

1. In two-dimensional steady homentropic gas flow, the velocity  $(u, v)$  and density  $\rho$  satisfy the equations

$$\begin{aligned}(\rho u)_x + (\rho v)_y &= 0, \\ \rho(uu_x + vu_y) + c(\rho)^2 \rho_x &= 0, \\ \rho(uv_x + vv_y) + c(\rho)^2 \rho_y &= 0,\end{aligned}$$

where  $c(\rho)$  is the *speed of sound* in the gas.

Show that the system is hyperbolic if the flow is *supersonic*, i.e. if  $u^2 + v^2 > c^2$ .

Also prove *Bernoulli's theorem*, that the Riemann invariant

$$R = \frac{1}{2}(u^2 + v^2) + \int \frac{c(\rho)^2 d\rho}{\rho}$$

is conserved along the characteristics  $dy/dx = v/u$ .

2. Reduce the following PDE to canonical form and then determine its general solution:

$$y^2 u_{xx} - 2xy u_{xy} + x^2 u_{yy} = \frac{1}{xy} (y^3 u_x + x^3 u_y).$$

3. Solve the PDE

$$u_{xx} + u_{xy} - 2u_{yy} + 1 = 0 \text{ in } 0 \leq x \leq 1, y > 0, \text{ with } u = u_y = x \text{ on } y = 0.$$

4. Reduce the following PDE to canonical form:

$$u_{xx} + u_{xy} + u_{yy} = 0.$$

5. Consider the following system of PDEs for  $u(x, y)$ ,  $v(x, y)$

$$\begin{aligned}2x^2 y u_x + 5xy^2 u_y + 2x^2 y^2 v_y + 5xyu + x &= 0, \\ yu_y - x^2 v_x + u - 2xv &= 0.\end{aligned}$$

- In the region  $x > 0, y > 0$ , determine whether the system is hyperbolic, elliptic, or parabolic.
- Show that the system is equivalent to a second order semilinear PDE.

6. Determine the characteristic coordinates  $\xi(x, y)$  and  $\eta(x, y)$  for the system

$$xu_{xx} + u_{yy} = 0$$

for the regions (i)  $x < 0$  and (ii)  $x > 0$ .

7. (i) Show that, if

$$\phi_{xx} - \phi_{tt} = f(x, t),$$

with

$$\phi = \phi_t = 0 \quad \text{at} \quad t = 0,$$

then

$$\phi(x, t) = \frac{1}{2} \iint_{\Delta} f(x, t) \, dx dt,$$

where  $\Delta$  is a triangle which you should specify.

(ii) Solve

$$\phi_{xx} - \phi_{tt} = -1 \quad \text{in} \quad x > 0, \, t > 0,$$

with

$$\phi = \phi_t = 0 \quad \text{on} \quad t = 0, \, x > 0,$$

and

$$\phi = 0 \quad \text{on} \quad x = 0, \, t > 0.$$

Show that there is a discontinuity of magnitude 1 in  $\partial^2\phi/\partial x^2$  across  $x = t$ .

8. Find the Riemann function for the PDE

$$u_{xy} + xyu_x = f(x, y)$$

and use it show that the solution to the problem

$$\begin{aligned} u_{xy} + xyu_x &= 0 \quad \text{in} \quad x + y > 0, \\ u &= x, \quad u_y = 0 \quad \text{on} \quad x + y = 0. \end{aligned}$$

is

$$u(\xi, \eta) = -\eta + \int_{-\eta}^{\xi} e^{x(x^2 - \eta^2)/2} dx.$$