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MÉCANIQUE DU SOLIDE DÉFORMABLE

TRAVAUX DIRIGÉS

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List of Acronyms

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List of Symbols

Abstract

1. Systèmes de coordonnées curvilignes

1.1. Énoncé

1.1.1. Problème A

Exprimer l'opérateur laplacien ∇^2 en

1. coordonnées cylindriques,
2. coordonnées sphériques.

1.1.2. Problème B

1.2. Corrigé

1.2.1. Problème A

Rappels théoriques

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

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

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

$$\nabla_{xyz}^2 f(x, y, z) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} \quad (4)$$

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

$$\begin{aligned}
\frac{\partial^2 f}{\partial y^2} &= \left(\frac{\partial \xi}{\partial y}\right)^2 \frac{\partial^2 f}{\partial \xi^2} + \left(\frac{\partial \eta}{\partial y}\right)^2 \frac{\partial^2 f}{\partial \eta^2} + \left(\frac{\partial \zeta}{\partial y}\right)^2 \frac{\partial^2 f}{\partial \zeta^2} + \\
&+ 2 \left(\frac{\partial \xi}{\partial y}\right) \left(\frac{\partial \eta}{\partial y}\right) \frac{\partial^2 f}{\partial \xi \partial \eta} + 2 \left(\frac{\partial \xi}{\partial y}\right) \left(\frac{\partial \zeta}{\partial y}\right) \frac{\partial^2 f}{\partial \xi \partial \zeta} + 2 \left(\frac{\partial \eta}{\partial y}\right) \left(\frac{\partial \zeta}{\partial y}\right) \frac{\partial^2 f}{\partial \eta \partial \zeta} + \\
&+ \frac{\partial f}{\partial \xi} \frac{\partial^2 \xi}{\partial y^2} + \frac{\partial f}{\partial \eta} \frac{\partial^2 \eta}{\partial y^2} + \frac{\partial f}{\partial \zeta} \frac{\partial^2 \zeta}{\partial y^2}
\end{aligned} \tag{13}$$

$$\begin{aligned}
\frac{\partial^2 f}{\partial z^2} &= \left(\frac{\partial \xi}{\partial z}\right)^2 \frac{\partial^2 f}{\partial \xi^2} + \left(\frac{\partial \eta}{\partial z}\right)^2 \frac{\partial^2 f}{\partial \eta^2} + \left(\frac{\partial \zeta}{\partial z}\right)^2 \frac{\partial^2 f}{\partial \zeta^2} + \\
&+ 2 \left(\frac{\partial \xi}{\partial z}\right) \left(\frac{\partial \eta}{\partial z}\right) \frac{\partial^2 f}{\partial \xi \partial \eta} + 2 \left(\frac{\partial \xi}{\partial z}\right) \left(\frac{\partial \zeta}{\partial z}\right) \frac{\partial^2 f}{\partial \xi \partial \zeta} + 2 \left(\frac{\partial \eta}{\partial z}\right) \left(\frac{\partial \zeta}{\partial z}\right) \frac{\partial^2 f}{\partial \eta \partial \zeta} + \\
&+ \frac{\partial f}{\partial \xi} \frac{\partial^2 \xi}{\partial z^2} + \frac{\partial f}{\partial \eta} \frac{\partial^2 \eta}{\partial z^2} + \frac{\partial f}{\partial \zeta} \frac{\partial^2 \zeta}{\partial z^2}
\end{aligned} \tag{14}$$

$$\begin{aligned}
\nabla_{\xi\eta\zeta}^2 f(\xi, \eta, \zeta) = & \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} + \\
& + \left(\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2} + \frac{\partial^2 \xi}{\partial z^2} \right) \frac{\partial f}{\partial \xi} + \left(\frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} + \frac{\partial^2 \eta}{\partial z^2} \right) \frac{\partial f}{\partial \eta} + \\
& + \left(\frac{\partial^2 \zeta}{\partial x^2} + \frac{\partial^2 \zeta}{\partial y^2} + \frac{\partial^2 \zeta}{\partial z^2} \right) \frac{\partial f}{\partial \zeta}
\end{aligned} \tag{15}$$

Coordonnées cylindriques

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \\ z = \tilde{z} \end{cases} \longleftrightarrow \begin{cases} r = \sqrt{x^2 + y^2} \\ \theta = \tan^{-1} \left(\frac{y}{x} \right) \\ \tilde{z} = z \end{cases} \tag{16}$$

$$\begin{cases} \frac{\partial r}{\partial x} = \frac{1}{2} \frac{2x}{\sqrt{x^2 + y^2}} = \frac{x}{\sqrt{x^2 + y^2}} \\ \frac{\partial r}{\partial y} = \frac{1}{2} \frac{2y}{\sqrt{x^2 + y^2}} = \frac{y}{\sqrt{x^2 + y^2}} \\ \frac{\partial r}{\partial z} = 0 \end{cases} \quad \begin{cases} \frac{\partial \theta}{\partial x} = -\frac{1}{1 + \left(\frac{y}{x} \right)^2} \frac{y}{x^2} = -\frac{1}{1 + \tan^2 \theta} \frac{r \sin \theta}{r^2 \cos^2 \theta} = -\frac{\sin \theta}{r} \\ \frac{\partial \theta}{\partial y} = \frac{1}{1 + \left(\frac{y}{x} \right)^2} \frac{1}{x} = \frac{1}{1 + \tan^2 \theta} \frac{1}{r \cos \theta} = \frac{\cos \theta}{r} \\ \frac{\partial \theta}{\partial z} = 0 \end{cases} \quad \begin{cases} \frac{\partial \tilde{z}}{\partial x} = 0 \\ \frac{\partial \tilde{z}}{\partial y} = 0 \\ \frac{\partial \tilde{z}}{\partial z} = 1 \end{cases} \tag{17}$$

$$\begin{cases} \frac{\partial^2 r}{\partial x^2} = \frac{\partial}{\partial x} (\cos \theta) = \\ = -\sin \theta \frac{\partial \theta}{\partial x} = \frac{\sin^2 \theta}{r} \\ \\ \frac{\partial^2 r}{\partial y^2} = \frac{\partial}{\partial y} (\sin \theta) = \\ = \cos \theta \frac{\partial \theta}{\partial y} = \frac{\cos^2 \theta}{r} \\ \\ \frac{\partial^2 r}{\partial z^2} = 0 \end{cases} \quad \begin{cases} \frac{\partial^2 \theta}{\partial x^2} = \frac{\partial}{\partial x} \left(-\frac{\sin \theta}{r} \right) = \\ = -\frac{1}{r} \frac{\partial}{\partial x} (\sin \theta) - \sin \theta \frac{\partial}{\partial x} \left(\frac{1}{r} \right) = \\ = -\frac{\cos \theta}{r} \frac{\partial \theta}{\partial x} + \frac{\sin \theta}{r^2} \frac{\partial r}{\partial x} = \\ = \frac{2 \sin \theta \cos \theta}{r^2} = \frac{\sin 2\theta}{r^2} \\ \\ \frac{\partial^2 \theta}{\partial y^2} = \frac{\partial}{\partial y} \left(\frac{\cos \theta}{r} \right) = \\ = \frac{1}{r} \frac{\partial}{\partial y} (\cos \theta) + \cos \theta \frac{\partial}{\partial y} \left(\frac{1}{r} \right) = \\ = -\frac{\sin \theta}{r} \frac{\partial \theta}{\partial y} - \frac{\cos \theta}{r^2} \frac{\partial r}{\partial y} = \\ = -\frac{2 \sin \theta \cos \theta}{r^2} = -\frac{\sin 2\theta}{r^2} \\ \\ \frac{\partial^2 \theta}{\partial z^2} = 0 \end{cases} \quad \begin{cases} \frac{\partial^2 \tilde{z}}{\partial x^2} = 0 \\ \\ \frac{\partial^2 \tilde{z}}{\partial y^2} = 0 \\ \\ \frac{\partial^2 \tilde{z}}{\partial z^2} = 0 \end{cases} \quad (18)$$

$$\begin{aligned} \nabla_{r\theta\tilde{z}}^2 f(r, \theta, \tilde{z}) &= [\cos^2 \theta + \sin^2 \theta] \frac{\partial^2 f}{\partial r^2} + \left[\frac{\sin^2 \theta}{r^2} + \frac{\cos^2 \theta}{r^2} \right] \frac{\partial^2 f}{\partial \theta^2} + \frac{\partial^2 f}{\partial \tilde{z}^2} + \\ &+ 2 \left[-\frac{\sin \theta \cos \theta}{r} + \frac{\sin \theta \cos \theta}{r} \right] \frac{\partial^2 f}{\partial r \partial \theta} + \\ &+ \left(\frac{\sin^2 \theta}{r} + \frac{\cos^2 \theta}{r} \right) \frac{\partial f}{\partial r} + \left(\frac{\sin 2\theta}{r^2} - \frac{\sin 2\theta}{r^2} \right) \frac{\partial f}{\partial \theta} = \\ &= \frac{\partial^2 f}{\partial r^2} + \frac{1}{r} \frac{\partial f}{\partial r} + \frac{1}{r^2} \frac{\partial^2 f}{\partial \theta^2} + \frac{\partial^2 f}{\partial \tilde{z}^2} \end{aligned} \quad (19)$$

Coordonnées sphériques

$$\begin{cases} x = r \sin \theta \cos \varphi \\ y = r \sin \theta \sin \varphi \\ z = r \cos \theta \end{cases} \longleftrightarrow \begin{cases} r = \sqrt{x^2 + y^2 + z^2} \\ \varphi = \tan^{-1} \left(\frac{y}{x} \right) \\ \theta = \tan^{-1} \left(\frac{\sqrt{x^2 + y^2}}{z} \right) \end{cases} \quad (20)$$

$$\begin{cases} \frac{\partial r}{\partial x} = \frac{1}{2} \frac{2x}{\sqrt{x^2+y^2+z^2}} = \\ = \cancel{r} \sin \theta \cos \varphi \\ \frac{\partial r}{\partial y} = \frac{1}{2} \frac{2y}{\sqrt{x^2+y^2+z^2}} = \\ = \cancel{r} \sin \theta \sin \varphi \\ \frac{\partial r}{\partial z} = \frac{1}{2} \frac{2z}{\sqrt{x^2+y^2+z^2}} = \\ = \cancel{r} \cos \theta \end{cases} \quad \begin{cases} \frac{\partial \varphi}{\partial x} = -\frac{1}{1+\left(\frac{y}{x}\right)^2} \frac{y}{x^2} = \\ = -\frac{\sin \varphi}{r \sin \theta} \\ \frac{\partial \varphi}{\partial y} = \frac{1}{1+\left(\frac{y}{x}\right)^2} \frac{1}{x} = \\ = \frac{\cos \varphi}{r \sin \theta} \\ \frac{\partial \varphi}{\partial z} = 0 \end{cases} \quad \begin{cases} \frac{\partial \theta}{\partial x} = \frac{1}{1+\left(\frac{\sqrt{x^2+y^2}}{z}\right)^2} \frac{\cancel{z}x}{\cancel{z}\sqrt{x^2+y^2}} = \\ = \frac{1}{r} \cos \theta \cos \varphi \\ \frac{\partial \theta}{\partial y} = \frac{1}{1+\left(\frac{\sqrt{x^2+y^2}}{z}\right)^2} \frac{\cancel{z}y}{\cancel{z}\sqrt{x^2+y^2}} = \\ = \frac{1}{r} \cos \theta \sin \varphi \\ \frac{\partial \theta}{\partial z} = -\frac{1}{1+\left(\frac{\sqrt{x^2+y^2}}{z}\right)^2} \frac{\sqrt{x^2+y^2}}{z^2} = \\ = -\frac{1}{r} \sin \theta \end{cases} \quad (21)$$

$$\begin{cases} \frac{\partial^2 r}{\partial x^2} = \frac{1}{2} \frac{2x}{\sqrt{x^2+y^2}} = \\ = \cancel{r} \cos \theta \\ \frac{\partial^2 r}{\partial y^2} = \frac{1}{2} \frac{2y}{\sqrt{x^2+y^2}} = \\ = \cancel{r} \sin \theta \\ \frac{\partial^2 r}{\partial z^2} = 0 \end{cases} \quad \begin{cases} \frac{\partial^2 \varphi}{\partial x^2} = -\frac{1}{1+\left(\frac{y}{x}\right)^2} \frac{y}{x^2} = \\ = -\frac{1}{1+\tan^2 \theta} \frac{r \sin \theta}{r^2 \cos^2 \theta} = -\frac{\sin \theta}{r} \\ \frac{\partial^2 \varphi}{\partial y^2} = \frac{1}{1+\left(\frac{y}{x}\right)^2} \frac{1}{x} = \\ = \frac{1}{1+\tan^2 \theta} \frac{1}{r \cos \theta} = \frac{\cos \theta}{r} \\ \frac{\partial^2 \varphi}{\partial z^2} = 0 \end{cases} \quad \begin{cases} \frac{\partial^2 \theta}{\partial x^2} = 0 \\ \frac{\partial^2 \theta}{\partial y^2} = 0 \\ \frac{\partial^2 \theta}{\partial z^2} = 1 \end{cases} \quad (22)$$

1.2.2. Problème B

$$\begin{cases} x = x(\xi, \eta, \zeta) \\ y = x(\xi, \eta, \zeta) \\ z = x(\xi, \eta, \zeta) \end{cases} \longleftrightarrow \begin{cases} \xi = \xi(x, y, z) \\ \eta = \eta(x, y, z) \\ \zeta = \zeta(x, y, z) \end{cases} \quad (23)$$

$$f(x, y, z) = f(x(\xi, \eta, \zeta), y(\xi, \eta, \zeta), z(\xi, \eta, \zeta)) \quad (24)$$

$$f(\xi, \eta, \zeta) = f(\xi(x, y, z), \eta(x, y, z), \zeta(x, y, z)) \quad (25)$$

$$\nabla f_{xyz} = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \frac{\partial f}{\partial x} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + \frac{\partial f}{\partial y} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + \frac{\partial f}{\partial z} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \frac{\partial f}{\partial x} \mathbf{i}_x + \frac{\partial f}{\partial y} \mathbf{j}_y + \frac{\partial f}{\partial z} \mathbf{k}_z \quad (26)$$

$$\nabla f = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial x} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial x} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial x} \\ \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial y} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial y} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial y} \\ \frac{\partial f}{\partial \xi} \frac{\partial \xi}{\partial z} + \frac{\partial f}{\partial \eta} \frac{\partial \eta}{\partial z} + \frac{\partial f}{\partial \zeta} \frac{\partial \zeta}{\partial z} \end{bmatrix} = \frac{\partial f}{\partial \xi} \begin{bmatrix} \frac{\partial \xi}{\partial x} \\ \frac{\partial \xi}{\partial y} \\ \frac{\partial \xi}{\partial z} \end{bmatrix} + \frac{\partial f}{\partial \eta} \begin{bmatrix} \frac{\partial \eta}{\partial x} \\ \frac{\partial \eta}{\partial y} \\ \frac{\partial \eta}{\partial z} \end{bmatrix} + \frac{\partial f}{\partial \zeta} \begin{bmatrix} \frac{\partial \zeta}{\partial x} \\ \frac{\partial \zeta}{\partial y} \\ \frac{\partial \zeta}{\partial z} \end{bmatrix} \quad (27)$$

$$\begin{aligned} \mathbf{i}_\xi &= \frac{1}{\sqrt{\left(\frac{\partial \xi}{\partial x}\right)^2 + \left(\frac{\partial \xi}{\partial y}\right)^2 + \left(\frac{\partial \xi}{\partial z}\right)^2}} \begin{bmatrix} \frac{\partial \xi}{\partial x} \\ \frac{\partial \xi}{\partial y} \\ \frac{\partial \xi}{\partial z} \end{bmatrix} \\ \mathbf{j}_\eta &= \frac{1}{\sqrt{\left(\frac{\partial \eta}{\partial x}\right)^2 + \left(\frac{\partial \eta}{\partial y}\right)^2 + \left(\frac{\partial \eta}{\partial z}\right)^2}} \begin{bmatrix} \frac{\partial \eta}{\partial x} \\ \frac{\partial \eta}{\partial y} \\ \frac{\partial \eta}{\partial z} \end{bmatrix} \\ \mathbf{k}_\zeta &= \frac{1}{\sqrt{\left(\frac{\partial \zeta}{\partial x}\right)^2 + \left(\frac{\partial \zeta}{\partial y}\right)^2 + \left(\frac{\partial \zeta}{\partial z}\right)^2}} \begin{bmatrix} \frac{\partial \zeta}{\partial x} \\ \frac{\partial \zeta}{\partial y} \\ \frac{\partial \zeta}{\partial z} \end{bmatrix} \end{aligned} \quad (28)$$

$$\begin{aligned}
\nabla_{\xi\eta\zeta} f &= \frac{\partial f}{\partial \xi} \sqrt{\left(\frac{\partial \xi}{\partial x}\right)^2 + \left(\frac{\partial \xi}{\partial y}\right)^2 + \left(\frac{\partial \xi}{\partial z}\right)^2} \cdot \mathbf{i}_\xi + \\
&\quad + \frac{\partial f}{\partial \eta} \sqrt{\left(\frac{\partial \eta}{\partial x}\right)^2 + \left(\frac{\partial \eta}{\partial y}\right)^2 + \left(\frac{\partial \eta}{\partial z}\right)^2} \cdot \mathbf{j}_\eta + \\
&\quad + \frac{\partial f}{\partial \zeta} \sqrt{\left(\frac{\partial \zeta}{\partial x}\right)^2 + \left(\frac{\partial \zeta}{\partial y}\right)^2 + \left(\frac{\partial \zeta}{\partial z}\right)^2} \cdot \mathbf{k}_\zeta = \\
&= \begin{bmatrix} \frac{\partial f}{\partial \xi} \sqrt{\left(\frac{\partial \xi}{\partial x}\right)^2 + \left(\frac{\partial \xi}{\partial y}\right)^2 + \left(\frac{\partial \xi}{\partial z}\right)^2} \\ \frac{\partial f}{\partial \eta} \sqrt{\left(\frac{\partial \eta}{\partial x}\right)^2 + \left(\frac{\partial \eta}{\partial y}\right)^2 + \left(\frac{\partial \eta}{\partial z}\right)^2} \\ \frac{\partial f}{\partial \zeta} \sqrt{\left(\frac{\partial \zeta}{\partial x}\right)^2 + \left(\frac{\partial \zeta}{\partial y}\right)^2 + \left(\frac{\partial \zeta}{\partial z}\right)^2} \end{bmatrix}
\end{aligned} \tag{29}$$

Coordonnées cylindriques

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \\ z = \tilde{z} \end{cases} \longleftrightarrow \begin{cases} r = \sqrt{x^2 + y^2} \\ \theta = \tan^{-1} \left(\frac{y}{x} \right) \\ \tilde{z} = z \end{cases} \tag{30}$$

$$\begin{cases} \frac{\partial r}{\partial x} = \frac{1}{2} \frac{2x}{\sqrt{x^2 + y^2}} = \frac{x}{\sqrt{x^2 + y^2}} \\ \frac{\partial r}{\partial y} = \frac{1}{2} \frac{2y}{\sqrt{x^2 + y^2}} = \frac{y}{\sqrt{x^2 + y^2}} \\ \frac{\partial r}{\partial z} = 0 \end{cases} \quad \begin{cases} \frac{\partial \theta}{\partial x} = -\frac{1}{1 + \left(\frac{y}{x}\right)^2} \frac{y}{x^2} = -\frac{1}{1 + \tan^2 \theta} \frac{r \sin \theta}{r^2 \cos^2 \theta} = -\frac{\sin \theta}{r} \\ \frac{\partial \theta}{\partial y} = \frac{1}{1 + \left(\frac{y}{x}\right)^2} \frac{1}{x} = \frac{1}{1 + \tan^2 \theta} \frac{1}{r \cos \theta} = \frac{\cos \theta}{r} \\ \frac{\partial \theta}{\partial z} = 0 \end{cases} \quad \begin{cases} \frac{\partial \tilde{z}}{\partial x} = 0 \\ \frac{\partial \tilde{z}}{\partial y} = 0 \\ \frac{\partial \tilde{z}}{\partial z} = 1 \end{cases} \tag{31}$$

$$\begin{cases} \frac{\partial^2 r}{\partial x^2} = \frac{\partial}{\partial x} (\cos \theta) = \\ = -\sin \theta \frac{\partial \theta}{\partial x} = \frac{\sin^2 \theta}{r} \\ \\ \frac{\partial^2 r}{\partial y^2} = \frac{\partial}{\partial y} (\sin \theta) = \\ = \cos \theta \frac{\partial \theta}{\partial y} = \frac{\cos^2 \theta}{r} \\ \\ \frac{\partial^2 r}{\partial z^2} = 0 \end{cases} \quad \begin{cases} \frac{\partial^2 \theta}{\partial x^2} = \frac{\partial}{\partial x} \left(-\frac{\sin \theta}{r} \right) = \\ = -\frac{1}{r} \frac{\partial}{\partial x} (\sin \theta) - \sin \theta \frac{\partial}{\partial x} \left(\frac{1}{r} \right) = \\ = -\frac{\cos \theta}{r} \frac{\partial \theta}{\partial x} + \frac{\sin \theta}{r^2} \frac{\partial r}{\partial x} = \\ = \frac{2 \sin \theta \cos \theta}{r^2} = \frac{\sin 2\theta}{r^2} \\ \\ \frac{\partial^2 \theta}{\partial y^2} = \frac{\partial}{\partial y} \left(\frac{\cos \theta}{r} \right) = \\ = \frac{1}{r} \frac{\partial}{\partial y} (\cos \theta) + \cos \theta \frac{\partial}{\partial y} \left(\frac{1}{r} \right) = \\ = -\frac{\sin \theta}{r} \frac{\partial \theta}{\partial y} - \frac{\cos \theta}{r^2} \frac{\partial r}{\partial y} = \\ = -\frac{2 \sin \theta \cos \theta}{r^2} = -\frac{\sin 2\theta}{r^2} \\ \\ \frac{\partial^2 \theta}{\partial z^2} = 0 \end{cases} \quad \begin{cases} \frac{\partial^2 \tilde{z}}{\partial x^2} = 0 \\ \\ \frac{\partial^2 \tilde{z}}{\partial y^2} = 0 \\ \\ \frac{\partial^2 \tilde{z}}{\partial z^2} = 0 \end{cases} \quad (32)$$

$$\begin{cases} \sqrt{\left(\frac{\partial r}{\partial x} \right)^2 + \left(\frac{\partial r}{\partial y} \right)^2 + \left(\frac{\partial r}{\partial z} \right)^2} = 1 \\ \sqrt{\left(\frac{\partial \theta}{\partial x} \right)^2 + \left(\frac{\partial \theta}{\partial y} \right)^2 + \left(\frac{\partial \theta}{\partial z} \right)^2} = \frac{1}{r} \\ \sqrt{\left(\frac{\partial \tilde{z}}{\partial x} \right)^2 + \left(\frac{\partial \tilde{z}}{\partial y} \right)^2 + \left(\frac{\partial \tilde{z}}{\partial z} \right)^2} = 1 \end{cases} \quad (33)$$

$$\begin{aligned} \mathbf{i}_r &= \begin{bmatrix} \cos \theta \\ \sin \theta \\ 0 \end{bmatrix} \\ \mathbf{j}_\theta &= \begin{bmatrix} -\sin \theta \\ \cos \theta \\ 0 \end{bmatrix} \\ \mathbf{k}_\zeta &= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{aligned} \quad (34)$$

$$\nabla_{r\theta\bar{z}}f = \begin{bmatrix} \frac{\partial f}{\partial r} \\ \frac{1}{r} \frac{\partial f}{\partial \theta} \\ \frac{\partial f}{\partial \bar{z}} \end{bmatrix} \quad (35)$$

Coordonnées sphériques

2. Second section

A. First appendix

