Finite Element Model based Optimization of Pulsed Eddy Current Excitation Rise Time

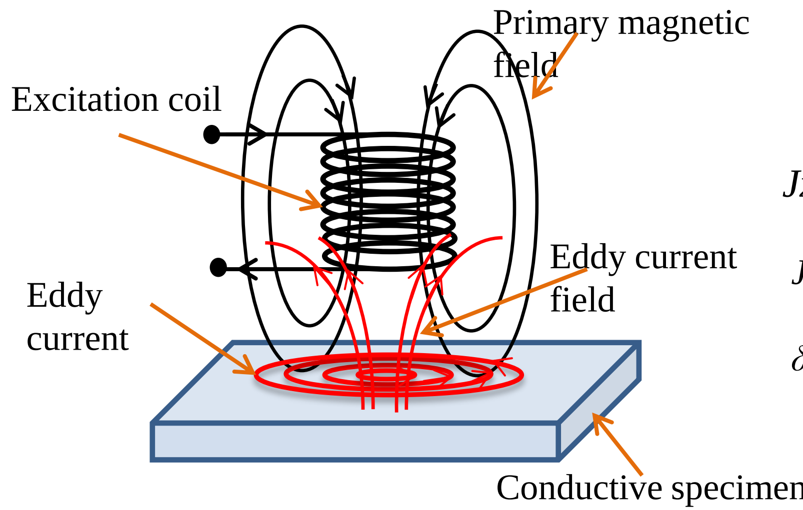
N. N. Bharadwaj, V. Arjun, B. Purnachandra Rao

Indira Gandhi Centre for Atomic Research,
Kalpakkam, India

COMSOL CONFERENCE
2015 PUNE

Eddy Current Testing

- Sinusoidal excitation
  - Single frequency content
  - Limited depth of investigation
  - For deep penetration
    - High excitation current
    - Low frequency



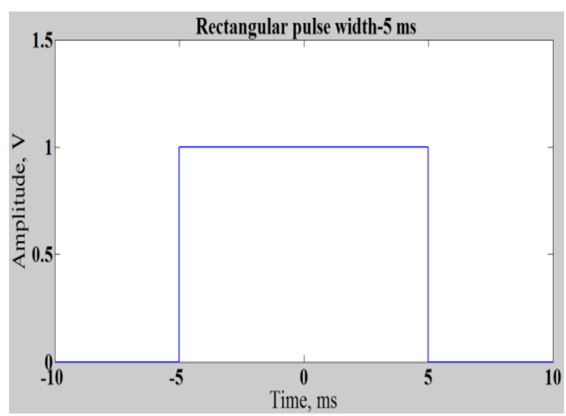
$$J_x = J_0\ e^{-x/\delta}$$

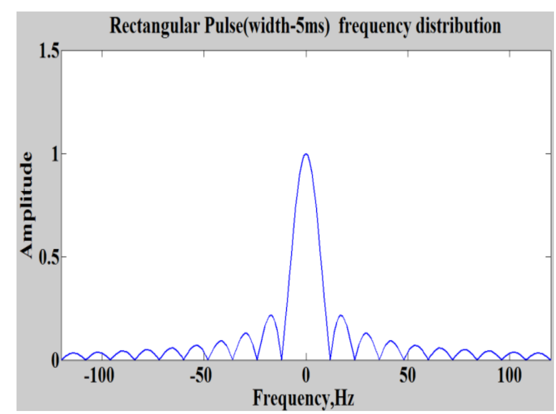
Jx - eddy current density at depth x

J_0 - eddy current density at surface

δ - skin depth = $1/(\pi\mu\sigma f)^{1/2}$

- Pulsed excitation
  - Rich in frequency content
  - Wide depth of investigation
  - short duration
  - high amplitude
  - Reduced heating





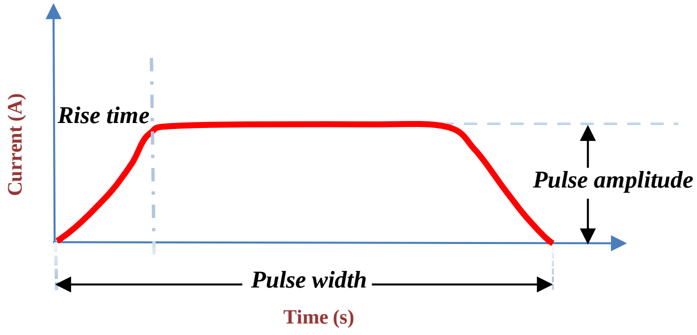
Optimisation of pulsed eddy current probe for detection of sub-surface defects in stainless steel plates

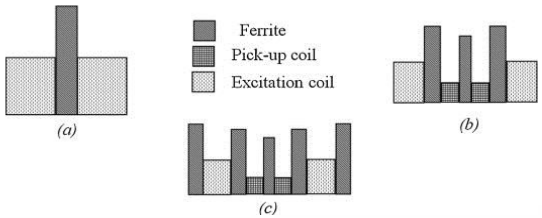
V. Arjun, B. Sasi, B. Purna Chandra Rao, C.K. Mukhopadhyay, T. Jayakumar

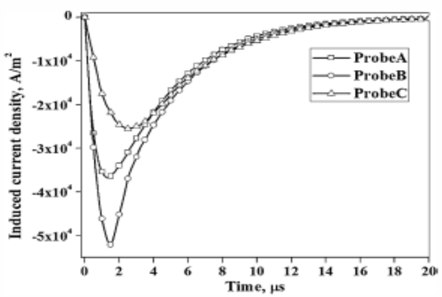
Highlights

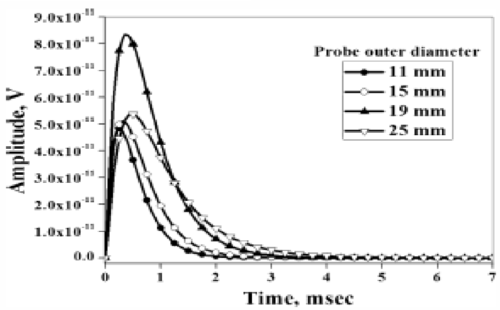
• **For effective detection of deeper defects, probe design plays a major role**.
•FEM based approach for optimizing probe configuration and dimensions.
•Send-receive type ferrite cored probe of 19mm outer diameter shows better detection sensitivity.
• Experimental study also confirms its detection sensitivity for sub-surface defects.

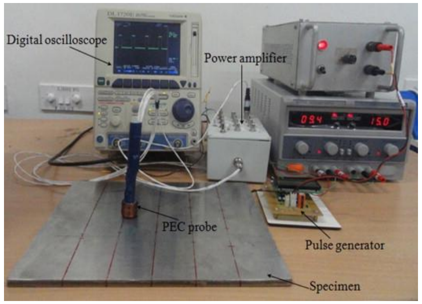
For defect detection, Excitation characteristics of the probe also play a crucial role.

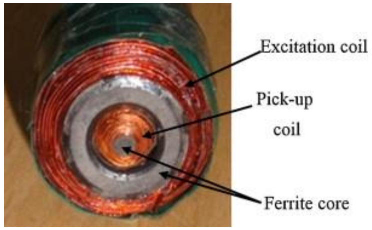






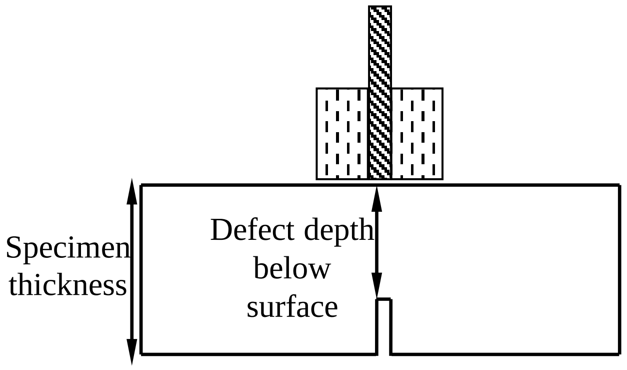




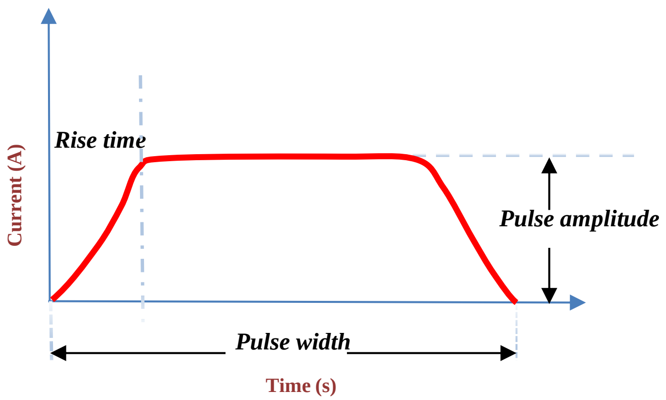


Objective

- I: FEM of PEC
  - Optimization of rise time for enhancement in detection of defects in a SS plate of 5 mm,8 mm,10 mm and 12 mm thickness.
- II: Analysis using Frequency spectrum.
- III: Study of different conductivity specimens.



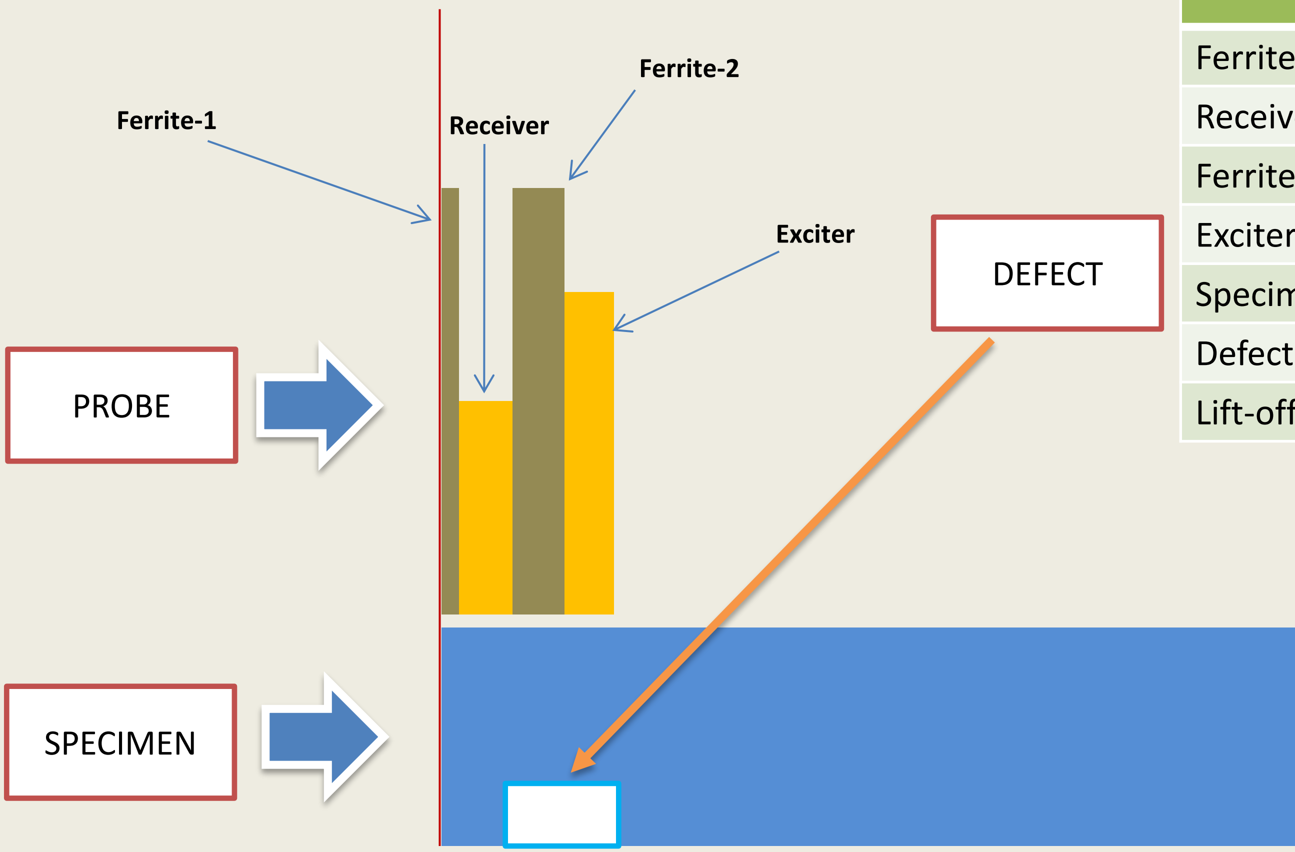
Defect detection



Exciter Signal

Modelling Study

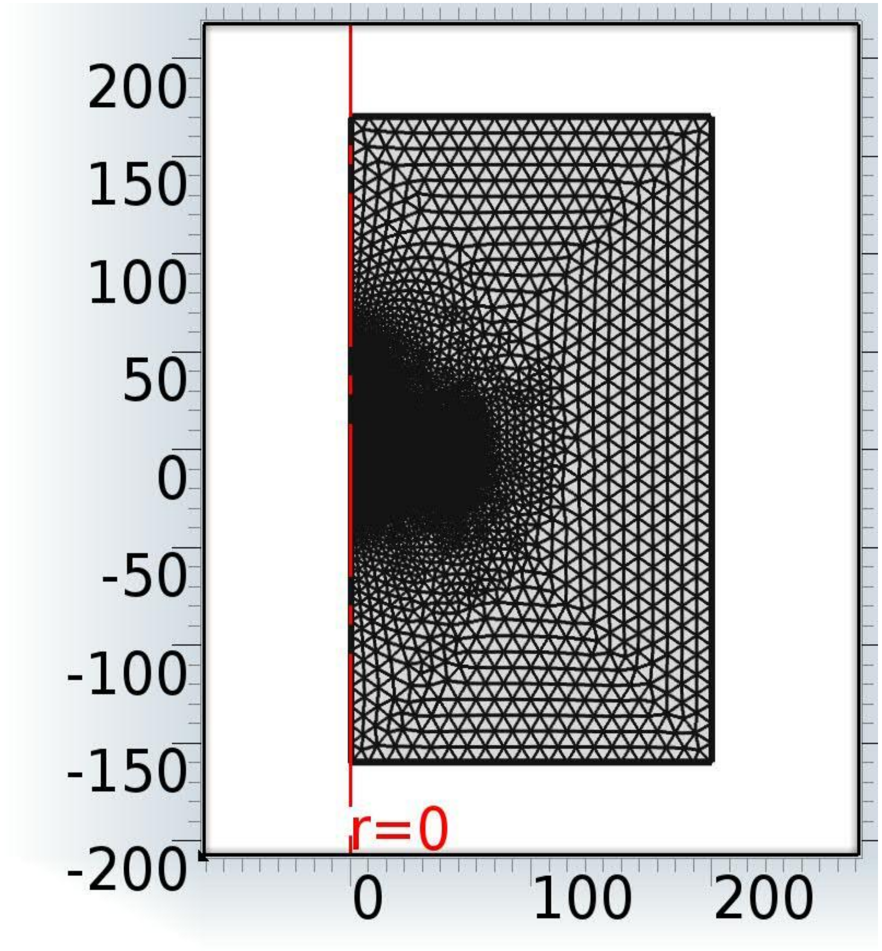
Geometry



	Height(mm)	Width(mm)
Ferrite-1	20	1
Receiver	10	3
Ferrite-2	20	3
Exciter	15	3
Specimen	Variable(5,8,10,12)	50
Defect	Variable(1-11)	5
Lift-off	0.1	-

Material	μ_r	ε_r	σ(S/m)
Ferrite	1500	1	100
Copper	1	1	6e7
Stainless steel	1	1	1.34e6
Air	1	1	5

Typical Model



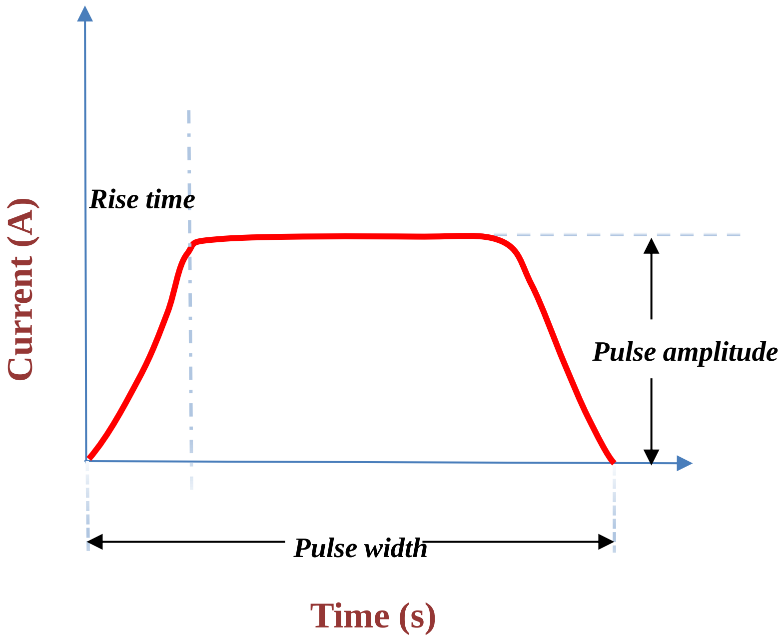
Number of meshes: 32489
Axi symmetry
Magnetic insulation
COMSOL Software
Magnetic Field domain
Transient time solving tool

Maxwell's Equation:

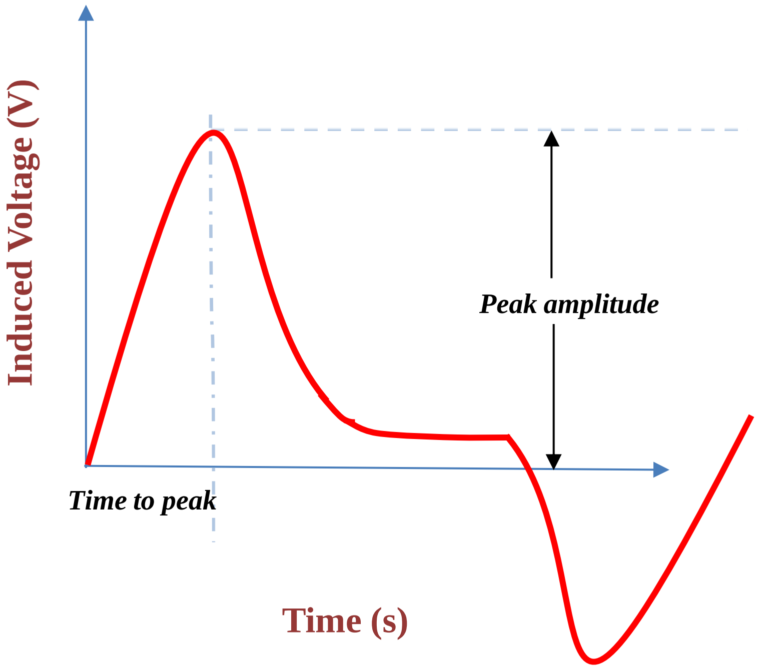
$$\nabla^2 \overline{A} = \mu\sigma \frac{\partial \overline{A}}{\partial t} + \mu\sigma \nabla V - \mu \overline{J}_s$$

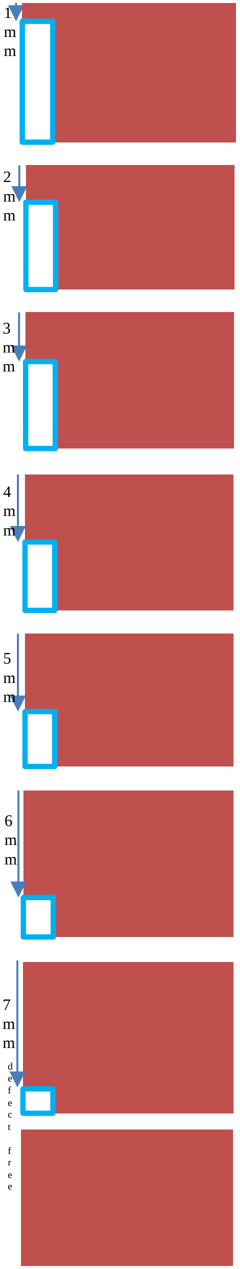
Simulation Results

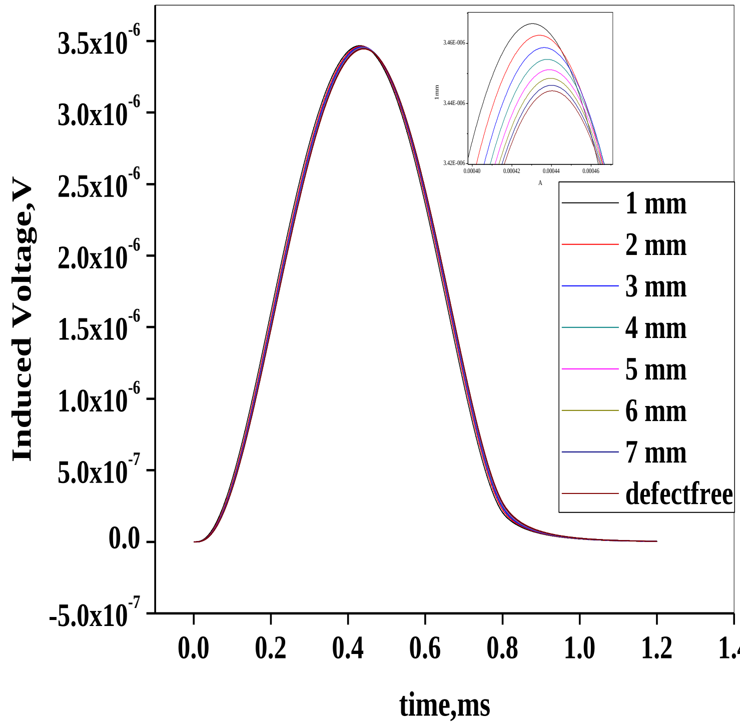
Exciter signal



Receiver signal







Detection Parameters

1. **Peak amplitude(pa)**
2. **Time to peak(ttp)**

→ Receiver Signal

Parameter to be optimised

Rise time → Exciter Signal

As defect depth increases, peak amplitude decreases, time to peak increases and the difference (in pa & ttp) between successive defects also decreases.

So, the effect of rise time on the difference(in pa & ttp) is studied for enhanced defect detection.

Rise Time Study

SS plate (2.23 % IACS)

- In this study, pulse amplitude is fixed at 0.5 A.
- Pulse width is fixed at 150 % of rise time.
- Rise time is varied to examine the sensitivity parameters.
- Rise times considered:

5 mm plate: 100 μs, 200 μs, 400 μs, 800 μs, 900 μs.

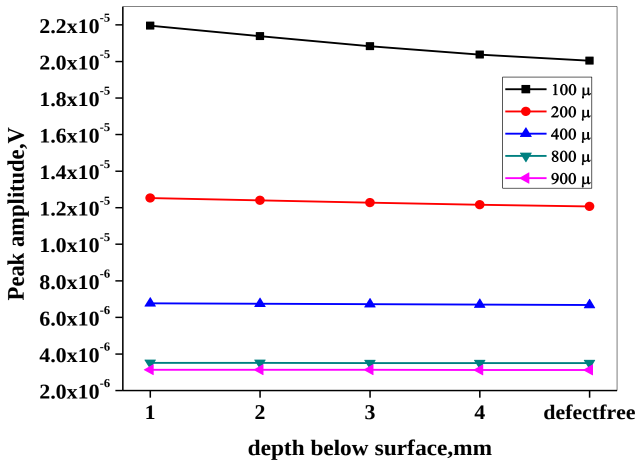
8 mm plate: 200 μs, 400 μs, 800 μs, 900 μs, 1000 μs.

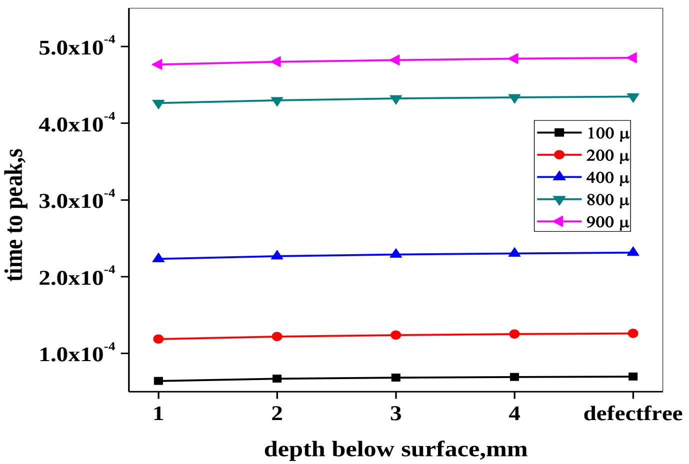
10 mm plate: 800 μs, 900 μs, 1000 μs, 1200 μs, 1500 μs.

12 mm plate: 1250 μs, 1500 μs, 1750 μs, 2000 μs, 2250 μs.

5 mm thick plate

Peak amplitude and time to peak variation with defect depth at different rise times

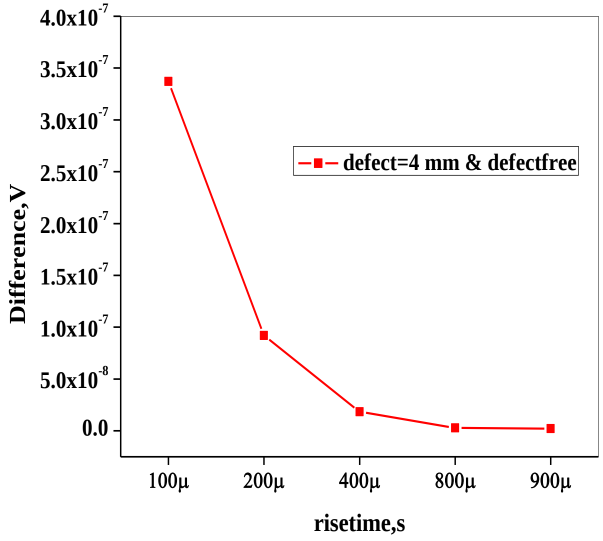


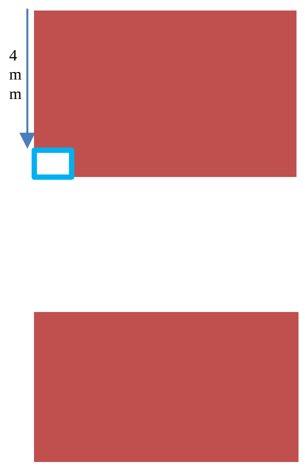


Peak amplitude reduces with increase in rise time.
Time to peak increases with increase in rise time.

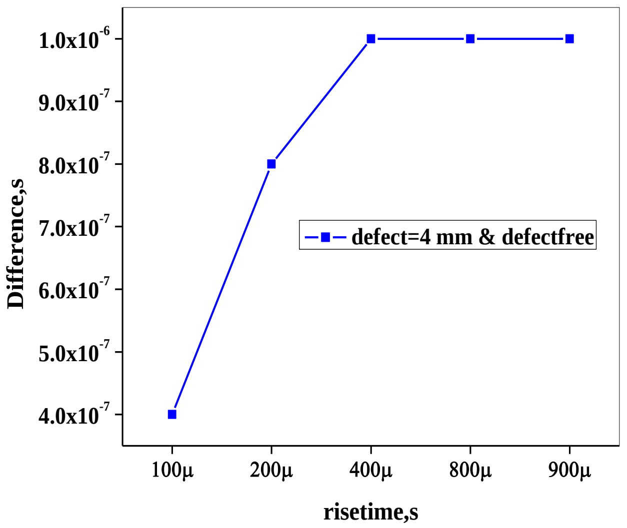
Difference variation with rise time

(Defect at 4 mm and defect-free plate)





Defect-free

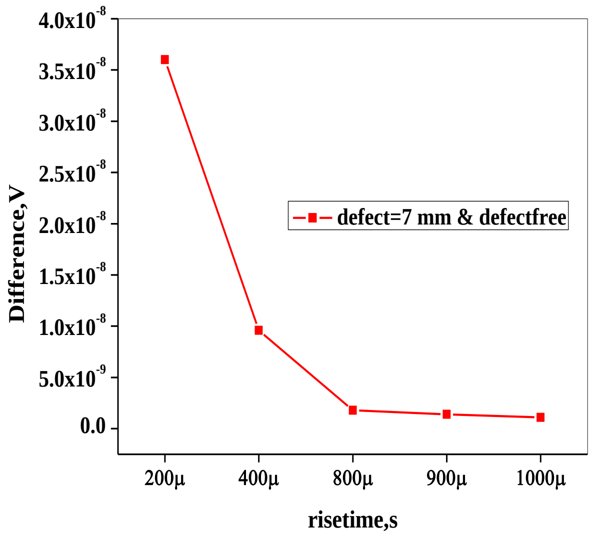


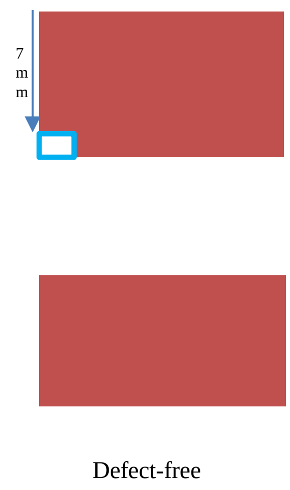
Good difference is obtained in peak amplitude and time to peak at rise time of 400 µs.

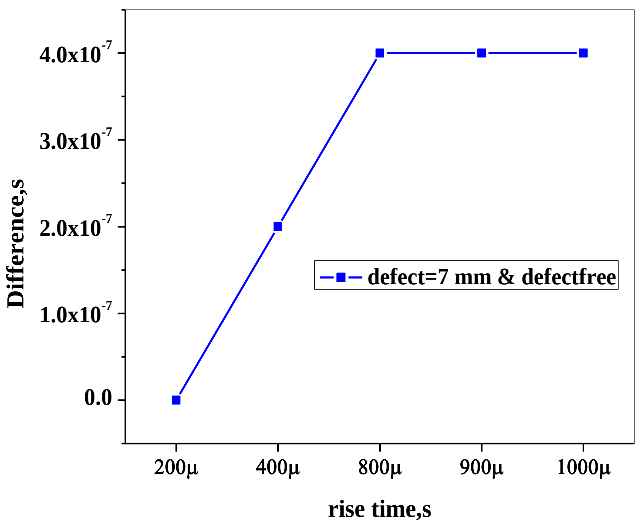
8 mm thick plate

Difference variation with rise time

(Defect at 7 mm and defect-free plate)





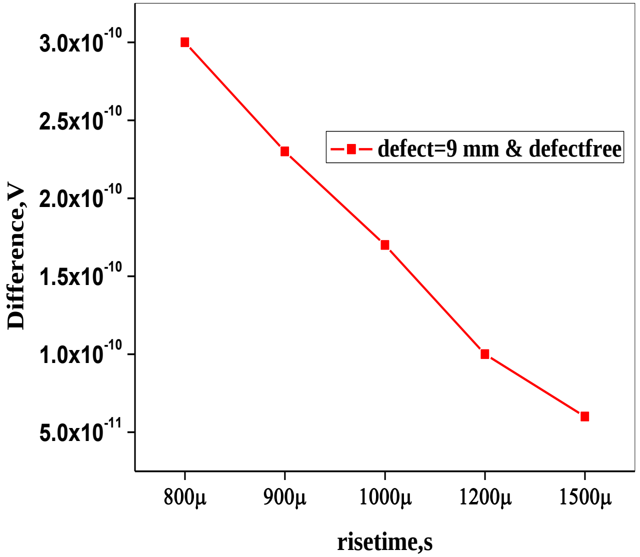


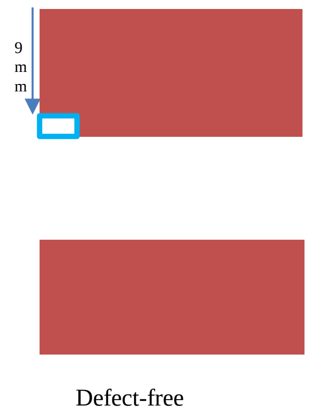
Good difference is obtained in peak amplitude and time to peak at rise time of 800 µs.

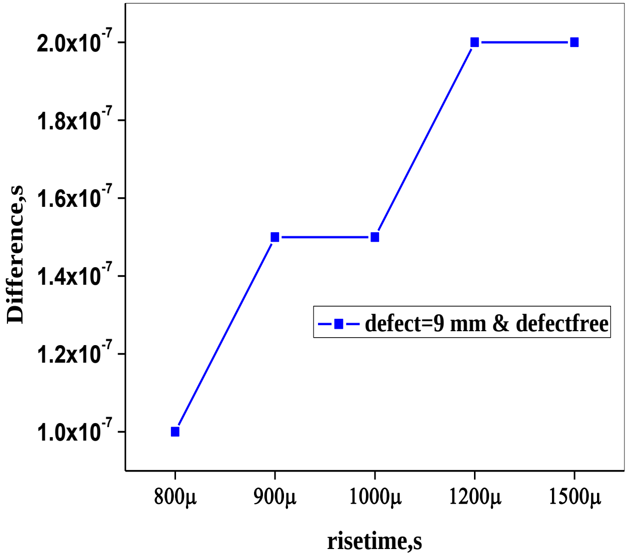
<u>10 mm thick plate</u>

Difference variation with rise time

(Defect at 9 mm and defect-free plate)





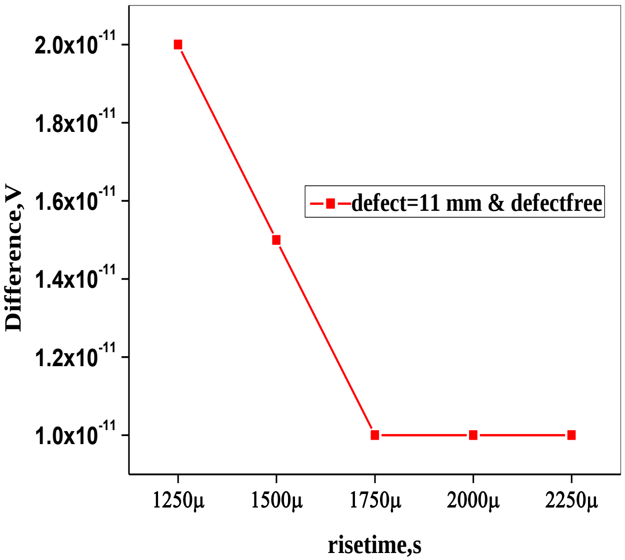


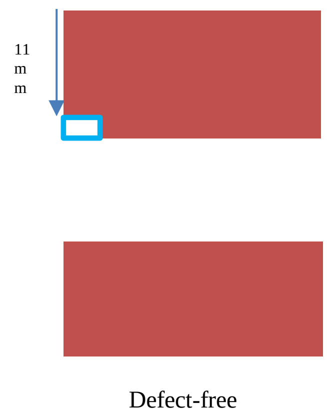
Good difference is obtained in peak amplitude and time to peak at rise time of 1200 µs.

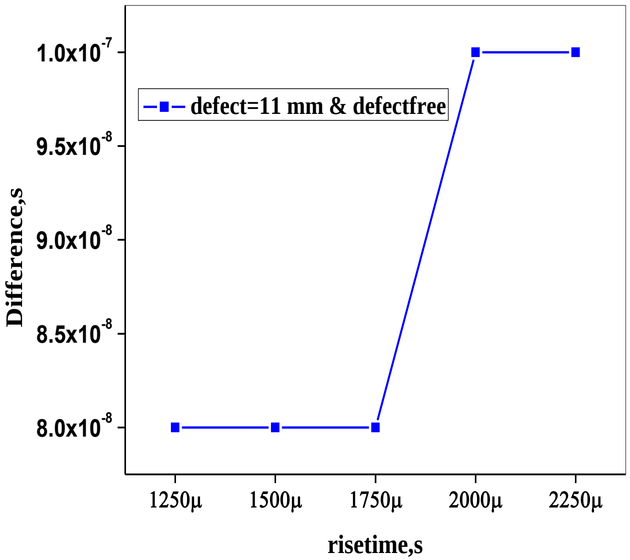
12 mm thick plate

Difference variation with rise time

(Defect at 11 mm and defect-free plate)

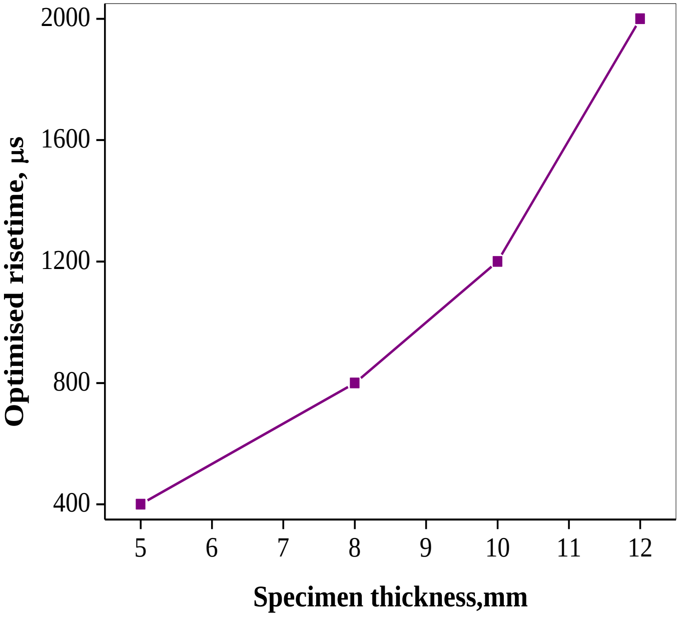






Good difference is obtained in peak amplitude and time to peak at rise time of 2000 µs.

Optimised Risetime variation with specimen thickness



As specimen thickness increases, optimised risetime also increases.

Time Frequency Analysis

- Used to find dominant frequency, time of occurrence of dominant frequency and its energy.

5 mm

Rise time(μs)	Fmax(Hz)	Emax(J)	Tmax(μs)
100	3906.3	2.5130e-4	74.6
200	2256.3	2.0891e-4	129.2
400	1302.1	1.6182e-4	232.8
800	680.8	1.1896e-4	435.4
900	611.25	1.1255e-4	485.6

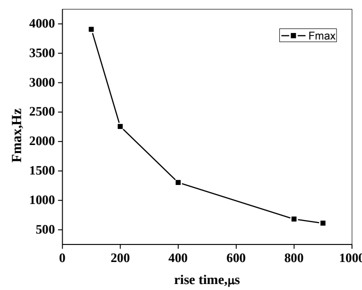
8 mm

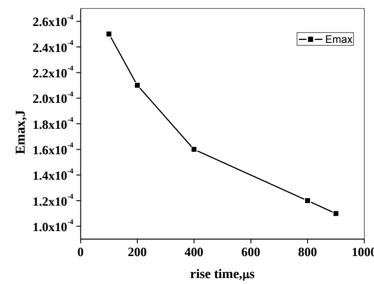
Rise time(μs)	Fmax(Hz)	Emax(J)	Tmax(μs)
200	2170.1	1.9795e-4	131.4
400	1223.1	1.5694e-4	`237.2
800	673.85	1.1732e-4	441.8
900	599.2	1.1123e-4	492.4
1000	543.24	1.0599e-4	542.8

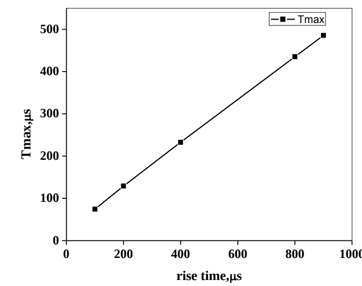
10 mm

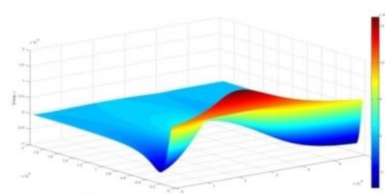
Rise time(μs)	Fmax(Hz)	Emax(J)	Tmax(μs)
800	662.77	5.8227e-5	443.75
900	592.48	5.5261e-5	495.4
1000	538.09	5.2695e-5	545.2
1200	454.66	4.8463e-5	646
1500	365.44	4.3629e-5	797

12mm:-2000 μs-279.01Hz,2.4002e-4J,.0011s.

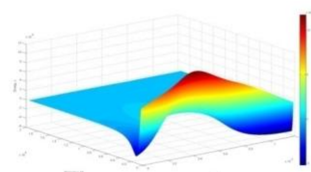






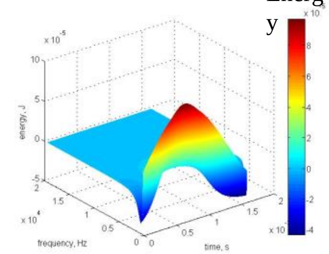


400 μs



800 μs

Energ
y



1200 μs

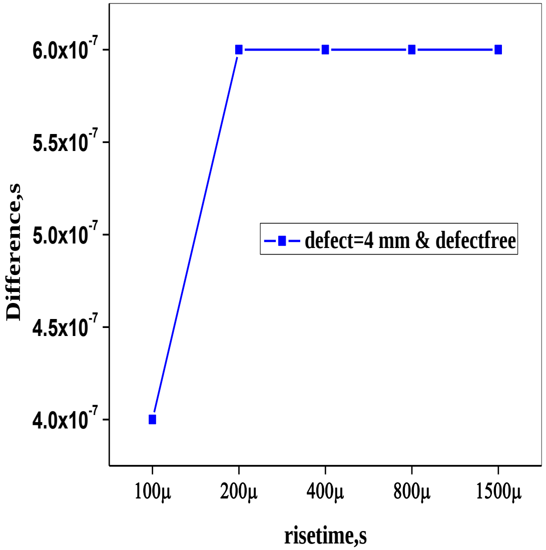
Correlation of rise time with specimen thickness

Thickness	Rise time	Dominant frequency	Skin depth $1/(\pi\mu\sigma f)^{1/2}$	
5 mm	400 µs	1302.1 Hz	11.97 mm	2.39*thickness
8 mm	800 µs	673 Hz	16.64 mm	2.08*thickness
10 mm	1200 µs	454.6 Hz	20.25 mm	2.03*thickness
12 mm	2000 µs	279 Hz	25.85 mm	2.15*thickness

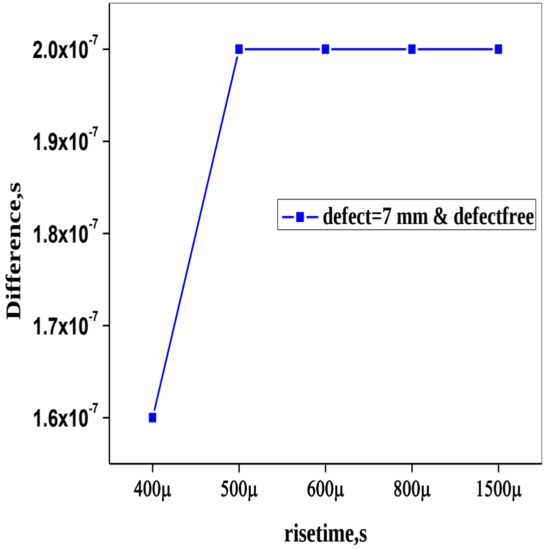
For any specimen thickness, the optimised rise time has dominant frequency that has skin depth at twice the specimen thickness.

Hastelloy Plate (1.5 % IACS)
Difference variation with rise time

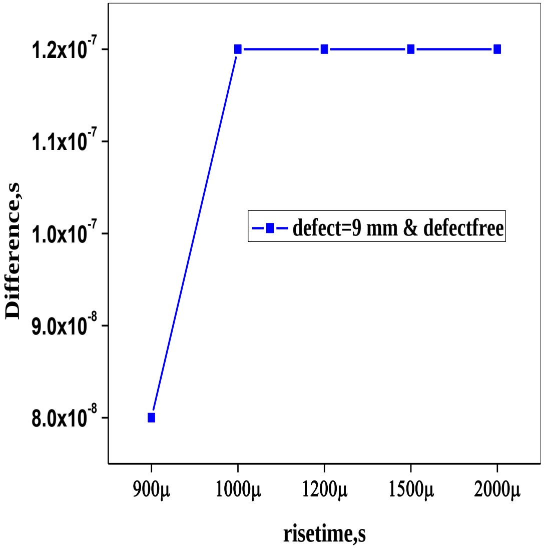
5 mm



8 mm



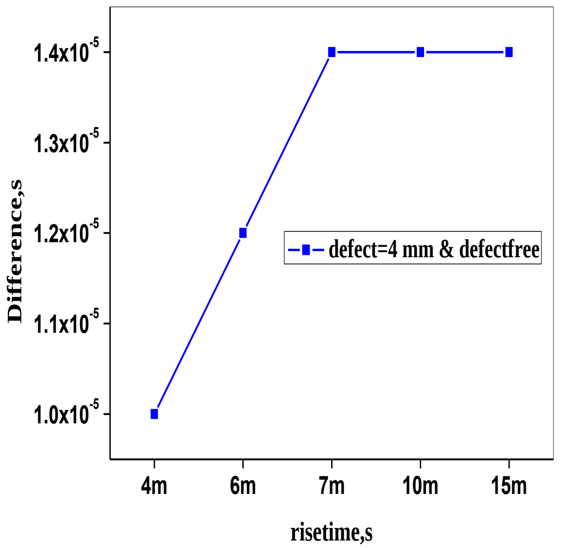
10 mm



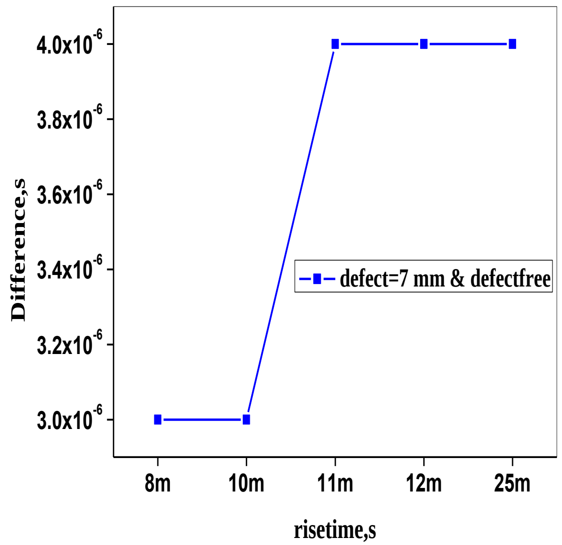
Optimum rise times obtained are 200 µs, 500 µs and 1000 µs for 5 mm, 8 mm and 10 mm plates respectively.

Aluminium plate (30 % IACS)
Difference variation with rise time

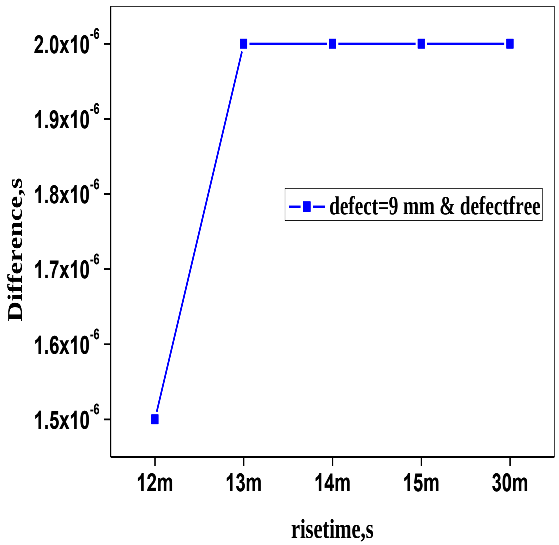
5 mm



8 mm



10 mm



Optimum rise times obtained are 7 ms, 10 ms and 13 ms for 5 mm, 8 mm and 10 mm plates respectively.

Empirical Relation

Optimum rise time = $p_{00} + p_{10} * T + p_{01} * C + p_{20} * T^2 + p_{11} * T * C + p_{02} * C^2$

(T – Thickness; C – Conductivity)

p_{00} = -971.3;
p_{10} = 202.3;
p_{01} = 29.47;
p_{20} = -7.778;
p_{11} = 37.44;
p_{02} = 0.8302.

Specimen	Conductivity(% IACS)	Thickness (mm)	Actual Rise time (µs)	Empirical Rise time(µs)	Error(%)
Hastelloy	1.5	5	200	172.623	13.69
		8	500	644.661	-28.93
		10	1000	881.573	11.84
Stainless Steel	2.23	5	400	333.053	16.74
		8	800	887.084	-10.89
		10	1200	1178.659	1.78
Aluminium	30	5	7000	7093.03	1.33
		8	11000	10766.19	2.13
		10	13000	13137.18	-1.06

Summary

- Pulsed eddy current rise time has been optimized for enhanced sub-surface defect detection in SS plate, Hastelloy plate and Aluminium plate of thickness 5 mm, 8 mm, 10 mm and 12 mm.
- An empirical relation is given for optimum pulse rise time as a function of specimen thickness and conductivity.
- Further, time-frequency analysis of the excitation signals revealed that the optimized rise time has dominant frequency that has skin depth at twice the specimen thickness.

THANKYOU