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MÉCANIQUE DU SOLIDE DÉFORMABLE

TRAVAUX DIRIGÉS

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Contents

Lis	ist of Acronyms							
Lis	ist of Symbols							
Αb	ostract	vi						
1.	Systèmes de coordonnées curvilignes 1.1. Énoncé	1 1 1						
2.	Second section	7						
Α.	First appendix	ć						

List of Acronyms

List of Acronyms

List of Acronyms

List of Sy.	mbols
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List of Symbols

List of Symbols

Abstract

Abstract

1. Systèmes de coordonnées curvilignes

1.1. Énoncé

1.1.1. Problème A

1.1.2. Problème B

1.2. Corrigé

1.2.1. Problème A

$$\begin{cases} x = x (\xi, \eta, \zeta) \\ y = x (\xi, \eta, \zeta) \\ z = x (\xi, \eta, \zeta) \end{cases} \longleftrightarrow \begin{cases} \xi = \xi (x, y, z) \\ \eta = \eta (x, y, z) \\ \zeta = \zeta (x, y, z) \end{cases}$$
(1)

$$f(x, y, z) = f(x(\xi, \eta, \zeta), y(\xi, \eta, \zeta), z(\xi, \eta, \zeta))$$
(2)

$$f(\xi, \eta, \zeta) = f(\xi(x, y, z), \eta(x, y, z), \zeta(x, y, z))$$
(3)

$$\nabla_{xyz}^{2} f(x, y, z) = \frac{\partial^{2} f}{\partial x^{2}} + \frac{\partial^{2} f}{\partial y^{2}} + \frac{\partial^{2} f}{\partial z^{2}}$$

$$\tag{4}$$

$$\begin{cases}
\frac{\partial f}{\partial x} = \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial x} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial x} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial x} \\
\frac{\partial f}{\partial y} = \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial y} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial y} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial y} \\
\frac{\partial f}{\partial z} = \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial z} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial z} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial z}
\end{cases}$$
(5)

$$\begin{cases} \frac{\partial^{2} f}{\partial x^{2}} &= \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial x} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial x} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial x} \right) = \\ &= \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial x} + \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial x} + \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial x} + \frac{\partial f}{\partial \xi} \frac{\partial^{2} \xi}{\partial x^{2}} + \frac{\partial f}{\partial \eta} \frac{\partial^{2} \eta}{\partial x^{2}} + \frac{\partial f}{\partial \zeta} \frac{\partial^{2} \zeta}{\partial x^{2}} \\ \frac{\partial^{2} f}{\partial y^{2}} &= \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial y} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial y} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial y} \right) = \\ &= \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial y} + \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial y} + \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial y} + \frac{\partial f}{\partial \xi} \frac{\partial^{2} \xi}{\partial y^{2}} + \frac{\partial f}{\partial \eta} \frac{\partial^{2} \eta}{\partial y^{2}} + \frac{\partial f}{\partial \zeta} \frac{\partial^{2} \zeta}{\partial y^{2}} \\ \frac{\partial^{2} f}{\partial z^{2}} &= \frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial z} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial z} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial z} \right) = \\ &= \frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial z} + \frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial z} + \frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial z} + \frac{\partial f}{\partial \xi} \frac{\partial^{2} \xi}{\partial z^{2}} + \frac{\partial f}{\partial \eta} \frac{\partial^{2} \eta}{\partial z^{2}} + \frac{\partial f}{\partial \zeta} \frac{\partial^{2} \zeta}{\partial z^{2}} \end{cases}$$

$$\begin{cases}
\frac{\partial}{\partial x} = \left(\frac{\partial \xi}{\partial x} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial x} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial x} \frac{\partial}{\partial \zeta}\right) \\
\frac{\partial}{\partial y} = \left(\frac{\partial \xi}{\partial y} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial y} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial y} \frac{\partial}{\partial \zeta}\right) \\
\frac{\partial}{\partial z} = \left(\frac{\partial \xi}{\partial z} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial z} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial z} \frac{\partial}{\partial \zeta}\right)
\end{cases} (7)$$

$$\begin{cases} \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial x} &= \left(\frac{\partial \xi}{\partial x} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial x} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial x} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial x} = \\ &= \left(\frac{\partial \xi}{\partial x} \right)^2 \frac{\partial^2 f}{\partial \xi^2} + \left(\frac{\partial \eta}{\partial x} \right) \left(\frac{\partial \xi}{\partial x} \right) \frac{\partial^2 f}{\partial \eta \partial \xi} + \left(\frac{\partial \zeta}{\partial x} \right) \left(\frac{\partial \xi}{\partial x} \right) \frac{\partial^2 f}{\partial \zeta \partial \xi} \\ \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial x} &= \left(\frac{\partial \xi}{\partial x} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial x} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial x} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial x} = \\ &= \left(\frac{\partial \xi}{\partial x} \right) \left(\frac{\partial \eta}{\partial x} \right) \frac{\partial^2 f}{\partial \xi \partial \eta} + \left(\frac{\partial \eta}{\partial x} \right)^2 \frac{\partial^2 f}{\partial \eta^2} + \left(\frac{\partial \zeta}{\partial x} \right) \left(\frac{\partial \eta}{\partial x} \right) \frac{\partial^2 f}{\partial \zeta \partial \eta} \\ \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial x} &= \left(\frac{\partial \xi}{\partial x} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial x} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial x} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial x} = \\ &= \left(\frac{\partial \xi}{\partial x} \right) \left(\frac{\partial \zeta}{\partial x} \right) \frac{\partial^2 f}{\partial \xi \partial \zeta} + \left(\frac{\partial \eta}{\partial x} \right) \left(\frac{\partial \zeta}{\partial x} \right) \frac{\partial^2 f}{\partial \eta \partial \zeta} + \left(\frac{\partial \zeta}{\partial x} \right)^2 \frac{\partial^2 f}{\partial \zeta^2} \end{cases}$$

$$(8)$$

$$\begin{cases}
\frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial y} &= \left(\frac{\partial \xi}{\partial y} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial y} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial y} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial y} = \\
&= \left(\frac{\partial \xi}{\partial y} \right)^2 \frac{\partial^2 f}{\partial \xi^2} + \left(\frac{\partial \eta}{\partial y} \right) \left(\frac{\partial \xi}{\partial y} \right) \frac{\partial^2 f}{\partial \eta \partial \xi} + \left(\frac{\partial \zeta}{\partial y} \right) \left(\frac{\partial \xi}{\partial y} \right) \frac{\partial^2 f}{\partial \zeta \partial \xi} \\
\frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial y} &= \left(\frac{\partial \xi}{\partial y} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial y} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial y} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial y} = \\
&= \left(\frac{\partial \xi}{\partial y} \right) \left(\frac{\partial \eta}{\partial y} \right) \frac{\partial^2 f}{\partial \xi \partial \eta} + \left(\frac{\partial \eta}{\partial y} \right)^2 \frac{\partial^2 f}{\partial \eta^2} + \left(\frac{\partial \zeta}{\partial y} \right) \left(\frac{\partial \eta}{\partial y} \right) \frac{\partial^2 f}{\partial \zeta \partial \eta} \\
\frac{\partial}{\partial y} \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial y} &= \left(\frac{\partial \xi}{\partial y} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial y} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial y} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial y} = \\
&= \left(\frac{\partial \xi}{\partial y} \right) \left(\frac{\partial \zeta}{\partial y} \right) \frac{\partial^2 f}{\partial \xi \partial \zeta} + \left(\frac{\partial \eta}{\partial y} \right) \left(\frac{\partial \zeta}{\partial y} \right) \frac{\partial^2 f}{\partial \eta \partial \zeta} + \left(\frac{\partial \zeta}{\partial y} \right)^2 \frac{\partial^2 f}{\partial \zeta^2}
\end{cases}$$

$$\begin{cases}
\frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial z} &= \left(\frac{\partial \xi}{\partial z} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial z} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial z} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \xi} \right) \frac{\partial \xi}{\partial z} = \\
&= \left(\frac{\partial \xi}{\partial z} \right)^2 \frac{\partial^2 f}{\partial \xi^2} + \left(\frac{\partial \eta}{\partial z} \right) \left(\frac{\partial \xi}{\partial z} \right) \frac{\partial^2 f}{\partial \eta \partial \xi} + \left(\frac{\partial \zeta}{\partial z} \right) \left(\frac{\partial \xi}{\partial z} \right) \frac{\partial^2 f}{\partial \zeta \partial \xi} \\
\begin{cases}
\frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial z} &= \left(\frac{\partial \xi}{\partial z} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial z} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial z} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \eta} \right) \frac{\partial \eta}{\partial z} = \\
&= \left(\frac{\partial \xi}{\partial x} \right) \left(\frac{\partial \eta}{\partial z} \right) \frac{\partial^2 f}{\partial \xi \partial \eta} + \left(\frac{\partial \eta}{\partial z} \right)^2 \frac{\partial^2 f}{\partial \eta^2} + \left(\frac{\partial \zeta}{\partial z} \right) \left(\frac{\partial \eta}{\partial z} \right) \frac{\partial^2 f}{\partial \zeta \partial \eta} \\
\end{cases} \\
\begin{cases}
\frac{\partial}{\partial z} \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial z} &= \left(\frac{\partial \xi}{\partial z} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial z} \frac{\partial}{\partial \eta} + \frac{\partial \zeta}{\partial z} \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial f}{\partial \zeta} \right) \frac{\partial \zeta}{\partial z} = \\
&= \left(\frac{\partial \xi}{\partial z} \right) \left(\frac{\partial \zeta}{\partial z} \right) \frac{\partial^2 f}{\partial \xi \partial \zeta} + \left(\frac{\partial \eta}{\partial z} \right) \left(\frac{\partial \zeta}{\partial z} \right) \frac{\partial^2 f}{\partial \eta \partial \zeta} + \left(\frac{\partial \zeta}{\partial z} \right)^2 \frac{\partial^2 f}{\partial \zeta^2}
\end{cases}$$

$$\frac{\partial^2 f}{\partial \eta \partial \xi} = \frac{\partial^2 f}{\partial \xi \partial \eta} \qquad \frac{\partial^2 f}{\partial \eta \partial \zeta} = \frac{\partial^2 f}{\partial \zeta \partial \eta} \qquad \frac{\partial^2 f}{\partial \xi \partial \zeta} = \frac{\partial^2 f}{\partial \zeta \partial \xi} \tag{11}$$

$$\frac{\partial^2 f}{\partial x^2} = \left(\frac{\partial \xi}{\partial x}\right)^2 \frac{\partial^2 f}{\partial \xi^2} + \left(\frac{\partial \eta}{\partial x}\right)^2 \frac{\partial^2 f}{\partial \eta^2} + \left(\frac{\partial \zeta}{\partial x}\right)^2 \frac{\partial^2 f}{\partial \zeta^2} + \\
+ 2\left(\frac{\partial \xi}{\partial x}\right) \left(\frac{\partial \eta}{\partial x}\right) \frac{\partial^2 f}{\partial \xi \partial \eta} + 2\left(\frac{\partial \xi}{\partial x}\right) \left(\frac{\partial \zeta}{\partial x}\right) \frac{\partial^2 f}{\partial \xi \partial \zeta} + 2\left(\frac{\partial \eta}{\partial x}\right) \left(\frac{\partial \zeta}{\partial x}\right) \frac{\partial^2 f}{\partial \eta \partial \zeta} + (12) \\
+ \frac{\partial f}{\partial \xi} \frac{\partial^2 \xi}{\partial x^2} + \frac{\partial f}{\partial \eta} \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial f}{\partial \zeta} \frac{\partial^2 \zeta}{\partial x^2}$$

$$\begin{cases}
\frac{\partial^{2} f}{\partial x^{2}} = \left(\frac{\partial \xi}{\partial x}\right)^{2} \frac{\partial^{2} f}{\partial \xi^{2}} + \left(\frac{\partial \eta}{\partial x}\right)^{2} \frac{\partial^{2} f}{\partial \eta^{2}} + \left(\frac{\partial \zeta}{\partial x}\right)^{2} \frac{\partial^{2} f}{\partial \zeta^{2}} + \\
+ 2 \left(\frac{\partial \xi}{\partial x}\right) \left(\frac{\partial \eta}{\partial x}\right) \frac{\partial^{2} f}{\partial \xi \partial \eta} + 2 \left(\frac{\partial \xi}{\partial x}\right) \left(\frac{\partial \zeta}{\partial x}\right) \frac{\partial^{2} f}{\partial \xi \partial \zeta} + 2 \left(\frac{\partial \eta}{\partial x}\right) \left(\frac{\partial \zeta}{\partial x}\right) \frac{\partial^{2} f}{\partial \eta \partial \zeta} \\
\frac{\partial^{2} f}{\partial y^{2}} = \left(\frac{\partial \xi}{\partial y}\right)^{2} \frac{\partial^{2} f}{\partial \xi^{2}} + \left(\frac{\partial \eta}{\partial y}\right)^{2} \frac{\partial^{2} f}{\partial \eta^{2}} + \left(\frac{\partial \zeta}{\partial y}\right)^{2} \frac{\partial^{2} f}{\partial \zeta^{2}} + \\
+ 2 \left(\frac{\partial \xi}{\partial y}\right) \left(\frac{\partial \eta}{\partial y}\right) \frac{\partial^{2} f}{\partial \xi \partial \eta} + 2 \left(\frac{\partial \xi}{\partial y}\right) \left(\frac{\partial \zeta}{\partial y}\right) \frac{\partial^{2} f}{\partial \xi \partial \zeta} + 2 \left(\frac{\partial \eta}{\partial y}\right) \left(\frac{\partial \zeta}{\partial y}\right) \frac{\partial^{2} f}{\partial \eta \partial \zeta} \\
\frac{\partial^{2} f}{\partial z^{2}} = \left(\frac{\partial \xi}{\partial z}\right)^{2} \frac{\partial^{2} f}{\partial \xi^{2}} + \left(\frac{\partial \eta}{\partial z}\right)^{2} \frac{\partial^{2} f}{\partial \eta^{2}} + \left(\frac{\partial \zeta}{\partial z}\right)^{2} \frac{\partial^{2} f}{\partial \zeta^{2}} + \\
+ 2 \left(\frac{\partial \xi}{\partial z}\right) \left(\frac{\partial \eta}{\partial z}\right) \frac{\partial^{2} f}{\partial \xi \partial \eta} + 2 \left(\frac{\partial \xi}{\partial z}\right) \left(\frac{\partial \zeta}{\partial z}\right) \frac{\partial^{2} f}{\partial \xi \partial \zeta} + 2 \left(\frac{\partial \eta}{\partial z}\right) \left(\frac{\partial \zeta}{\partial z}\right) \frac{\partial^{2} f}{\partial \eta \partial \zeta}
\end{cases}$$

$$(13)$$

$$\nabla_{\xi\eta\zeta}^{2}f\left(\xi,\eta,\zeta\right) = \left[\left(\frac{\partial\xi}{\partial x}\right)^{2} + \left(\frac{\partial\xi}{\partial y}\right)^{2} + \left(\frac{\partial\xi}{\partial z}\right)^{2}\right] \frac{\partial^{2}f}{\partial\xi^{2}} + \\
+ \left[\left(\frac{\partial\eta}{\partial x}\right)^{2} + \left(\frac{\partial\eta}{\partial y}\right)^{2} + \left(\frac{\partial\eta}{\partial z}\right)^{2}\right] \frac{\partial^{2}f}{\partial\eta^{2}} + \\
+ \left[\left(\frac{\partial\zeta}{\partial x}\right)^{2} + \left(\frac{\partial\zeta}{\partial y}\right)^{2} + \left(\frac{\partial\zeta}{\partial z}\right)^{2}\right] \frac{\partial^{2}f}{\partial\zeta^{2}} + \\
+ 2\left[\left(\frac{\partial\xi}{\partial x}\right)\left(\frac{\partial\eta}{\partial x}\right) + \left(\frac{\partial\xi}{\partial y}\right)\left(\frac{\partial\eta}{\partial y}\right) + \left(\frac{\partial\xi}{\partial z}\right)\left(\frac{\partial\eta}{\partial z}\right)\right] \frac{\partial^{2}f}{\partial\xi\partial\eta} + \\
+ 2\left[\left(\frac{\partial\eta}{\partial x}\right)\left(\frac{\partial\zeta}{\partial x}\right) + \left(\frac{\partial\eta}{\partial y}\right)\left(\frac{\partial\zeta}{\partial y}\right) + \left(\frac{\partial\eta}{\partial z}\right)\left(\frac{\partial\zeta}{\partial z}\right)\right] \frac{\partial^{2}f}{\partial\eta\partial\zeta} + \\
+ 2\left[\left(\frac{\partial\xi}{\partial x}\right)\left(\frac{\partial\zeta}{\partial x}\right) + \left(\frac{\partial\xi}{\partial y}\right)\left(\frac{\partial\zeta}{\partial y}\right) + \left(\frac{\partial\xi}{\partial z}\right)\left(\frac{\partial\zeta}{\partial z}\right)\right] \frac{\partial^{2}f}{\partial\xi\partial\zeta}$$

Coordonnées cylindriques

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \end{cases} \longleftrightarrow \begin{cases} r = \sqrt{x^2 + y^2} \\ \theta = \tan^{-1} \left(\frac{y}{x}\right) \\ z = z \end{cases}$$
 (15)

$$\begin{cases}
\frac{\partial r}{\partial x} = \frac{1}{2} \frac{2x}{\sqrt{x^2 + y^2}} = \frac{r \cos \theta}{r} \\
\frac{\partial r}{\partial y} = \frac{1}{2} \frac{2y}{\sqrt{x^2 + y^2}} = \frac{r \sin \theta}{r} \\
\frac{\partial r}{\partial z} = 0
\end{cases}$$
(16)

Coordonnées spheriques

1.2.2. Problème B

$$\begin{cases} x = x (\xi, \eta, \zeta) \\ y = x (\xi, \eta, \zeta) \\ z = x (\xi, \eta, \zeta) \end{cases} \longleftrightarrow \begin{cases} \xi = \xi (x, y, z) \\ \eta = \eta (x, y, z) \\ \zeta = \zeta (x, y, z) \end{cases}$$
(17)

$$f(x, y, z) = f(x(\xi, \eta, \zeta), y(\xi, \eta, \zeta), z(\xi, \eta, \zeta))$$
(18)

$$f(\xi, \eta, \zeta) = f(\xi(x, y, z), \eta(x, y, z), \zeta(x, y, z))$$

$$(19)$$

$$\nabla f_{xyz} = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \frac{\partial f}{\partial x} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + \frac{\partial f}{\partial y} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + \frac{\partial f}{\partial z} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \frac{\partial f}{\partial x} \mathbf{i}_x + \frac{\partial f}{\partial y} \mathbf{j}_y + \frac{\partial f}{\partial z} \mathbf{k}_z$$
 (20)

$$\nabla f = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial x} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial x} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial x} \\ \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial y} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial y} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial y} \\ \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial z} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial z} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial z} \end{bmatrix} = \frac{\partial f}{\partial \xi} \begin{bmatrix} \frac{\partial \xi}{\partial x} \\ \frac{\partial \xi}{\partial y} \\ \frac{\partial \xi}{\partial z} \end{bmatrix} + \frac{\partial f}{\partial \eta} \begin{bmatrix} \frac{\partial \eta}{\partial x} \\ \frac{\partial \eta}{\partial y} \\ \frac{\partial \eta}{\partial z} \end{bmatrix} + \frac{\partial f}{\partial \zeta} \begin{bmatrix} \frac{\partial \zeta}{\partial x} \\ \frac{\partial \zeta}{\partial y} \\ \frac{\partial \zeta}{\partial z} \end{bmatrix}$$
(21)

$$\mathbf{i}_{\xi} = \frac{1}{\sqrt{\left(\frac{\partial \xi}{\partial x}\right)^{2} + \left(\frac{\partial \xi}{\partial y}\right)^{2} + \left(\frac{\partial \xi}{\partial z}\right)^{2}}} \begin{bmatrix} \frac{\partial \xi}{\partial x} \\ \frac{\partial \xi}{\partial y} \\ \frac{\partial \xi}{\partial z} \end{bmatrix}
\mathbf{j}_{\eta} = \frac{1}{\sqrt{\left(\frac{\partial \eta}{\partial x}\right)^{2} + \left(\frac{\partial \eta}{\partial y}\right)^{2} + \left(\frac{\partial \eta}{\partial z}\right)^{2}}} \begin{bmatrix} \frac{\partial \eta}{\partial x} \\ \frac{\partial \eta}{\partial y} \\ \frac{\partial \eta}{\partial y} \\ \frac{\partial \eta}{\partial z} \end{bmatrix}
\mathbf{k}_{\zeta} = \frac{1}{\sqrt{\left(\frac{\partial \zeta}{\partial x}\right)^{2} + \left(\frac{\partial \zeta}{\partial y}\right)^{2} + \left(\frac{\partial \zeta}{\partial z}\right)^{2}}} \begin{bmatrix} \frac{\partial \zeta}{\partial x} \\ \frac{\partial \zeta}{\partial y} \\ \frac{\partial \zeta}{\partial z} \end{bmatrix}$$
(22)

$$\nabla_{\xi\eta\zeta}f = \frac{\partial f}{\partial \xi} \sqrt{\left(\frac{\partial \xi}{\partial x}\right)^{2} + \left(\frac{\partial \xi}{\partial y}\right)^{2} + \left(\frac{\partial \xi}{\partial z}\right)^{2}} \cdot \mathbf{i}_{\xi} +
+ \frac{\partial f}{\partial \eta} \sqrt{\left(\frac{\partial \eta}{\partial x}\right)^{2} + \left(\frac{\partial \eta}{\partial y}\right)^{2} + \left(\frac{\partial \eta}{\partial z}\right)^{2}} \cdot \mathbf{j}_{\eta} +
+ \frac{\partial f}{\partial \zeta} \sqrt{\left(\frac{\partial \zeta}{\partial x}\right)^{2} + \left(\frac{\partial \zeta}{\partial y}\right)^{2} + \left(\frac{\partial \zeta}{\partial z}\right)^{2}} \cdot \mathbf{k}_{\zeta} =
= \begin{bmatrix} \frac{\partial f}{\partial \xi} \sqrt{\left(\frac{\partial \xi}{\partial x}\right)^{2} + \left(\frac{\partial \xi}{\partial y}\right)^{2} + \left(\frac{\partial \xi}{\partial z}\right)^{2}} \\ \frac{\partial f}{\partial \zeta} \sqrt{\left(\frac{\partial \eta}{\partial x}\right)^{2} + \left(\frac{\partial \eta}{\partial y}\right)^{2} + \left(\frac{\partial \eta}{\partial z}\right)^{2}} \\ \frac{\partial f}{\partial \zeta} \sqrt{\left(\frac{\partial \zeta}{\partial x}\right)^{2} + \left(\frac{\partial \zeta}{\partial y}\right)^{2} + \left(\frac{\partial \zeta}{\partial z}\right)^{2}} \end{bmatrix}$$
(23)

Coordonnées cylindriques

Coordonnées spheriques

2. Second section

Second section

Λ	•	nond	1:	Λ
\mathcal{A}	μ	pena	IΧ	Α

A. First appendix

Appen	dix	\overline{A}