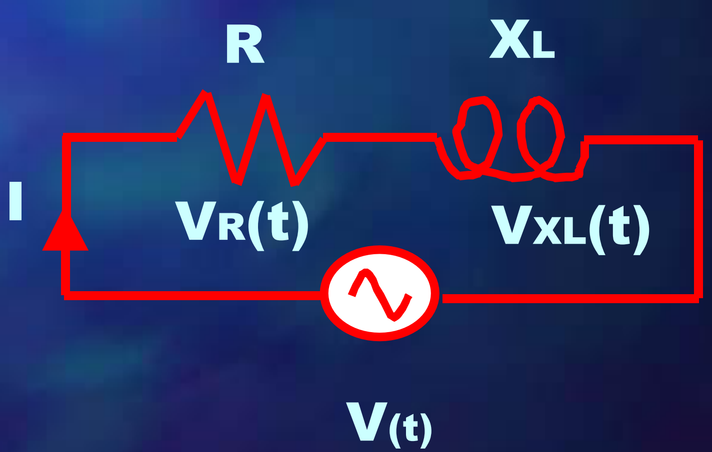
→ A primary magnetic field is generated.



Eddy-Current Testing (ECT)

- The primary magnetic field induces circular Eddy Currents in the fuel tube which generates a secondary magnetic field opposite to the primary field.
- The electric circuit have resistive *(R)* and inductive *(X_L)* components.

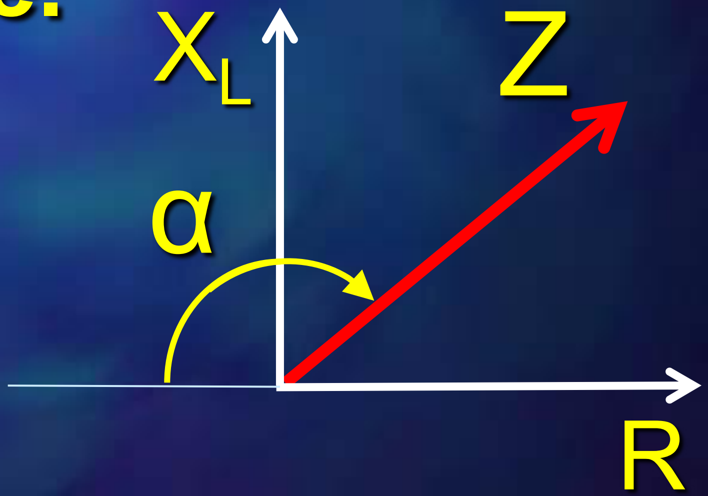




Eddy-Current Testing (ECT)

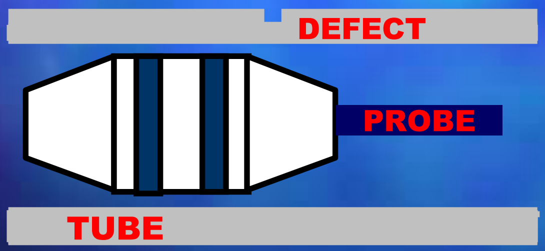
- **By using the complex plan to represent the resistance *R* and the inductive reactance X_L, the impedance of the circuit is represented by a vector which length is *Z*.**
- **α is the Phase Angle.**

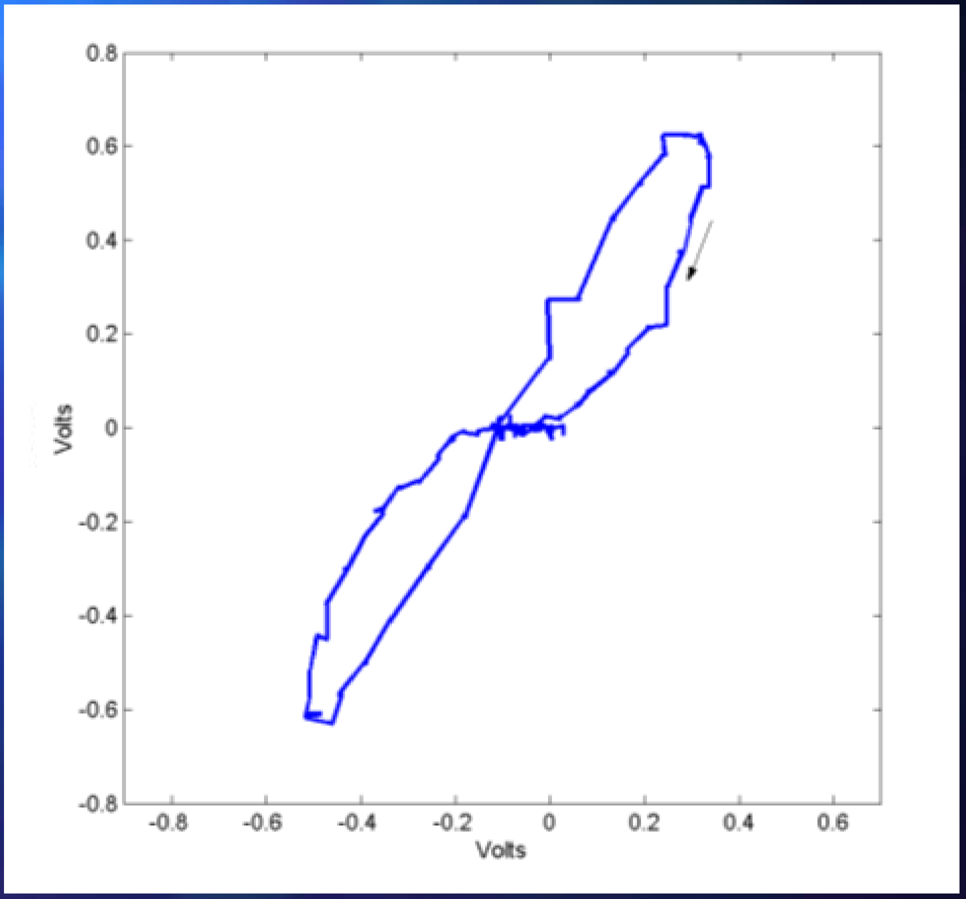
$$Z = \sqrt{R^2 + X_L^2}$$



Eddy-Current Testing (ECT)

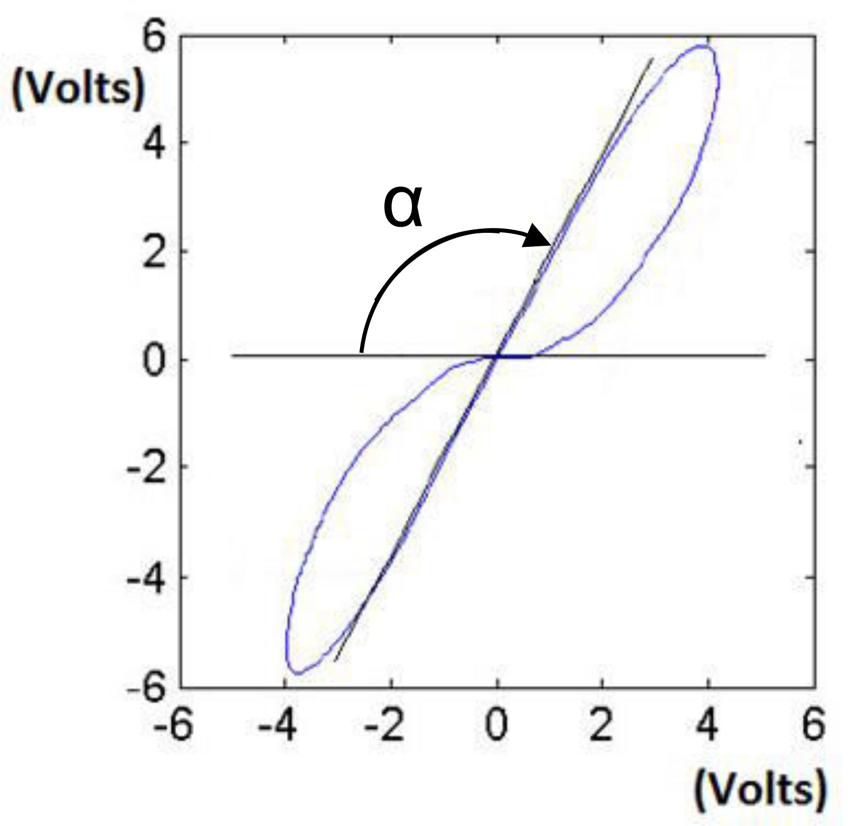
- When the probe passes through a defect, the impedance forms an “8” shaped Lissajous figure.





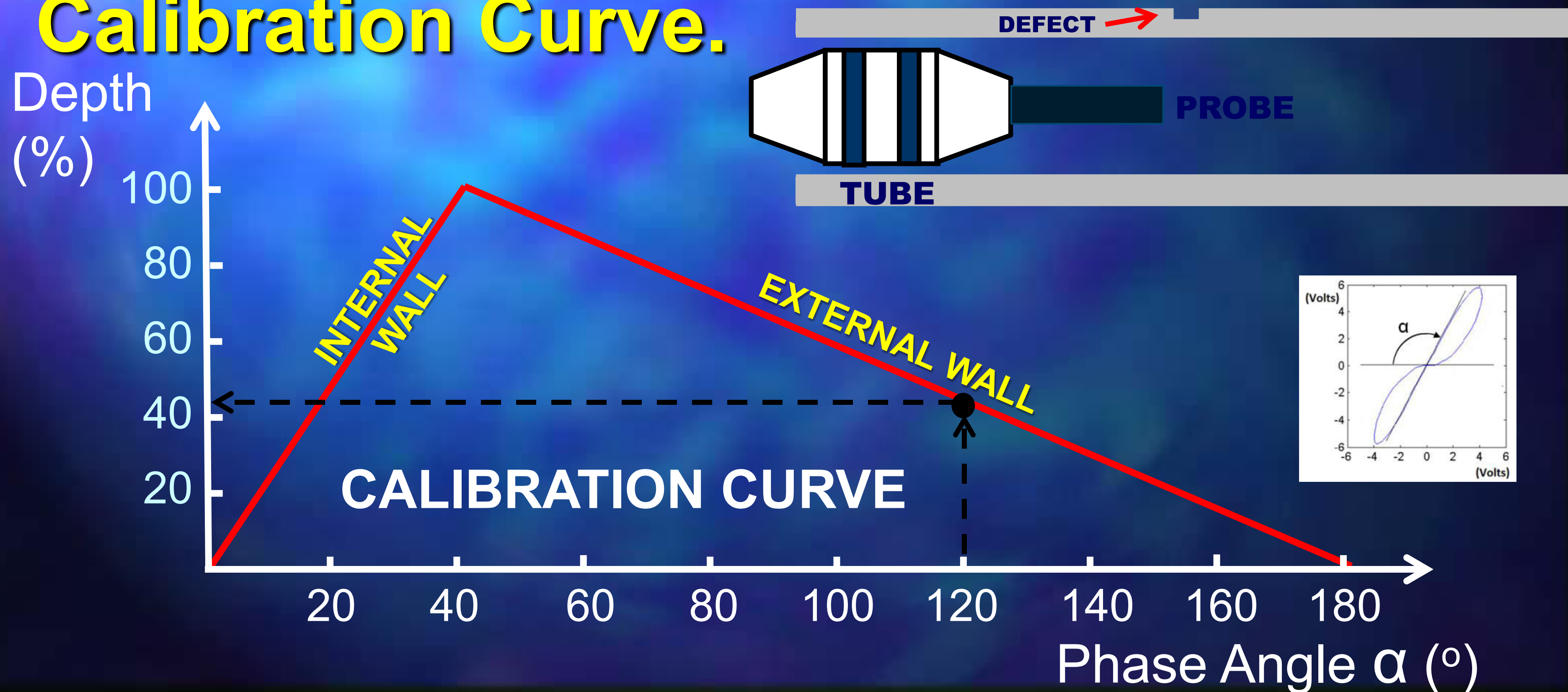
Eddy-Current Testing (ECT)

✈ One of the most important signal characterists is the Phase Angle α formed by a horizontal line and the straight line common to the two petals of the Lissajous figure, clockwise measured.



Defect Depth and Localization

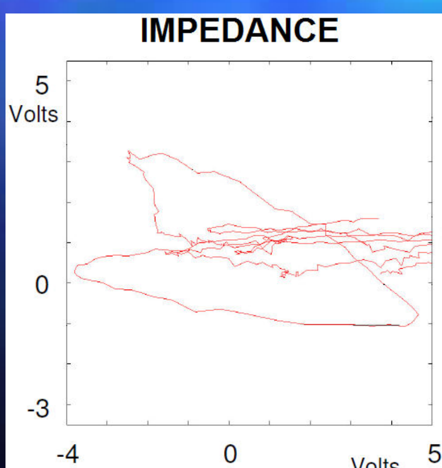
- The Phase Angle determines the depth of the defect and if it is internal or external to the fuel tube by using the Calibration Curve.

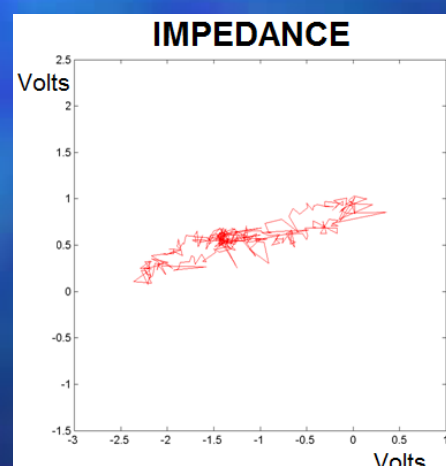


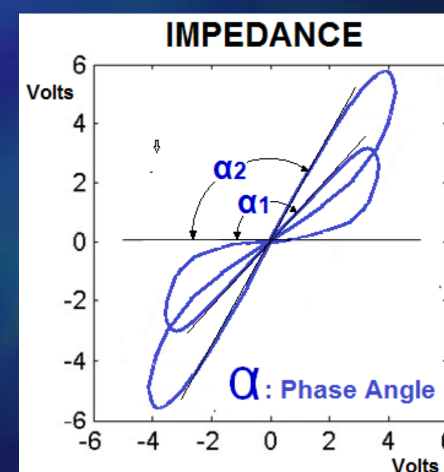
Eddy Current Signal Noises

- ECT signals contain noises which can strongly interfere in their analysis.
- These noises have many origins:

Material Itself	Data Acquisition	Probe Wobble

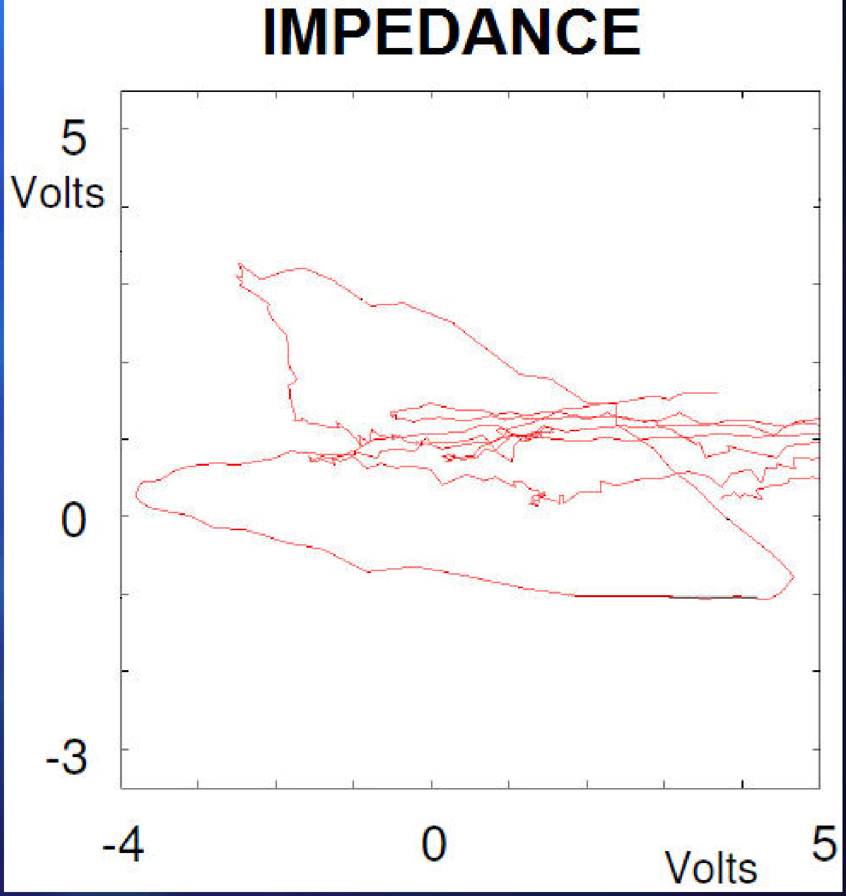






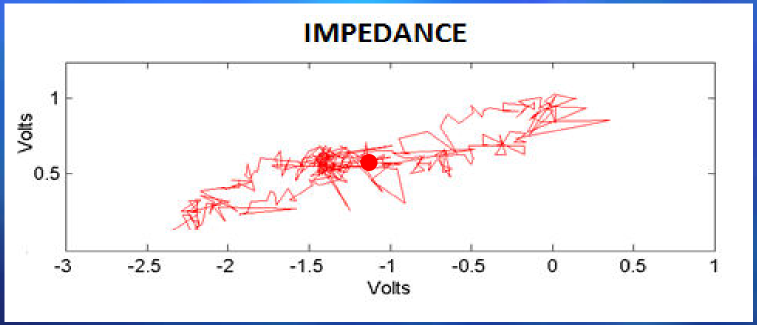
Eddy Current Material Noise

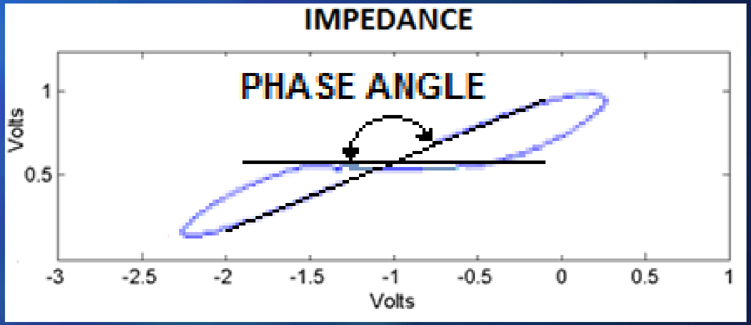
- This noise is originated in the variations of magnetic properties of fuel tube material.
  - It produces distortions in the Lissajous figures to such an extension that Phase Angle reading is simply impossible at all.

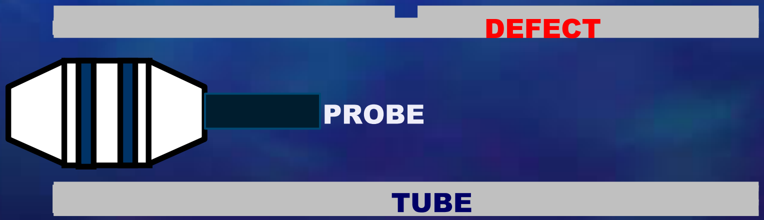


Data Acquisition Noise

- The instrumentation noise produces a blurry Lissajous figure which can jeopardize Phase Angle determination.
- The Wavelet Transform methodology is used for the removal of this noise.







The Wavelet Transform (WT)

→ WT is a time-scale signal transformation which combines the use of variable time and scale windows.

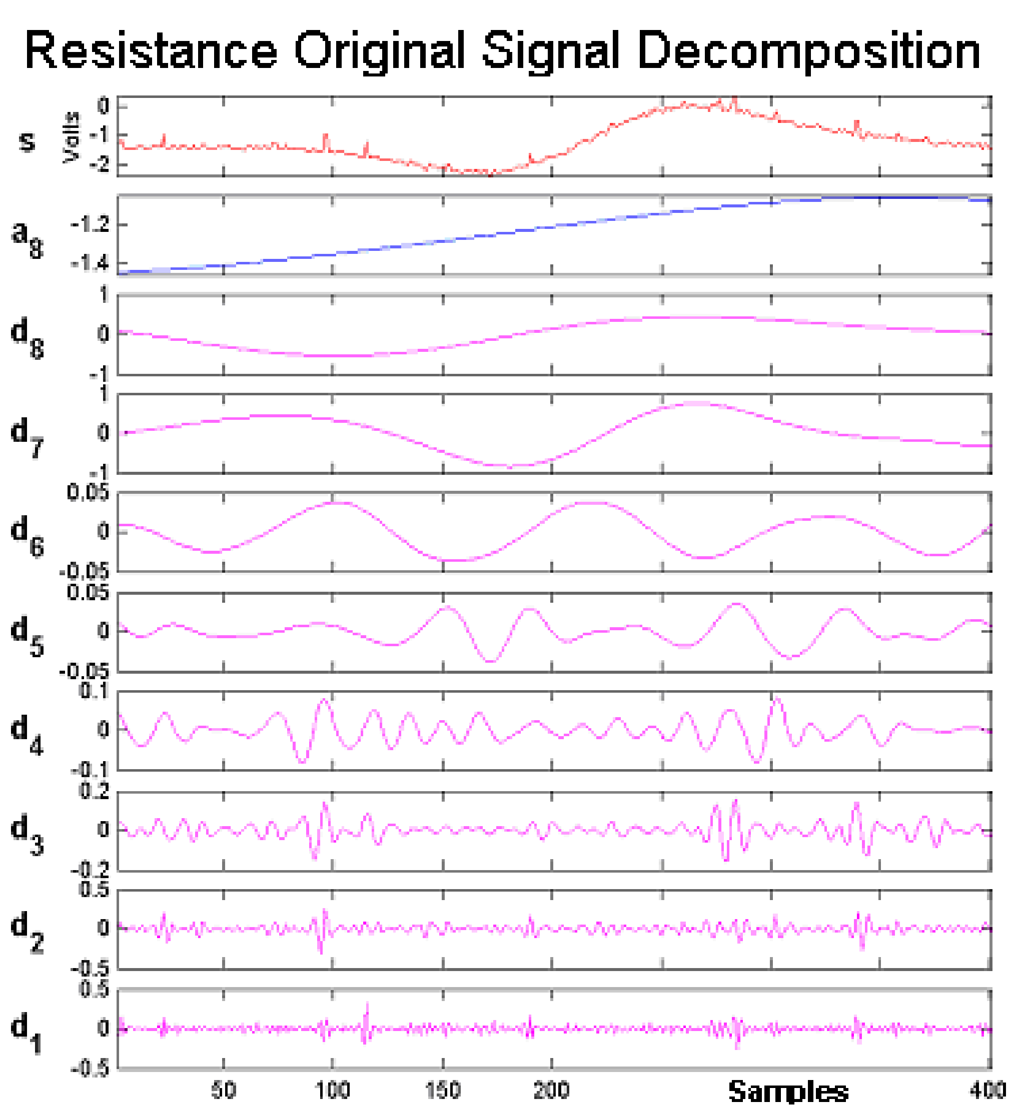
→ When lower frequency information is needed, large time intervals are used and vice versa.

The Wavelet Transform (WT)

- ✈ The Wavelet Transform is very sensitive to discontinuities in time domain, which is typical of Eddy Current signals.
- ✈ It is a method where the transformed time-frequency domain can be varied, allowing for a more detailed description of the time-frequency behavior of the signal being analyzed.

The Wavelet Transform (WT)

- Through the Matlab tool, the signal can be decomposed and analysed in how many separate frequency bands are needed.



The Wavelet Transform (WT)

✈ For a given Eddy-Current signal *s(x)*, the WT is the convolution of *s(x)* with a set of Wavelet functions $\psi_{a,b}(x)$ resulting in a set of coefficients $C_{a,b}$:

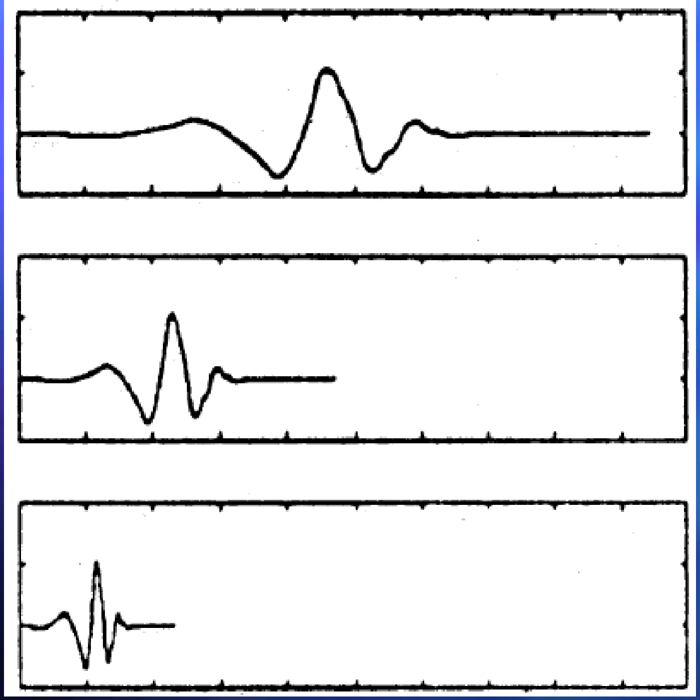
$$C_{(a,b)} = \int_{-\infty}^{+\infty} s(x)\ \psi_{a,b}(x)\,dx$$

✈ A Wavelet function $\psi_{a,b}(x)$ has two characteristic parameters: the *scale "a"* and the *position "b"* which change continually.

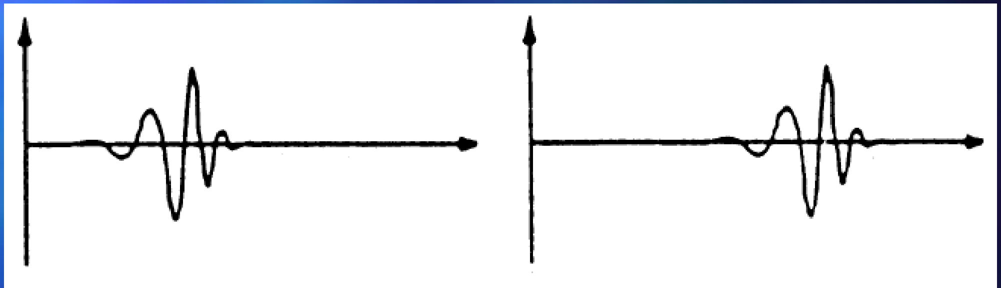
The Wavelet Function $\psi_{a,b}(x)$

→ **The characteristic parameters:**

Scale "a"



Position "b"



$$C_{(a,b)} = \int_{-\infty}^{+\infty} s(x)\ \psi_{a,b}(x)\,dx$$

The Wavelet Function $\psi_{a,b}(x)$

→ A complete set of basic Wavelet functions $\psi_{a,b}(x)$ can be obtained by the dilation and shifting of $\psi(x)$ according to:

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}}\,\psi\left(\frac{x-b}{a}\right)$$

where $(a,b) \in R$ and $a \neq 0$.

$$C_{(a,b)} = \int_{-\infty}^{+\infty} s(x)\ \psi_{a,b}(x)\,dx$$

The Wavelet Function $\psi_{a,b}(x)$

- If one multiplies each coefficient by the properly dilated and shifted Wavelet function, one should regenerate the original function *s(x)*.

The Wavelet Function $\psi_{a,b}(x)$

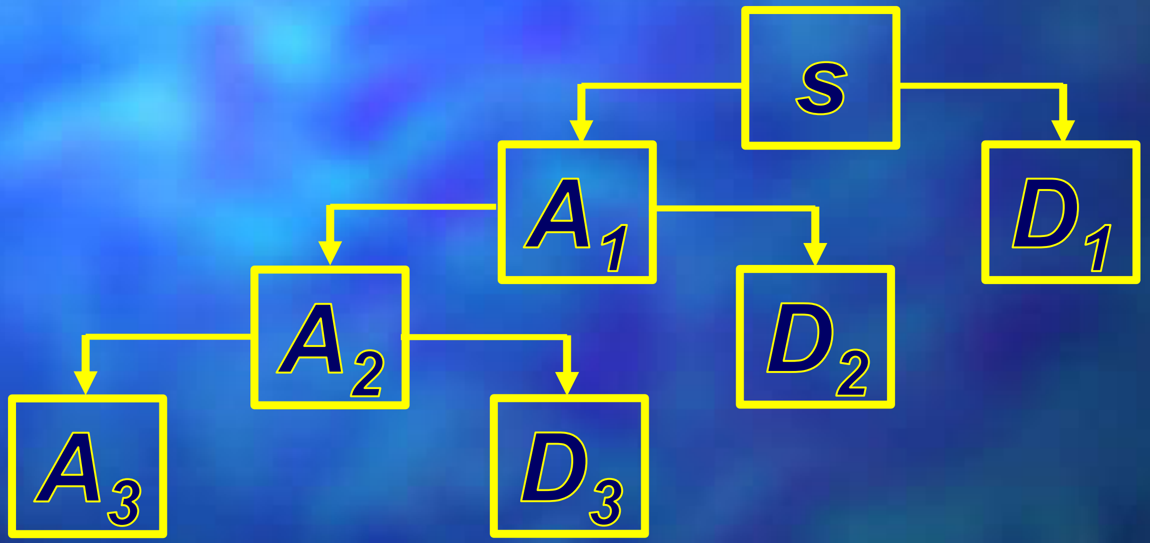
- There exists a relationship between the Wavelet scale and the frequency.
- A small scale will produces compressed Wavelet where the details changes rapidly in higher frequencies.
- With a large scale, the Wavelet is expanded and details change slowly with lower frequencies.

De-noising Methodology

- Eddy-Current signals de-noising is performed by transforming the data to the time frequency domain using multiple scale levels by a Wavelet transform.
- A given signal *s(x)* is decomposed in each scale level into an *"approximation"* component A_i and a *"detail"* component D_i .

De-noising Methodology

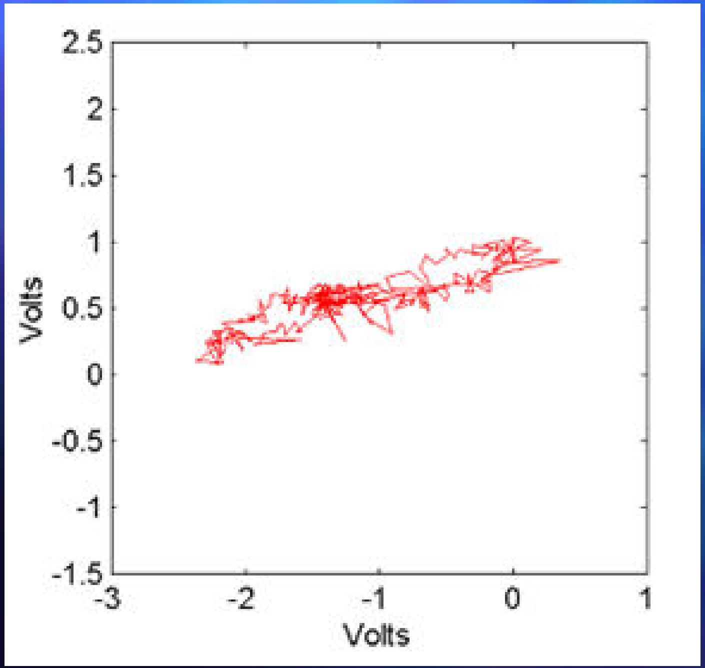
- Example: 3 level decomposition tree of a signal *s* into approximations and details.

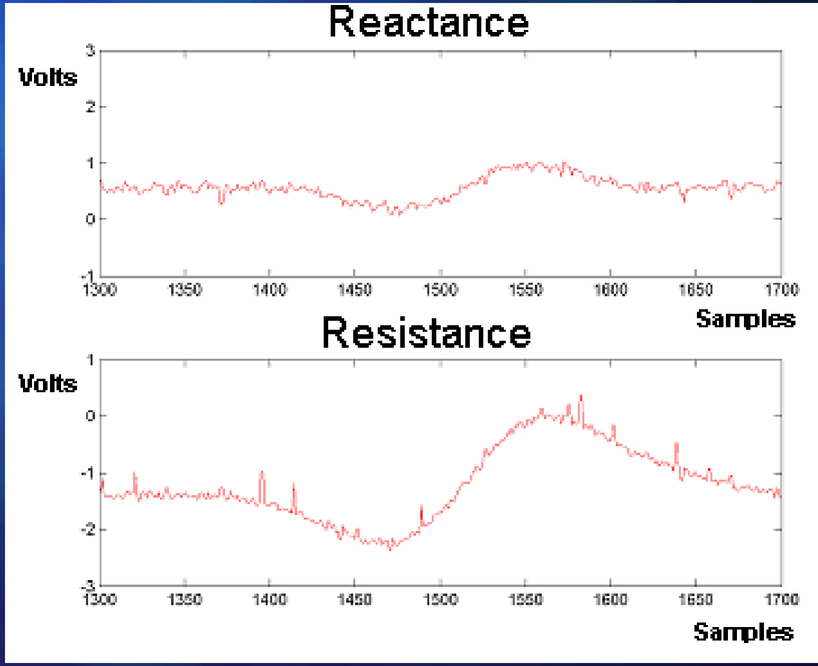


s* = *A3+D3+D2+D1=A2+D2+D1=A1+D1

Applying the Methodology

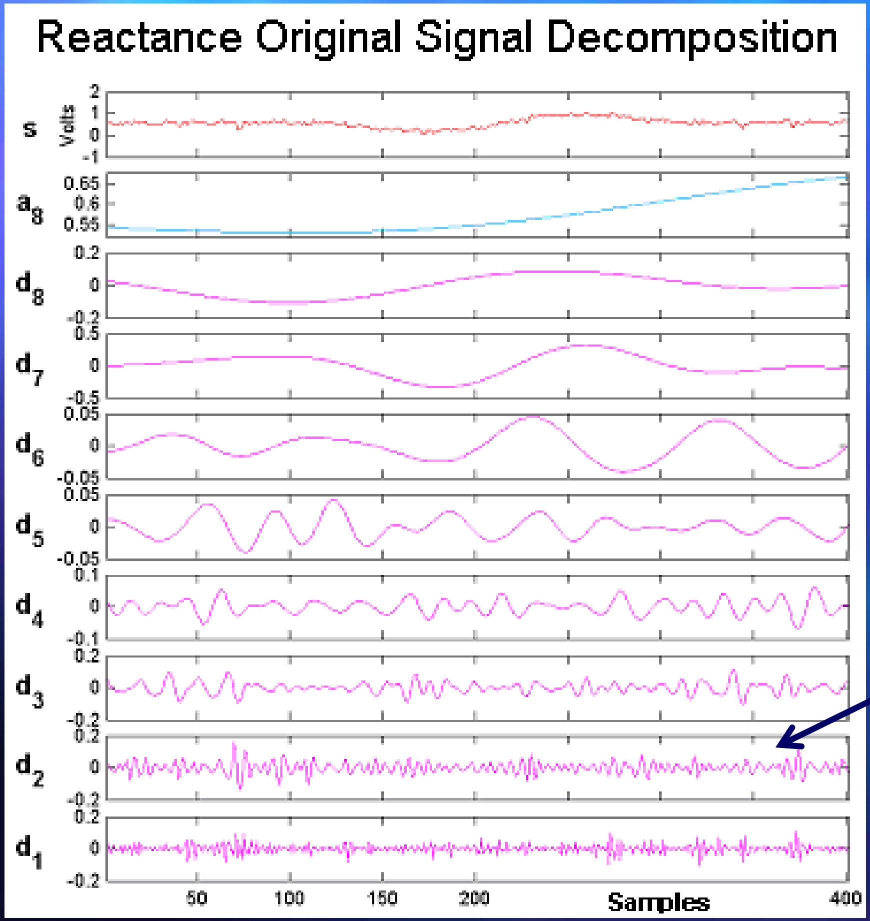
✈ The first step is to separate the inductive component (X_L) and the resistive component *(R)* of the noisy Eddy Current signal:

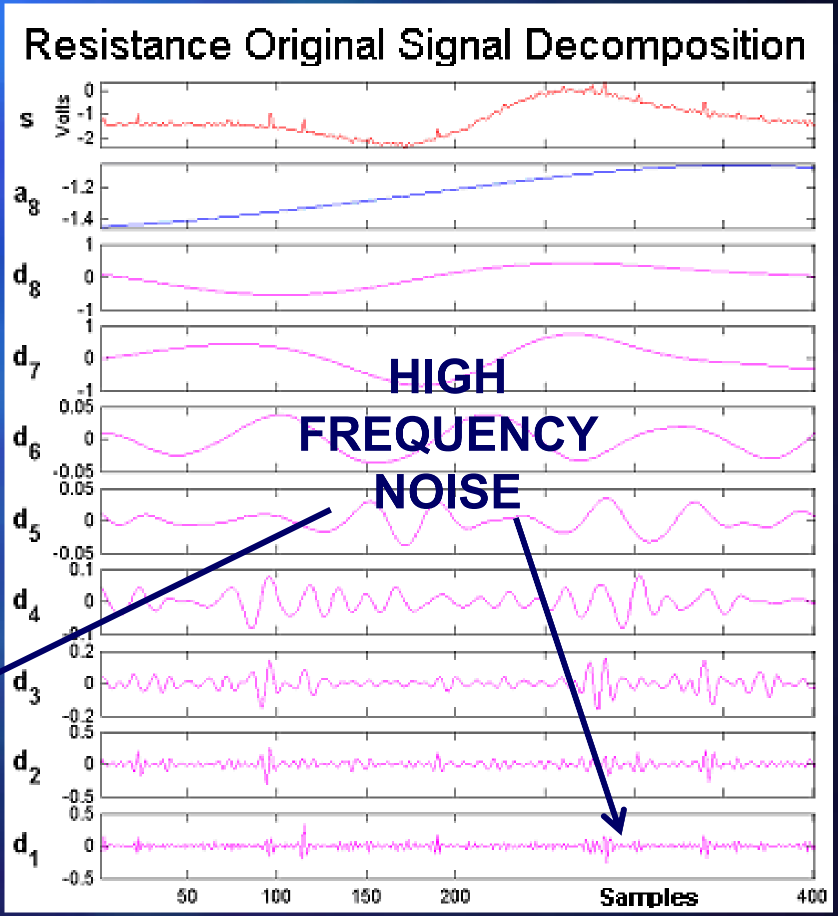




Frequency Decomposition

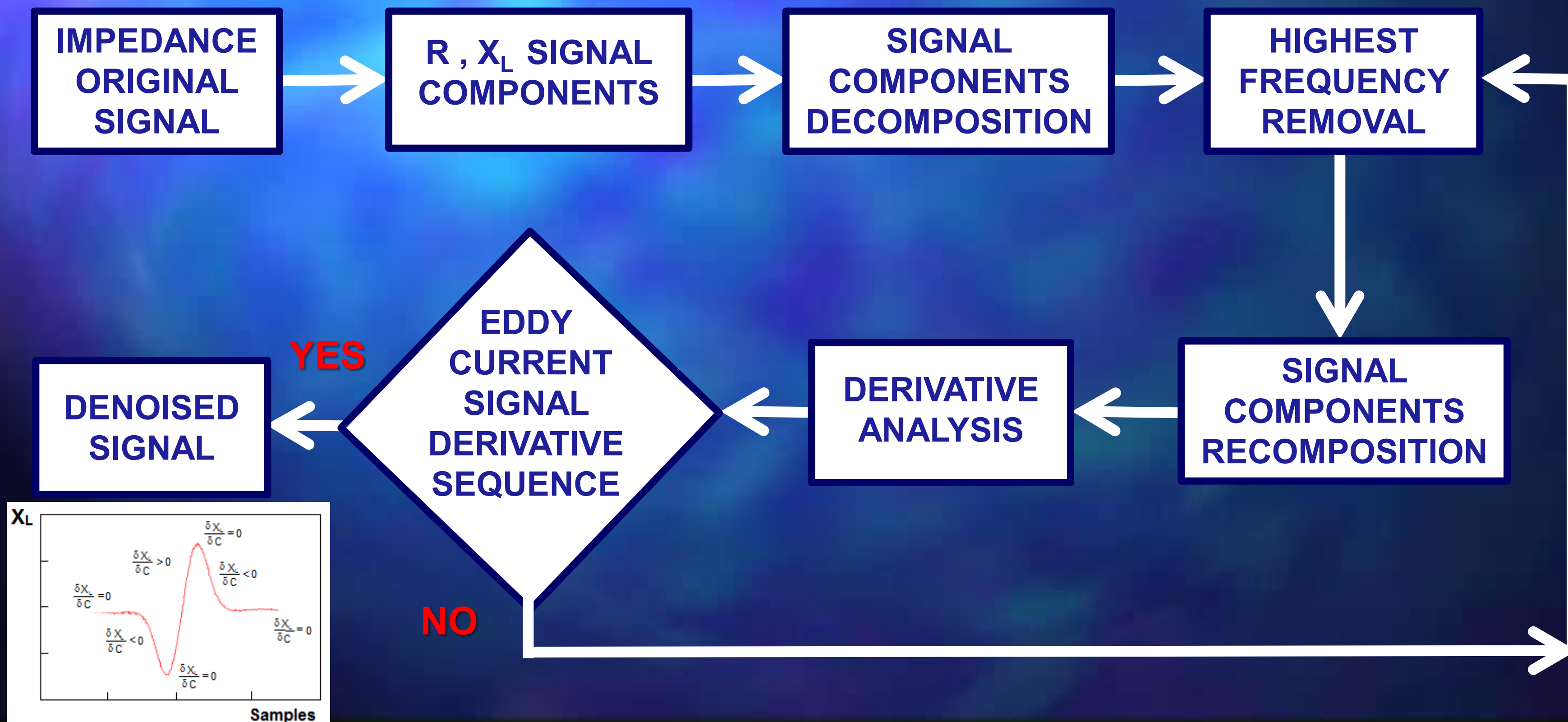
- Then, X_L and R are multi level frequency decomposed through WT:





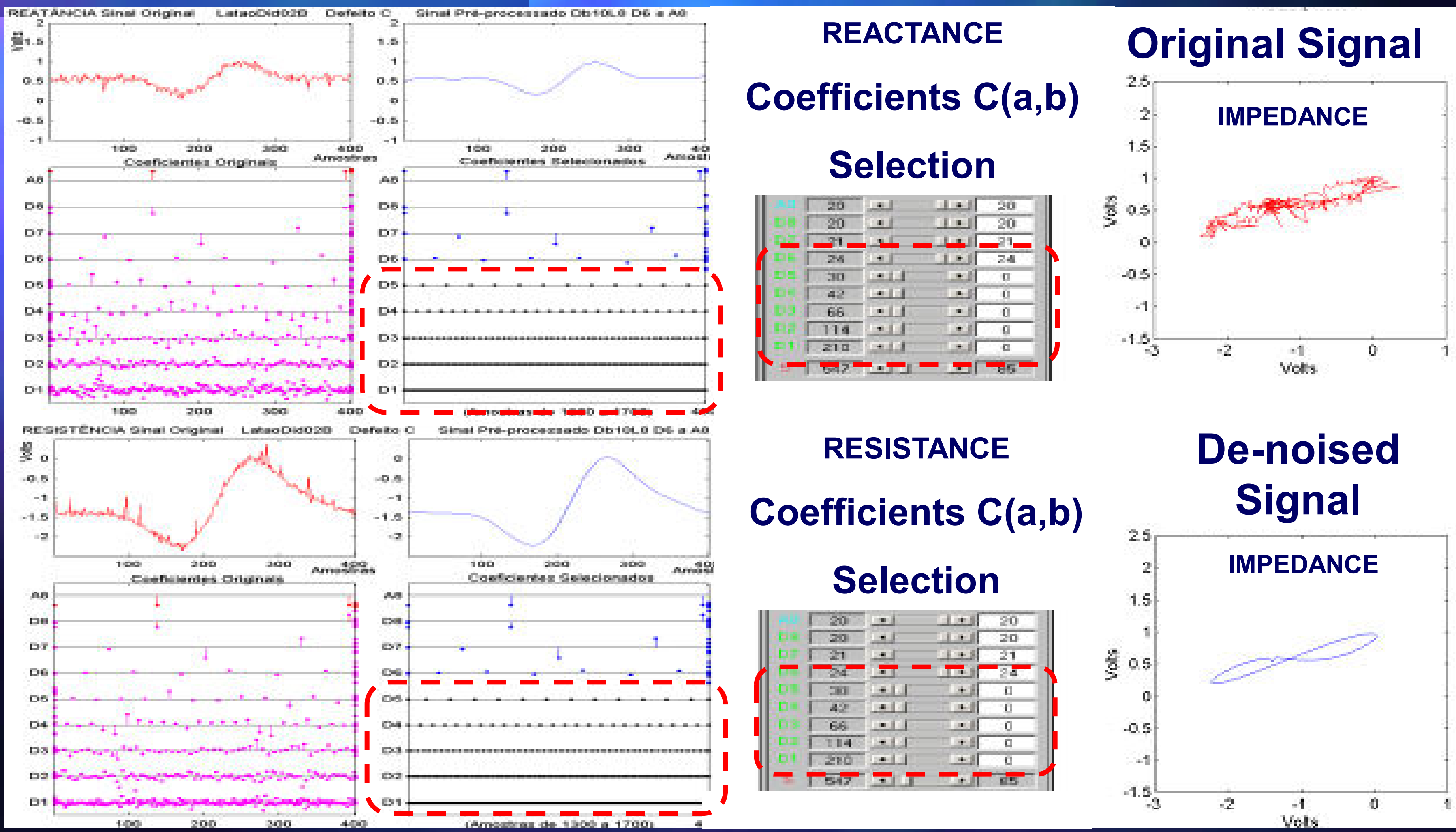
Derivative Analysis Algorithm

- The noise presented is a typical high frequency noise which is removed through a derivative analysis algorithm.



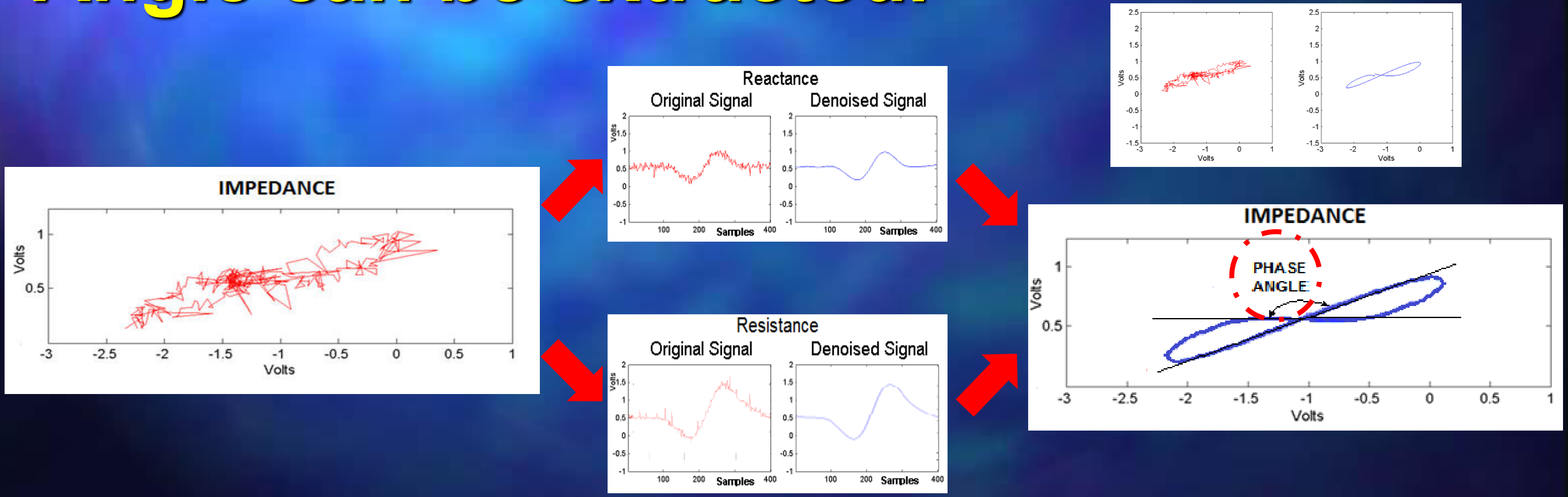
Wavelet *C(a,b)* Coef. Selection

✈ Frequencies removal:



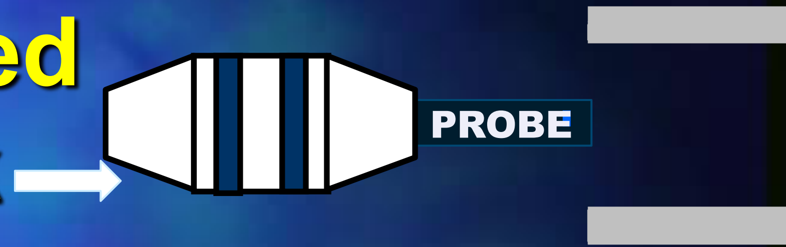
Signal Recomposition

→ **After noise removal, the de-noised reactance and resistance components are recomposed producing a clean Lissajous figure from which the Phase Angle can be extracted.**

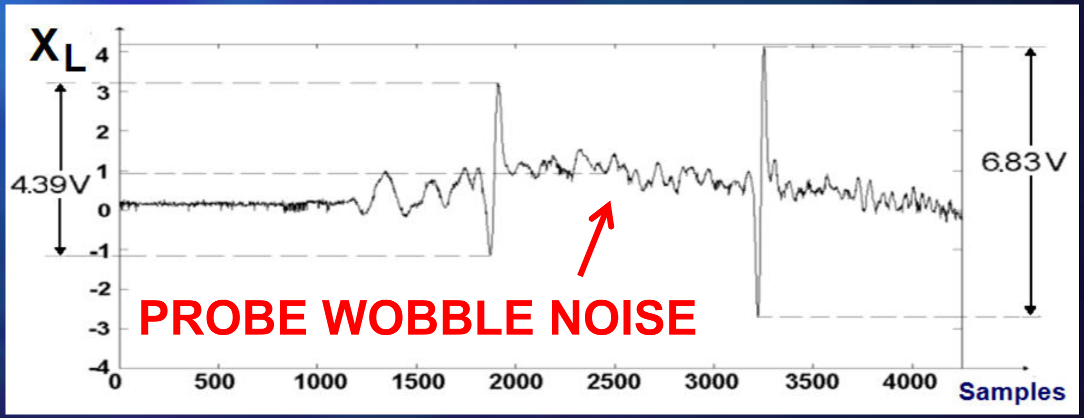


Probe Wobble Noise

- This noise is generated by the necessary slack between the probe and the fuel tube.



- The greather the radial movement of the probe, the greather the inductive component variation of the Eddy Current signal.

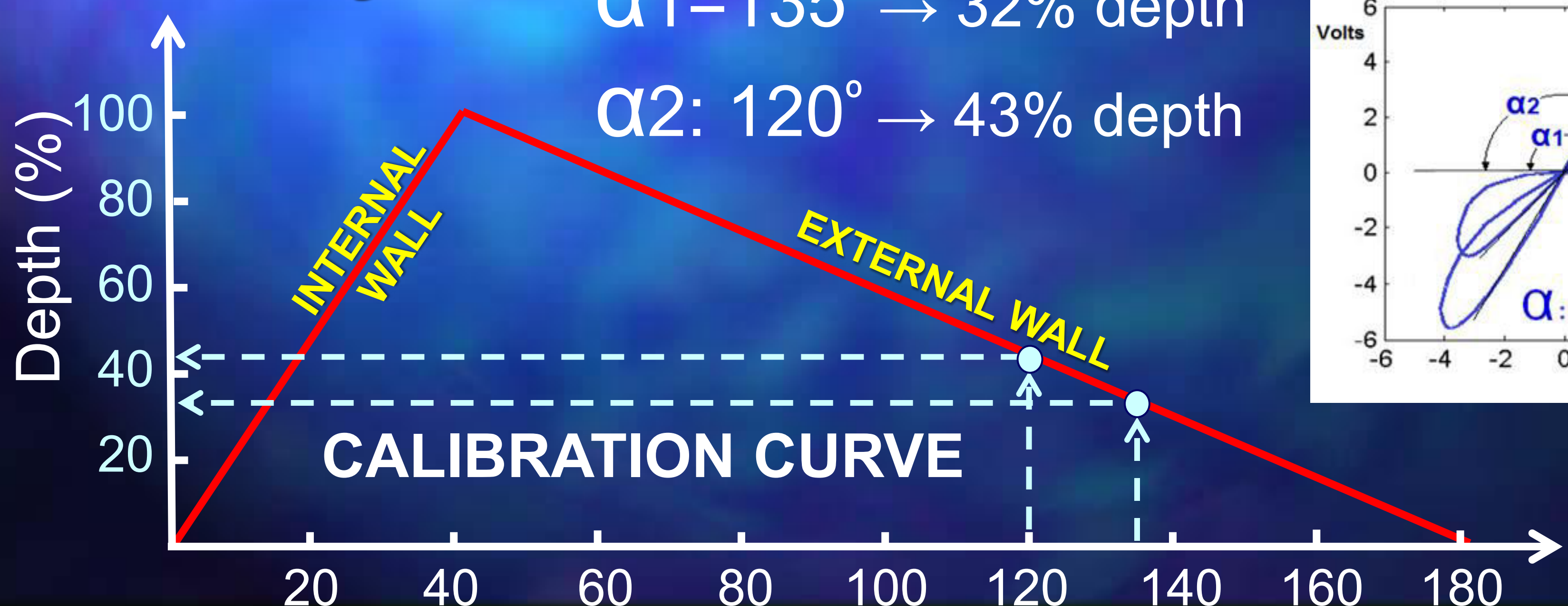


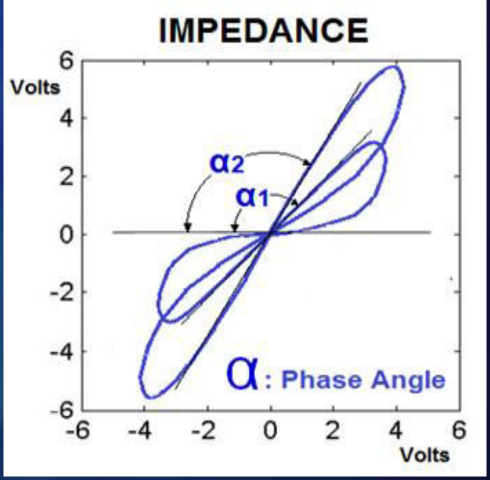
Probe Wobble Noise

- Due to this noise, the Lissajous figure changes as well as its Phase Angle α.
- Consequently, this noise hinders the signal analysis and reduces inspection reliability.

$\alpha 1 = 135^{\circ} \rightarrow$ 32% depth

$\alpha 2$: $120^{\circ} \rightarrow$ 43% depth

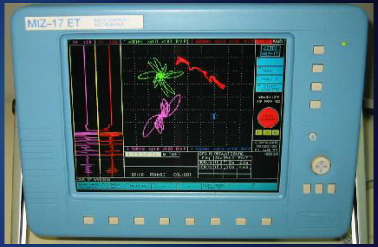


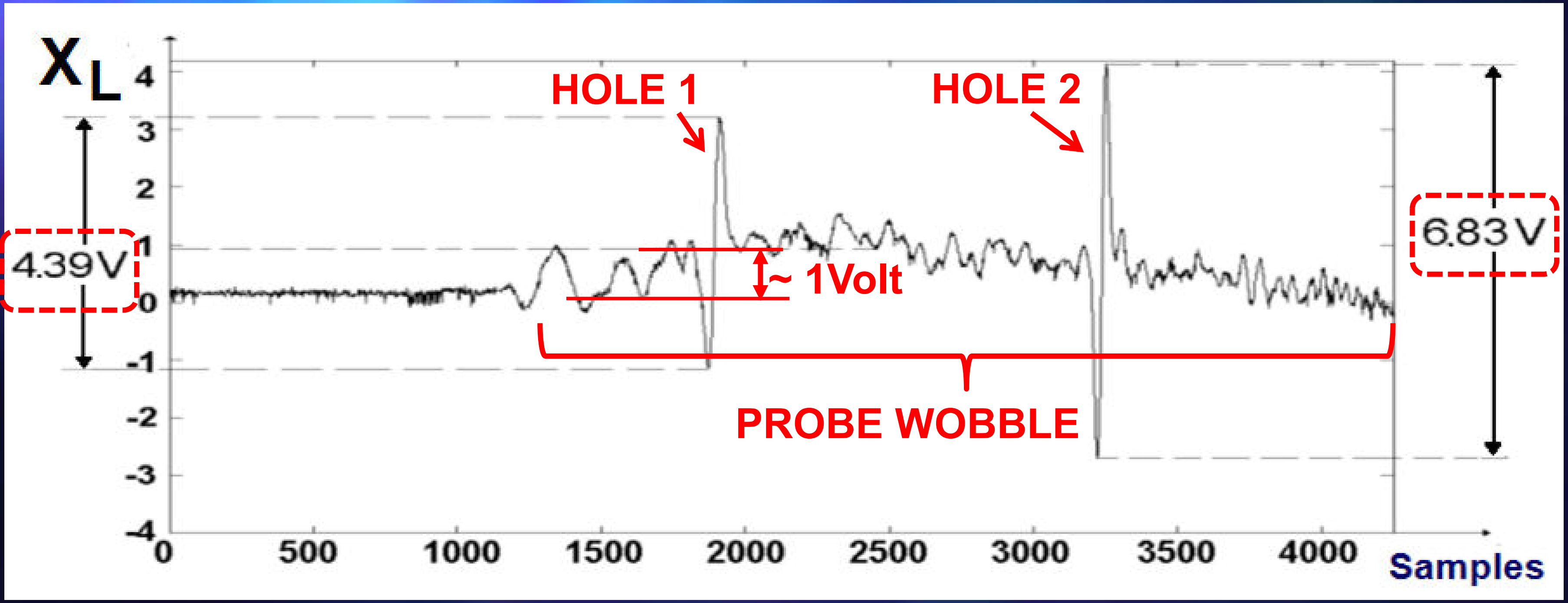


Probe Wobble De-Noising

→ <u>Example:</u> X_L component, Ø19.05mm fuel tube with 2 artificial holes.

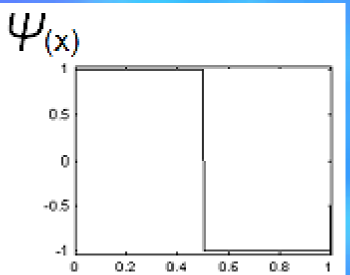
→ The signal was generated by a MIZ-17ET equipment.



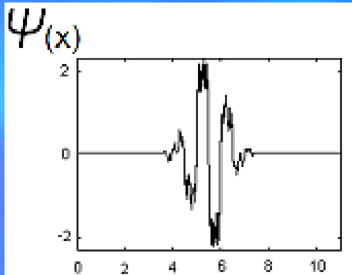


Probe Wobble De-Noising

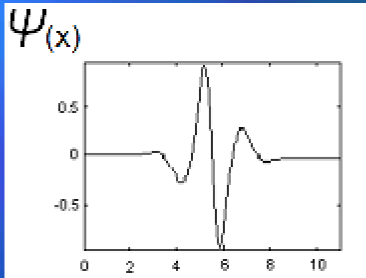
✈ **Four wavelet functions were used for de-noising:**



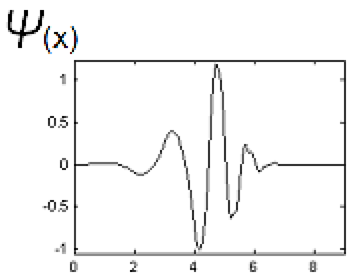
HAAR



SYMLET



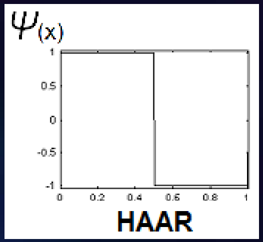
BIORTOGONAL



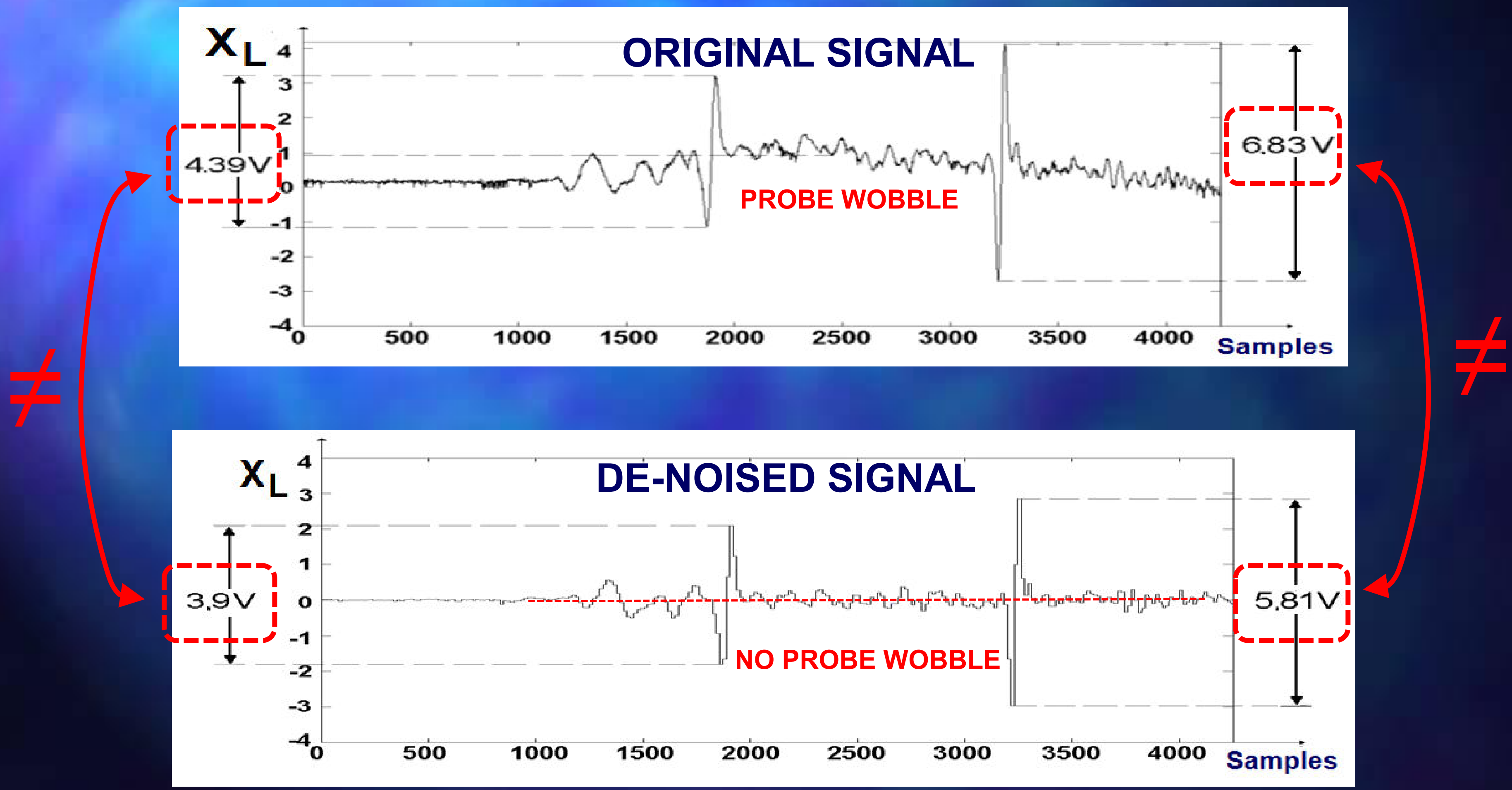
DAUBECHIES

✈ **An 8 level frequency decomposition allowed a convenient selection of the approximation (A_i) and the detail (D_i) components.**

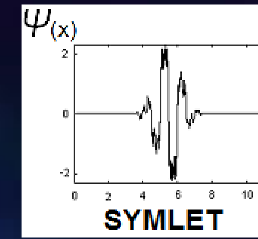
De-Noising – Haar wavelet



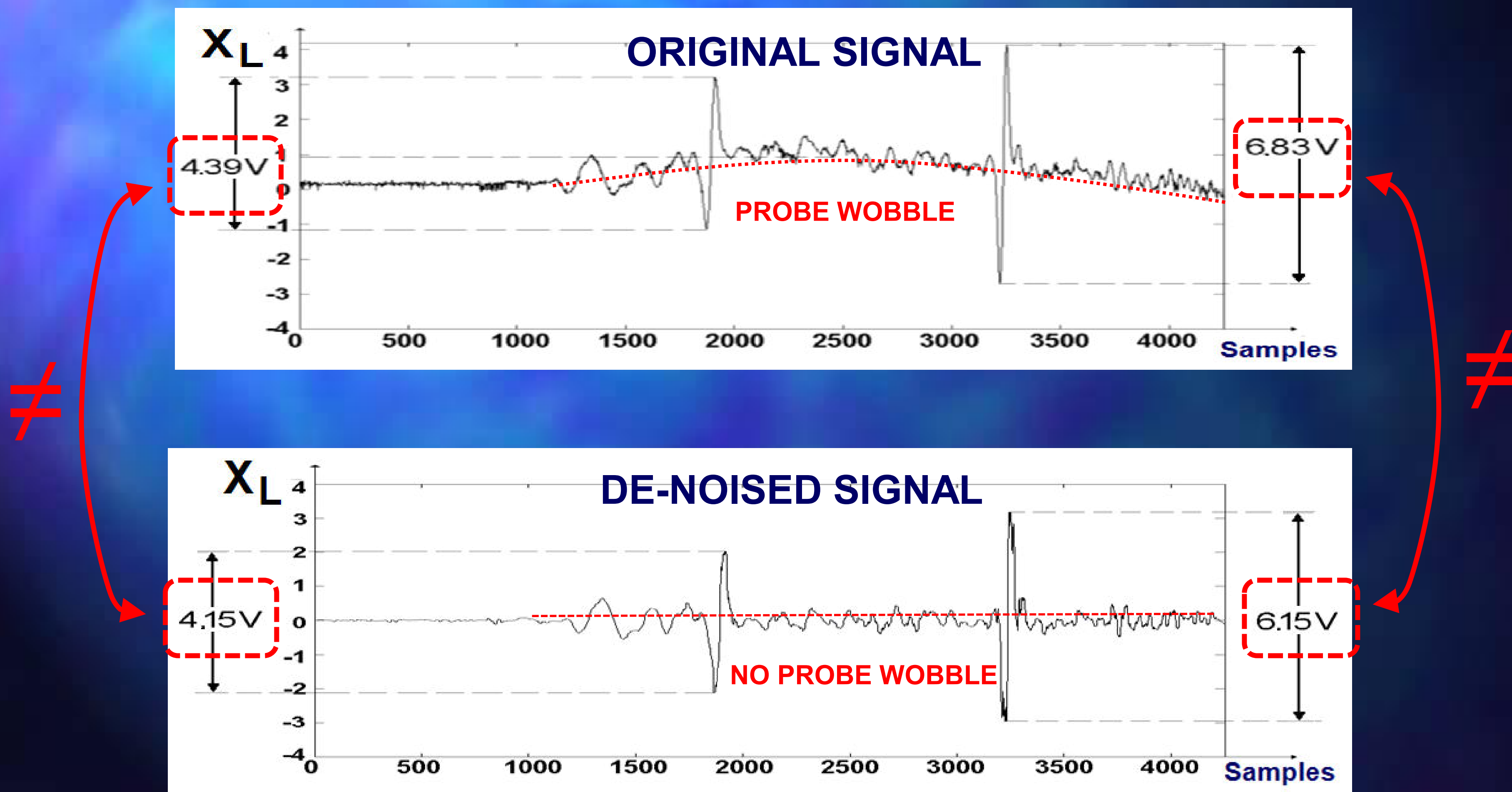
✈ No probe wobble; different X_L ...



De-Noising – Symlet wavelet

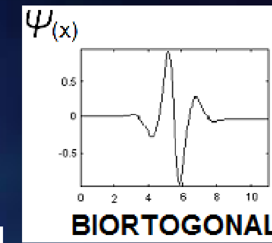


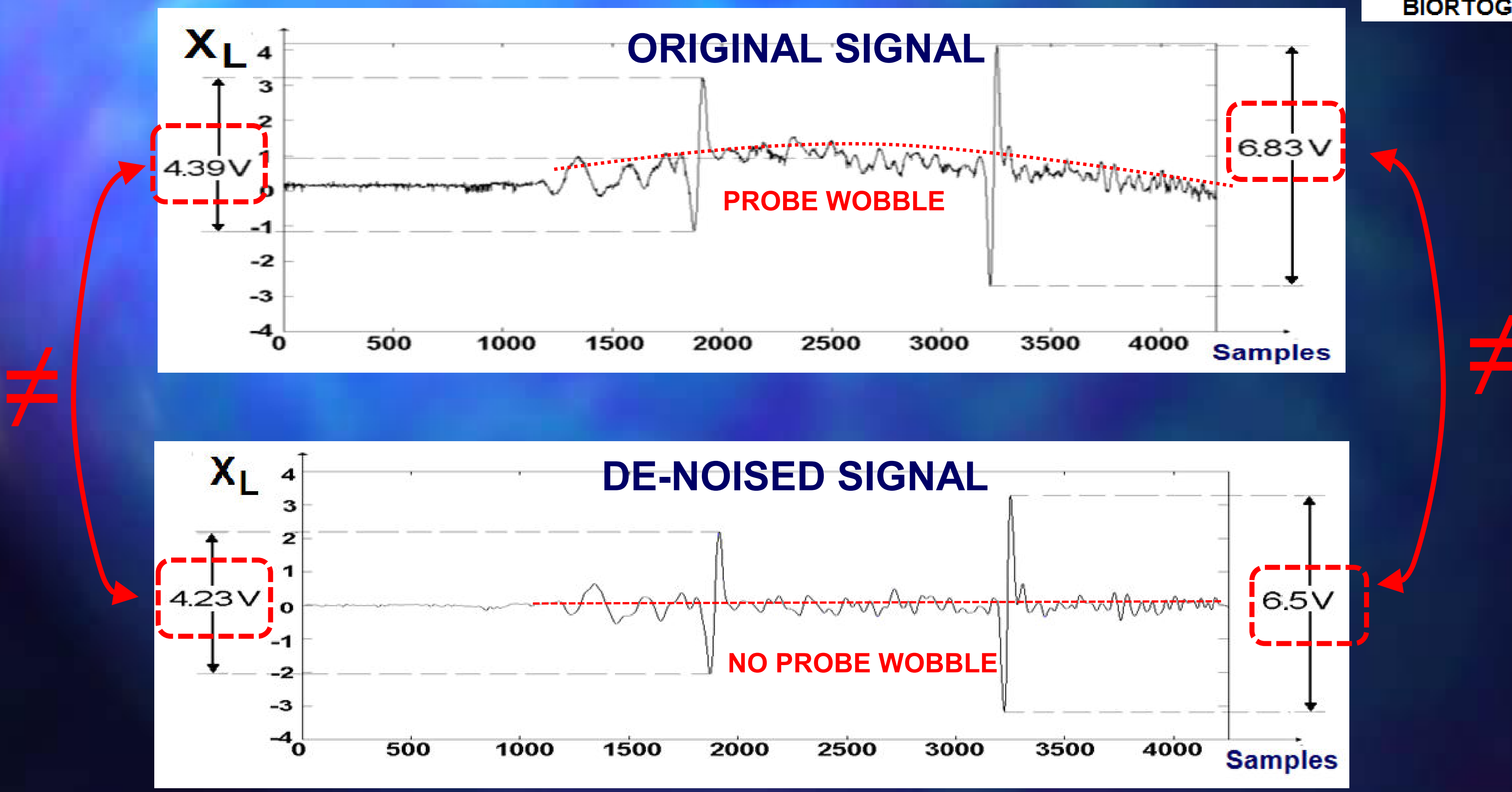
- ✈ No probe wobble; different X_L ...



De-Noising – Biortogonal wavelet

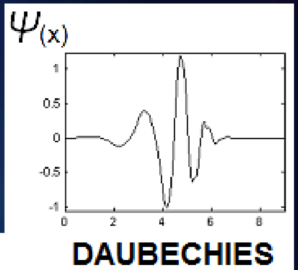
✈ No probe wobble; different X_L ...

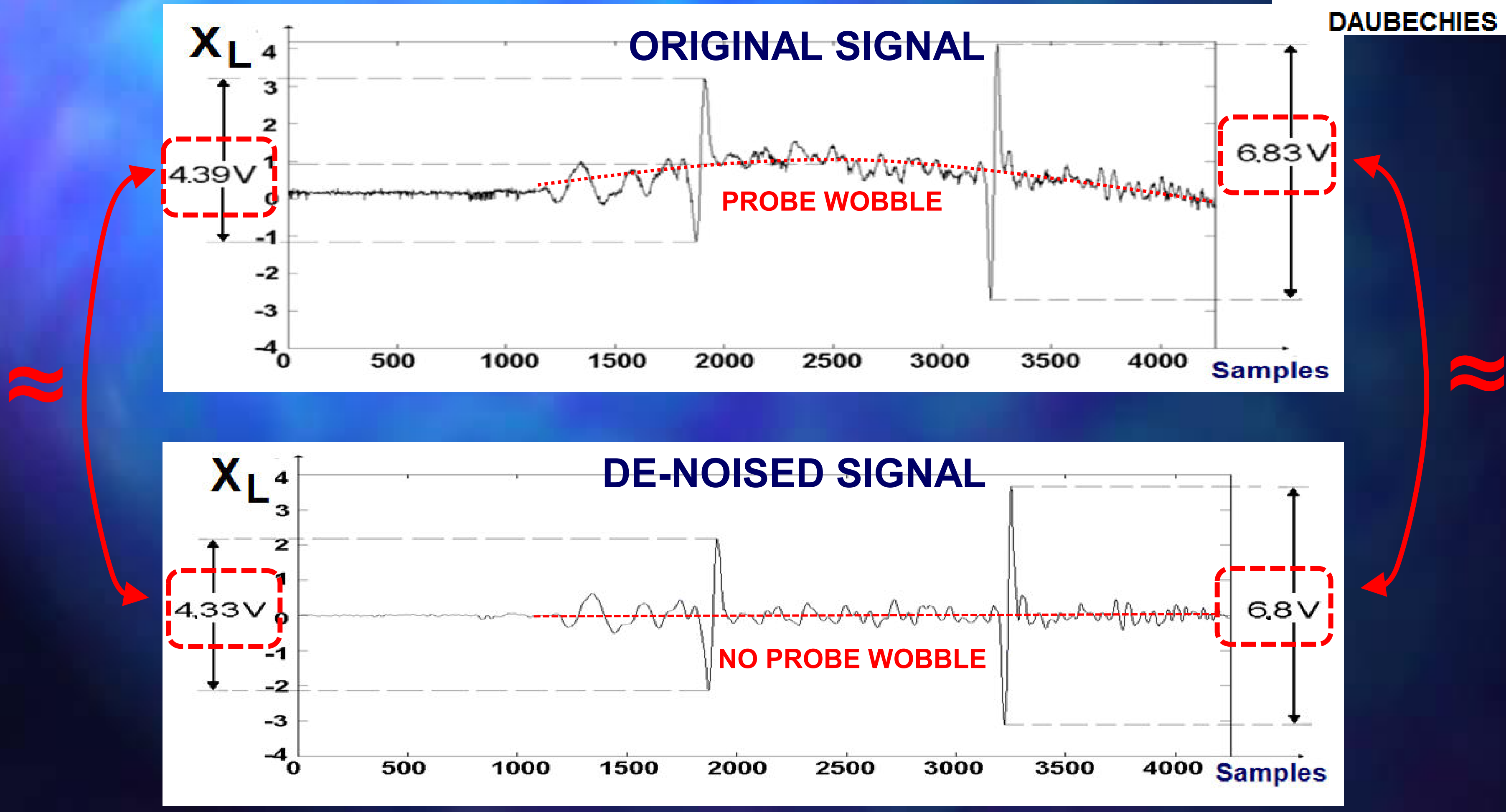




De-Noising – Daubechies wavelet

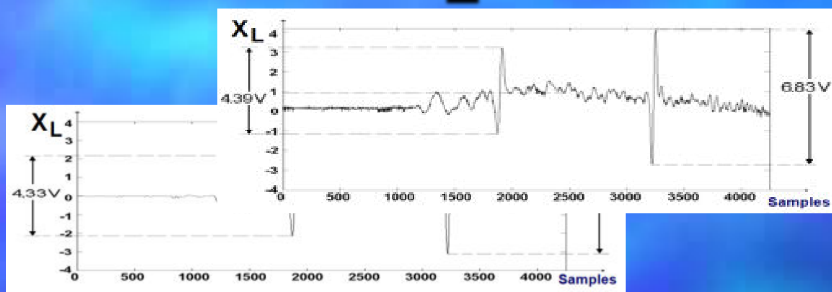
→ No probe wobble, similar X_L !

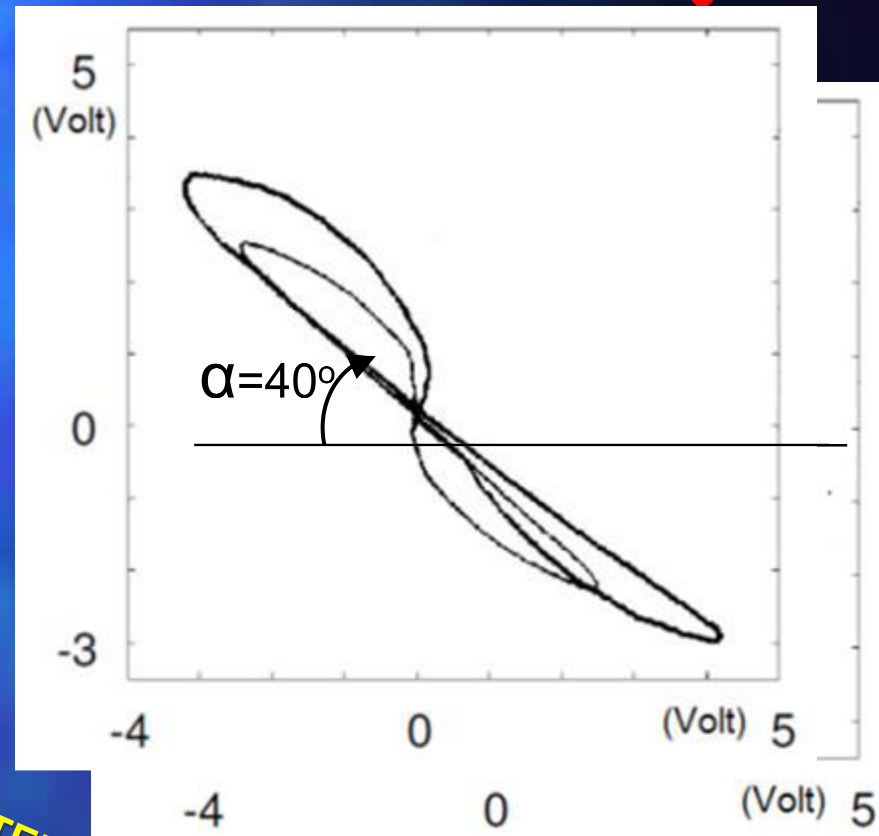


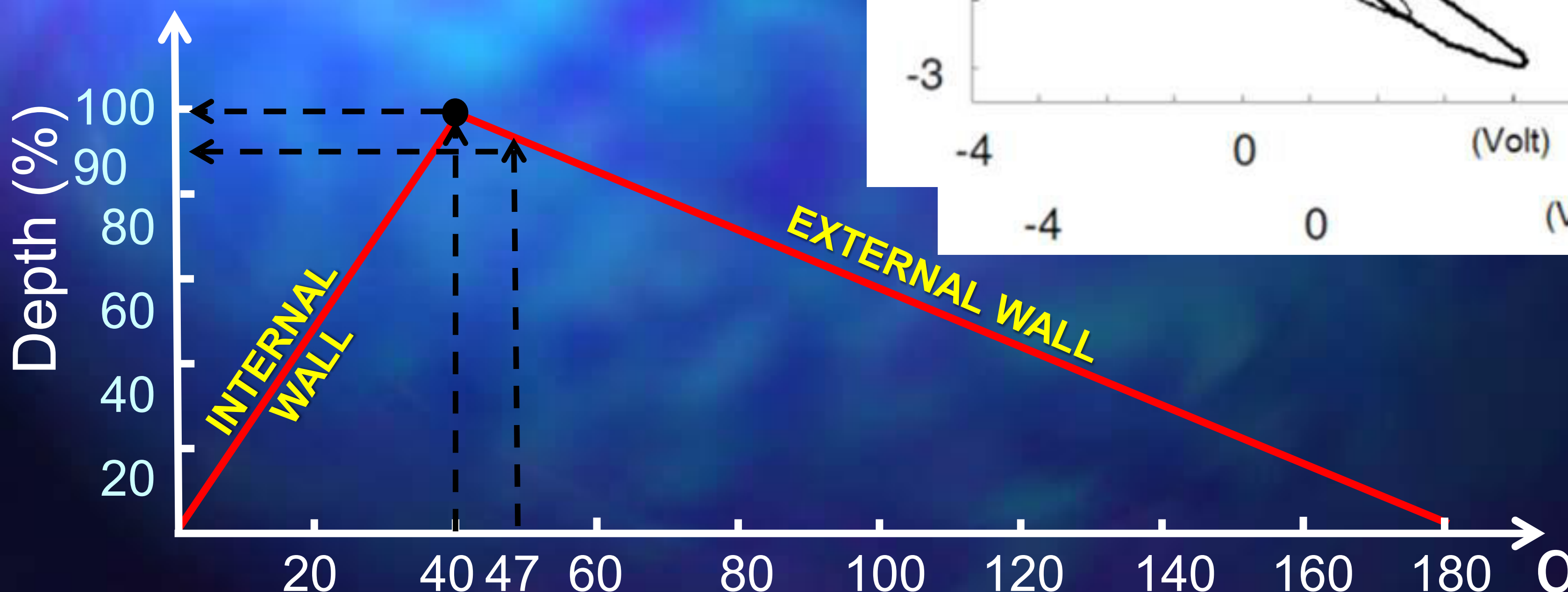


De-Noising – Daubechies wavelet

- ✈ No probe wobble
- ✈ Similar X_L !

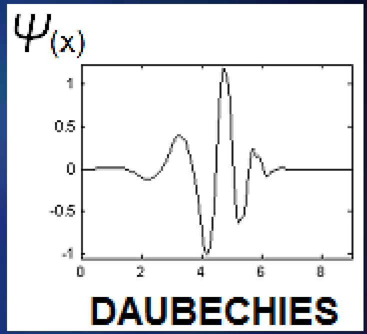




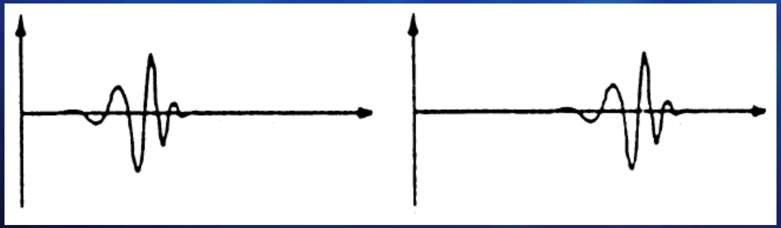


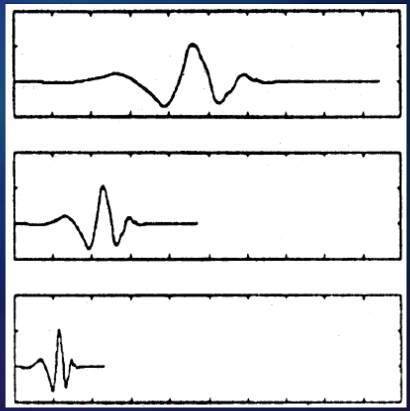
Conclusions

→ The denoising of Eddy Current signals is a process which determines the better Wavelet function $\psi_{a,b}(x)$:



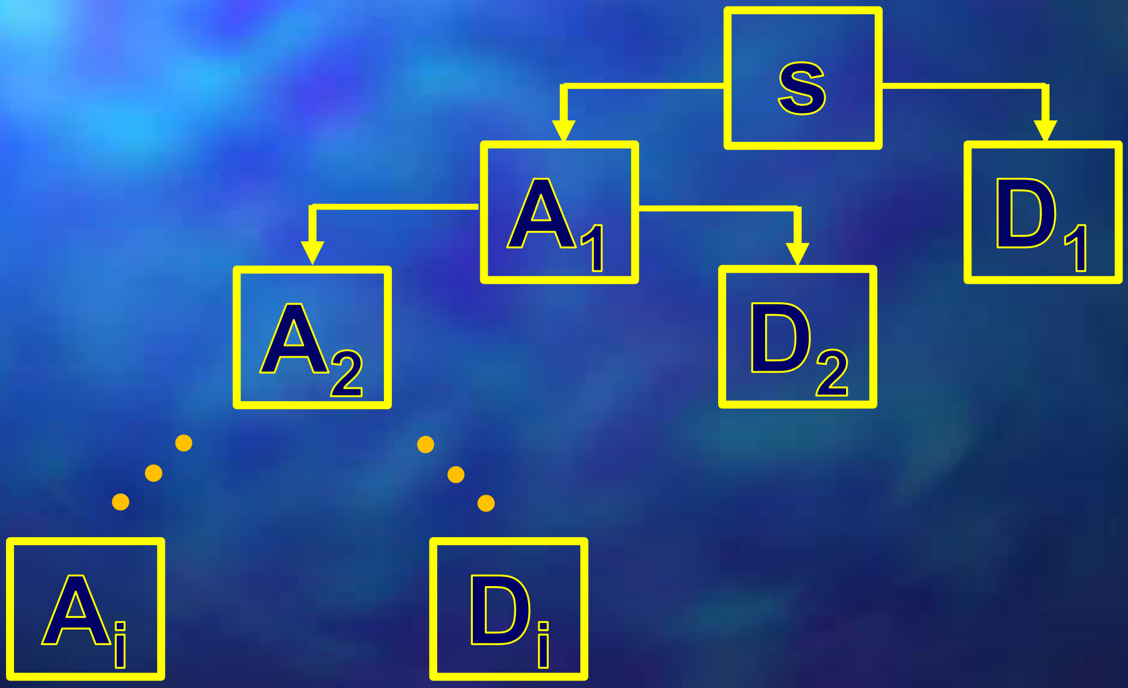
→ ... and the adequate set of coefficients $C_{a,b}$, whith the characteristic parameters *"a" scale* and *"b" position*.





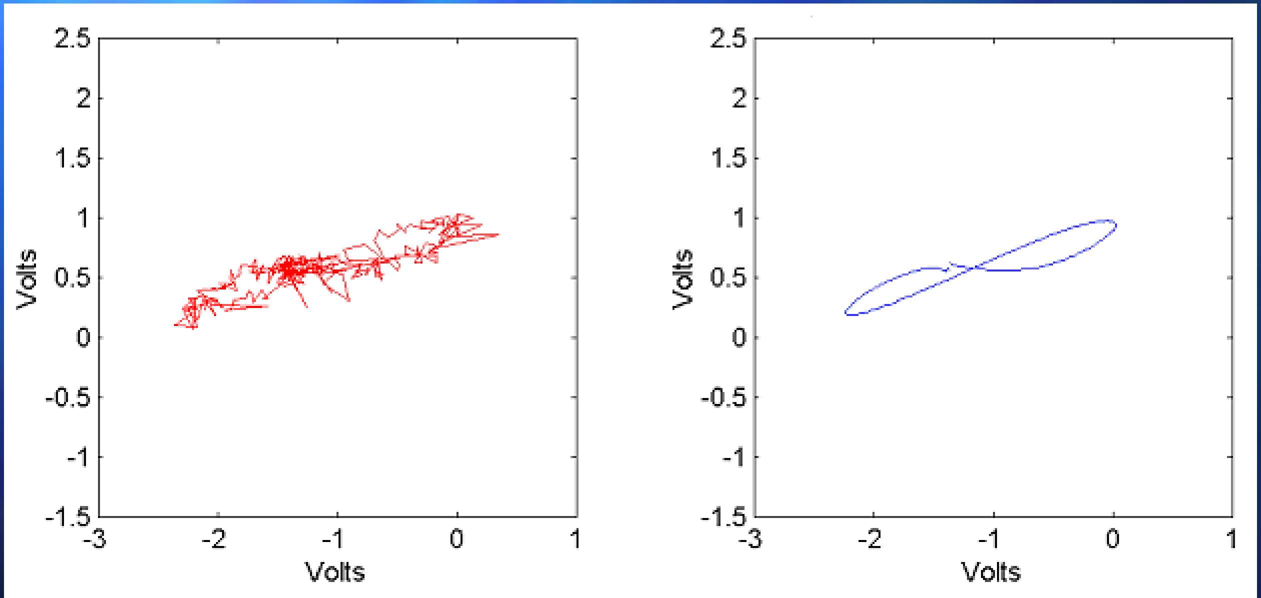
Conclusions

✈ Besides that, the noisy signal *s* must be decomposed in each scale level into an *"approximation"* component A_i and a *"detail"* component D_i .



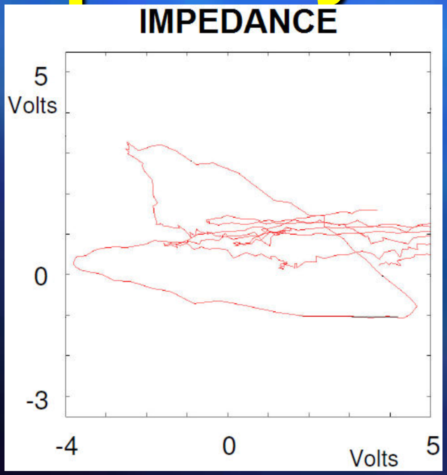
Conclusions

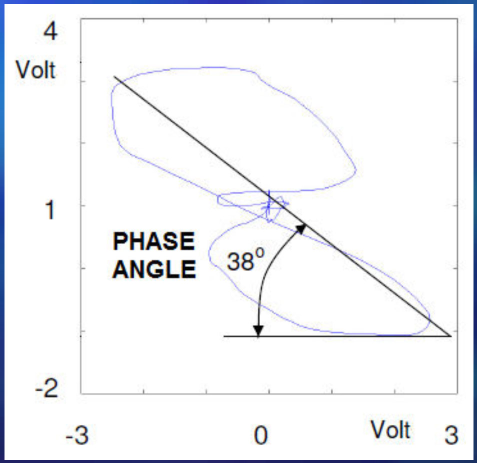
- The data acquisition instrumentation noise, although it may distorts a lot the signal, it is not difficult to be removed as it is a high frequency noise.



Conclusions

- ✈ The material noise is originated in the magnetic properties variations caused for example by the manufacturing process of the tube.
- ✈ The Eddy Current Lissajous figure is completely distorted by this noise.





Conclusions

- ✈ The probe wobble signal de-noising offers reliable results as it allows an efficient removal of noise, maintaining the essential signal information.
- ✈ The methodology above described is being applied in inspection automation of fuel tubes by using a Matlab software enhanced by artificial inteligence.