



The Phased Array Company

Cours École Centrale de Nantes - Option DataSIM

Contrôle non destructif par ultrasons Généralités, imagerie et applications

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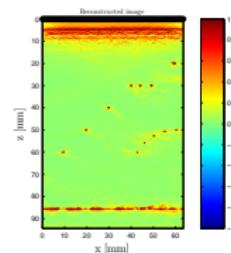
Nantes, le 4 Février 2022

Société et activités

www.thephasedarraycompany.com



- Basée en France, USA, Japon
- 30 personnes
- Activités à l'internationale (Europe, USA, Canada, Japon, etc.)
- Conception d'électroniques pour le CND par ultrasons
- Développement de logiciels
- Recherche appliquée (électronique, traitement du signal et de l'image, acoustique)





Sommaire

1 Généralités CND

- Le contrôle non destructif
- Domaines d'application du CND
- Méthodes
- Ultrasons

2 CND par ultrasons

3 Le CND avec des sondes multi-éléments

4 Imagerie avancée

5 Application réelle : Inspection de soudures de pipelines

6 Fin

Le contrôle non destructif (CND)

- Le principe du **contrôle non destructif** est d'inspecter des pièces sans les endommager
 - Le but du CND est
 - ① de répondre à une démarche qualité
 - ② de contrôler l'intégrité des pièces
 - ③ de prévenir des situations dangereuses



Qualité



Intégrité



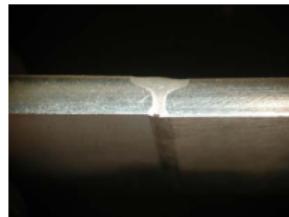
Sécurité

- Le CND est devenu incontournable dans l'industrie
 - Marché est en pleine croissance ~ Chiffre d'affaire **7 Milliards d'euros** prévu en 2020



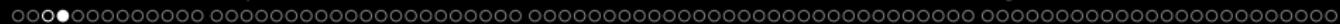
Domaines d'application du CND

- Production :



- Transport de matières premières (gaz, pétrole, eau)





Domaines d'application du CND

- Génération d'énergie



- Transports



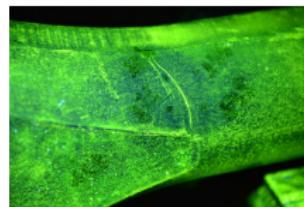
Méthodes de CND



Contrôle visuel



Ressuage



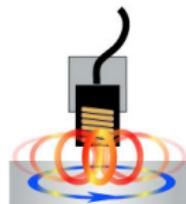
Magnétoscopie



Radiographie



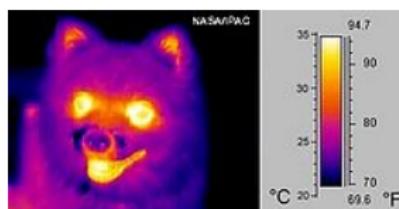
Ultrasons



Courants de Foucault

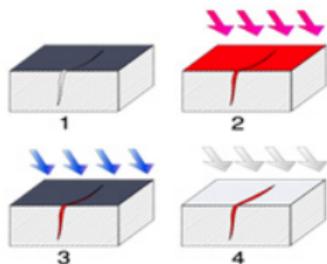


Émission acoustique



Infrarouge

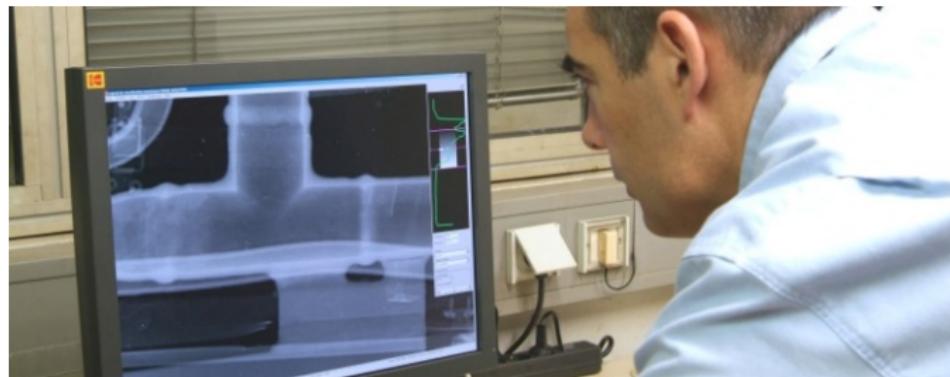
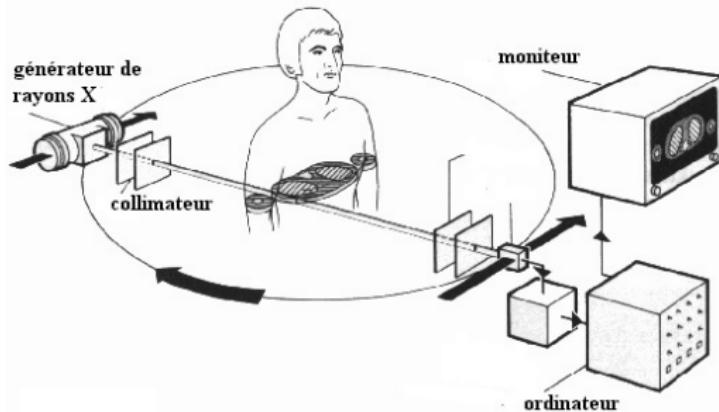
Ressuage



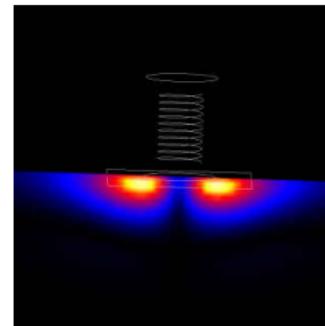
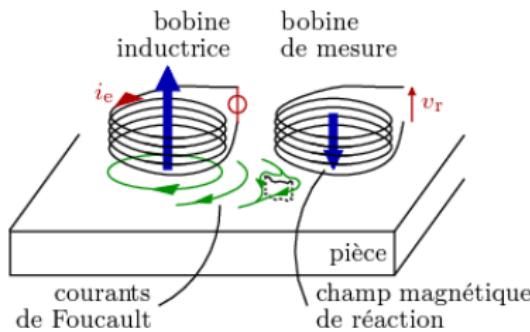
1. Coupe d'un matériau comportant un défaut débouchant type fissure
2. La surface du matériau est enduite de pénétrant.
3. Le pénétrant est éliminé par lavage.
4. Le matériau est enduit de révélateur. le défaut devient visible.



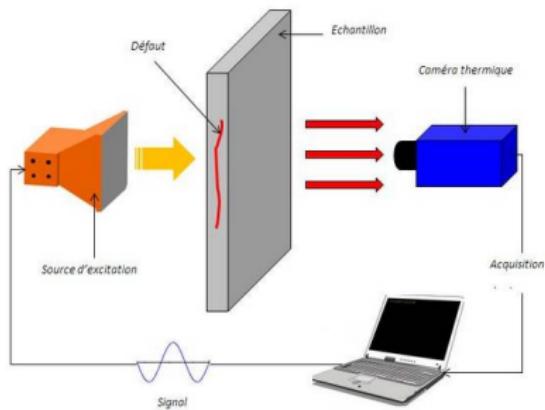
Radiographie



Courants de Foucault



Thermographie



Principe de la thermographie infrarouge active



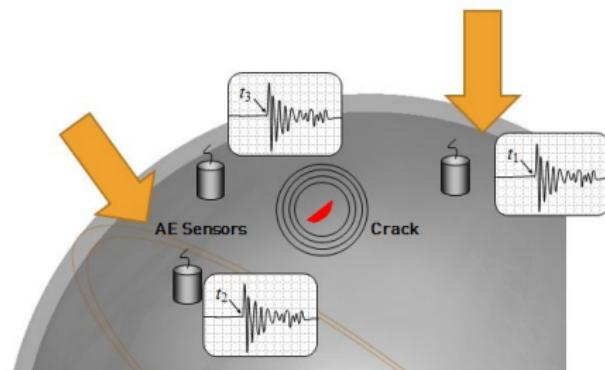
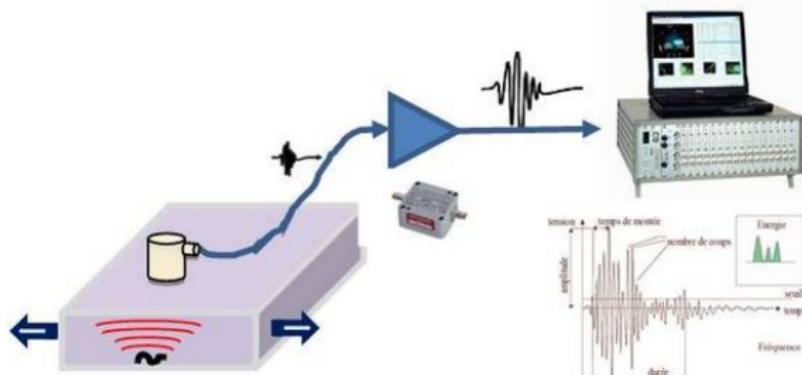
Image visible



Image infrarouge

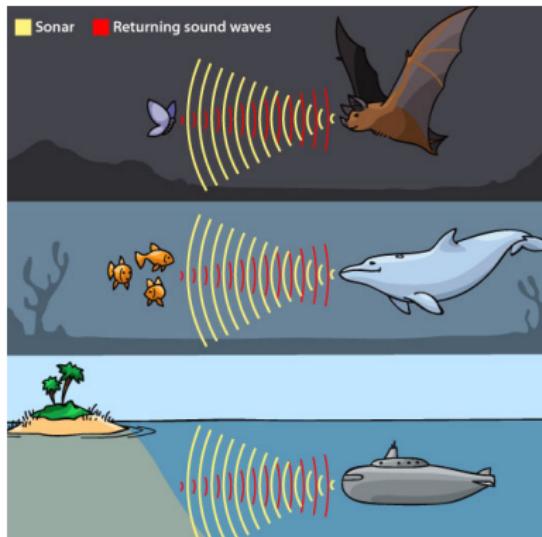
Contrôle de défaut de calorifuge par thermographie sur un équipement sous pression

Émission Acoustique

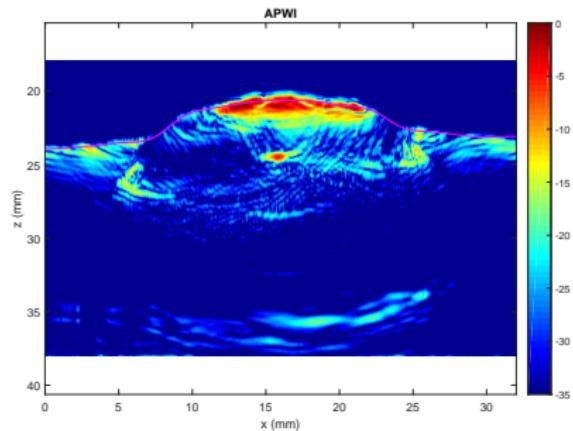




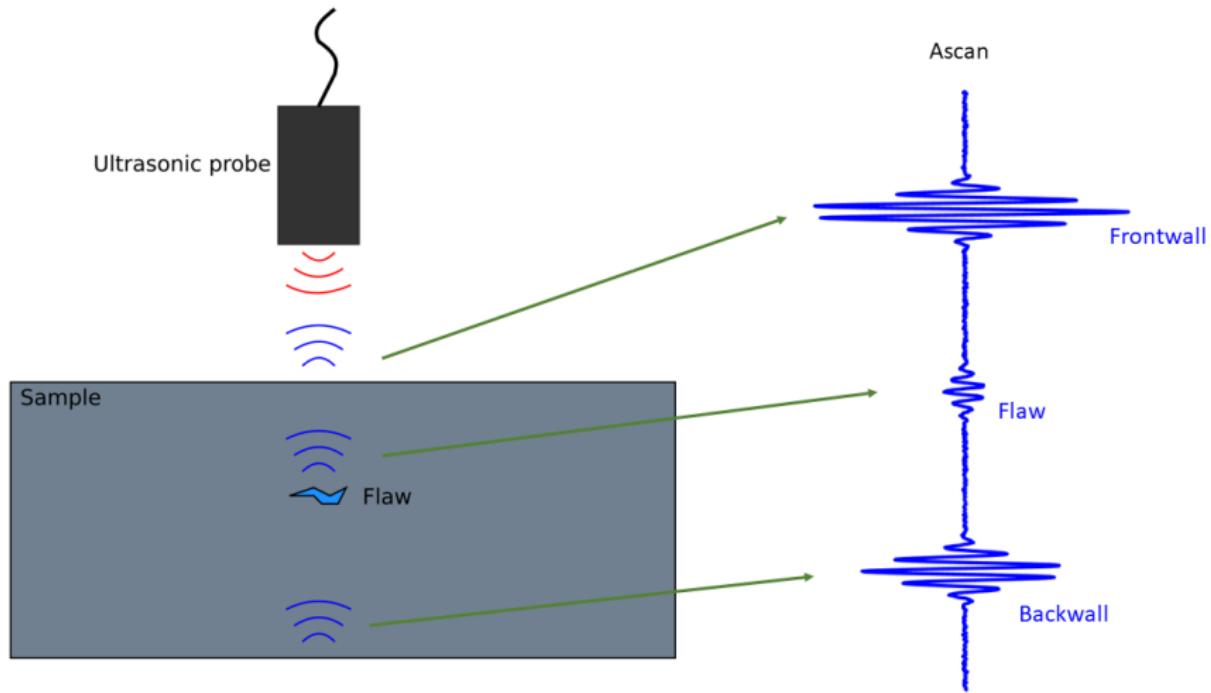
Contrôle par ultrasons



Contrôle par ultrasons



Contrôle par ultrasons



Sommaire

1 Généralités CND

2 CND par ultrasons

- Qu'est-ce qu'une onde acoustique ?
- Types d'ondes
- Propriétés des ondes acoustiques
- Transducteurs
- Directivité
- Champ proche
- Acoustique
- Modalités d'inspection
- Ascan, Bscan, Cscan, Dscan

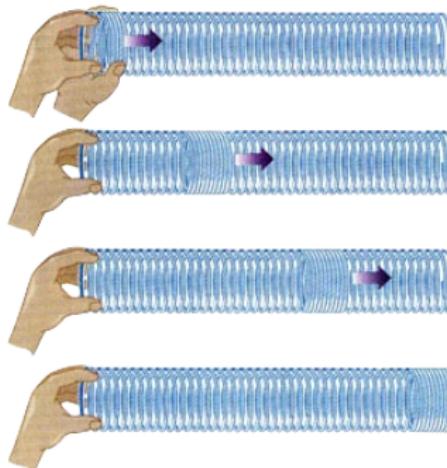
3 Le CND avec des sondes multi-éléments

4 Imagerie avancée

5 Application réelle : Inspection de soudures de pipelines

Qu'est-ce qu'une onde acoustique ?

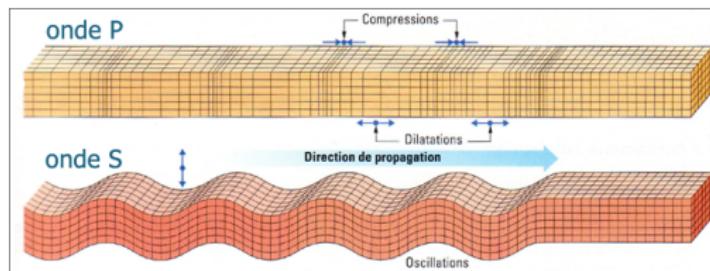
- Perturbation locale qui provoque une propagation d'énergie
- Induit un déplacement des particules \leadsto changement de pression et de vitesse des particules
- Fonction de l'espace et du temps : $p(x, y, z, t)$



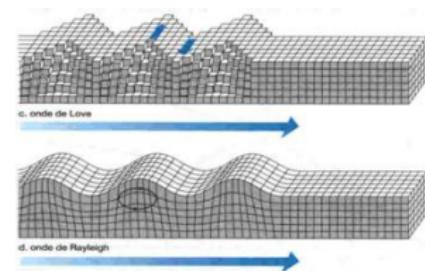
Types d'ondes

2 type d'ondes :

- Ondes de volume : très utilisé en CND
- Ondes de surface : marginal en CND (applications plaques)



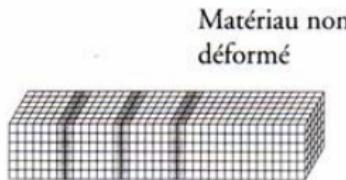
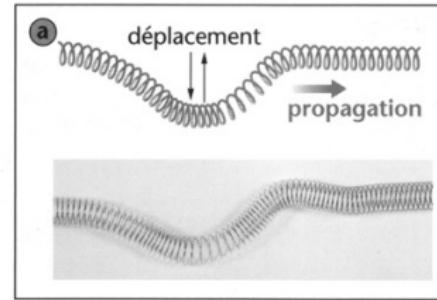
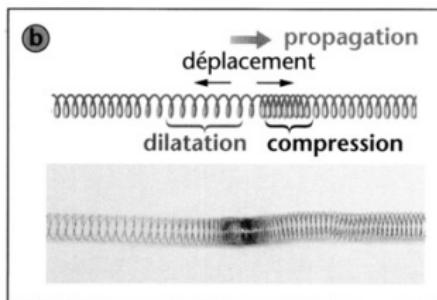
Ondes de volume



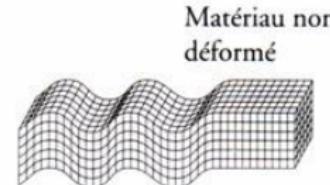
Ondes de surface

Types d'ondes

- Ondes volumiques :
 - Ondes longitudinales
 - Ondes transversales

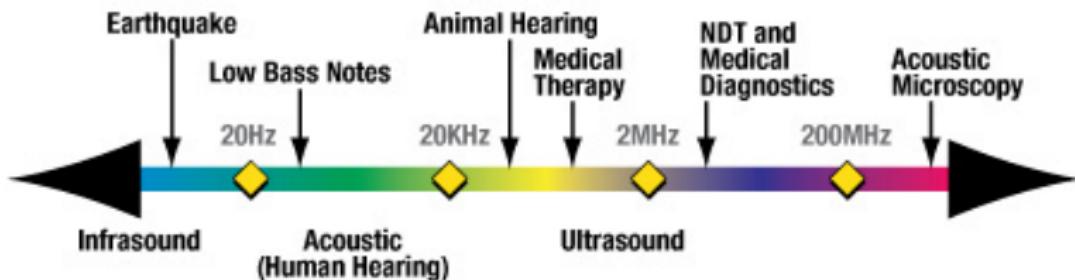


Sens de propagation de l'onde
Schéma A



Sens de propagation de l'onde
Schéma B

Fréquences

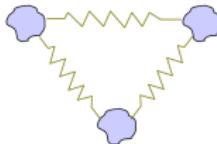


- <20 Hz : Infrasons
- 20 Hz-20 kHz : sons (audibles)
- 20 kHz-1 GHz : **ultrasons**
- >1 GHz : hypersons

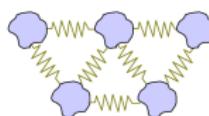
~ CND : 0.5-20 MHz

Vitesse des ondes

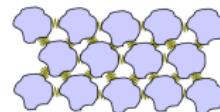
GAZ



LIQUIDE



SOLIDE



$$V_{\text{air}} = 340 \text{ m/s}$$

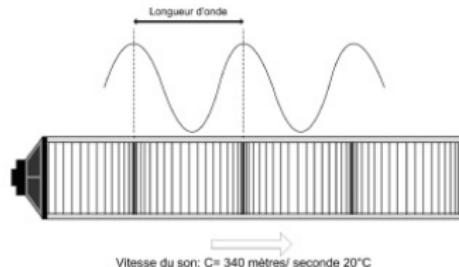
$$V_{\text{eau}} = 1500 \text{ m/s}$$

$$V_{\text{métal}} \cong 6000 \text{ m/s}$$

Matériaux	c_L	c_T
Air	340	—
Eau	1480	—
Plexiglas	2800	—
Acier	5900	3240
Aluminium	6320	3130

Table – Vitesse des ondes en m/s dans différents milieux

Longueur d'onde



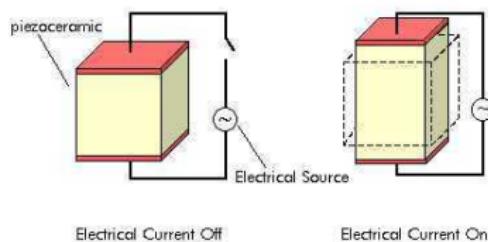
- La longueur λ d'onde est la distance entre deux nœuds
- $\lambda = \frac{c}{f}$ (c : vitesse, f : fréquence)

Matériau	1 MHz	5 MHz	10 MHz
Air	0.34	0.07	0.03
Eau	1.48	0.30	0.15
Plexiglas	2.80	0.56	0.28
Acier	5.90	1.18	0.59
Aluminium	6.32	1.26	0.63

Table – Longueurs d'onde en mm dans différents milieux (ondes longitudinales)

Transducteurs

- Plusieurs manières de générer une onde mécanique
- Plus répandue : Effet piézoélectrique
- Cristaux soumis à une tension électrique génèrent une vibration mécanique (et inversement)

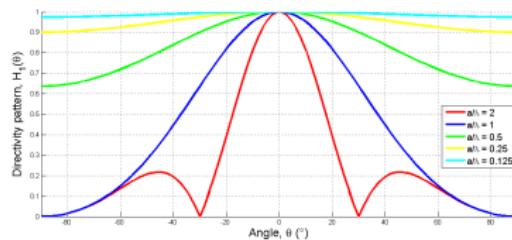
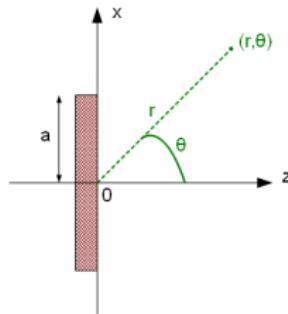


sondes mono-élément

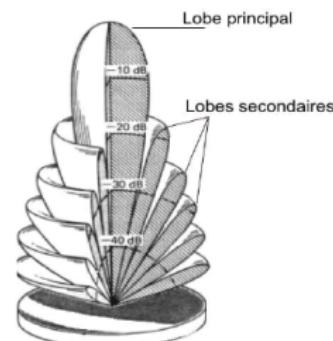


sondes multi-éléments

Directivité

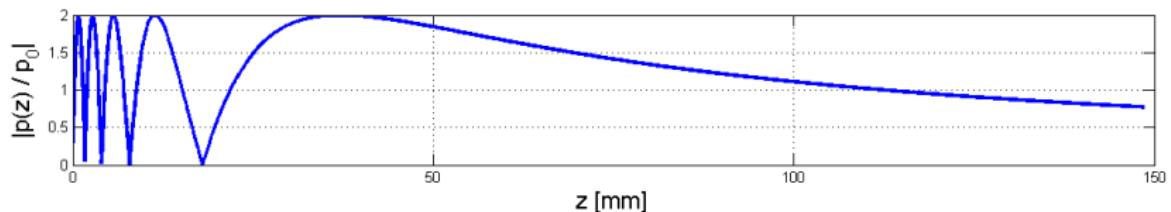
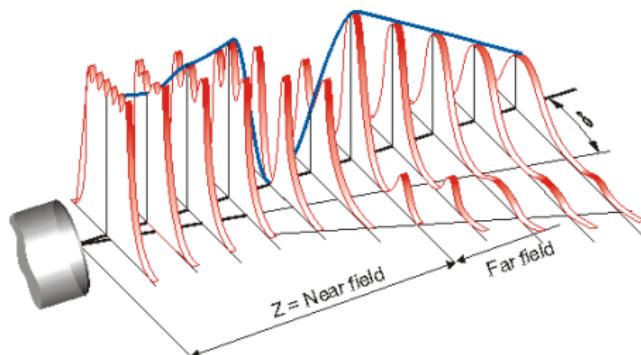


Angle de divergence :
 $\theta_{\text{div}} = \arcsin(0.61 \frac{\lambda}{a})$



► ANIMATIONS

Champ proche/champ lointain



$$z_{NF} = \frac{a^2}{\lambda} \quad (1)$$

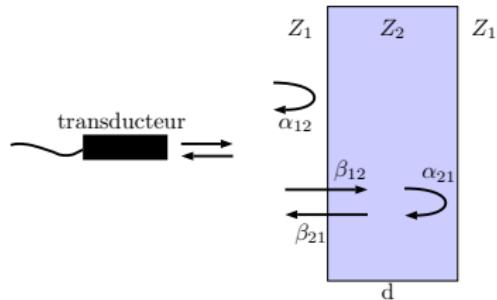
Impédance acoustique

Impédance acoustique : $Z = \rho c$

Matériau	ρ (kg/m ³)	c_L (m/s)	Z (Pa.s/m)
Air	1.2	340	408
Eau	1000	1480	1.48 M
Plexiglas	1180	2800	3.30 M
Acier	7850	5900	46.31 M
Aluminium	2700	6320	17.06 M

Table – Impédances acoustiques (ondes longitudinales)

Coefficients de réflexion et de transmission

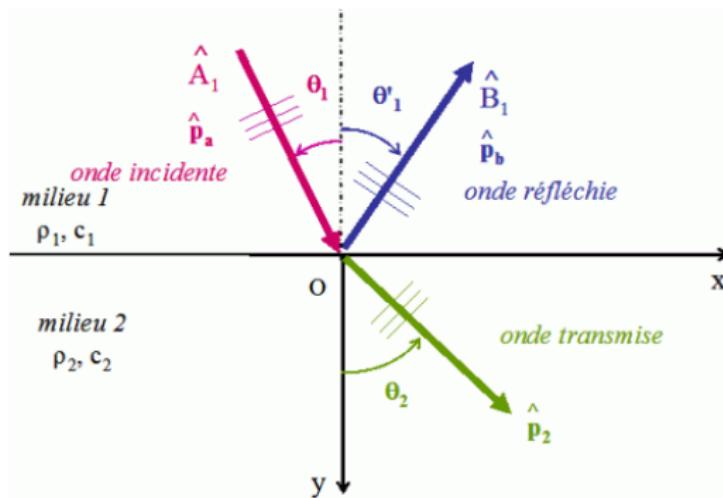


- Coefficient de réflexion : $\alpha_{ij} = \frac{(Z_j - Z_i)^2}{(Z_i + Z_j)^2}$
- Coefficient de transmission : $\beta_{ij} = 1 - \alpha_{ij} = \frac{4Z_i Z_j}{(Z_i + Z_j)^2}$

Matériau 1	Matériau 2	α_{12}	β_{12}
Air	Air	0.00000	1.00000
Air	Eau	0.99890	0.00110
Air	Acier	0.99996	0.00004
Eau	Acier	0.87997	0.12003
Eau	Aluminium	0.70624	0.29376

Table – Coefficients de réflexion et de transmission (ondes longitudinales)

Loi de Snell-Descartes

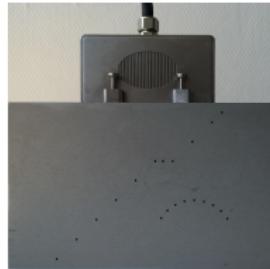


Loi de Snell-Descartes :

- Réflexion : $\theta_1 = \theta'_1$
- Transmission :
$$\frac{\sin(\theta_1)}{c_1} = \frac{\sin(\theta_2)}{c_2}$$

Modalités d'inspection

Contact



Immersion



Dans l'air



Contact avec sabot rigide

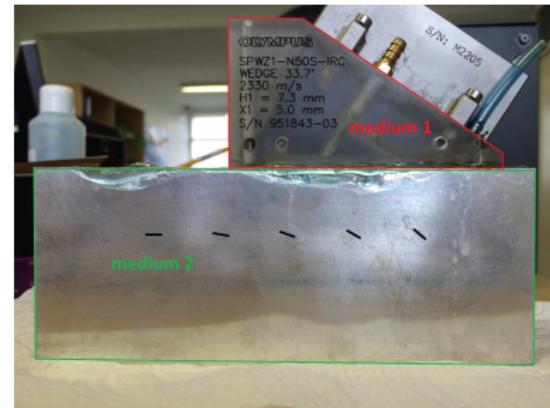


Contact avec sabot à eau



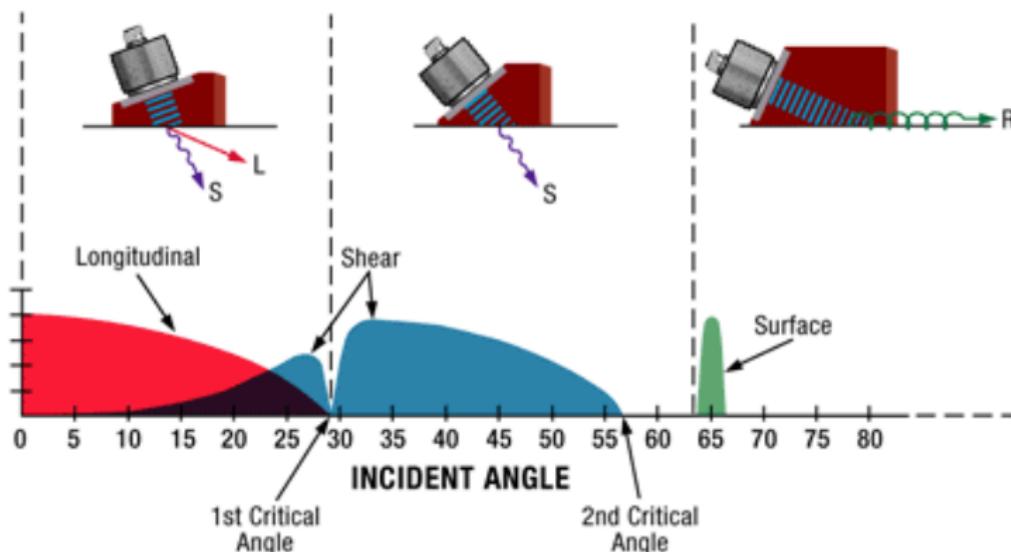
Inspection avec Sabot

- Tir avec angle (génération d'ondes transversales ou d'ondes de surface)
- Surface non accessible
- Visualisation de défauts très orientés (fissures)
- Application typique : **contrôle de soudure**

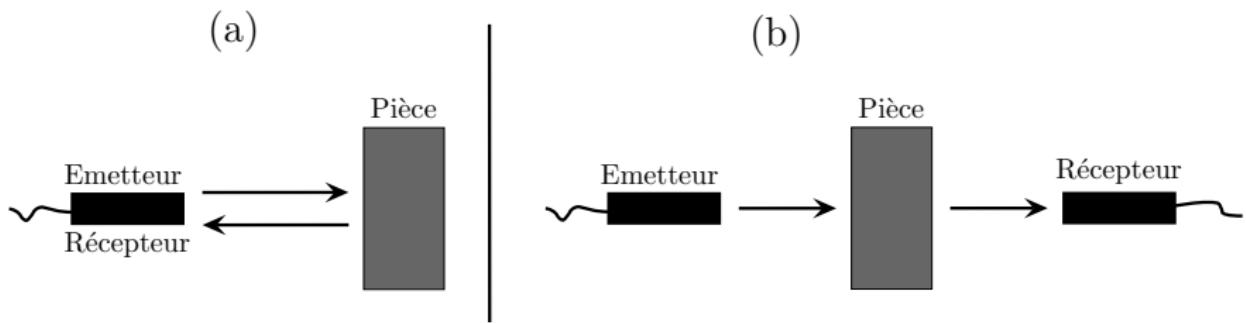


Inspection avec Sabot

RELATIVE AMPLITUDE OF WAVE MODES



Pulse-écho/transmission

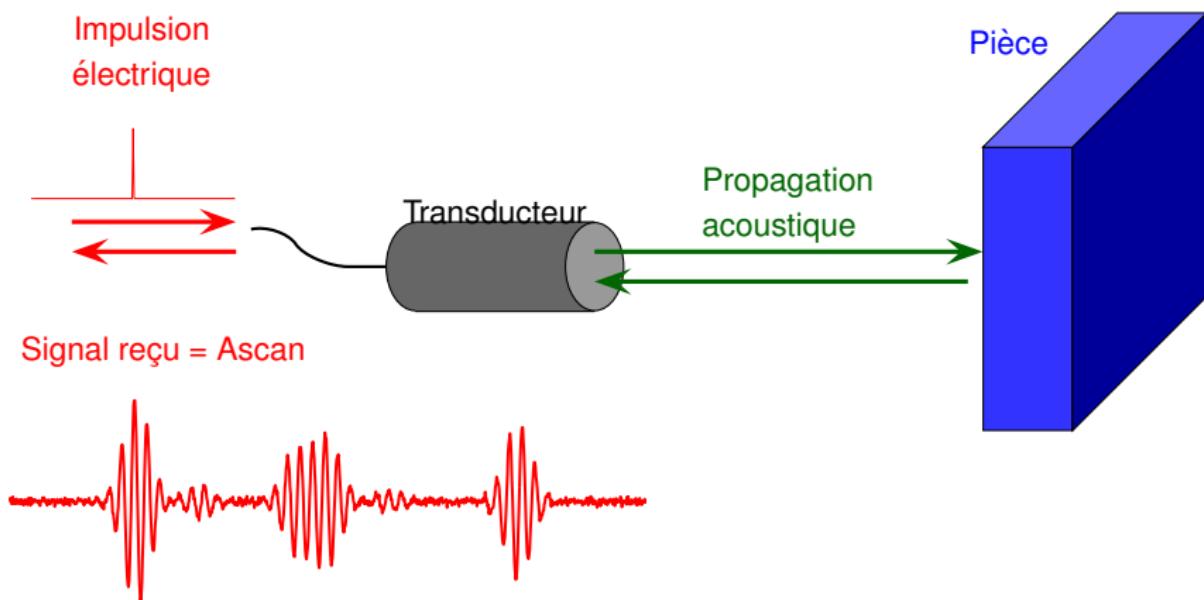


Pulse-écho



Transmission

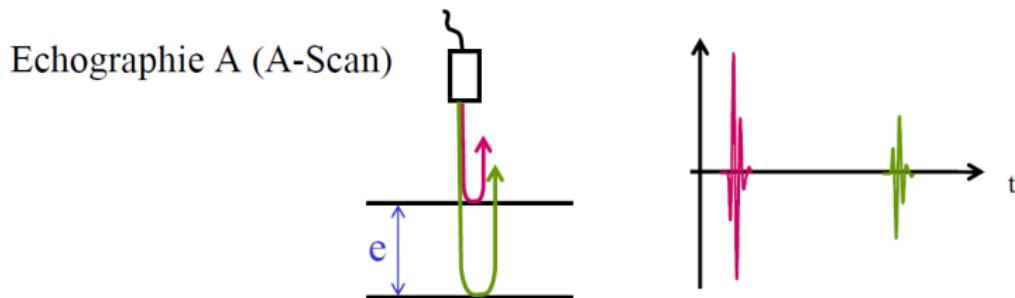
Signal de base : Ascan



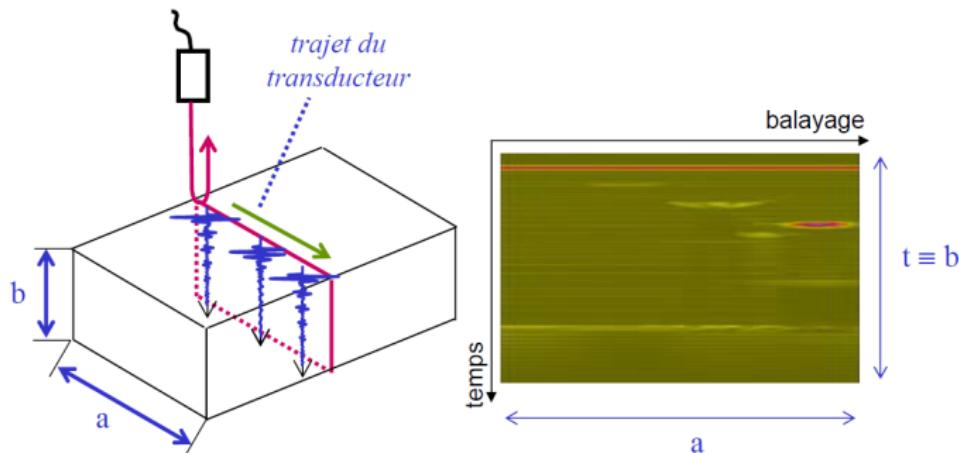
Note sur l'impulsion électrique :

- 1 généralement de tension fixe (100~150V)
- 2 plus rarement avec un générateur de fonctions (sinus, sinus modulé, etc.)

Ascan, Bscan

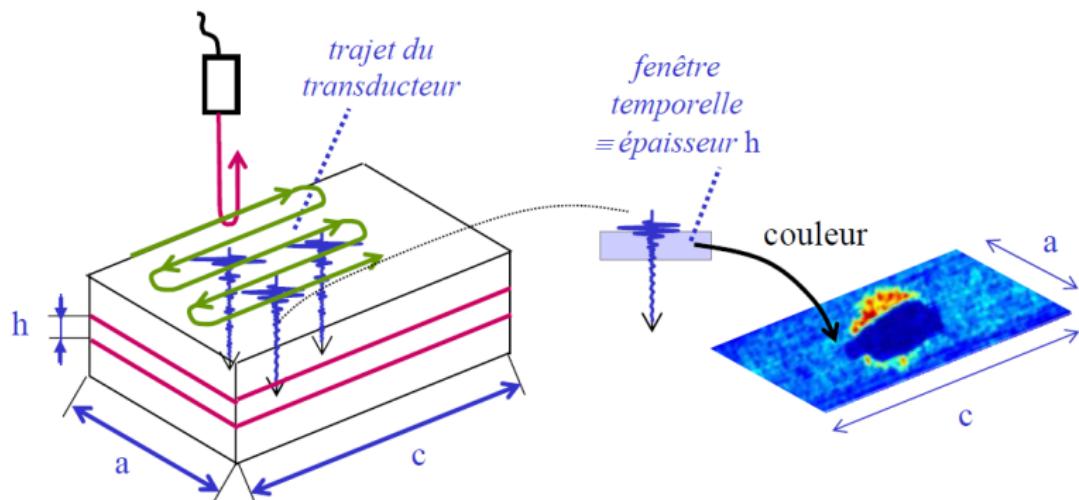


Echographie B (B-Scan) : correspond à une **coupe du matériau**

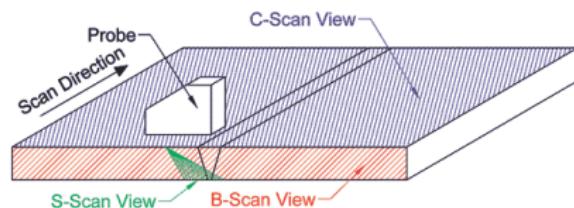
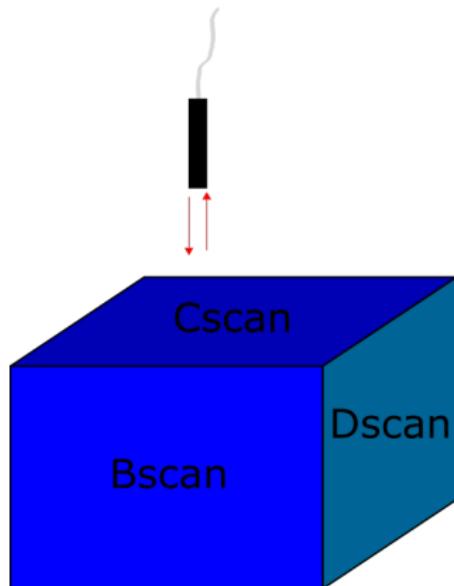


Cscan

Echographie C : correspond à une
représentation d'une tranche de matériau



Différentes vues d'une pièce



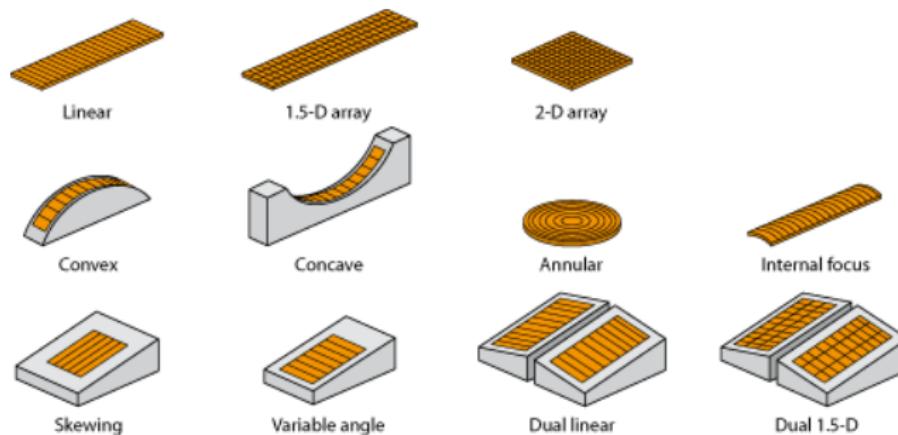
Lien animations

Sommaire

- 1 Généralités CND
- 2 CND par ultrasons
- 3 Le CND avec des sondes multi-éléments
 - Définitions
 - Techniques d'inspection
 - Avantages-inconvénients
 - Focalisation
 - Scan Linéaire
 - Scan sectoriel
 - Matrices : Cscan
 - Matrices : Tandem
 - Matrices : Ondes de surface
- 4 Imagerie avancée
- 5 Application réelle : Inspection de soudures de pipelines

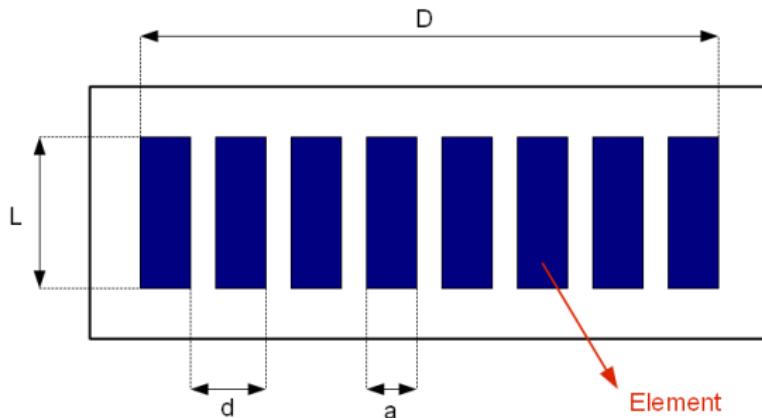
Définition

- Une sonde multi-éléments est composé de plusieurs cellules mono-élément
- Différentes géométries sont possibles :





Notations

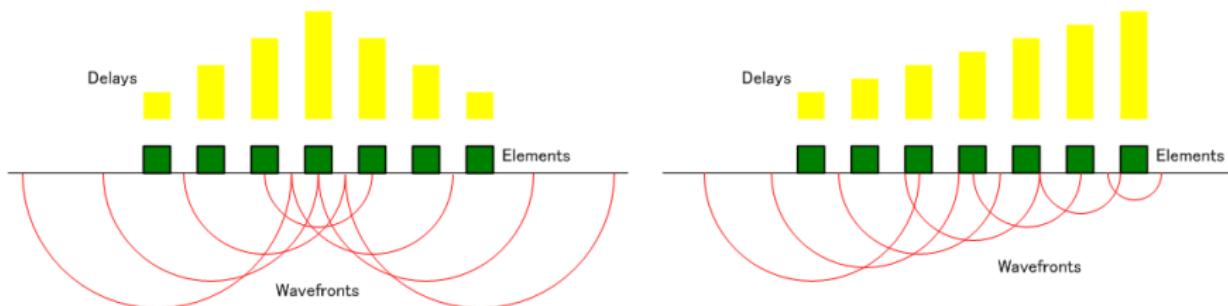


- d : espace inter-élément (pitch)
- a : taille de l'élément
- L : élévation
- D : ouverture



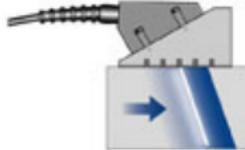
Application de retards aux éléments

- Possibilité de contrôler électroniquement chaque élément indépendamment
- Application de retards aux éléments
- ↗ focalisation en un point
- ↗ génération de l'onde dans une direction donnée

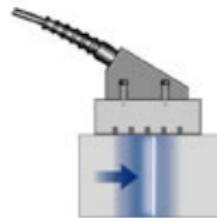


Possibilités variées

BEAM STEERING



LINEAR ANGLE



LINEAR 0°



SECTORIAL



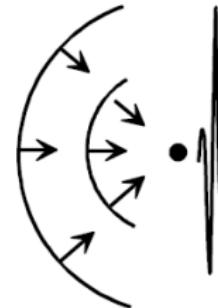
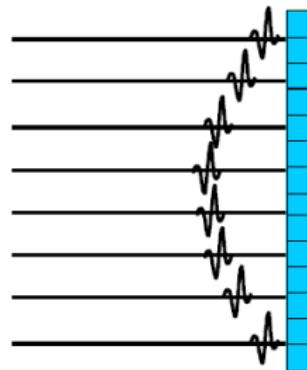
SECTORIAL ANGLE



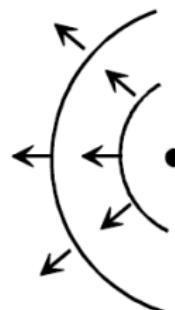
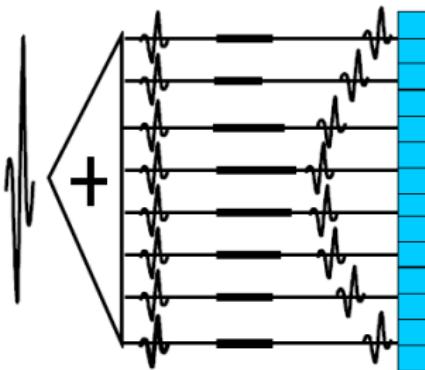
DEPTH

Focalisation

Emission



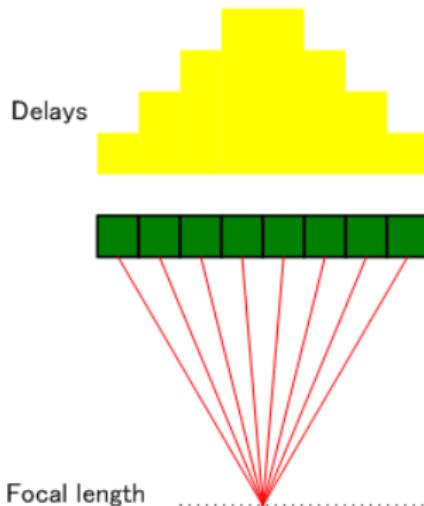
Réception



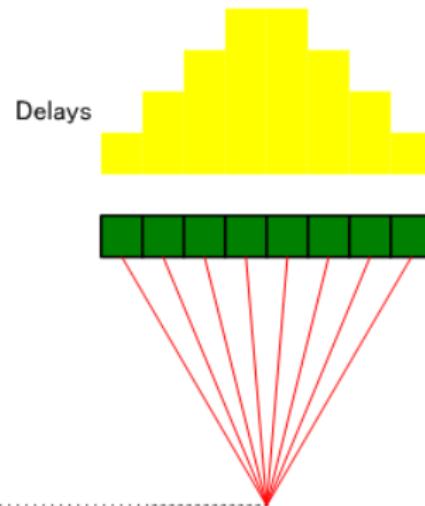


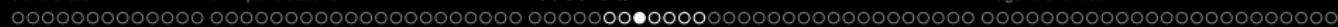
Focalisation

Emission



Reception

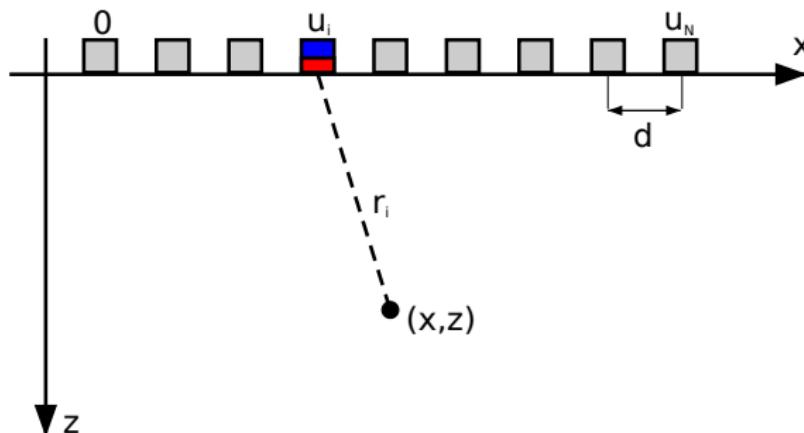


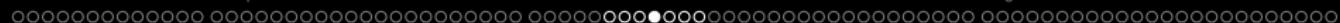


Exercice : Calcul d'une loi de retard en focalisation

- La sonde placée au contact a N éléments espacés de d
- La milieu a une vitesse c
- On veut focaliser au point (x, z)

~ **Calculer la loi de retard $\tau(i)$ à appliquer aux éléments $(1 \dots N)$ pour focaliser au point (x, z)**





Correction et application numérique

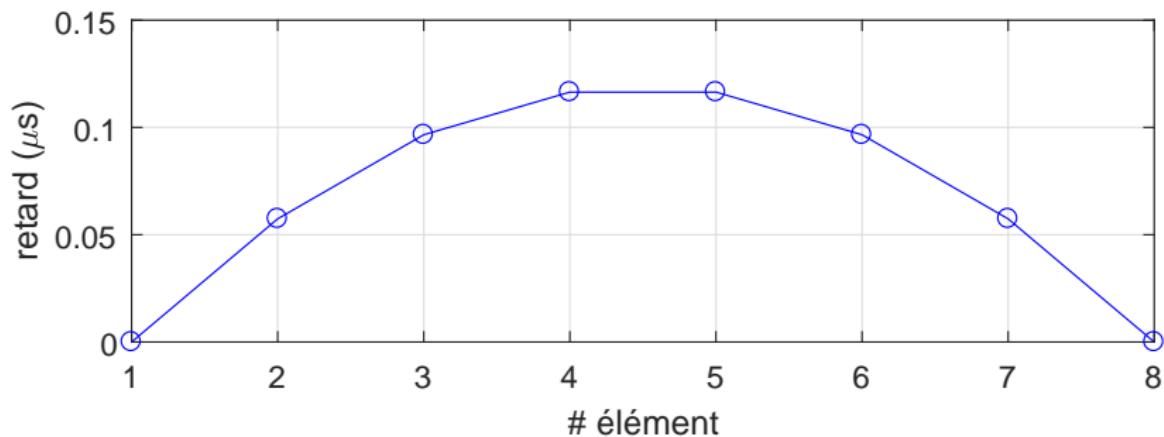
- $u(i) = (i - 1)d$
- $r(i) = \sqrt{(u(i) - x)^2 + z^2}$
- $\tau(i) = \frac{r(i)}{c}$
- $\tau(i) = \max(\tau(i)) - \tau(i)$

~ Application numérique :

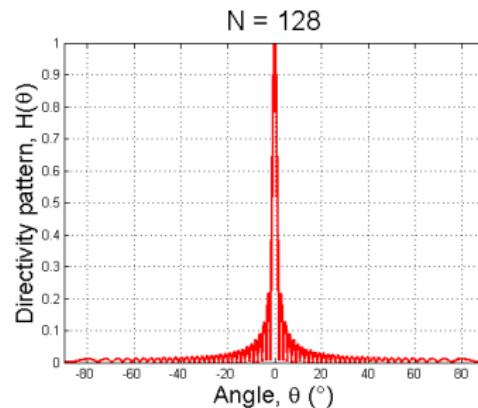
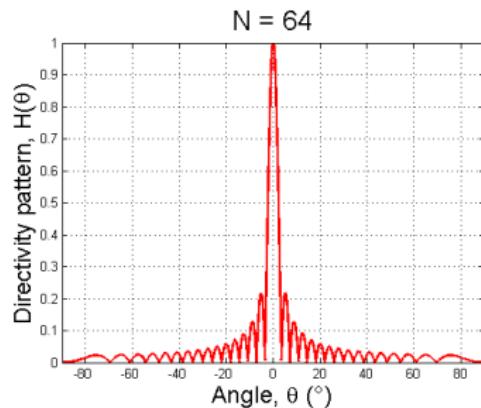
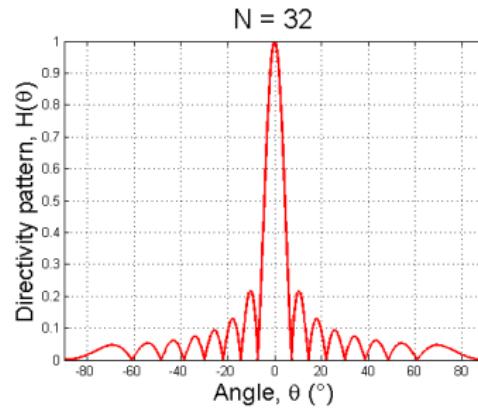
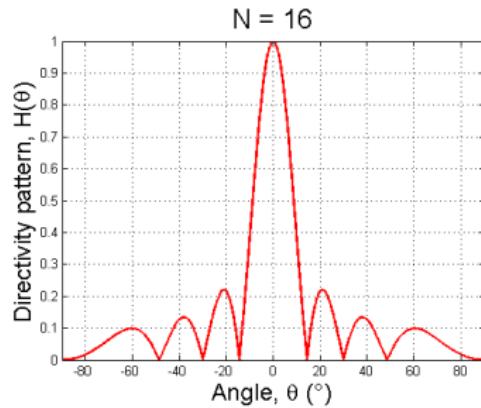
$N = 8, d = 1 \text{ mm}, c = 5.0 \text{ mm/us}, x = 3.5 \text{ mm}, z = 10 \text{ mm}$

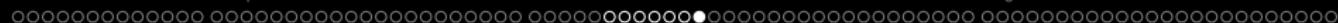
Correction et application numérique

i	1	2	3	4	5	6	7	8
u(i)	0	1	2	3	4	5	6	7
$\tau(i)$	0.000	0.0574	0.0966	0.1165	0.1165	0.0966	0.0574	0.000

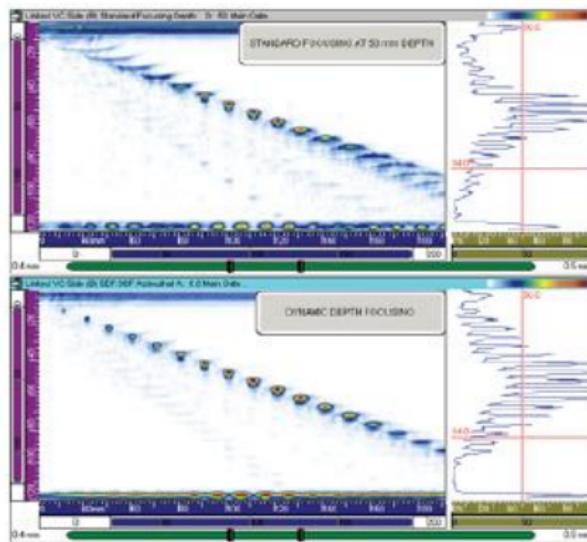
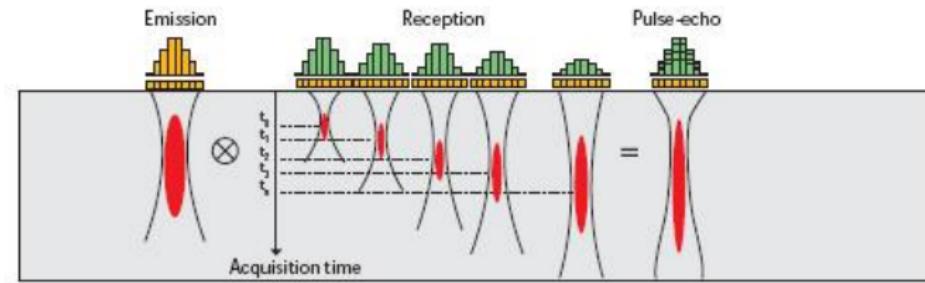


Influence du nombre d'éléments

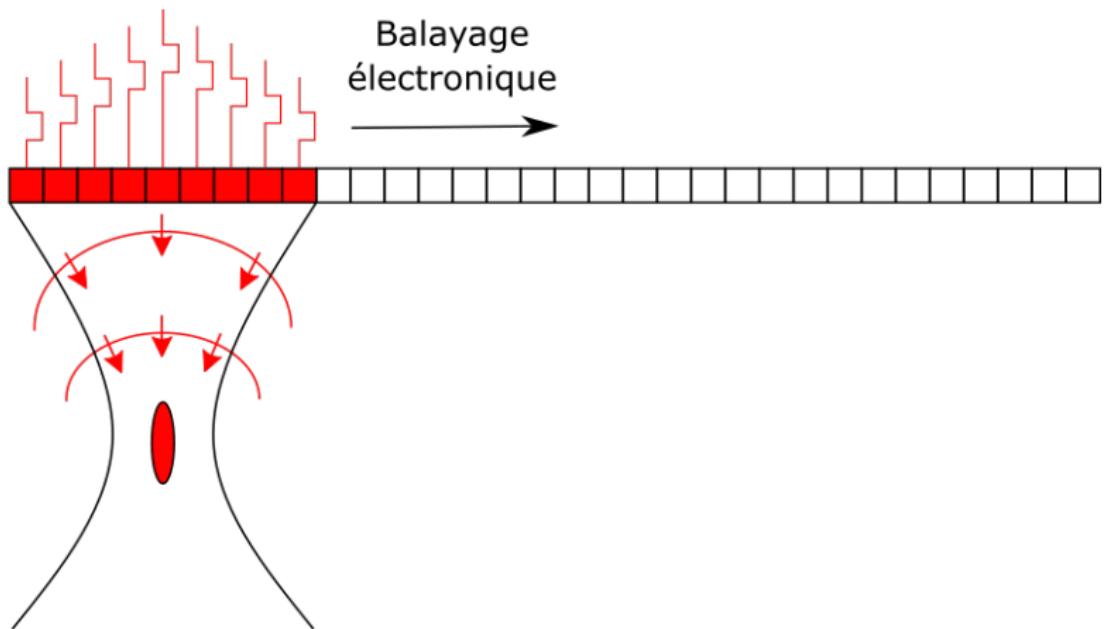




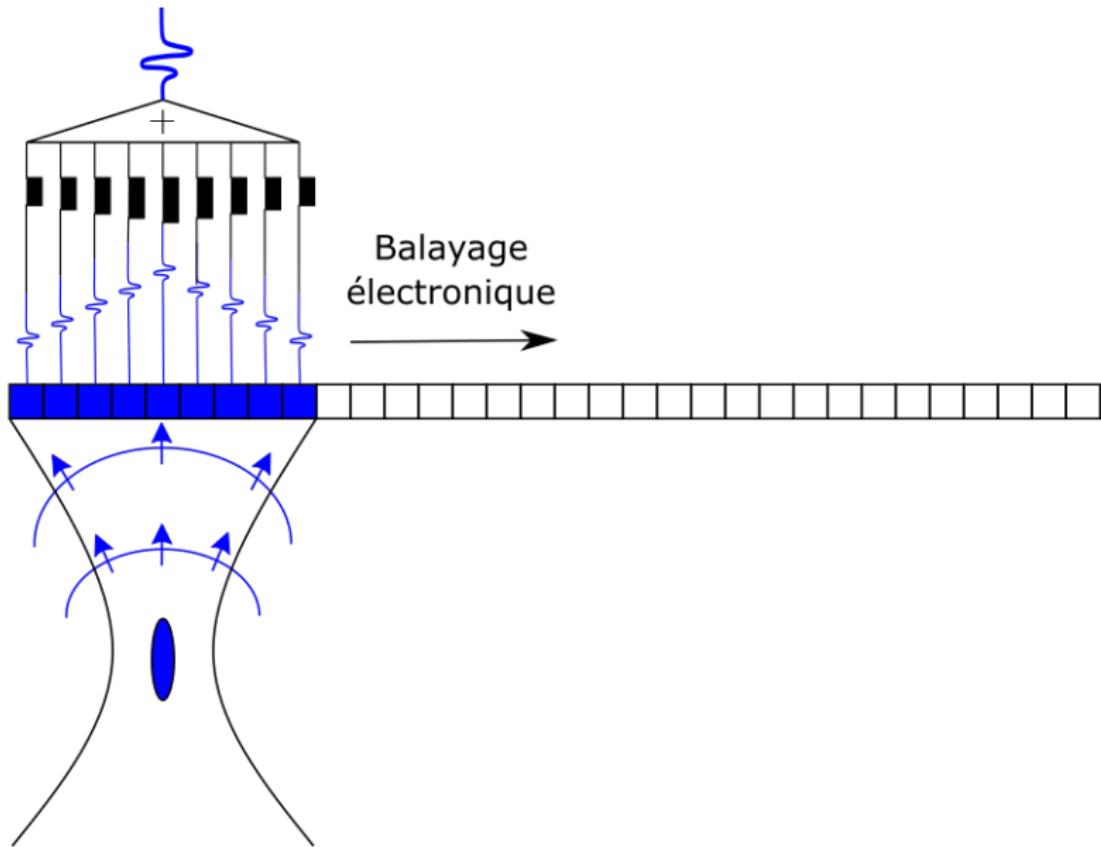
Focalisation dynamique



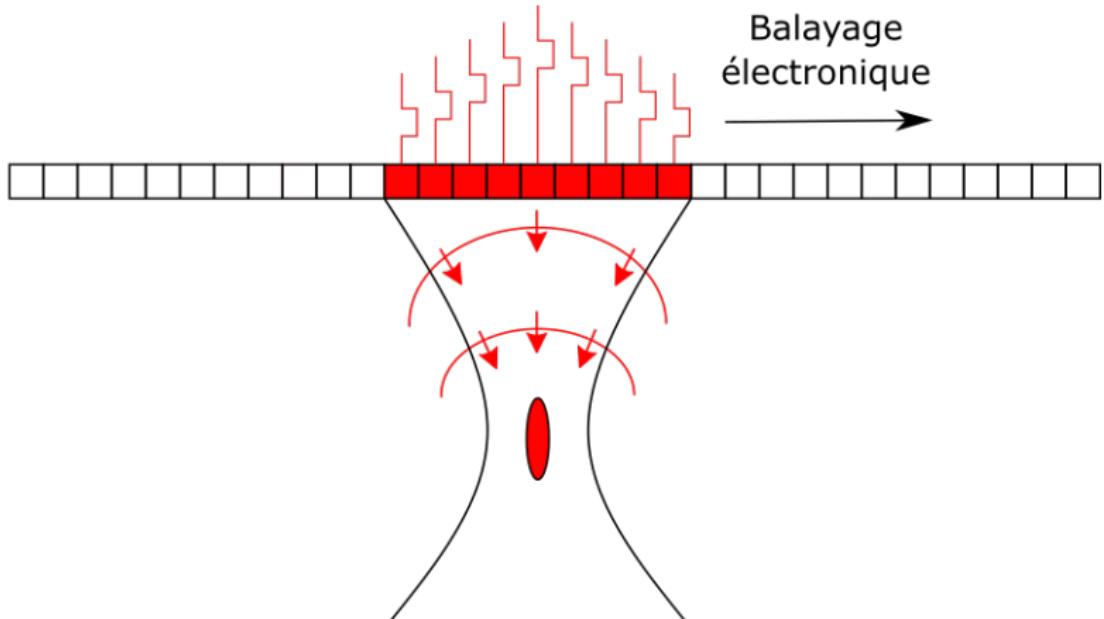
Scan linéaire



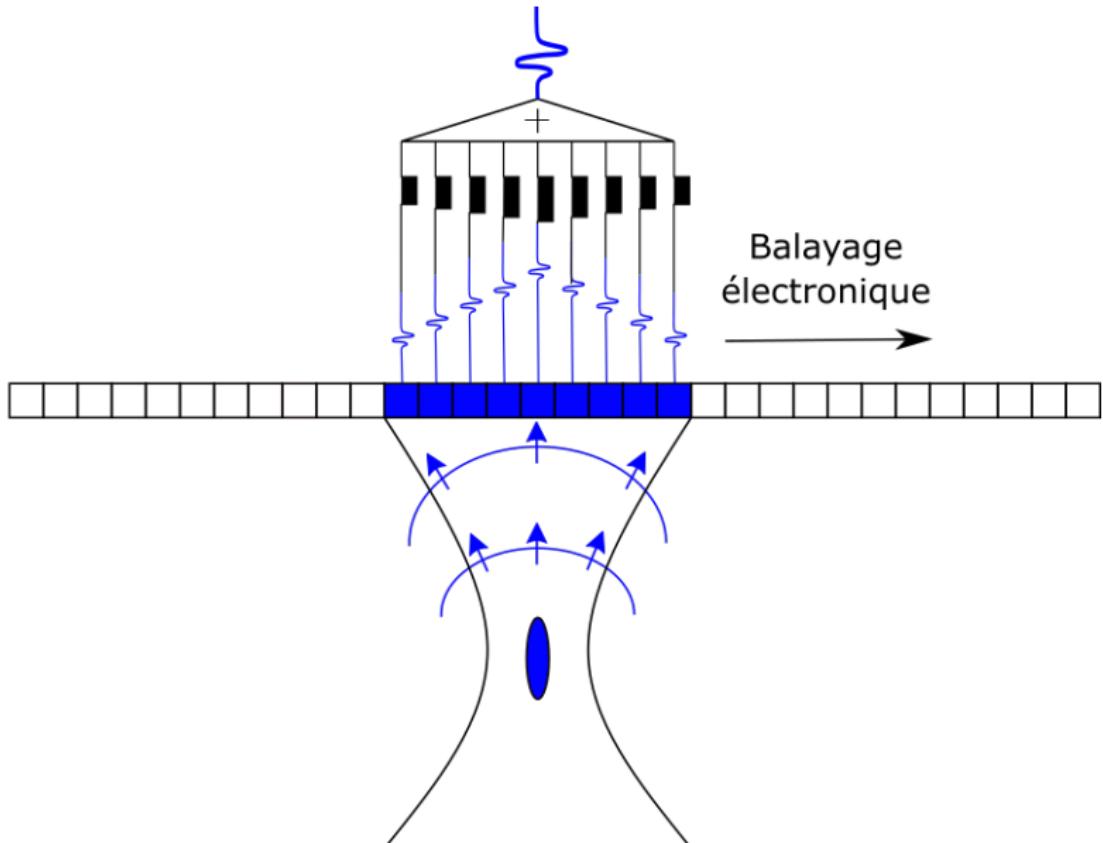
Scan linéaire



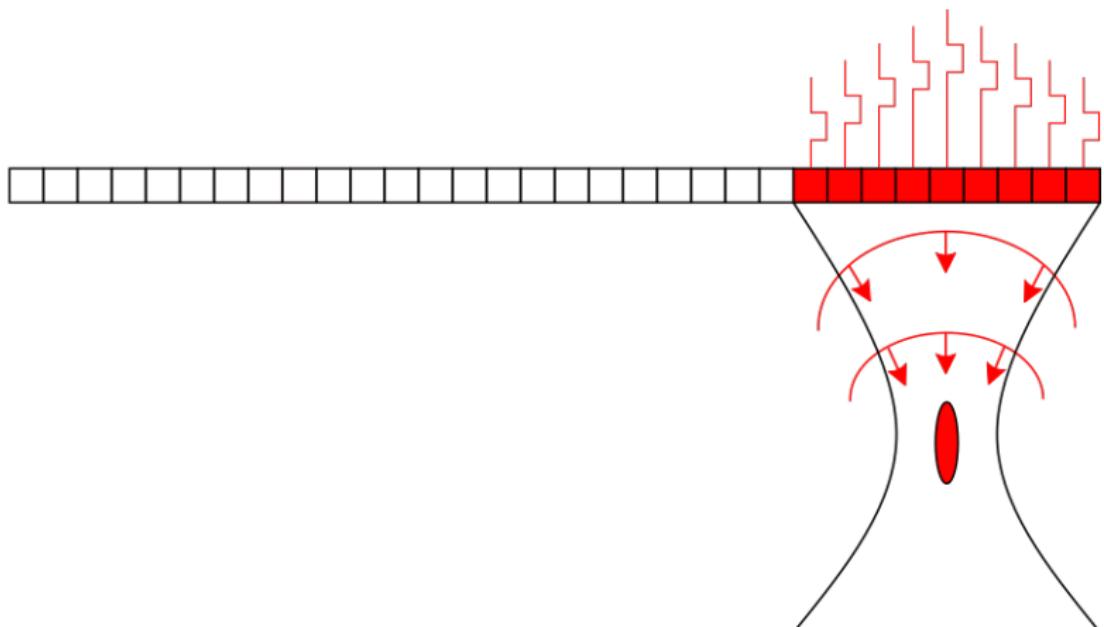
Scan linéaire



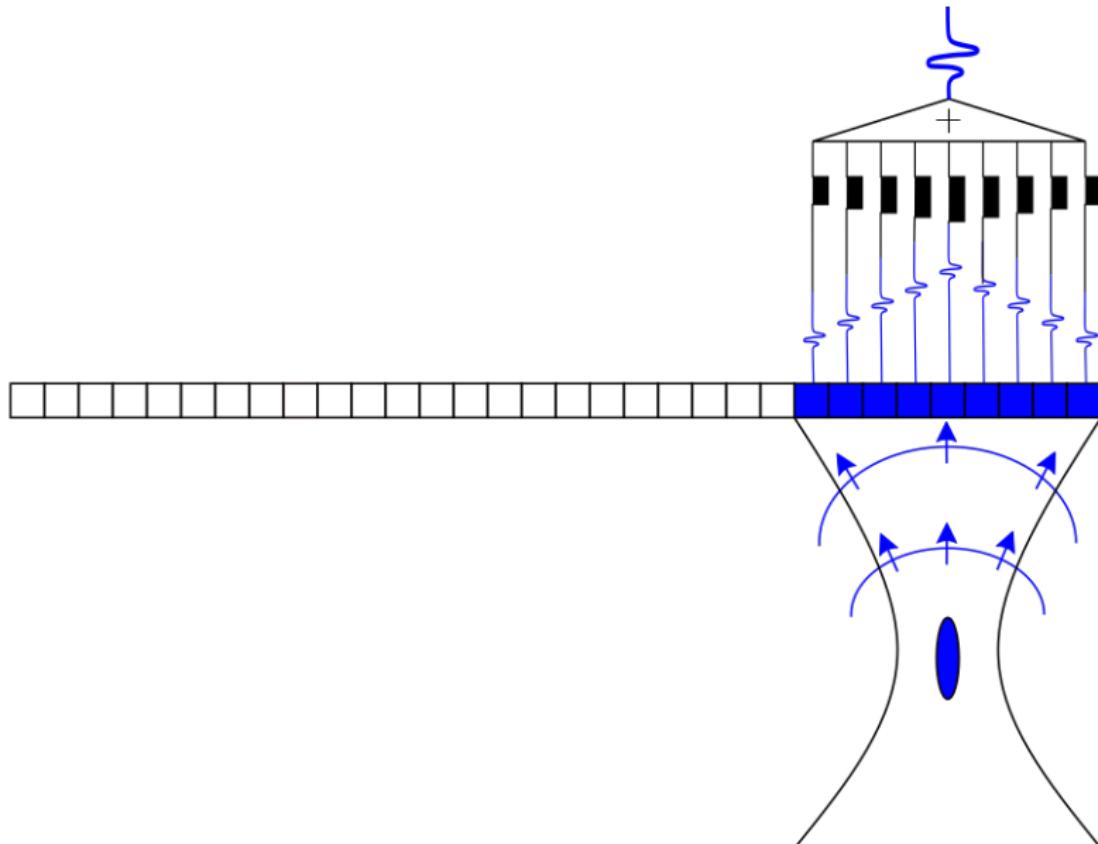
Scan linéaire



Scan linéaire

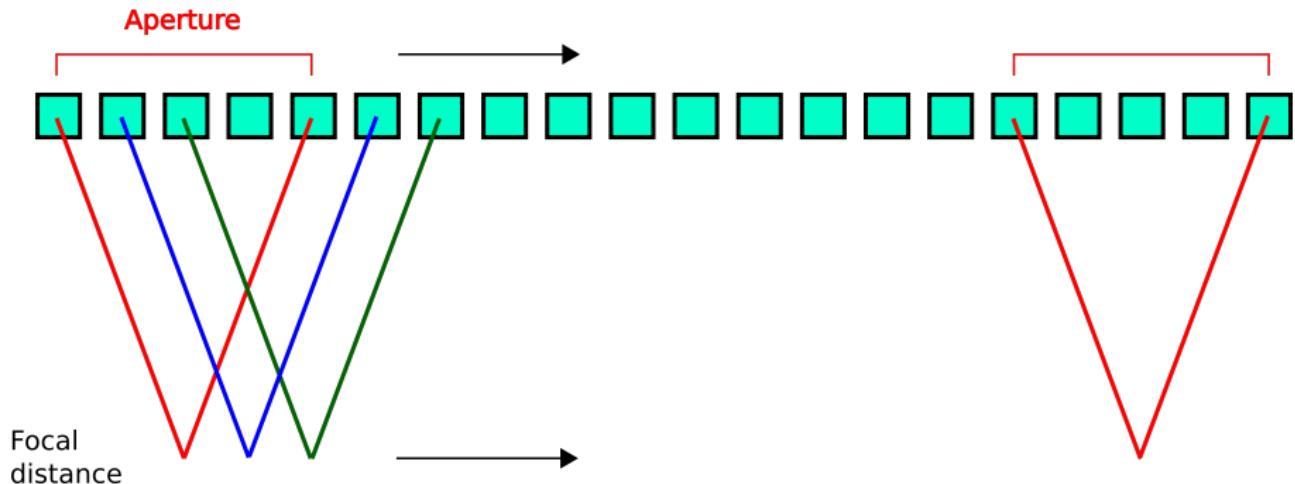


Scan linéaire



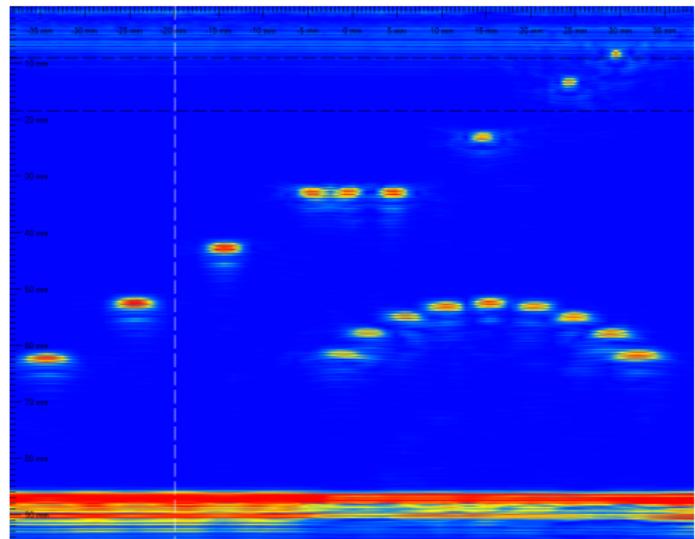
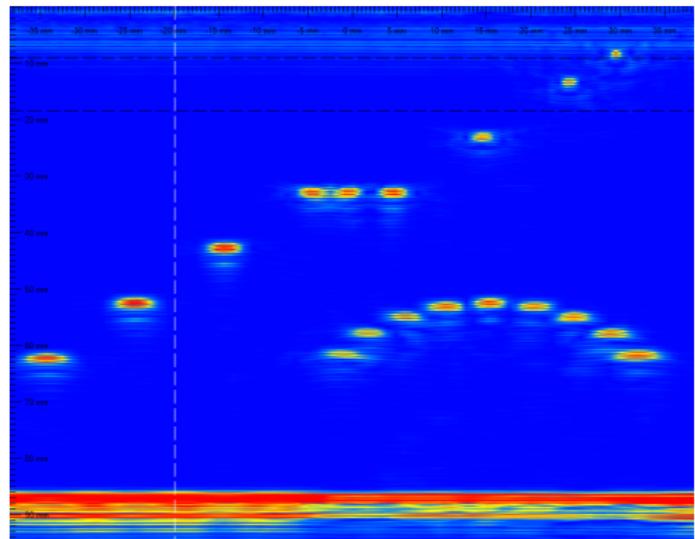
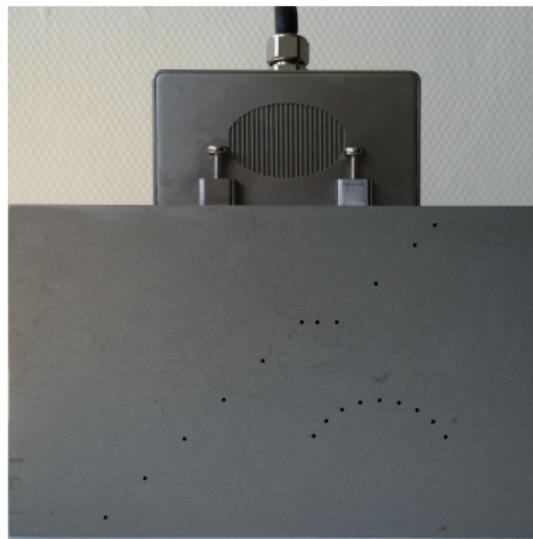


Scan linéaire

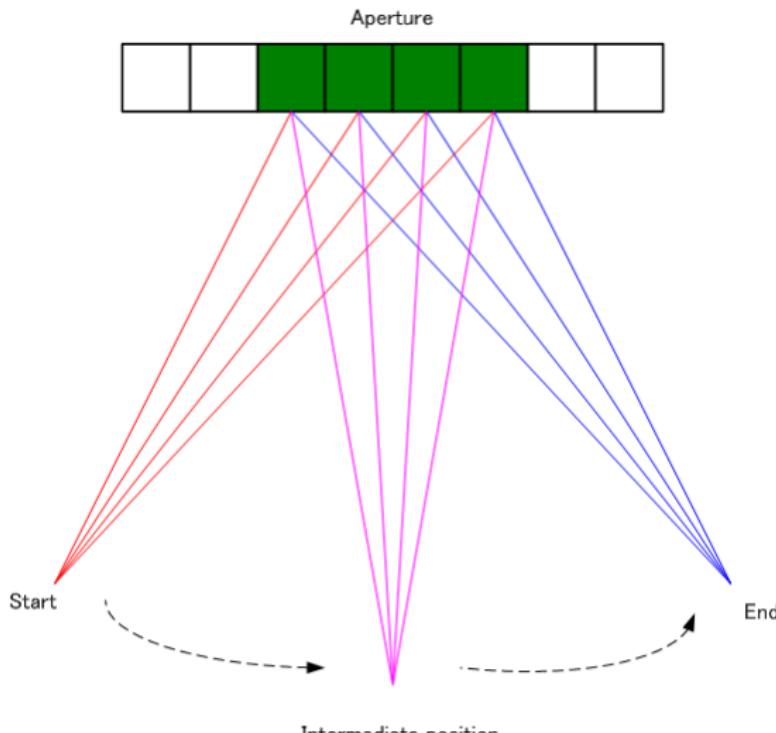


~ 1 Ascan par ouverture

Scan linéaire : exemple



Scan sectoriel



~ 1 Ascan par angle

Scan sectoriel



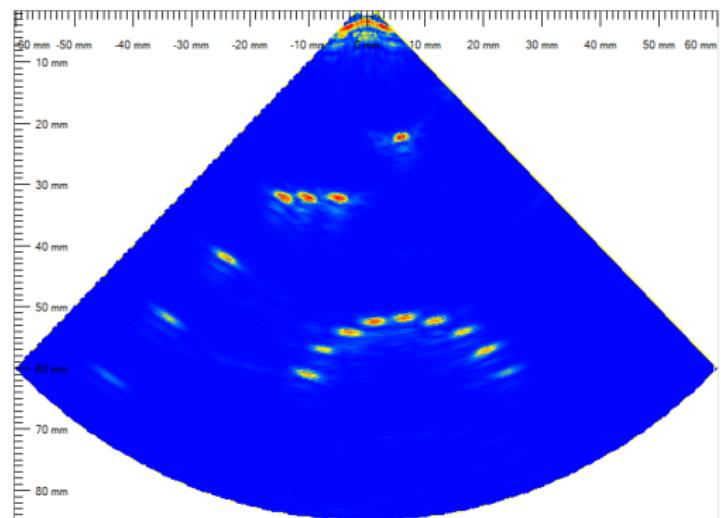
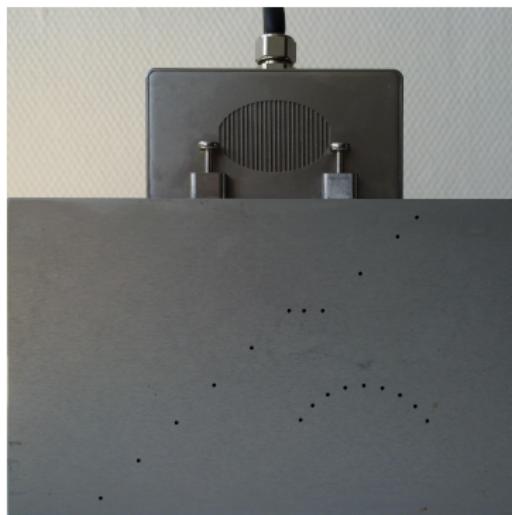
SECTORIAL



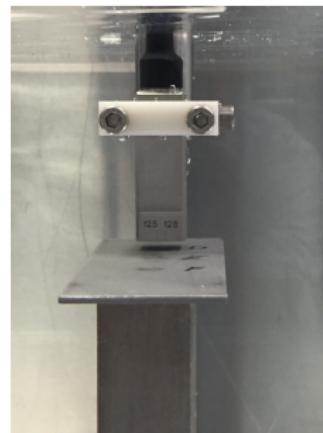
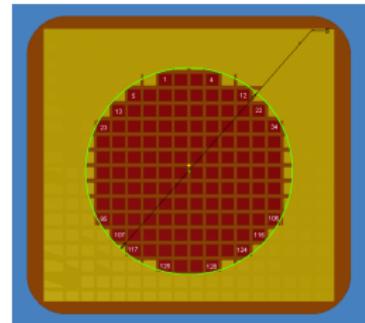
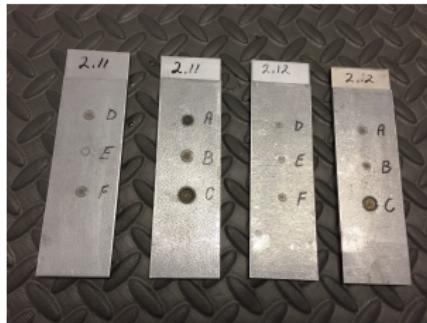
SECTORIAL ANGLE

[Lien animation](#)

Scan sectoriel : exemple

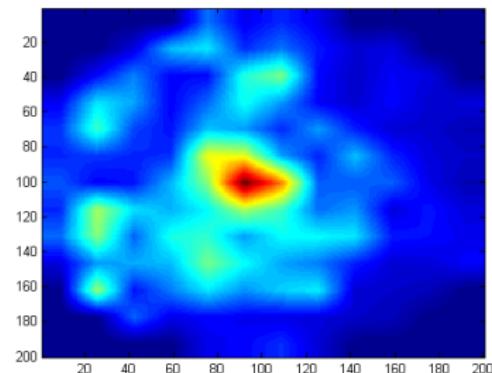
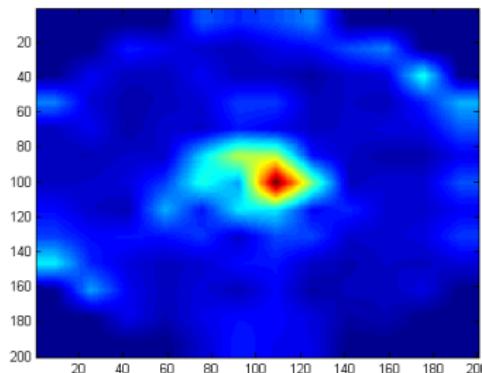
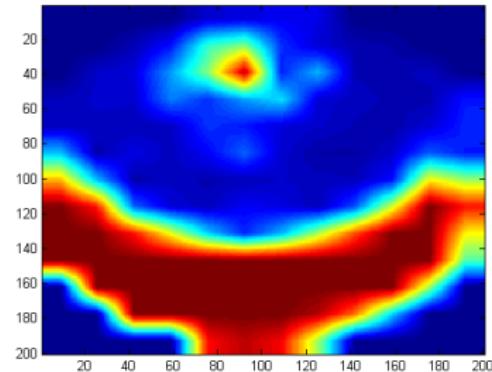
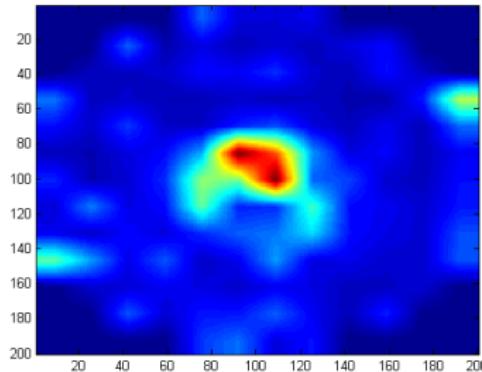


Applications matrice : Cscan (15 MHz)



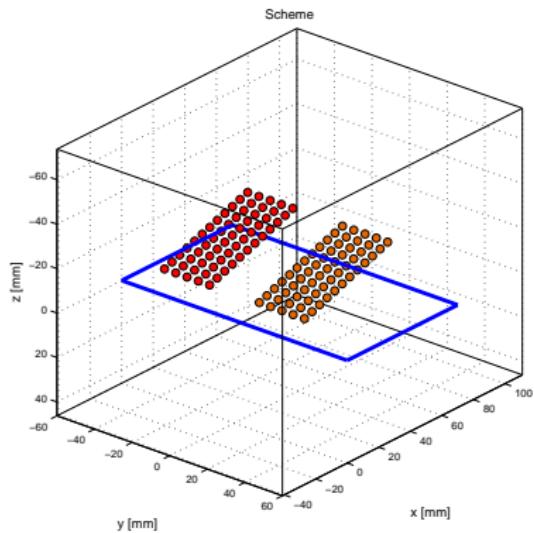
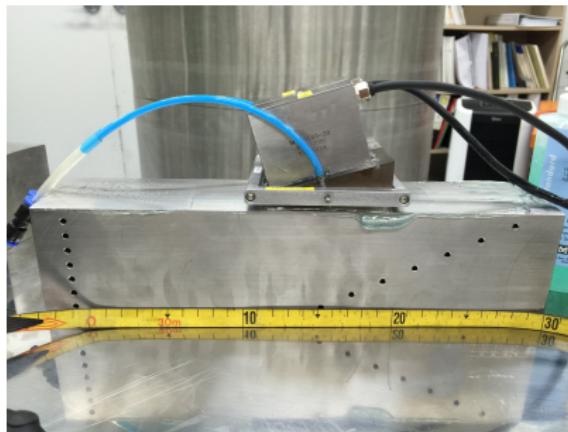


Applications matrice : Cscan (15 MHz)

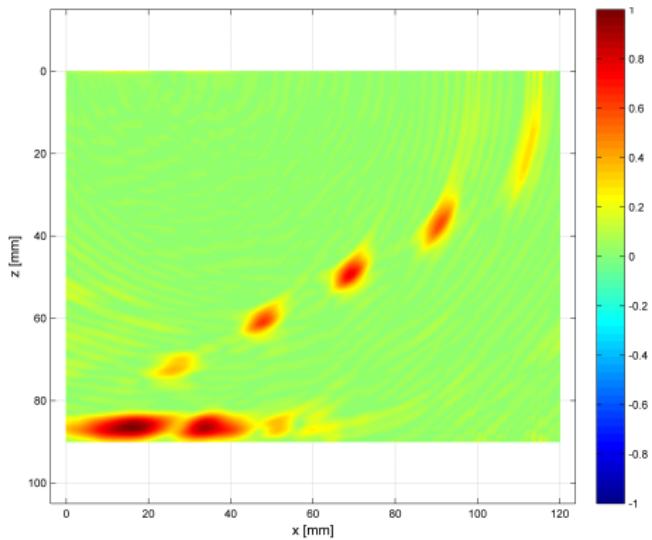
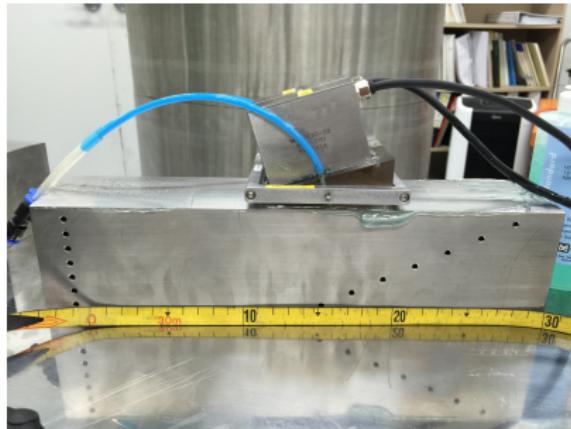


Applications matrice : Tandem

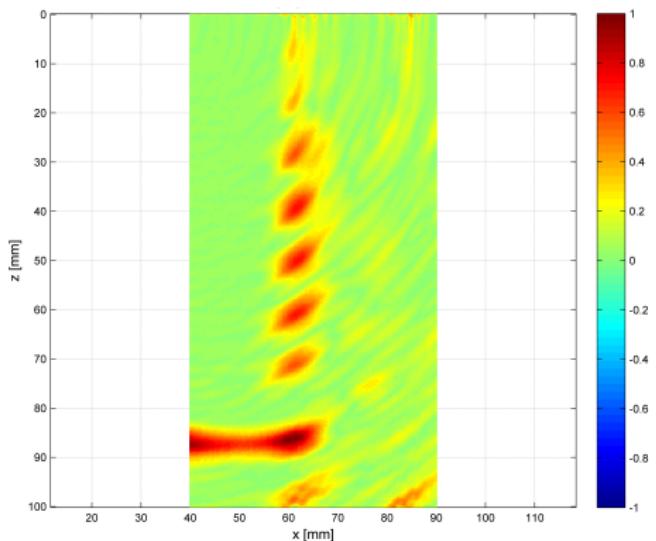
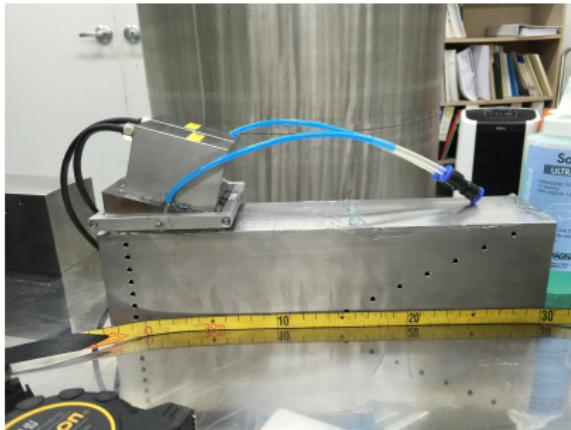
2 sondes 10×5 éléments à 1 MHz



Applications matrice : sondes en tandem



Applications matrice : sondes en tandem



Applications matrice : Ondes de surface

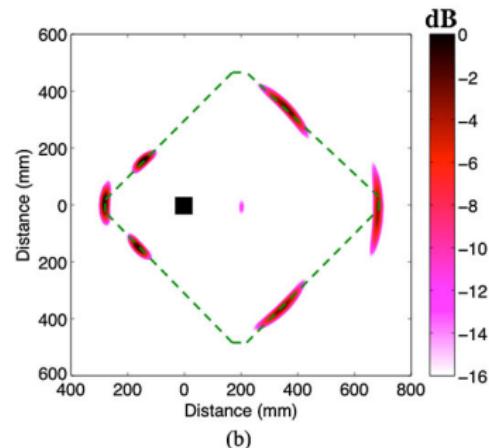
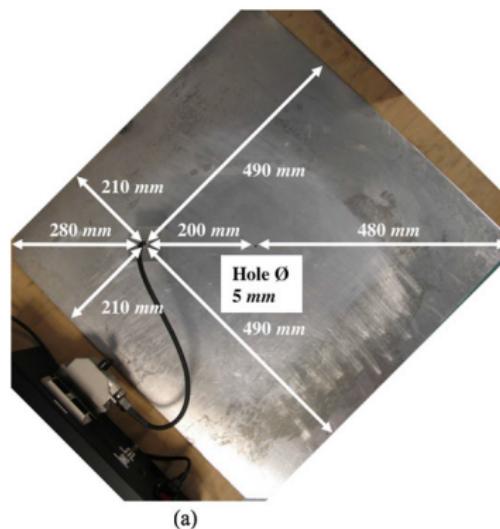


Fig. 6 Detection and localization of a through-thickness hole in 4-mm thick aluminium plate, using one multi-element probe in pulse-echo mode for launching/receiving the S_0 Lamb mode in/from all directions around its fixed position on the plate, at 0.35 MHz: (a) photograph

of the experimental set-up, (b) obtained image with maximum localization error ± 5 mm. The dB scale reference is the maximum signal amplitude corresponding to the echo of one edge

Applications matrice : Ondes de surface

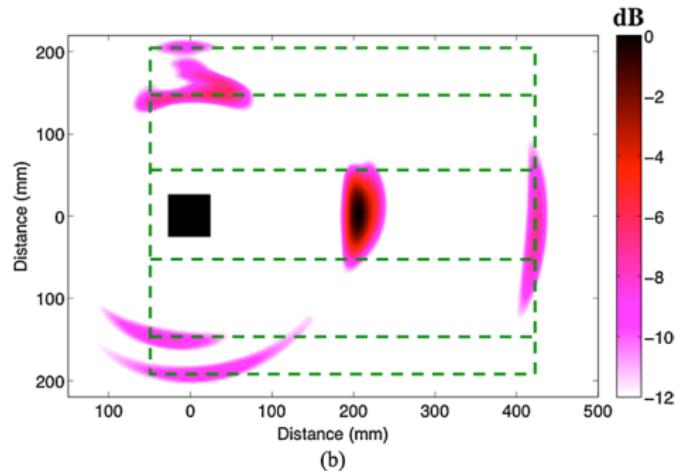
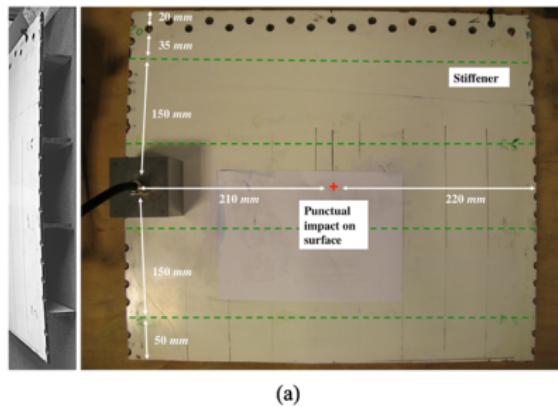


Fig. 9 Detection and localization of an impact damage realized on a 4-mm thick stiffened aerospace curved composite structure, using the S_0 Lamb mode at 0.5 MHz: (a) photograph of the experimental set-up, (b) obtained image with maximum localization error ± 10 mm. The

plate edges, the impact damage, the hole with diameter of 5 mm close to one edge and two stiffeners are detected and localized. The dB scale reference is the maximum signal amplitude corresponding to the plate edge echo

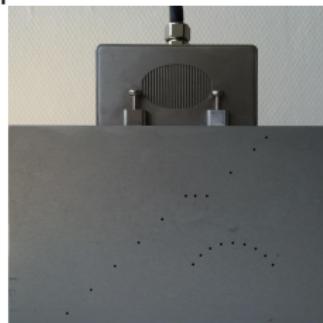
Sommaire

- 1 Généralités CND
- 2 CND par ultrasons
- 3 Le CND avec des sondes multi-éléments
- 4 Imagerie avancée
 - Principe de l'imagerie avancée
 - Imagerie SAFT
 - Focalisation en tout point
 - Imagerie par ondes planes
 - Calcul sur carte graphique
 - Imagerie par migration
- 5 Application réelle : Inspection de soudures de pipelines
- 6 Fin



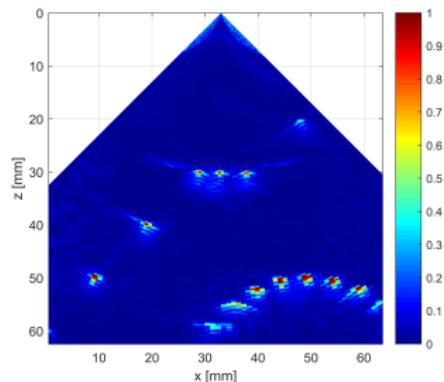
Principle of ultrasonic imaging

Acquisition avec multiéléments



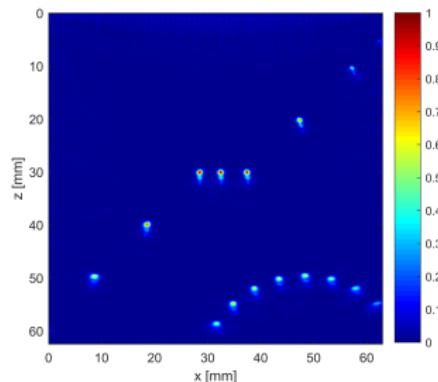
Imagerie conventionnelle

~ Affichage direct des données



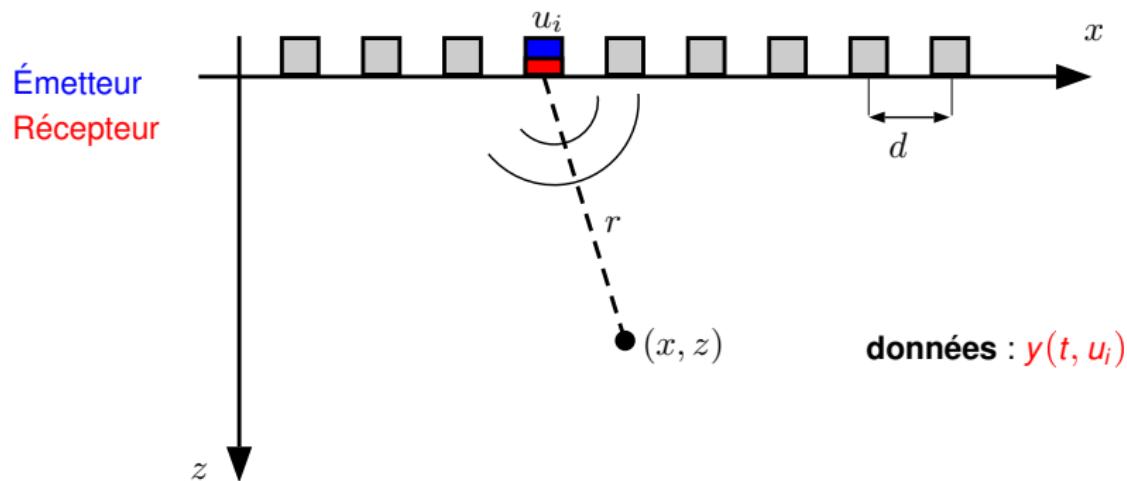
Imagerie avancée

Données brutes ~ Post traitement



Imagerie Synthetic Aperture Focusing Technique (SAFT)

- Acquisition monostatique :

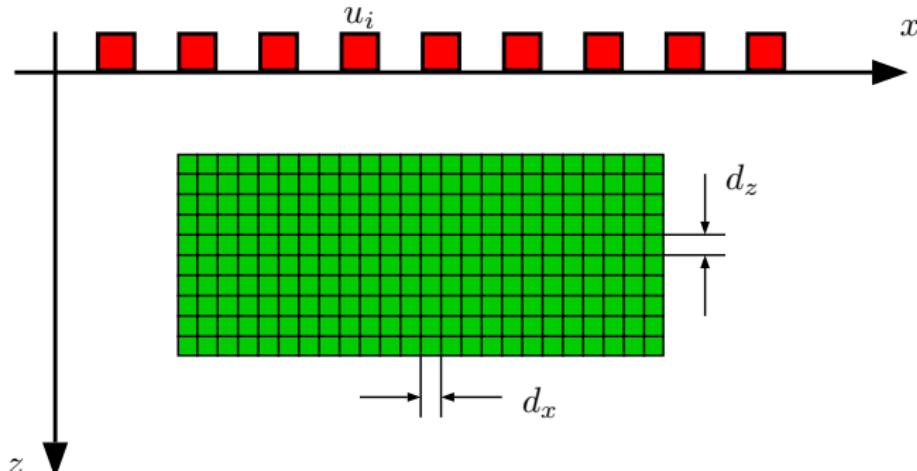


- Point $(x, z) \Rightarrow$ temps de propagation : $\tau = \frac{2r}{c} = \frac{\sqrt{(x - u_i)^2 + z^2}}{c}$

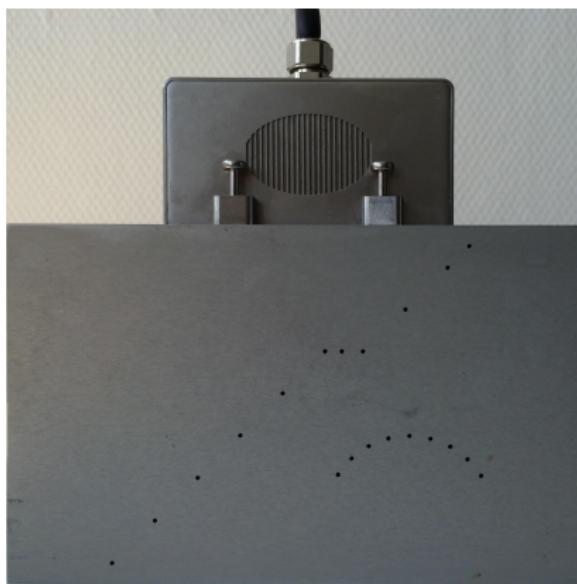


Imagerie SAFT

- Reconstruction : $O(x, z) = \sum_{i=1}^N y \left(\frac{2\sqrt{(x - u_i)^2 + z^2}}{c}, u_i \right)$ △ Vitesse constante
- Grille de reconstruction flexible :



Bloc de test avec *side drilled holes* (SDH) Ø 1 mm



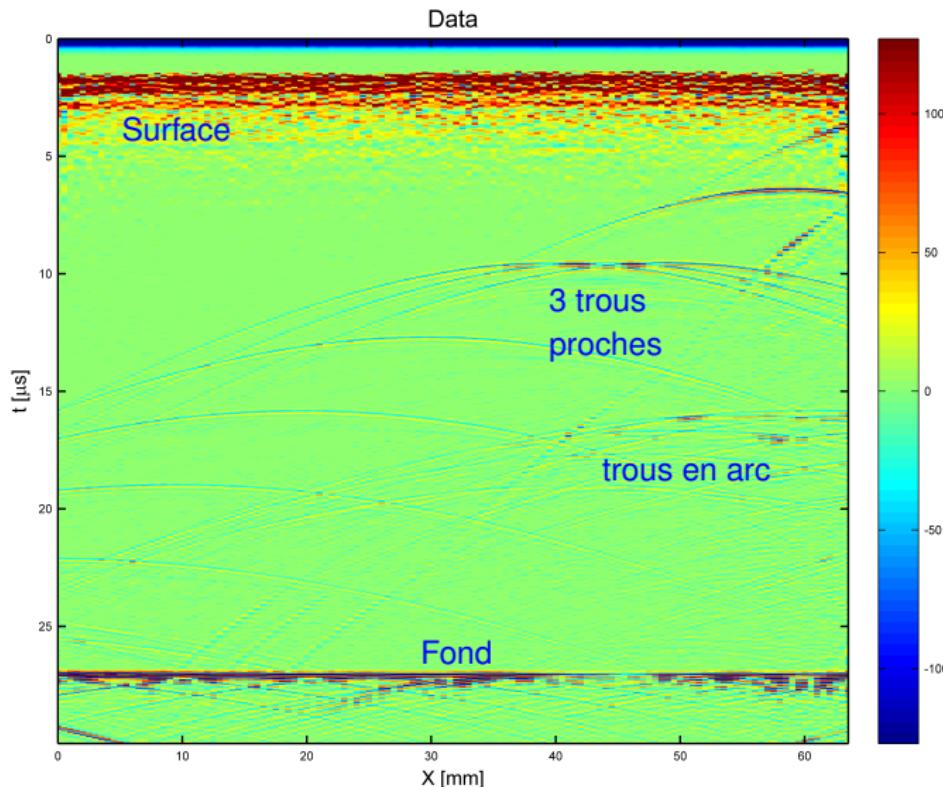
Bloc d'aluminium avec SDH Ø 1 mm



instrument multi-voies OEMPA

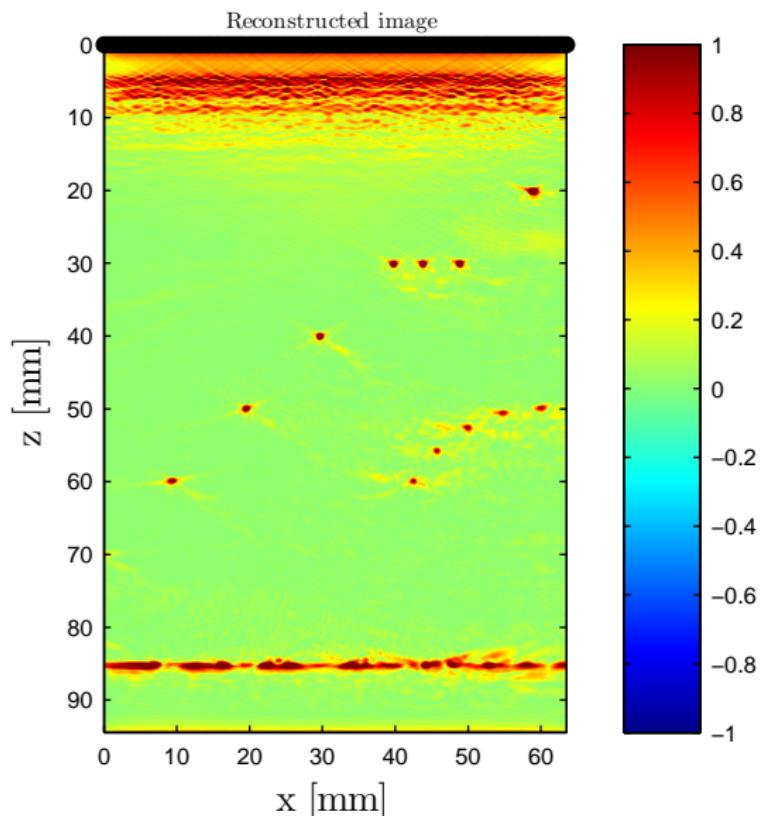
www-aos-ndt.com

Acquisition mono-statique : exemple de données



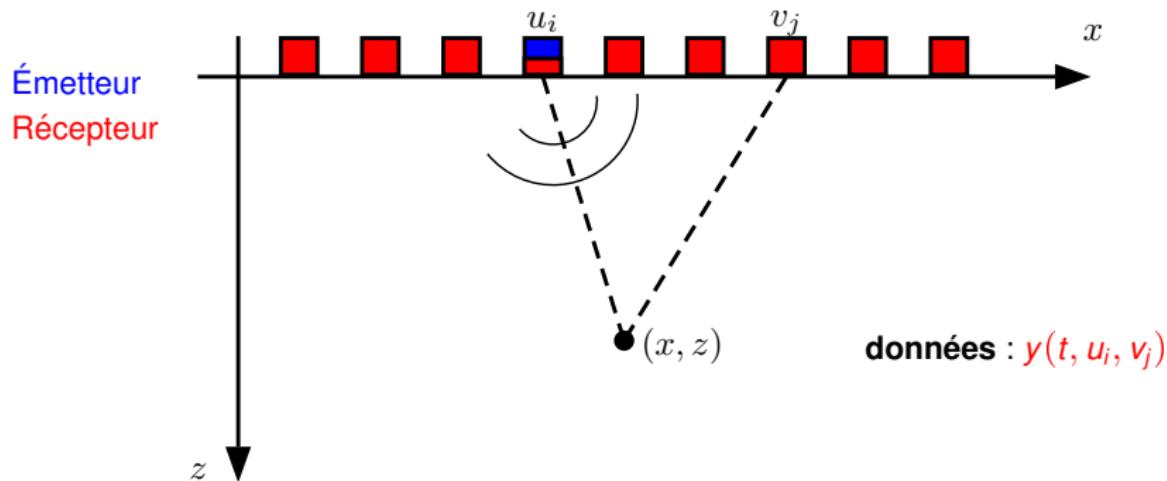


Imagerie SAFT



Imagerie Focalisation en tout point (FTP)

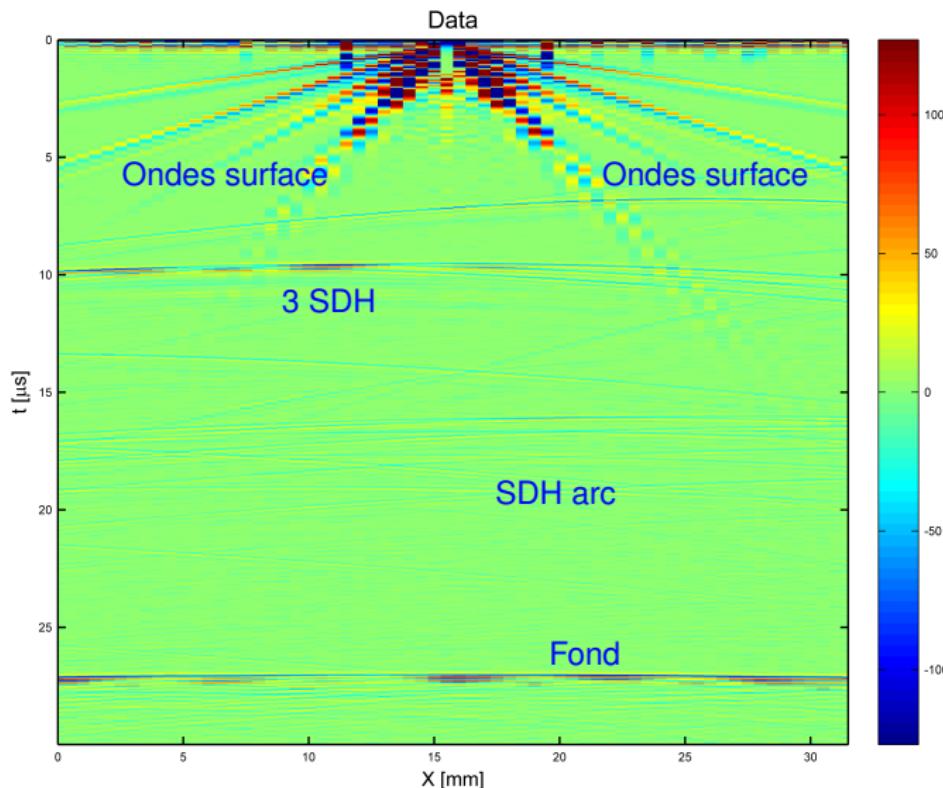
- Acquisition multistatique :



- Reconstruction :

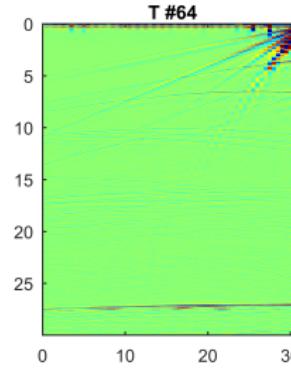
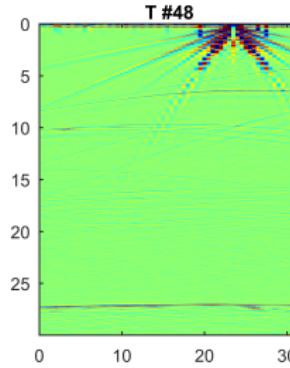
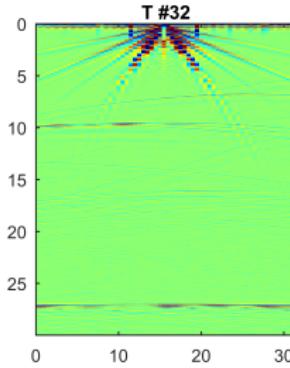
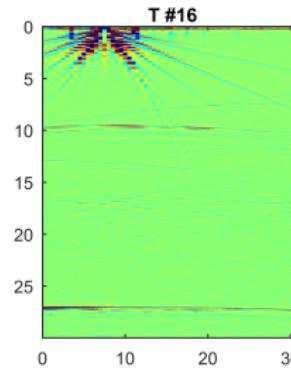
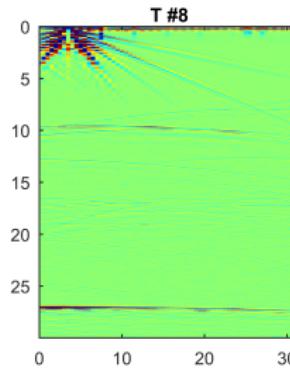
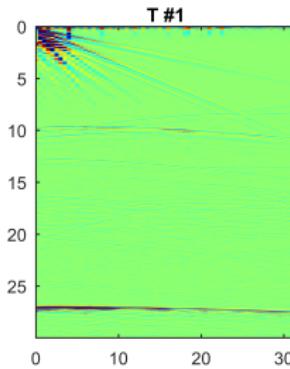
$$O(x, z) = \sum_{i=1}^N \sum_{j=1}^N y \left(\frac{\sqrt{(x - u_i)^2 + z^2} + \sqrt{(x - v_j)^2 + z^2}}{c}, u_i, v_j \right)$$

Exemple de données (émetteur # 32)





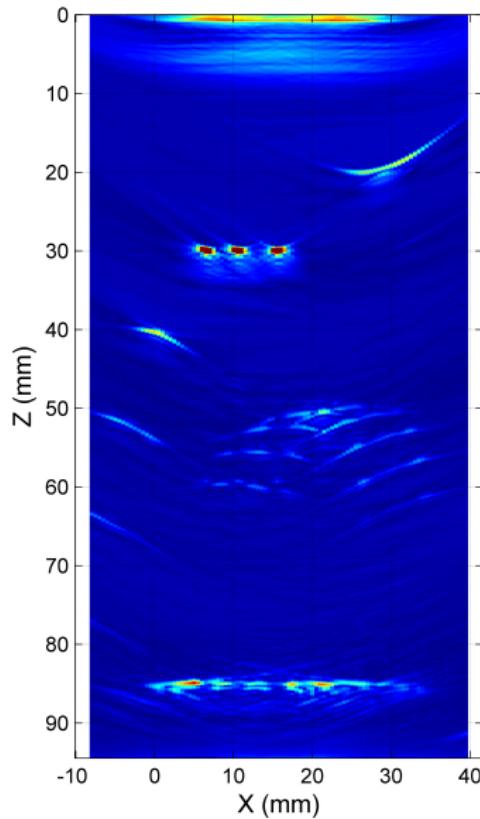
Exemple de données FMC



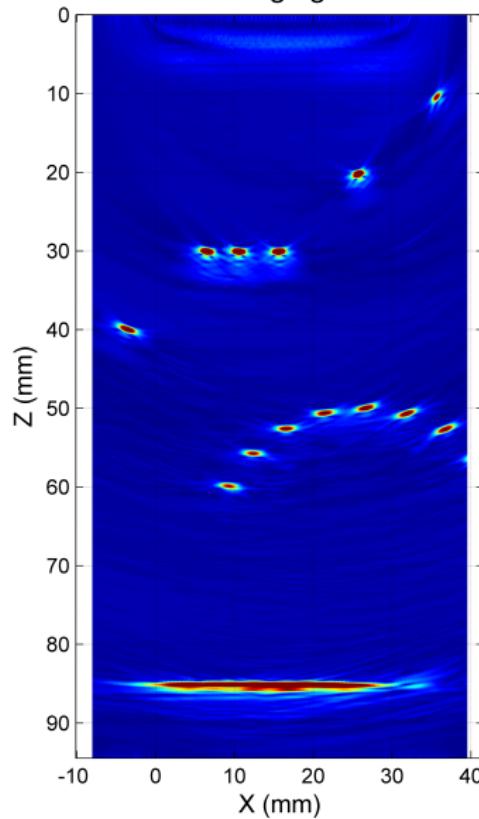


Imagerie FTP

Linear scan 64 el.

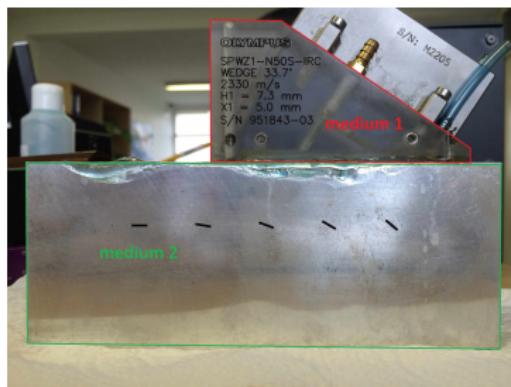


TFM imaging 64 el.



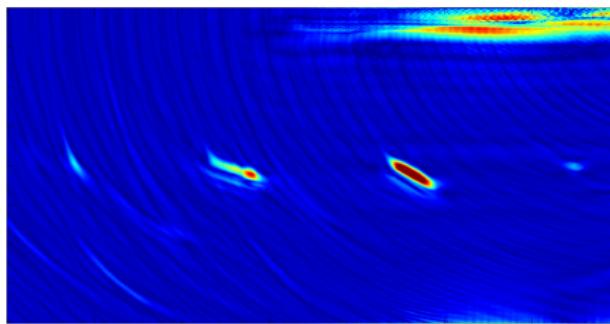
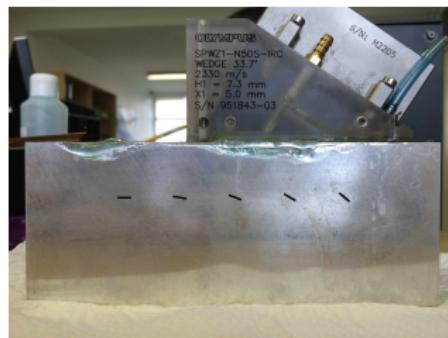
Focalisation en tout point avec sabot

- Nécessaire pour les inspections en immersion ou avec sabot
- Possibilité d'utiliser les ondes longitudinales et les ondes transversales
- Deux milieux à considérer (deux vitesses différentes)

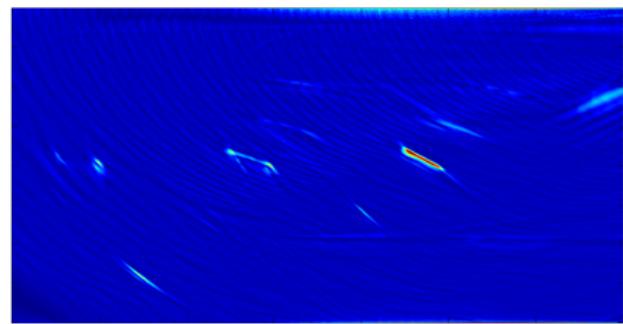


Inspection d'un bloc d'aluminium contenant des entailles de 5 mm
avec une sonde de 60 éléments et un sabot

Résultats en imagerie FTP



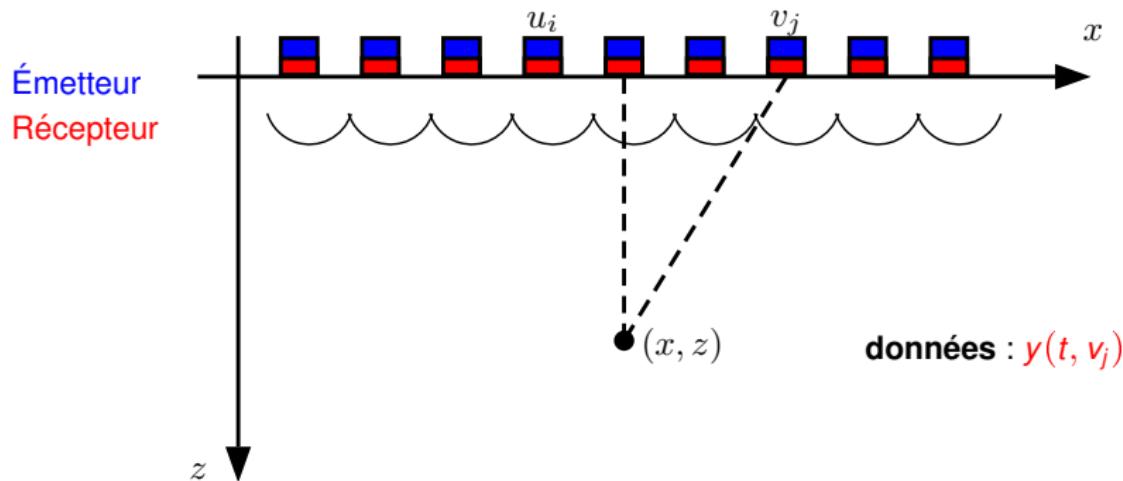
Ondes longitudinales ($\lambda = 0.84 \text{ mm}$)



Ondes transversales ($\lambda = 0.40 \text{ mm}$)

Imagerie par ondes planes (*Plane Wave Imaging : PWI*)

- Acquisition PWI :



- Reconstruction : $O(x, z) = \sum_{j=1}^N \textcolor{red}{y} \left(\frac{z + \sqrt{(x - v_j)^2 + z^2}}{c}, v_j \right)$

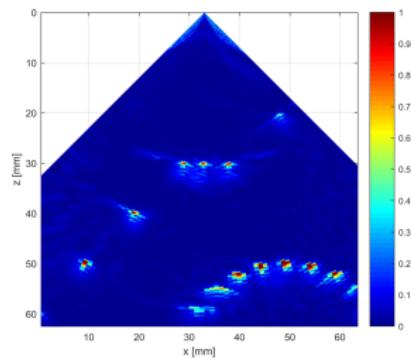


Imagerie par ondes planes

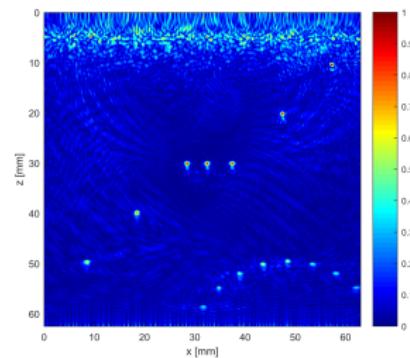


Comparaison imagerie conventionnelle/SAFT/FTP

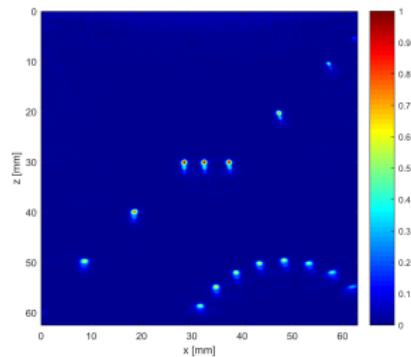
Conventionnel



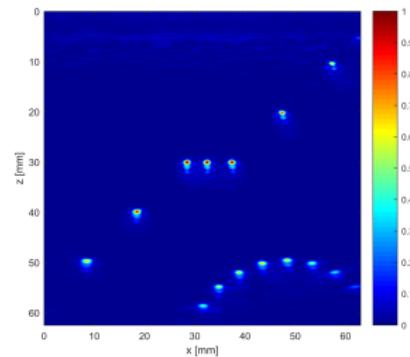
SAFT



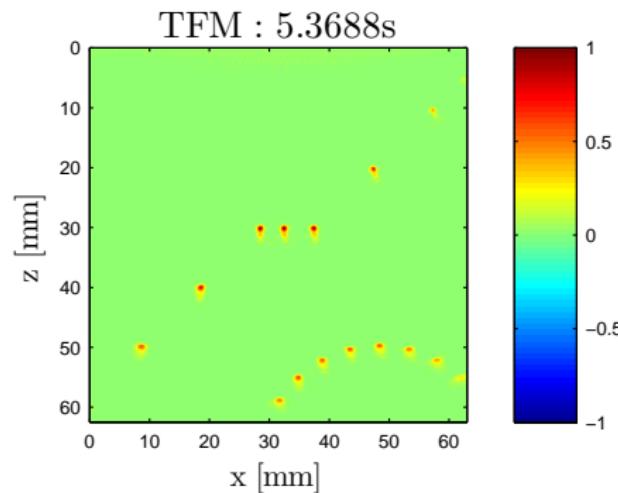
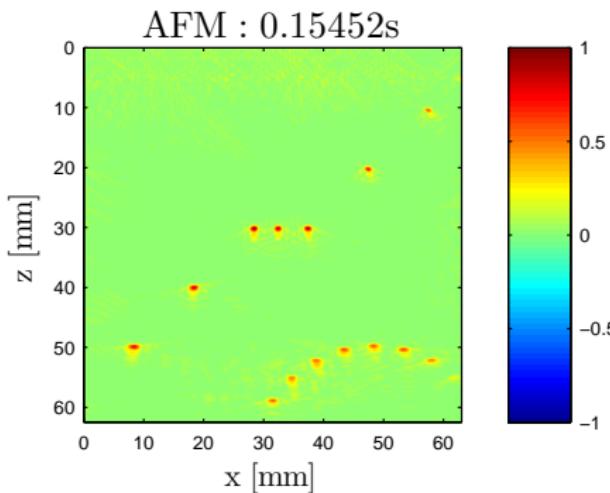
FTP



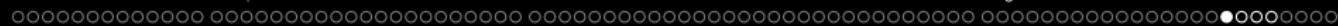
PWI



Comparaison SAFT, FTP et PWI

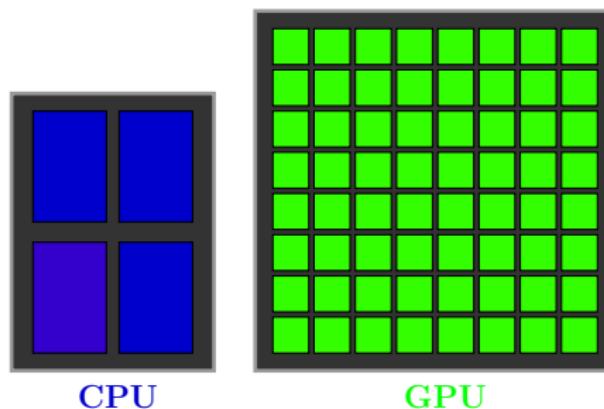


	PWI	SAFT	FTP
Temps d'acquisition	😊	😢	😢
Temps de calcul	😊	😊	😢
SNR	😊	😢	😊
Résolution	😢	😊	😊
Flexibilité	😢	😊	😊



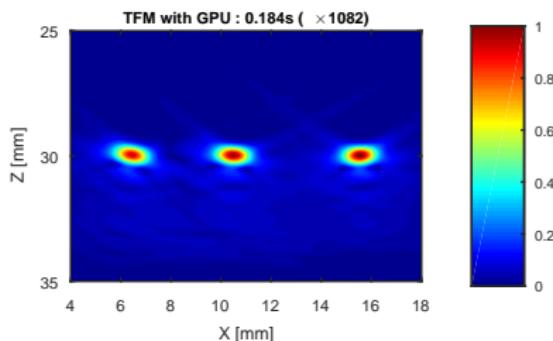
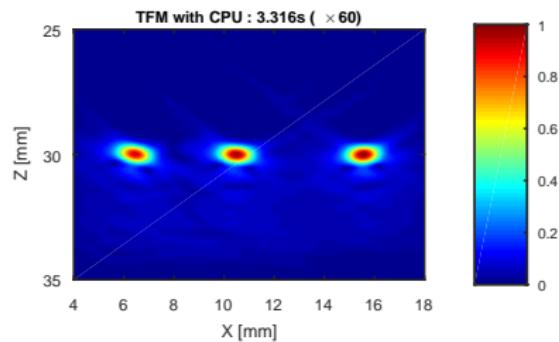
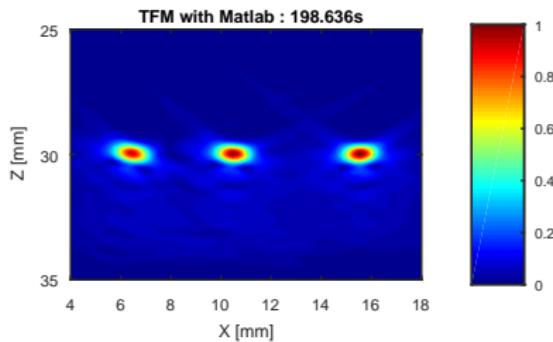
Calcul sur carte graphique (GPU)

- Principe :
 - CPU : quelques cœurs
 - GPU : plusieurs centaines de cœurs



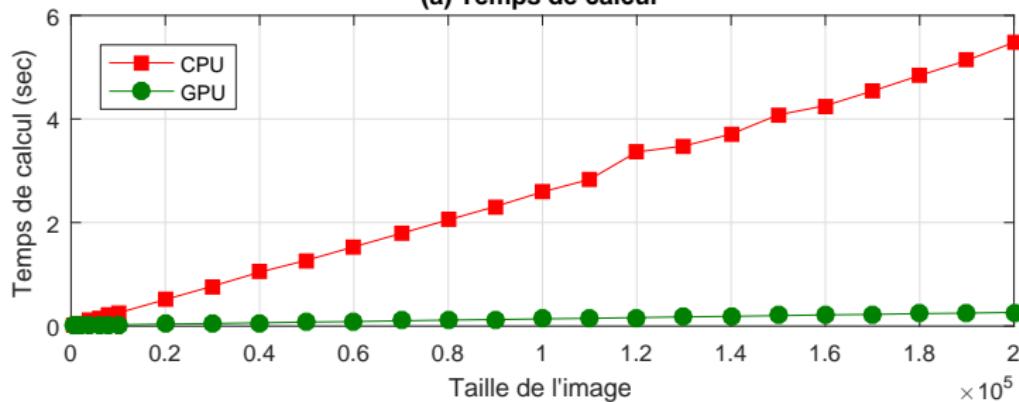
Comparaison CPU/GPU avec imagerie FTP

Taille de l'image : $512 \times 256 = 131\,072$ pixels

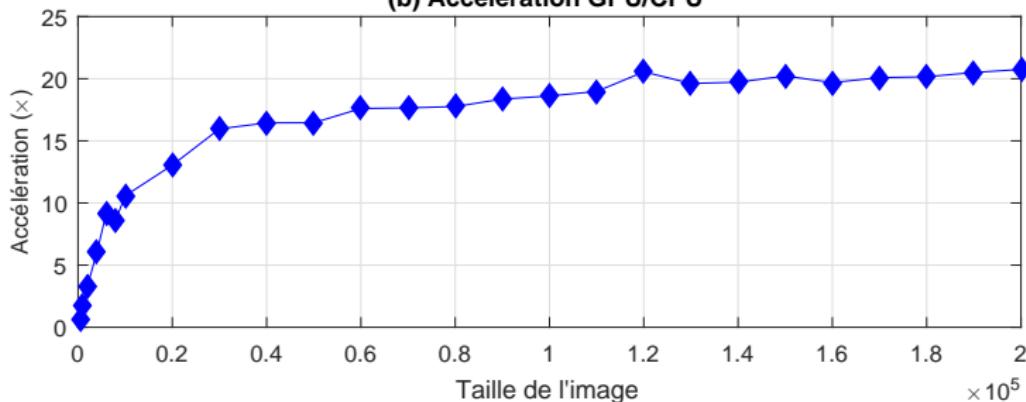


Comparaison CPU/GPU

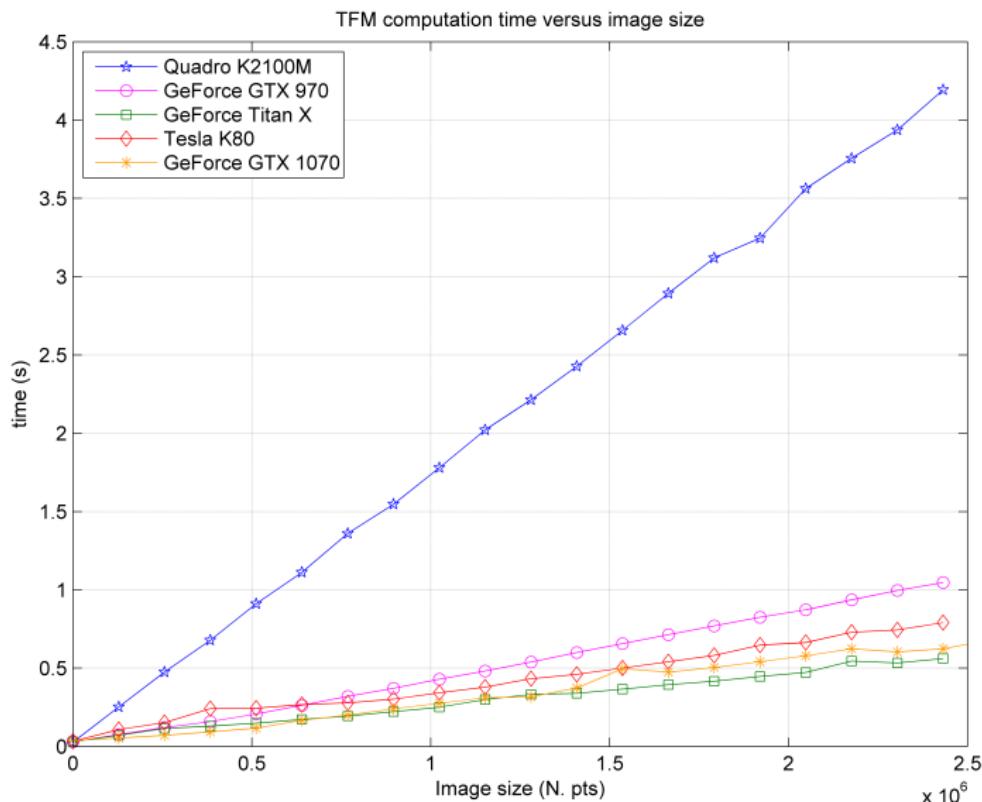
(a) Temps de calcul



(b) Accélération GPU/CPU



Comparaison de plusieurs cartes graphiques

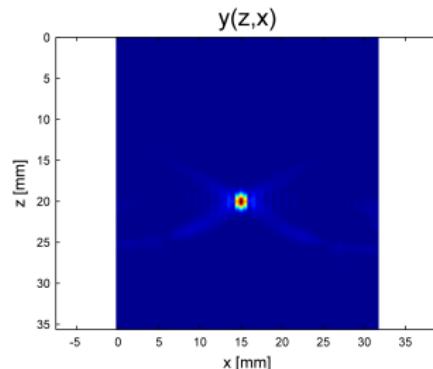
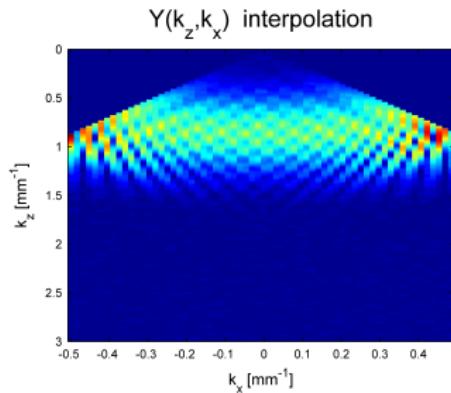
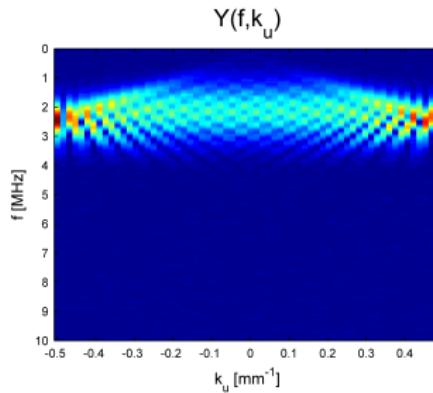
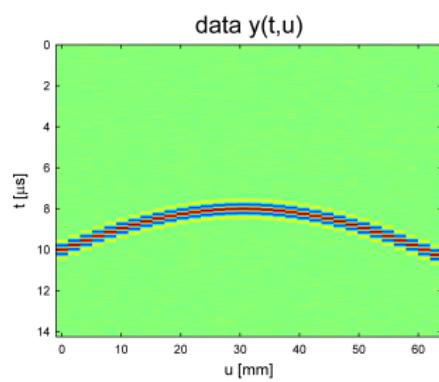


Imagerie par migration

- Vient de la communauté géophysique
- Seulement pour les inspections en contact ou en incidence normale
- Applicable au SAFT, FTP et PWI
- Principe :

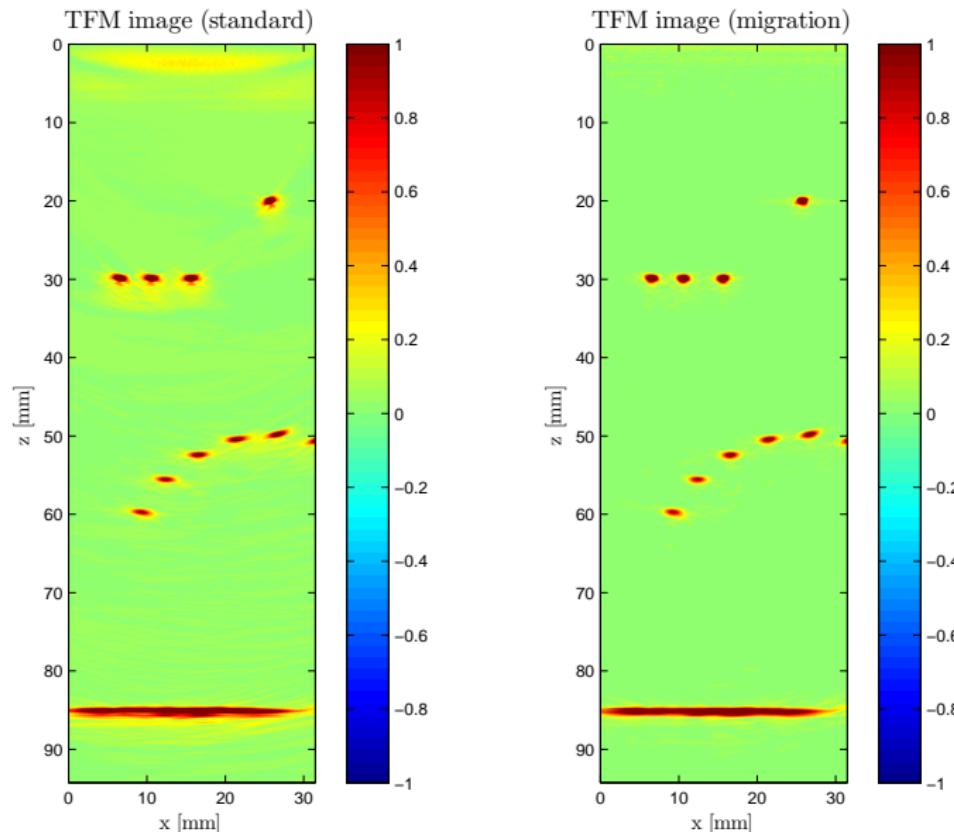
$$y(t, u) \xrightarrow{\text{F.T.}} Y(f, k_u) \xrightarrow{\text{mig.}} Y(k_z, k_x) \xrightarrow{\text{F.T.}^{-1}} y(z, x)$$

Principe de la migration avec des données synthétiques

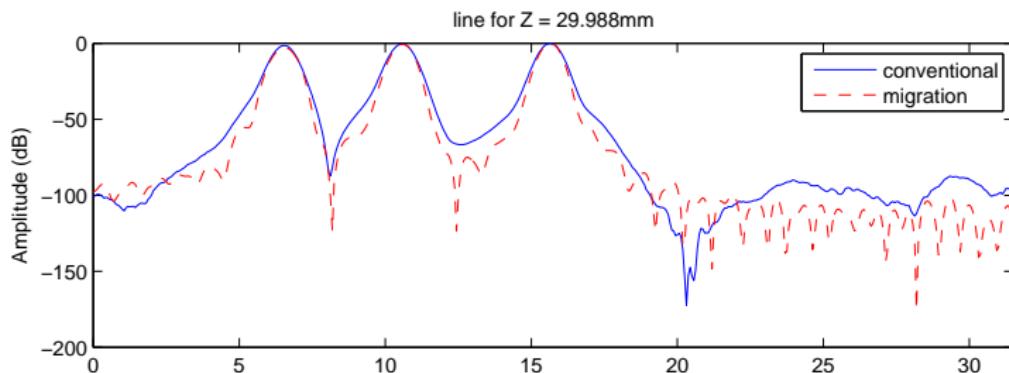
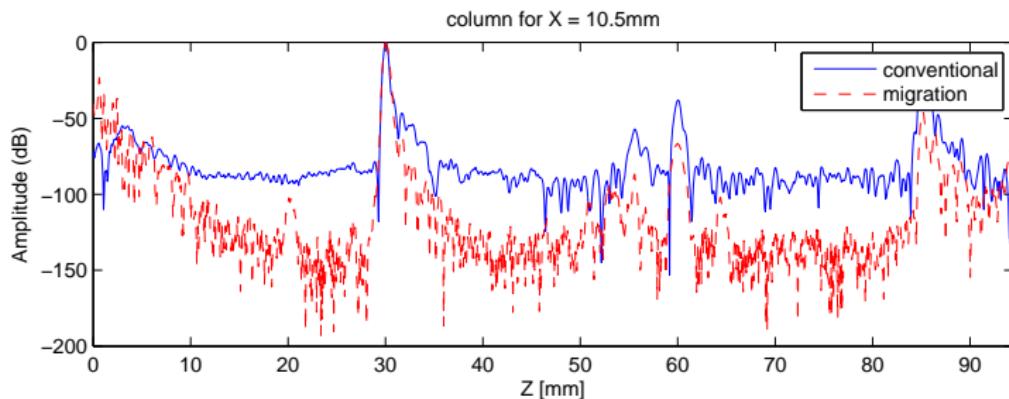




Résultats pour l'imagerie FTP

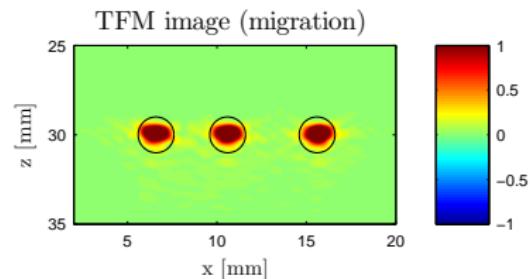
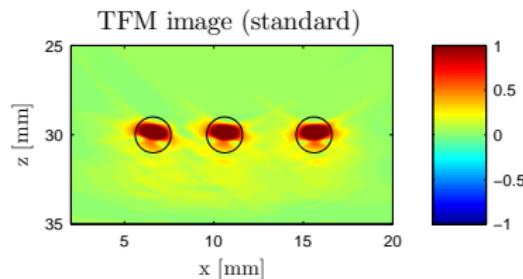


Résultats pour l'imagerie FTP

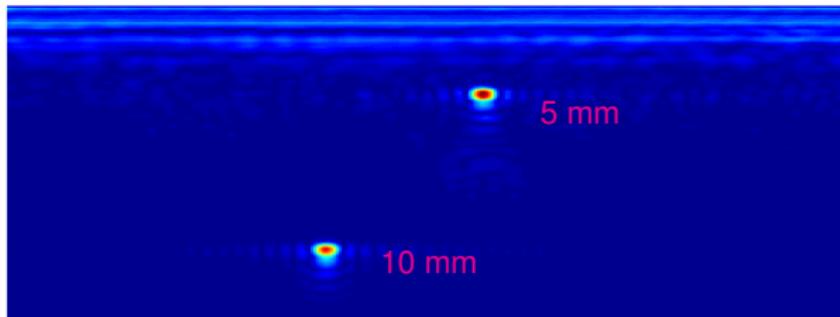


Résultats pour l'imagerie FTP

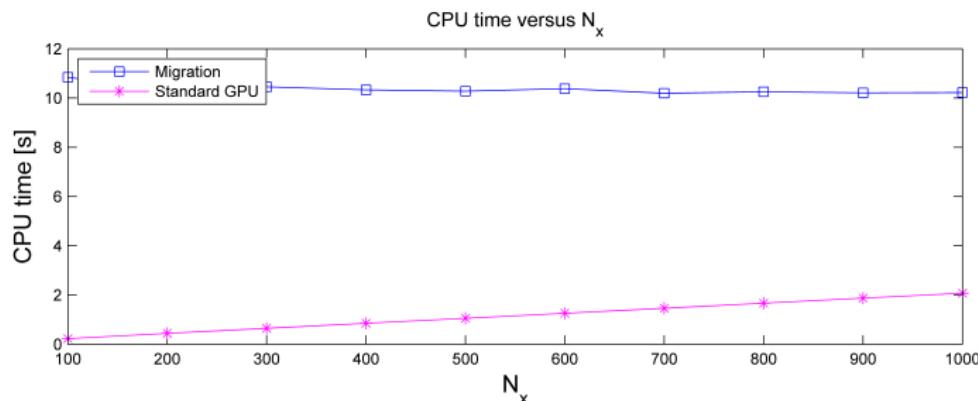
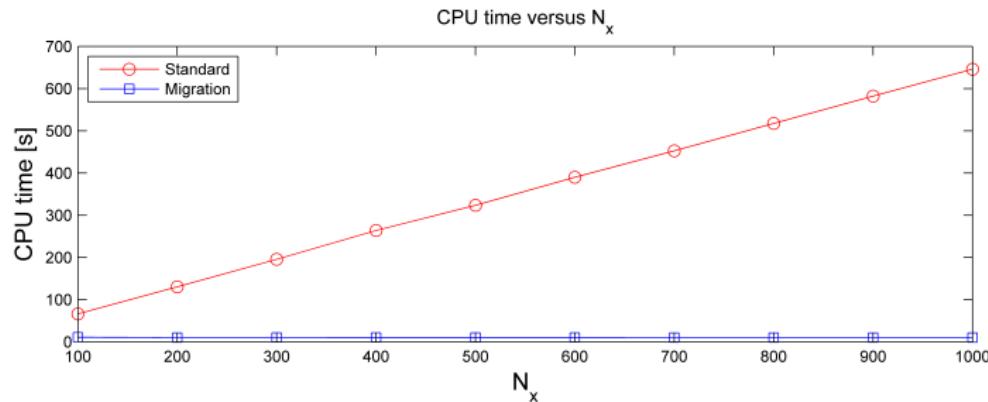
- Meilleur SNR et résolution des défauts :



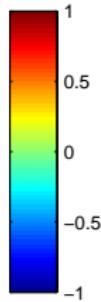
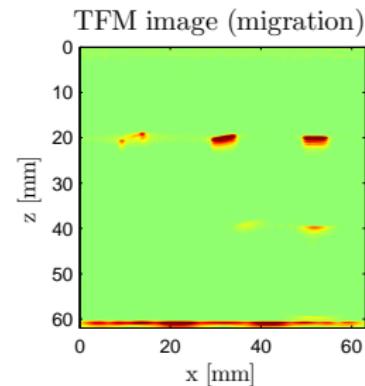
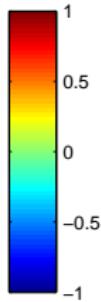
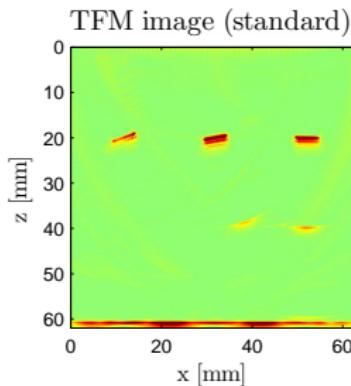
- Imagerie sous la surface de la pièce :



Temps de calcul



Comparaison imagerie FTP conventionnel/migration



	FTP conventionnel	FTP migration
geometrie	flexible	contact/objets plats
SNR	:(:)
résolution	:(:)
temps CPU	:(:)
temps GPU	:)	?

Sommaire

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- 4 Imagerie avancée
- 5 Application réelle : Inspection de soudures de pipelines
 - Inspection de soudures de pipelines
 - Défauts de soudures
 - Pièces inspectées
 - Inspection
 - Imagerie FTP
- 6 Fin

Inspection de soudures de pipelines

- PINC : Pipeline Inspection Company
- Basé à Istres, France
- Inspection de soudures de pipelines pour le transport de gaz et de pétrole



Sections de pipelines



Soudage



Dépose

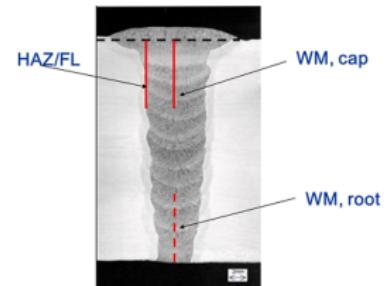
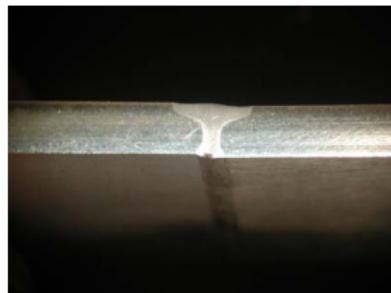
Inspection de soudures de pipelines

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration

Recent Girth Weld Incidents

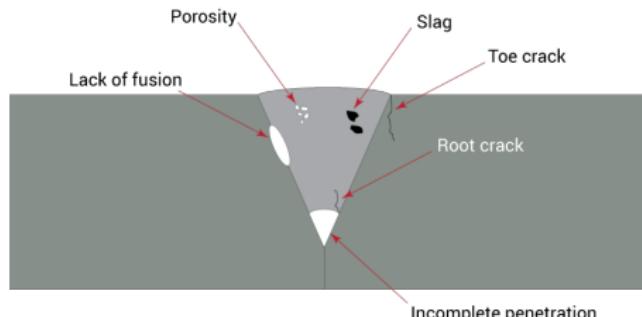


Soudures



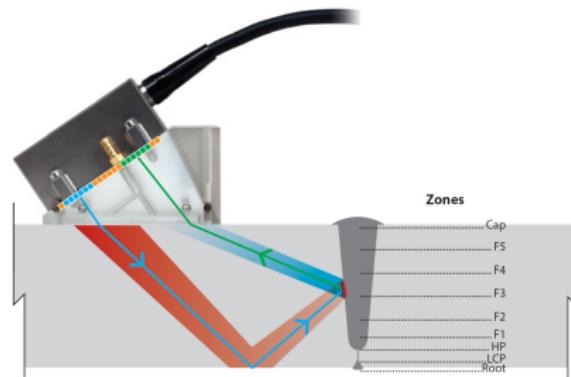
Défauts de soudures :

- Manque de fusion
- Porosité
- Inclusion

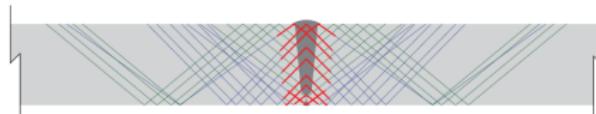


Méthode de référence : Automatic Ultrasonic Testing (AUT)

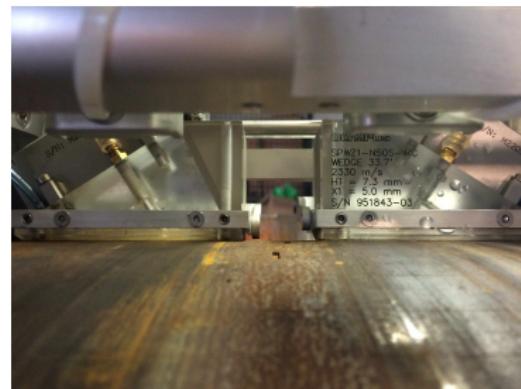
- Discrimination zonale par focalisation avec sondes multiéléments



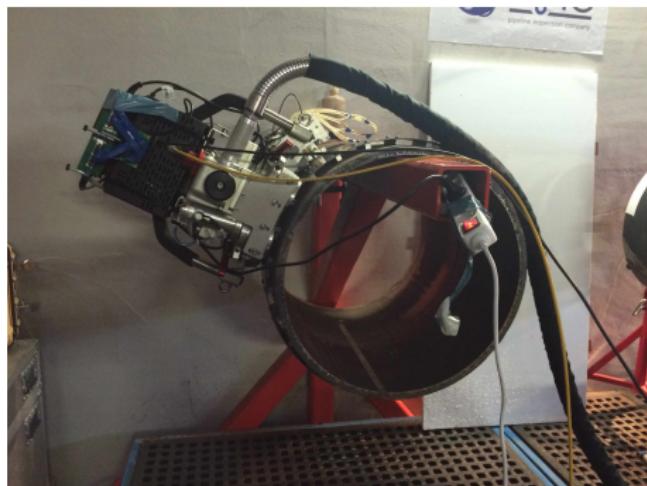
- Differentes zones sont couvertes



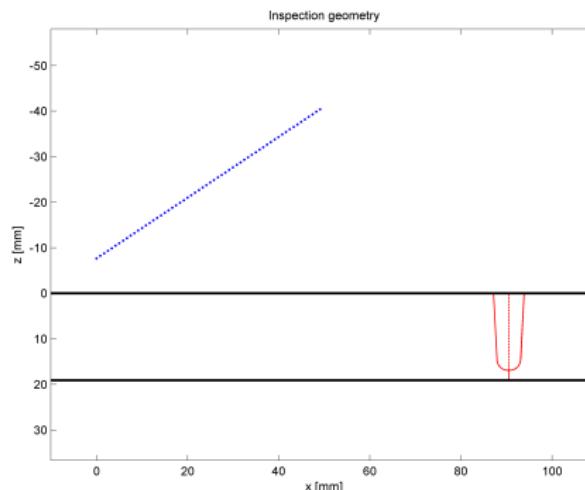
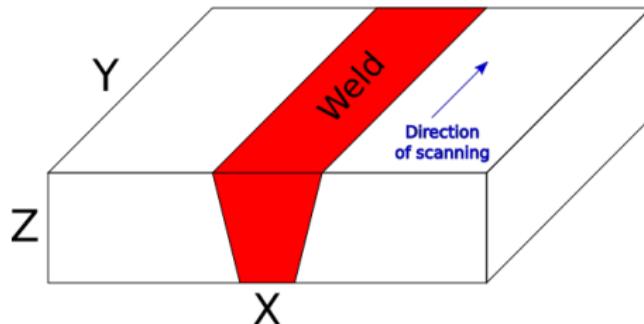
Pièces inspectées



Dispositif expérimental

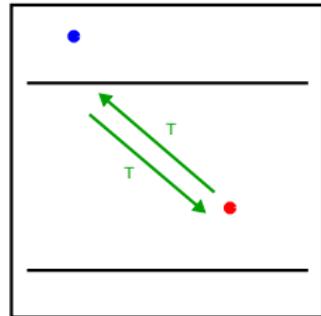


Scan le long de la soudure

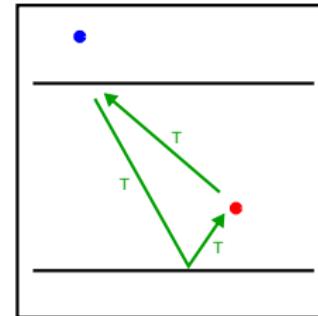


Imagerie FTP avec des ondes transversales

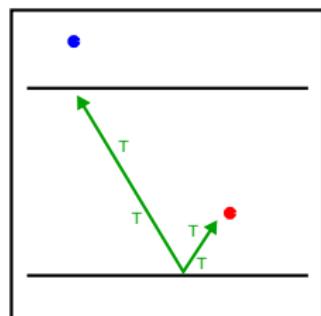
TT



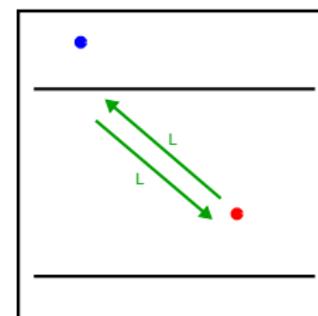
TTT



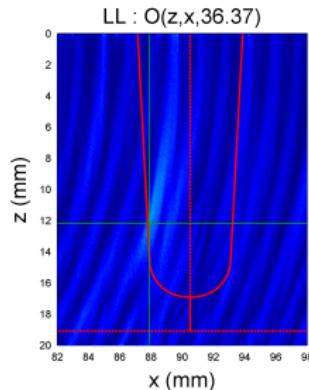
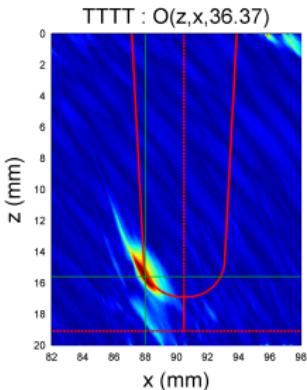
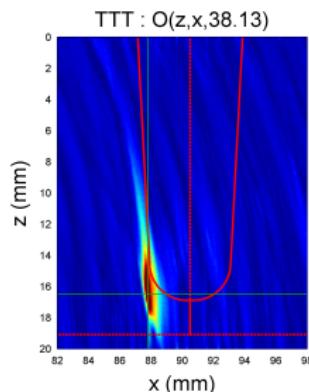
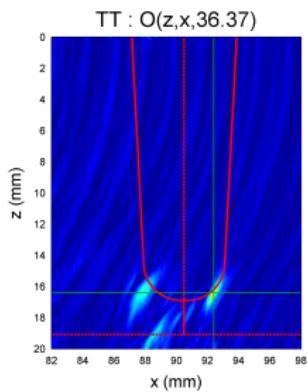
TTTT



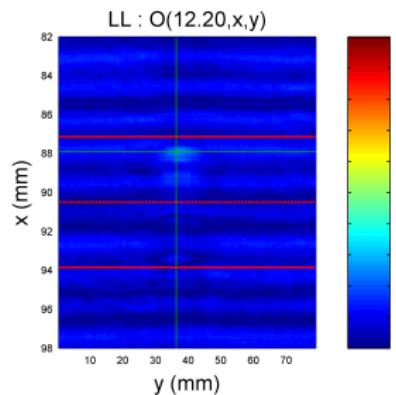
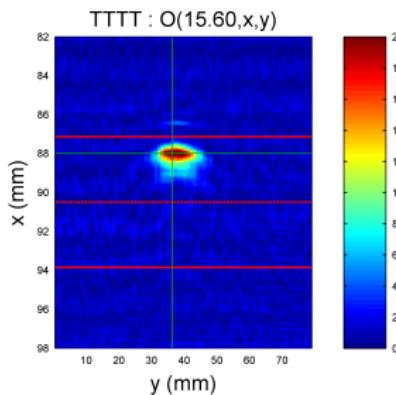
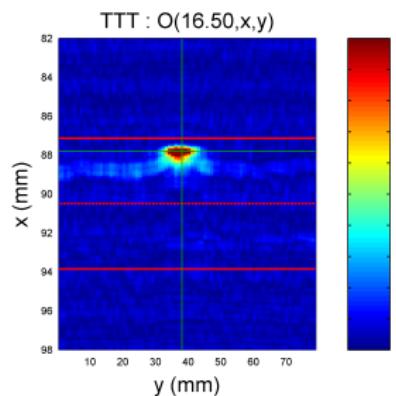
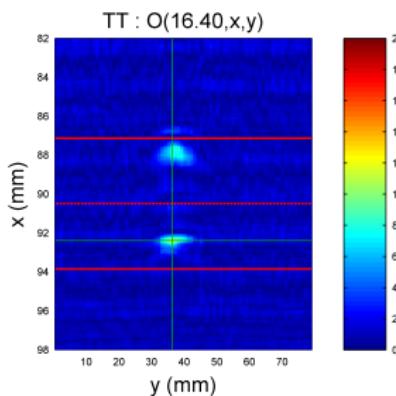
LL



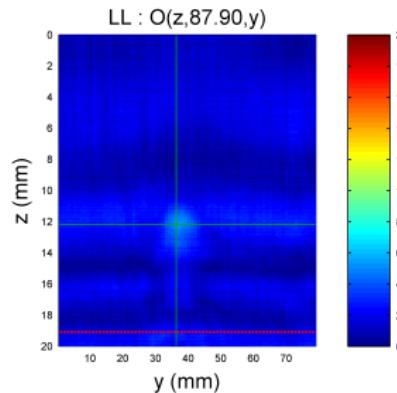
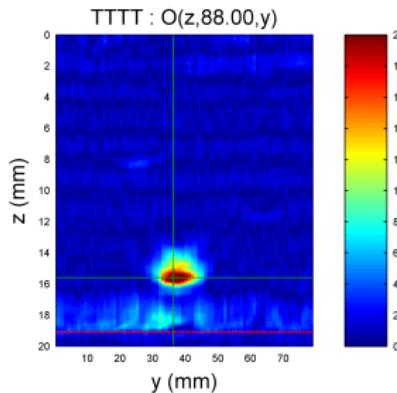
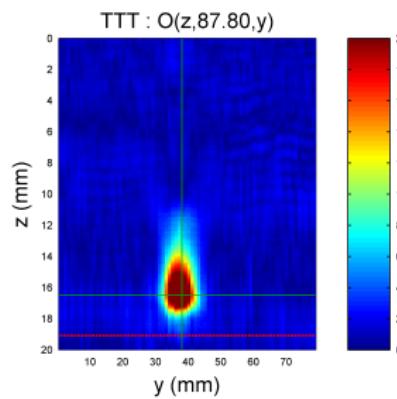
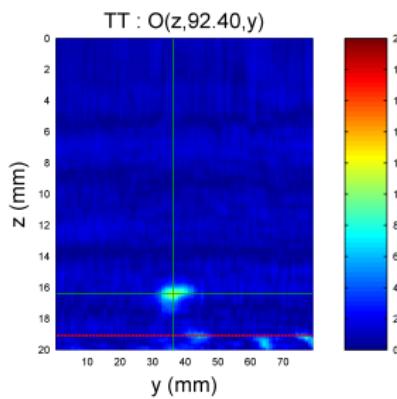
Manque de fusion : vue XZ



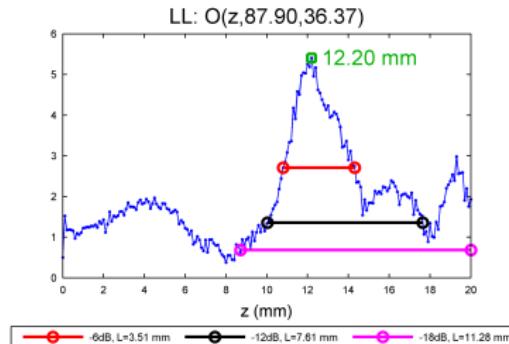
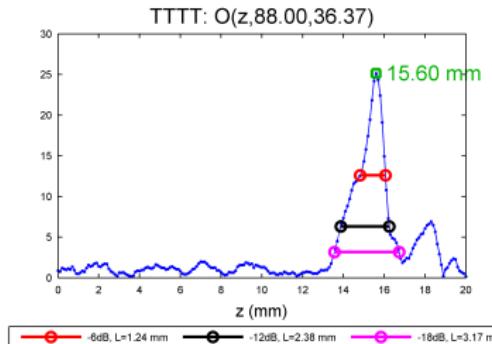
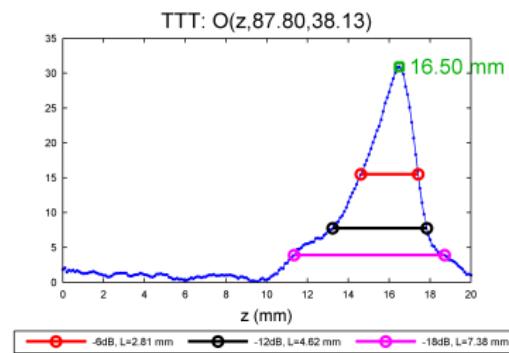
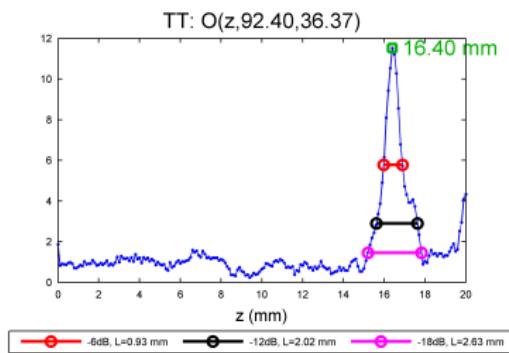
Manque de fusion : vue XY (top view)



Manque de fusion : vue YZ (side view)

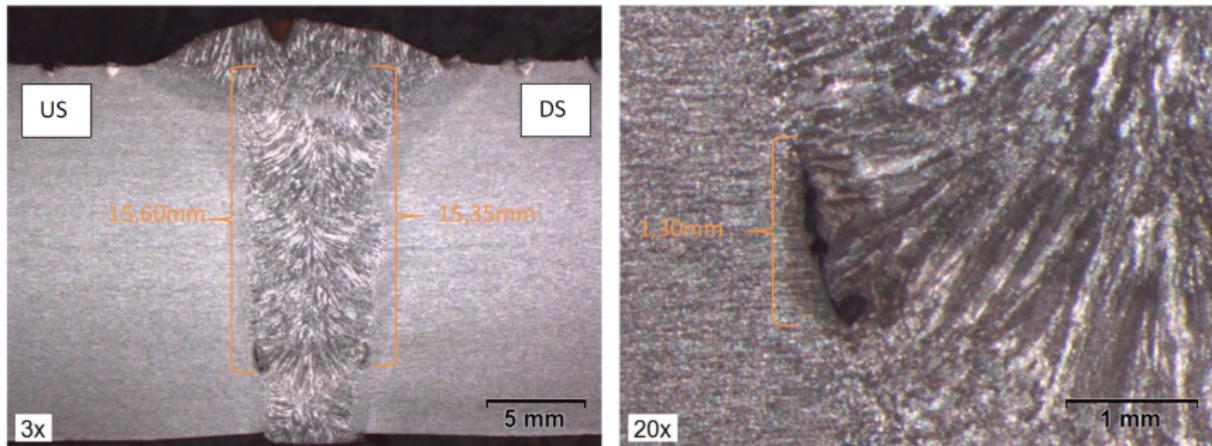


Dimensionnement du défaut à partir de la vue XZ



Comparaison macrographie / AUT / TFM

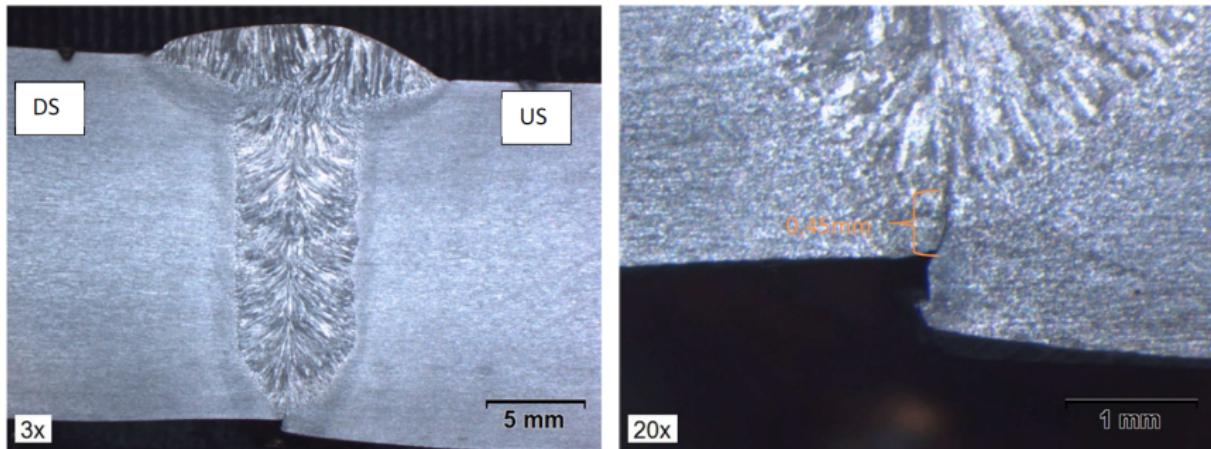
Macrographie :



Valeur	Macrographie	AUT	TFM (TTTT)
Profondeur (mm)	15.60	17.0	15.60
Hauteur (mm)	1.30	1.60	1.24
Erreur hauteur (%)	-	23.1	4.6

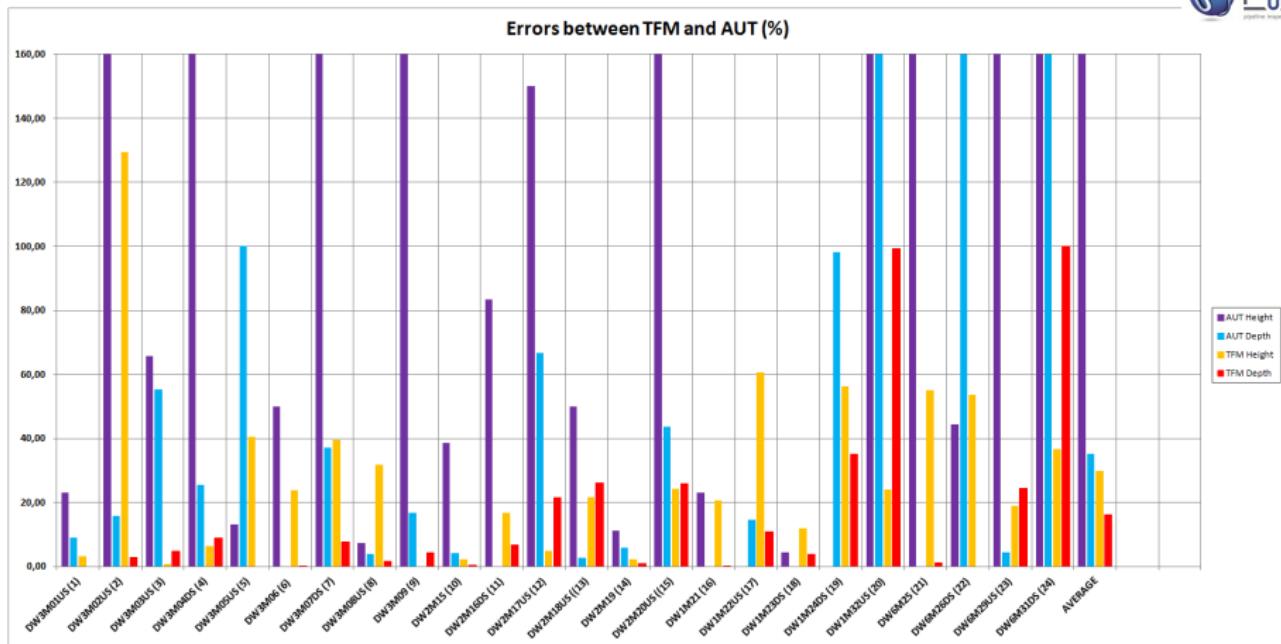
Comparaison macrographie / AUT / TFM

Macrographie :



Valeur	Macrographie	AUT	TFM (TTTT)
Profondeur (mm)	root	19.10	18.10
Hauteur (mm)	0.45	1.3	0.77
Erreur hauteur (%)	-	188.9	71.1

Erreurs entre AUT et TFM : 24 défauts



	AUT	TFM
Moyenne erreur profondeur (%)	197.0	29.8
Moyenne erreur hauteur (%)	35.1	16.1

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 - Conclusions

Conclusions

- Domaine utilisant des notions variées (acoustique, électronique, mécanique, informatique, traitement du signal, *etc.*)
- Cet après-midi, TP sur l'imagerie SAFT
- Possibilités de recrutement en France et à l'international (USA)
- N'hésitez pas à me contacter à ewen.carcreff@tpac-ndt.com



www.thephasedarraycompany.com