

Cambridge Part III Maths

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Astrophysical Fluid Dynamics

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Notes created based on Josh Kirklin's L^AT_EX packages & classes. Please do not distribute these notes other than to fellow Part III students. Please send errors and suggestions to cwp29@cam.ac.uk.

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1 Introduction

1.1 Areas of application

Astrophysical fluid dynamics (AFD) is relevant to the description of the interiors of stars and planets, exterior phenomena such as discs, winds and jets, the interstellar medium, the intergalactic medium, and cosmology itself. A fluid description is not applicable in regions that are solidified, such as the rocky or icy cores of giant planets and the crusts of neutron stars, and also in very gaseous regions where the medium is not sufficiently collisional.

1.2 Theoretical varieties

Various flavours of AFD are in use. The basic models we will consider are:

Hydrodynamics (HD) / Newtonian gas dynamics: This model is non-relativistic, compressible, ideal (inviscid and adiabatic), self-gravitating, and usually assumes a perfect gas.

Magnetohydrodynamics (MHD): This model is the same as above, with the addition of a magnetic field. We will often use ideal MHD, which assumes a perfectly conducting fluid.

1.3 Characteristic features

The elements of theory often important in AFD are compressibility, gravitation, and thermal physics. Sometimes, magnetic fields, radiation forces, and relativity are important. Rarely important aspects are viscosity, surface tension, and solid boundaries.

1.4 Useful data

Some useful data for the course, in CGS (centimetres, grams, seconds) units:

Newton's constant	$G = 6.674 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$
Boltzmann's constant	$k = 1.381 \times 10^{-16} \text{ erg K}^{-1}$
Stefan's constant	$\sigma = 5.670 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ K}^{-4}$
Speed of light	$c = 2.998 \times 10^{10} \text{ cm s}^{-1}$
Hydrogen mass	$m_H = 1.674 \times 10^{-24} \text{ g}$
Solar mass	$M_s = 1.988 \times 10^{33} \text{ g}$
Solar radius	$R_s = 6.957 \times 10^{10} \text{ cm}$
Solar luminosity	$L_s = 3.828 \times 10^{33} \text{ erg s}^{-1}$
Parsec	$pc = 3.086 \times 10^{18} \text{ cm}$
Astronomical unit (AU)	$au = 1.496 \times 10^{13} \text{ cm}$
Joule erg conversion	$1 \text{ J} = 10^7 \text{ erg}$

2 Ideal gas dynamics

2.1 Fluid variables

A fluid is characterised by a velocity field $\mathbf{u}(\mathbf{x}, t)$ and two independent thermodynamic properties. Most useful are the dynamical variables: the pressure $p(\mathbf{x}, t)$ and the mass density $\rho(\mathbf{x}, t)$. Other properties, e.g. temperature T , can be regarded as functions of p and ρ . The *specific volume* (volume per unit mass) is $v = 1/\rho$.

We neglect the possible complications of variable chemical composition associated with chemical and nuclear reactions, ionisation and recombination.

2.2 Eulerian and Lagrangian viewpoints

In the *Eulerian* viewpoint we consider how fluid properties vary in time at a point which is fixed in space, i.e. attached to the (usually inertial) coordinate system. The Eulerian time derivative is simply ∂_t .

In the *Lagrangian* viewpoint we consider how fluid properties vary in time at a point which moves with the fluid at velocity $\mathbf{u}(\mathbf{x}, t)$. The Lagrangian time derivative (or material derivative) is

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla$$

2.3 Material points and structures

A material point is an idealised fluid element, a point that moves with the bulk velocity $\mathbf{u}(\mathbf{x}, t)$ of the fluid. Note that the true particles of which the fluid is composed also have random thermal motion.

Material curves, surfaces and volumes are geometrical structures composed of fluid elements; they move with the fluid flow and are deformed by it. An infinitesimal material line element $\delta\mathbf{x}$ evolves according to

$$\frac{D\delta\mathbf{x}}{Dt} = \delta\mathbf{u} = \delta\mathbf{x} \cdot \nabla \mathbf{u}$$

It changes its length and/or orientation in the presence of a velocity gradient.

Infinitesimal material surface or volume elements can be defined from two or three material line elements according to the vector product and the triple scalar product.

$$\begin{aligned}\delta\mathbf{S} &= \delta\mathbf{x}^{(1)} \times \delta\mathbf{x}^{(2)} \\ \delta V &= \delta\mathbf{x}^{(1)} \cdot \delta\mathbf{x}^{(2)} \times \delta\mathbf{x}^{(3)}\end{aligned}$$

They evolve according to

$$\begin{aligned}\frac{D\delta\mathbf{S}}{Dt} &= (\nabla \cdot \mathbf{u})\delta\mathbf{S} - \nabla \mathbf{u} \cdot \delta\mathbf{S} \\ \frac{D\delta V}{Dt} &= (\nabla \cdot \mathbf{u})\delta V\end{aligned}$$

The second result is easier to understand: the volume element increases when the flow is divergent.

2.4 Equation of mass conservation

The equation of mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

has typical form of conservation law: rate of change of a density and divergence of a flux. Here, ρ is mass density and $\rho \mathbf{u}$ is mass flux density. An alternative form of the same equation is

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{u}$$

If $\delta m = \rho \delta V$ is a material mass element, it can be seen that mass is conserved in the form

$$\frac{D\delta m}{Dt} = 0$$

2.5 Equation of motion

The equation of motion

$$\rho \frac{D\mathbf{u}}{Dt} = -\rho \nabla \Phi - \nabla p$$

derives from Newton's second law per unit volume with gravitational and pressure forces. The gravitational potential is $\Phi(\mathbf{x}, t)$ and $\mathbf{g} = -\nabla \Phi$ is the gravitational field.

The force due to pressure acting on a volume V with bounding surface S is

$$-\int_S p d\mathbf{S} = \int_V (-\nabla p) dV$$

Viscous forces are neglected in ideal gas dynamics.

2.6 Poisson's equation

The gravitational potential is related to the mass density by Poisson's equation

$$\nabla^2 \Phi = 4\pi G \rho$$

where G is Newton's constant. The solution

$$\Phi = \Phi_{\text{int}} + \Phi_{\text{ext}} = -G \int_V \frac{\rho(\mathbf{x}', t)}{|\mathbf{x}' - \mathbf{x}|} d^3\mathbf{x}' - G \int_{\hat{V}} \frac{\rho(\mathbf{x}', t)}{|\mathbf{x}' - \mathbf{x}|} d^3\mathbf{x}'$$

generally involves contributions from both the fluid region V under consideration and the exterior region \hat{V} . A *non-self-gravitating* fluid is one of negligible mass for which Φ_{int} can be neglected. More generally, the *Cowling approximation* consists of treating Φ as being specified in advance, so that Poisson's equation is not coupled to the other equations.

2.7 Thermal energy equation and equation of state

In the absence of non-adiabatic heating (e.g. by viscous dissipation or nuclear reactions) and cooling (e.g. by radiation or conduction),

$$\frac{Ds}{Dt} = 0$$

where s is the *specific entropy* (entropy per unit mass). Fluid element undergo reversible thermodynamic changes and preserve their entropy (adiabatic flow). This condition is violated in shocks (see section 6).

The thermal variables (T, s) can be related to the dynamical variables (P, ρ) via an *equation of state* and standard thermodynamic identities. The most important case is that of an *ideal gas* with *blackbody radiation*

$$p = p_g + p_r = \frac{k\rho T}{\mu m_H} + \frac{4\sigma T^4}{3c}$$

where k is Boltzmann's constant, m_H is mass of a hydrogen atom, σ is Stefan's constant, c is the speed of light, and μ is the mean molecular weight, defined as the average mass of the particles in units of m_H , equal to

- 2.0 for molecular hydrogen
- 1.0 for atomic hydrogen
- 0.5 for fully ionised hydrogen
- about 0.6 for ionised matter of typical cosmic abundances.

The component p_g is the *gas pressure* and p_r is the *radiation pressure*. Radiation pressure is usually negligible except in the centres of high mass stars and in the immediate environments of neutron stars and black holes. The pressure of an ideal gas is often written in the form $\mathcal{R}\rho T/\mu$ where $\mathcal{R} = k/m_H$ is a version of the universal gas constant.

We define the *first adiabatic exponent*

$$\Gamma_1 = \left(\frac{\partial \log p}{\partial \log \rho} \right)_S$$

which is related to the ratio of specific heat capacities

$$\gamma = \frac{c_p}{c_v} = \frac{T \left(\frac{\partial s}{\partial T} \right)_p}{T \left(\frac{\partial s}{\partial T} \right)_v}$$

by $\Gamma_1 = \chi_\rho \gamma$ where

$$\chi_\rho = \left(\frac{\partial \log p}{\partial \log \rho} \right)_T$$

can be found from the equation of state. We can then rewrite the thermal energy equation as

$$\frac{Dp}{Dt} = \frac{\Gamma_1 p}{\rho} \frac{D\rho}{Dt} = -\Gamma_1 p \nabla \cdot \mathbf{u}$$

For an ideal gas with negligible radiation pressure, $\chi_\rho = 1$ and so $\Gamma_1 = \gamma$. Adopting this very common assumption, we write

$$\frac{Dp}{Dt} = -\gamma p \nabla \cdot \mathbf{u}$$

2.8 Simplified models

A *perfect gas* may be defined as an ideal gas with constant c_v, c_p, γ and μ . Equipartition of energy for a classical gas with n degrees of freedom per particle gives

$$\gamma = 1 + \frac{2}{n}$$

For a classical monatomic gas with $n = 3$ translational degrees of freedom, $\gamma = 5/3$. This is relevant for fully ionised matter. For a classical diatomic gas with two additional rotational degrees of freedom, $n = 5$ and $\gamma = 7/5$. This is relevant for molecular hydrogen. In reality, Γ_1 is variable when the gas undergoes ionisation or when the gas and radiation pressures are comparable.

The specific *internal energy* (or *thermal energy*) of a perfect gas is

$$e = \frac{p}{(\gamma - 1)\rho} = \frac{n}{\mu m_H} \frac{1}{2} kT$$

Note that each particle has an internal energy of $\frac{1}{2}kT$ per degree of freedom, and the number of particles per unit mass is $1/\mu m_H$.

A *barotropic* fluid is an idealised situation in which the relation $p(\rho)$ is known in advance. We can then dispense with the thermal energy equation. For example, if the gas is strictly isothermal and perfect, $p = c_s^2 \rho$ with the constant c_s being the isothermal sound speed. Alternatively, if the gas is strictly homentropic (constant s) and perfect, then $p = K\rho^\gamma$ with K constant.

An *incompressible* fluid is an idealised situation in which $\frac{D\rho}{Dt} = 0$, implying $\nabla \cdot \mathbf{u} = 0$. This can be achieved formally by taking the limit $\gamma \rightarrow \infty$. The approximation of incompressibility eliminates acoustic phenomena from the dynamics. The ideal gas law itself is not valid at very high densities or where quantum degeneracy is important.

2.9 Microphysical basis

It is useful to understand the way in which the fluid-dynamical equations are derived microphysical considerations. The simplest model involves identical neutral particles of mass m of negligible size with no internal degrees of freedom.

2.9.1 Boltzmann equation

Between collisions, particles follow Hamiltonian trajectories in their six dimensional (\mathbf{x}, \mathbf{v}) phase space:

$$\dot{x}_i = v_i, \quad \dot{v}_i = a_i - \frac{\partial \Phi}{\partial x_i}$$

The distribution function $f(\mathbf{x}, \mathbf{v}, t)$ specifies the number density of particles in phase space. The velocity moments of f define the number $n(\mathbf{x}, t)$ in real space, the bulk velocity $\mathbf{u}(\mathbf{x}, t)$ and the velocity dispersion $c(\mathbf{x}, t)$ according to

$$\begin{aligned} \int f d^3\mathbf{v} &= n \\ \int \mathbf{v} f d^3\mathbf{v} &= n\mathbf{u} \\ \int |\mathbf{v} - \mathbf{u}|^2 f d^3\mathbf{v} &= 3nc^2 \end{aligned}$$

Equivalently,

$$\int v^2 f d^3\mathbf{v} = n(\mathbf{u}^2 + 3c^2)$$

The relation between velocity dispersion and temperature is $kT = mc^2$. In the absence of collisions, f is conserved following the Hamiltonian flow in phase space. This is because particles are conserved and the flow in phase space is incompressible. More generally, f evolves according to *Boltzmann's equation*

$$\frac{\partial f}{\partial t} + v_j \frac{\partial f}{\partial x_j} + a_j \frac{\partial f}{\partial v_j} = \left(\frac{\partial f}{\partial t} \right)_c$$

The collision term on the RHS is a complicated integral operator but has 3 simple properties corresponding to the conservation of mass, momentum and energy in collisions.

$$\begin{aligned}\int m \left(\frac{\partial f}{\partial t} \right)_c d^3\mathbf{v} &= 0 \\ \int m\mathbf{v} \left(\frac{\partial f}{\partial t} \right)_c d^3\mathbf{v} &= 0 \\ \int \frac{1}{2}m\mathbf{v}^2 \left(\frac{\partial f}{\partial t} \right)_c d^3\mathbf{v} &= 0\end{aligned}$$

The collision term is local in \mathbf{x} (not even involving derivatives) although it does involve integrals over \mathbf{v} . The equation $\left(\frac{\partial f}{\partial t} \right)_c = 0$ has the general solution

$$f = f_M = (2\pi c^2)^{-3/2} n \exp \left(-\frac{|\mathbf{v} - \mathbf{u}|^2}{2c^2} \right)$$

with parameters n, \mathbf{u} and c that may depend on \mathbf{x} . This is the *Maxwellian distribution*.

2.9.2 Derivation of fluid equations

A crude but illuminating model of the collision operator is the *BGK approximation*

$$\left(\frac{\partial f}{\partial t} \right)_c \approx -\frac{1}{\tau}(f - f_M)$$

where f_M is a Maxwellian distribution with the same n, \mathbf{u} and c as f , and τ is the *relaxation time*. This timescale τ can be identified approximately with the mean flight time of particles between collisions. The collisions attempt to restore a Maxwellian distribution on a characteristic timescale τ . They do this by randomising the particle velocities in a way consistent with the conservation of momentum and energy. If the characteristic timescale of the fluid flow is much greater than τ , then the collision term dominates the Boltzmann equation and f is very close to f_m . This is the *hydrodynamic limit*.

The velocity moments of f_M can be determined from standard Gaussian integrals, in particular

$$\begin{aligned}\int f_M d^3\mathbf{v} &= n \\ \int v_i f_M d^3\mathbf{v} &= nu_i \\ \int v_i v_j f_M d^3\mathbf{v} &= n(u_i u_j + c^2 \delta_{ij}) \\ \int \mathbf{v}^2 v_i f_M d^3\mathbf{v} &= n(\mathbf{u}^2 + 5c^2)u_i\end{aligned}$$

We obtain equations for mass, momentum and energy by taking moments of the Boltzmann equation weighted by $(m, mv_i, \frac{1}{2}m\mathbf{v}^2)$. In each case the collision term integrates to 0 because of its conservative properties, and the $\partial/\partial v_j$ term can be integrated by parts. We replace f with f_M

when evaluating the LHS and note that $mn = \rho$:

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) &= 0 \\ \frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}[\rho(u_i u_j + c^2 \delta_{ij})] - \rho a_i &= 0 \\ \frac{\partial}{\partial t}\left[\frac{1}{2}\rho \mathbf{u}^2 + \frac{3}{2}\rho c^2\right] + \frac{\partial}{\partial x_i}\left[\left(\frac{1}{2}\rho \mathbf{u}^2 + \frac{5}{2}\rho c^2\right)u_i\right] - \rho u_i a_i &= 0\end{aligned}$$

These are equivalent to the equations of ideal gas dynamics in conservative form (see section 4) for a monatomic ideal gas ($\gamma = 5/3$). The specific internal energy is $\rho = \frac{3}{2}c^2 = \frac{3}{2}\frac{kT}{m}$.

2.10 Validity of fluid approach

Deviations from Maxwellian distribution are small when collisions are frequent compared to the characteristic timescale of the flow. In higher-order approximations these deviations can be estimated, leading to the equations of dissipative gas dynamics including transport effects (viscosity and heat conduction).

The fluid approach breaks down if the mean flight time τ is not much less than the characteristic timescale of the flow, or if the mean free path $\lambda \approx c\tau$ between collisions is not much less than the characteristic lengthscale of the flow.

The Coulomb cross-section for ‘collisions’ (i.e. large-angle scatterings) between charged particles (electrons or ions) is

$$\sigma \approx 1 \times 10^{-4} (T/K)^{-2} \text{cm}^2$$

The mean free path is $\lambda = 1/n\sigma$.

3 Ideal magnetohydrodynamics

3.1 Elementary derivation of MHD equations

Magnetohydrodynamics (MHD) is the dynamics of an electrically conducting fluid (a full or partially ionised gas or a liquid metal) containing a magnetic field. It is a fusion of fluid dynamics and electromagnetism.

3.1.1 Galilean electromagnetism

The equations of Newtonian gas dynamics are invariant under the Galilean transformation to a frame of reference moving with uniform velocity \mathbf{v} ,

$$\mathbf{x}' = \mathbf{x} - \mathbf{v}t, \quad t' = t$$

Under this change of frame, the fluid velocity transforms according to

$$\mathbf{u}' = \mathbf{u} - \mathbf{v}$$

while scalar variables such as p , ρ , and Φ are invariant. The Lagrangian time derivative D/Dt is also invariant, because the partial derivatives transform according to

$$\nabla' = \nabla, \quad \frac{\partial}{\partial t'} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla$$

To derive a consistent Newtonian theory of MHD, valid for situations in which the fluid motions are slow compared to the speed of light, we use Maxwell's equations without the displacement current:

$$\begin{aligned}\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J}\end{aligned}$$

We will not require the fourth Maxwell equation, involving $\nabla \cdot \mathbf{E}$, because the charge density will be found to be unimportant. The equation of energy conservation is

$$\frac{\partial}{\partial t} \left(\frac{B^2}{2\mu_0} \right) + \nabla \cdot \left(\frac{\mathbf{E} \times \mathbf{B}}{\mu_0} \right) = -\mathbf{E} \cdot \mathbf{J}$$

in which the energy density $B^2/2\mu_0$ is purely magnetic, while the energy flux density has the usual form of the *Poynting vector* $\mathbf{E} \times \mathbf{B}/\mu_0$. These 'pre-Maxwell' equations are invariant under the Galilean transformation, provided that the fields transform according to

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}, \quad \mathbf{B}' = \mathbf{B}, \quad \mathbf{J}' = \mathbf{J}$$

3.1.2 Induction equation

In the *ideal MHD approximation* we regard the fluid as a perfect electrical conductor. The electric field in the rest frame of the fluid therefore vanishes, implying that

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B}$$

in a frame in which the fluid velocity is $\mathbf{u}(\mathbf{x}, t)$. This condition can be regarded as the limit of a constitutive relationship such as Ohm's law, in which the effects of resistivity (i.e. finite conductivity) are neglected. From Maxwell's equations, we then obtain the *ideal induction equation*

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

This is an evolutionary equation for \mathbf{B} alone, having eliminated \mathbf{E} and \mathbf{J} . The divergence of the induction equation,

$$\frac{\partial}{\partial t} (\nabla \cdot \mathbf{B}) = 0$$

ensures that \mathbf{B} remains solenoidal.

3.1.3 Lorentz force

A fluid carrying a current density \mathbf{J} in a magnetic field \mathbf{B} experiences a Lorentz force

$$\mathbf{F}_m = \mathbf{J} \times \mathbf{B} = \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B}$$

per unit volume. This can be understood as the sum of the Lorentz forces on individual particles of charge q and velocity \mathbf{v} ,

$$\sum q\mathbf{v} \times \mathbf{B} = \left(\sum q\mathbf{v} \right) \times \mathbf{B}$$

The electrostatic force can be shown to be negligible in the Newtonian limit. In Cartesian co-ordinates we have

$$\begin{aligned} (\mu_0 \mathbf{F}_m)_i &= \varepsilon_{ijk} \varepsilon_{jlm} \frac{\partial B_m}{\partial x_l} B_k \\ &= \left(\frac{\partial B_i}{\partial x_k} - \frac{\partial B_k}{\partial x_i} \right) B_k \\ &= B_k \frac{\partial B_i}{\partial x_k} - \frac{\partial}{\partial x_i} \left(\frac{B^2}{2} \right) \end{aligned}$$

Thus the Lorentz force can be written as

$$\mathbf{F}_m = \frac{1}{\mu_0} \mathbf{B} \cdot \nabla \mathbf{B} - \nabla \left(\frac{B^2}{2\mu_0} \right)$$

The first term can be interpreted as a *curvature force* due to a *magnetic tension* $T_m = B^2/\mu_0$ per unit area in the field lines. The second term is the gradient of an isotropic *magnetic pressure* $p_m = B^2/2\mu_0$ which is also the magnetic energy density. The magnetic tension gives rise to *Alfvén waves* (see later), which travel parallel to the magnetic field with characteristic speed

$$v_a = \left(\frac{T_m}{\rho} \right)^{1/2} = \frac{B}{\sqrt{\mu_0 \rho}}$$

the *Alfvén speed*, or (vector) *Alfvén velocity*

$$\mathbf{v}_a = \frac{\mathbf{B}}{\sqrt{\mu_0 \rho}}$$

The magnetic pressure also affects the propagation of sound waves, which become *magnetoacoustic waves* (see later). The combination

$$\Pi = p + \frac{B^2}{2\mu_0}$$

is often referred to as the *total pressure*, while the ratio

$$\beta = \frac{p}{B^2/2\mu_0}$$

is known as the *plasma beta*.

3.1.4 Summary of the MHD equations

The full set of ideal MHD equations is

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\ \rho \frac{D\mathbf{u}}{Dt} &= -\rho \nabla \Phi - \nabla p + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} \\ \frac{Ds}{Dt} &= 0 \\ \frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{u} \times \mathbf{B}) \\ \nabla \cdot \mathbf{B} &= 0 \end{aligned}$$

together with the equation of state, Poisson's equation, etc., as required. Most of these equations can be written in at least one other way that may be useful in different circumstances.

3.2 Physical interpretation of MHD

There are two aspects to MHD:

- Advection of \mathbf{B} by \mathbf{u} (induction equation)
- Dynamical back-reaction of \mathbf{B} on \mathbf{u} .

3.2.1 Kinematics of the magnetic field

The ideal induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

has a beautiful geometric interpretation: magnetic field lines are ‘frozen in’ to the fluid and can be identified with material curves. One way to show this result is to use the identity

$$\nabla \times (\mathbf{u} \times \mathbf{B}) = (\mathbf{B} \cdot \nabla) \mathbf{u} - \mathbf{B}(\nabla \cdot \mathbf{u}) - (\mathbf{u} \cdot \nabla) \mathbf{B} + \mathbf{u}(\nabla \cdot \mathbf{B})$$

to write the induction equation in the form

$$\frac{D\mathbf{B}}{Dt} = (\mathbf{B} \cdot \nabla) \mathbf{u} - \mathbf{B}(\nabla \cdot \mathbf{u})$$

and use the equation of mass conservation

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{u}$$

to obtain

$$\frac{D}{Dt} \left(\frac{\mathbf{B}}{\rho} \right) = \left(\frac{\mathbf{B}}{\rho} \right) \cdot \nabla \mathbf{u}$$

This is exactly the same equation satisfied by a material line element (section 2.3). Therefore a magnetic field line (an integral curve of \mathbf{B}/ρ) is advected and distorted by the fluid in the same way as a material curve. A complementary property is that the magnetic flux $\delta\Phi = \mathbf{B} \cdot \delta\mathbf{S}$ through a material surface is conserved:

$$\begin{aligned} \frac{D\Phi}{Dt} &= \frac{D\mathbf{B}}{Dt} \cdot \delta\mathbf{S} + \mathbf{B} \cdot \frac{D\delta\mathbf{S}}{Dt} \\ &= \left(B_j \frac{\partial u_i}{\partial x_j} - B_i \frac{\partial u_j}{\partial x_j} \right) \delta S_i + B_i \left(\frac{\partial u_j}{\partial x_j} \delta S_i - \frac{\partial u_j}{\partial x_i} \delta S_j \right) \\ &= 0 \end{aligned}$$

By extension, we have conservation of the magnetic flux $\Phi = \int \mathbf{B} \cdot d\mathbf{S}$ passing through any material surface.

3.2.2 (Partial) analogy with vorticity

In homentropic (uniform entropy) or barotropic ideal fluid dynamics in the absence of a magnetic field, the vorticity $\boldsymbol{\omega} = \nabla \times \mathbf{u}$ satisfies

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = \nabla \times (\mathbf{u} \times \boldsymbol{\omega})$$

Vortex lines are then ‘frozen in’ to the fluid. Conserved quantity

$$\int_S \boldsymbol{\omega} \cdot d\mathbf{S} = \oint_C \mathbf{u} \cdot d\mathbf{x}$$

is analogous to

$$\int_S \mathbf{B} \cdot d\mathbf{S} = \oint_C \mathbf{A} \cdot d\mathbf{x}$$

However, $\boldsymbol{\omega}$ and \mathbf{u} are directly related by $\boldsymbol{\omega} = \nabla \times \mathbf{u}$ whereas in MHD \mathbf{B} and \mathbf{u} are indirectly related through the equation of motion and the Lorentz force, so the analogy between vorticity dynamics and MHD is limited in scope.

3.2.3 Lorentz force

The Lorentz force per unit volume,

$$\mathbf{F}_m = \frac{1}{\mu_0} \mathbf{B} \cdot \nabla \mathbf{B} - \nabla (B^2/2\mu_0)$$

can also be written as the divergence of the *Maxwell stress tensor*

$$\mathbf{F}_m = \nabla \cdot \mathbf{M}, \quad \mathbf{M} = \frac{1}{\mu_0} \left(\mathbf{B}\mathbf{B} - \frac{B^2}{2} \mathbf{I} \right)$$

where \mathbf{I} is the identity tensor. In Cartesian components,

$$(\mathbf{F}_m)_i = \frac{\partial M_{ji}}{\partial x_j}, \quad M_{ij} = \frac{1}{\mu_0} \left(B_i B_j - \frac{B^2}{2} \delta_{ij} \right)$$

If \mathbf{B} is locally aligned with the x -axis, then

$$\mathbf{M} = \begin{pmatrix} T_m & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} - \begin{pmatrix} p_m & 0 & 0 \\ 0 & p_m & 0 \\ 0 & 0 & p_m \end{pmatrix}$$

showing the magnetic tension and pressure. Combining the ideas of magnetic tension and a frozen-in field leads to the picture of field lines as elastic strings embedded in the fluid. There is a close analogy between MHD and the dynamics of polymer solutions. The magnetic field imparts elasticity to the fluid.

3.2.4 Differential rotation and torsional Alfvén waves

First consider the kinematic behaviour of a magnetic field in the presence of a prescribed velocity field involving differential rotation. In cylindrical polar coordinates (r, ϕ, z) let

$$\mathbf{u} = r\Omega(r, z)\hat{\phi}$$

Consider an axisymmetric magnetic field, which we separate into *poloidal* (meridional: r and z) and *toroidal* (azimuthal: ϕ) parts:

$$\mathbf{B} = \mathbf{B}_p(r, z, t) + B_\phi(r, z, t)\hat{\phi}$$

The ideal induction equation reduces to

$$\frac{\partial \mathbf{B}_p}{\partial t} = 0, \quad \frac{\partial B_\phi}{\partial t} = r\mathbf{B}_p \cdot \nabla \Omega$$

Differential rotation winds the poloidal field to generate a torsional field. To obtain a steady state without winding, we require the angular velocity to be constant along each magnetic field line:

$$\mathbf{B}_p \cdot \nabla \Omega = 0$$

a result known as *Ferraro's law of isorotation*.

There is an energetic cost to winding the field, as work is done against magnetic tension. In a dynamical situation a strong magnetic field tends to enforce isorotation along its length. Generalise the analysis to allow for axisymmetric torsional oscillations:

$$\mathbf{u} = r\Omega(r, z, t)\hat{\phi}$$

The azimuthal component of the equation of motion is then

$$\rho r \frac{\partial \Omega}{\partial t} = \frac{1}{\mu_0 9r} \mathbf{B}_p \cdot \nabla (r \mathbf{B}_\phi)$$

Combine with the induction equation above to give

$$\frac{\partial^2 \Omega}{\partial t^2} = \frac{1}{\mu_0 \rho r^2} \mathbf{B}_p \cdot \nabla (r^2 \mathbf{B}_p \cdot \nabla \Omega)$$

This equation describes *torsional Alfvén waves*. For example, if $\mathbf{B}_p = B_z \hat{\mathbf{z}}$ is vertical and uniform, then

$$\frac{\partial^2 \Omega}{\partial t^2} = v_a^2 \frac{\partial^2 \Omega}{\partial z^2}$$

This is not strictly an exact non-linear analysis because we have neglected the force balance (and indeed motion) in the meridional plane.

3.2.5 Force-free fields

In regions of low density, e.g. the solar corona, \mathbf{B} may be dynamically dominant over inertia, gravity and gas pressure. We then have (approximately) a force-free magnetic field such that

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$

Since $\nabla \times \mathbf{B}$ must be parallel to \mathbf{B} in this case, we may write

$$\nabla \times \mathbf{B} = \lambda \mathbf{B} \tag{1}$$

for some scalar field $\lambda(\mathbf{x})$. Taking the divergence of (1) gives

$$0 = \mathbf{B} \cdot \nabla \lambda$$

so λ is constant along each magnetic field line. In the special case where λ is constant, known as a *linear force-free magnetic field*, the curl of (1) results in the *Helmholtz equation*

$$-\nabla^2 \mathbf{B} = \lambda^2 \mathbf{B}$$

which admits a wide variety of solutions. A subset of force-free magnetic fields consists of *potential* or *current-free* magnetic fields for which

$$\nabla \times \mathbf{B} = 0$$

In a true vacuum, \mathbf{B} must be potential. However, only an extremely low density of electrons is needed to make the force-free description more relevant.

An example of a force-free field in cylindrical polar coordinates (r, ϕ, z) is

$$\begin{aligned} \mathbf{B} &= B_\phi(r)\hat{\phi} + B_z(r)\hat{\mathbf{z}} \\ \nabla \times \mathbf{B} &= -\frac{dB_z}{dr}\hat{\phi} + \frac{1}{r}\frac{d}{dr}(rB_\phi)\hat{\mathbf{z}} \end{aligned}$$

Now $\nabla \times \mathbf{B} = \lambda \mathbf{B}$ implies

$$-\frac{1}{r} \frac{d}{dr} \left(r \frac{dB_z}{dr} \right) = \lambda^2 B_z$$

which is the z component of the Helmholtz equation. The solution regular at $r = 0$ is

$$B_z = B_0 J_0(\lambda r), \quad B_\phi = B_0 J_1(\lambda r)$$

where J_n is the Bessel function of order n . Note that $J_0(x)$ satisfies

$$(xJ_0')' + xJ_0 = 0, \quad J_1(x) = -J_0'(x)$$

The helical nature of this field is typical of force-free fields with $\lambda \neq 0$.