

# 1 Problem statement

## 1.1 Strong formulation

We will work on a two-dimensional Helmholtz problem. Let  $\Omega \subset \mathbb{R}^2$  be an open bounded region whose border  $\delta\Omega$  is sufficiently smooth. Our strong formulation is the following:

$$\text{Find } u \text{ such that: } \begin{cases} \Delta u + k^2 u = -f & \text{in } \Omega \\ u = 0 & \text{on } \partial\Omega \end{cases}$$

$\Delta = \nabla^2$  is the Laplace operator,  $u$  could be the unknown acoustic pressure field,  $k$  is the wavenumber and  $f$  is a source term. In general,  $u$  and  $k$  can be complex-valued. However, the parameter studies will be conducted on real-valued cases, with  $k > 0$ . The extension to complex-valued cases should be straightforward.

## 1.2 Galerkin formulation

The usual Galerkin formulation for our problem is the following:

$$\text{Find } u^h \in \mathcal{V}^h \text{ such that } \forall v^h \in \mathcal{V}^h, a_G(u^h, v^h) = \langle f, v^h \rangle_{L^2(\Omega)}$$

Where  $\mathcal{V}^h \subset H_0^1(\Omega)$  is finite-dimensional,  $\langle u, v \rangle_{L^2(\Omega)}$  is the  $L^2(\Omega)$  scalar product, and  $a_G$  is the following sesquilinear form:

$$\begin{aligned} a_G : H_0^1(\Omega)^2 &\rightarrow \mathbb{C} \\ (u, v) &\mapsto \langle \nabla u, \nabla v \rangle_{L^2(\Omega)} - k^2 \langle u, v \rangle_{L^2(\Omega)} \end{aligned}$$

We will use a mesh method to build  $\mathcal{V}^h$ , partitioning  $\Omega$  in mutually exclusive elements.

## 1.3 GLS

The Galerkin/least-squares formulation uses the previous formulation and adds other terms whose purpose is to minimize the square of the residue over the element interiors  $\tilde{\Omega}$ . Their contribution is weighted by a parameter  $\tau$ :

$$\text{Find } u^h \in \mathcal{V}^h, \forall v^h \in \mathcal{V}^h, a_{GLS}(u^h, v^h) = \langle f, v^h \rangle_{L^2(\Omega)} + \langle \tau f, \mathcal{L}v^h \rangle_{L^2(\tilde{\Omega})}$$

Where  $\mathcal{L} = \Delta + k^2$  is the Helmholtz operator, and  $a_{GLS}$  is the following sesquilinear form:

$$\begin{aligned} a_{GLS} : H_0^1(\Omega)^2 &\rightarrow \mathbb{C} \\ (u, v) &\mapsto a_G(u, v) + \langle \tau \mathcal{L}u, \mathcal{L}v \rangle_{L^2(\tilde{\Omega})} \end{aligned}$$

# 2 Dispersion analysis and optimal parameter

The Helmholtz equation suffers from the pollution effect, causing numerical wavenumbers to lose accuracy with the physical wavenumber increasing.

**Exact solutions** When considering the sourceless ( $f = 0$ ) and free-space version of our problem, the exact solutions are  $\forall x \in \mathbb{R}$ ,  $u(x) = Ce^{i(k_x x + k_y y)}$ . With  $k^2 = k_x^2 + k_y^2$  Our studies will revolve around this case.

## 2.1 Dispersion analysis

### 2.1.1 Numerical resolution

Using bilinear interpolation with nodal shape functions  $N_{(i,j)}$  that respect the partition of unity and Kronecker delta properties yields the linear system  $AU^h = 0$ , where  $U^h$  is a the vector of nodal values and  $A$  is the impedance matrix.

When using our Galerkine formulation, the matrix is  $A_{G,(i,j)(l,m)} = \sum_{e \in E} K_{(i,j)(l,m)}^e - k^2 M_{(i,j)(l,m)}^e$  where  $E$  is the set of elements whose boundary contain both nodes  $(i, j)$  and  $(l, m)$ , and  $K_{(i,j)(l,m)}^e$  and  $M_{(i,j)(l,m)}^e$  are respectively stiffness and masse terms assembled using shape functions  $(i, j)$  and  $(l, m)$  over the element  $e$ .

$$\sum_{i,j \in \{-1,0,1\}} A_{G,0,0}^{i,j} U_{i,j}^h = 0 \quad (1)$$

Setting  $2h_\xi = h_\xi^- + h_\xi^+$  with  $\xi$  being  $x$  or  $y$ .

The values of the nonzero entries are the following:

Four corner nodes ( $i, j \in \{-, +\}$ ):

$$A_{G,0,0}^{i,j} = \frac{k^2 h_x^i h_y^j}{36} + \frac{h_x^i}{6h_y^j} + \frac{h_y^j}{6h_x^i}$$

Four side nodes:

$$\begin{aligned} A_{G,0,0}^{\pm,0} &= \frac{k^2 h_x^\pm h_y}{9} + \frac{2h_y}{3h_x^\pm} - \frac{h_x^\pm}{3} \frac{h_y}{h_y^- h_y^+} \\ A_{G,0,0}^{0,\pm} &= \frac{k^2 h_x h_y^\pm}{9} + \frac{2h_x}{3h_y^\pm} - \frac{h_y^\pm}{3} \frac{h_x}{h_x^- h_x^+} \end{aligned}$$

Center node:

$$A_{G,0,0}^{0,0} = \frac{4k^2 h_x h_y}{9} - \frac{4h_x}{3} \frac{h_y}{h_y^- h_y^+} - \frac{4h_y}{3} \frac{h_x}{h_x^- h_x^+}$$

Setting  $\alpha_\xi^\pm h_\xi = h_\xi^\pm$  with  $\xi$  being  $x$  or  $y$ .

Four side nodes:

$$\begin{aligned} A_{G,0,0}^{\pm,0} &= \frac{k^2 h_x^\pm h_y}{9} + \frac{2h_y}{3h_x^\pm} - \frac{h_x^\pm}{3\alpha_y^- \alpha_y^+ h_y} \\ A_{G,0,0}^{0,\pm} &= \frac{k^2 h_x h_y^\pm}{9} + \frac{2h_x}{3h_y^\pm} - \frac{h_y^\pm}{3\alpha_x^- \alpha_x^+ h_x} \end{aligned}$$

Center node:

$$A_{G,0,0}^{0,0} = \frac{4k^2 h_x h_y}{9} - \frac{4h_x}{3\alpha_y^- \alpha_y^+ h_y} - \frac{4h_y}{3\alpha_x^- \alpha_x^+ h_x}$$

$$k^2 = \frac{6 \left( 2f_x^+ h_x^- \left( (h_x^+)^2 h_y - (h_y^+)^2 h_y^- - h_y^+ (h_y^-)^2 \right) + 2f_x^- h_x^+ \left( (h_x^-)^2 h_y - (h_y^+)^2 h_y^- - h_y^+ (h_y^-)^2 \right) + 2f_y^+ h_y^- \left( h_x \right) \right)}{1}$$

$$\gamma_0 + \sum_{\xi \in \{x,y\}} \sum_{i \in \{-,+ \}} \gamma_\xi^i f_\xi^i + \quad (2)$$

Terme indépendant en haut

$$\begin{aligned} & + 12h_x^- h_y^+ \left( (h_x^+)^2 + (h_y^-)^2 \right) \\ & + 12h_x^- h_y^- \left( (h_x^+)^2 + (h_y^+)^2 \right) \\ & + 12h_x^+ h_y^+ \left( (h_x^-)^2 + (h_y^-)^2 \right) \\ & + 12h_x^+ h_y^- \left( (h_x^-)^2 + (h_y^+)^2 \right) \end{aligned}$$

Termes en f en haut

$$\begin{aligned} & 12f_x^+ h_x^- \left( (h_x^+)^2 h_y - (h_y^+)^2 h_y^- - h_y^+ (h_y^-)^2 \right) + 12f_x^- h_x^+ \left( (h_x^-)^2 h_y - (h_y^+)^2 h_y^- - h_y^+ (h_y^-)^2 \right) \\ & + 12f_y^+ h_y^- \left( h_x (h_y^+)^2 - (h_x^+)^2 h_x^- - h_x^+ (h_x^-)^2 \right) + 12f_y^- h_y^+ \left( h_x (h_y^-)^2 - h_x^+ (h_x^-)^2 - (h_x^+)^2 h_x^- \right) \end{aligned}$$

Terme indépendant en bas (en facteur des 4h)

$$16h_x h_y$$

Termes en f en bas (en facteur des 4h)

$$4f_x^+ h_x^+ h_y \quad + \quad 4f_x^- h_x^- h_y \quad + \quad 4f_y^+ h_x h_y^+ \quad + \quad 4f_y^- h_x h_y^-$$

Termes en g en bas (en facteur des 4h)

$$+ h_x^+ h_y^+ g^{++} + h_x^+ h_y^- g^{+-} + h_x^- h_y^+ g^{-+} + h_x^- h_y^- g^{--}$$