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E. A. Witalis

Abstract

Rigorous derivations are given of the basic equations and methods available for the analysis of transverse MHD flow when Hall currents are not suppressed. The gas flow is taken to be incompressible and viscous with uniform tensor conductivity and arbitrary magnetic Reynold's number. The magnetic field is perpendicular to the flow and has variable strength. Analytical solutions can be obtained either in terms of the induced magnetic field or from two types of electric potential. The relevant set of suitable simplifications, restrictive conditions and boundary value considerations for each method is given.

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1. Introduction

In the presence of a magnetic field the electrical conductivity of an ionized gas becomes anisotropic and it is appropriately described by its tensor properties. Often, however, an easier way to introduce this magnetic field effect is simply to add to the charge transport equation the Hall effect terms (Rosa 1962) which then account for the anisotropy. It will be shown that these terms give rise to considerable difficulties when investigating the gas dynamical and electrical properties of a flowing plasma which is permeated by an externally applied magnetic field. Such an arrangement is typical for most MHD power generation concepts and consequently, various aspects of it have been treated in a large number of papers, which usually are restricted to quasi-one-dimensional cases where an infinite number of external conductors force the current flow pattern to be uniform.

A critical examination of the possible two-dimensional analysis methods does not seem to have been carried out previously. By deriving them rigorously their inherent limitations and applicability will be evident. A few representative works will finally be mentioned.

The basic geometry is taken as follows: A conducting gas flows in the positive x-direction of a Cartesian co-ordinate system and a uniform or varying magnetic field with constant direction is perpendicular to the flow and acts along the z-axis. The additional assumptions have also been found to represent necessary conditions for making the treatment mathematically tractable. Thus only incompressible flow of constant conductivity in the magnetic field direction seems susceptible to analytical solution. The two-dimensionality combined with incompressibility then imply that the flow can be bounded only by parallel x-z-planes.

2. Fundamental equations

The velocity $\underline{V}$ of a steady incompressible gas flow satisfies the continuity equation written as

$$\text{div}\ \underline{V} = 0 \qquad (1)$$

Eq. (1) can be supplemented with the basic assumptions $V_y = V_z = 0$ and $\frac{\partial}{\partial z} = 0$ to prove that $\underline{V}$ is a function only of y, $V = V_x(y)$. The convective derivative of $\underline{V}$ then vanishes so that the equation of motion can be written

$$\underline{j} \times \underline{B} - \text{grad}\, p + \rho\nu\Delta\underline{V} = 0 \qquad (2)$$

where $\underline{j}$ is the current density and $\underline{B}$ is the magnetic field strength. p denotes the gas pressure, ρ is the density and ν is the kinematic viscosity.

The generalized Ohm's law is taken as (Cowling, 1957)

$$\underline{j} = \sigma(\underline{E} + \underline{V} \times \underline{B}) + \mu(\underline{j} \times \underline{B}) \qquad (3)$$

where $\underline{E}$ is the electric field strength. μ is the electron mobility which is assumed to be independent of position and given by

$$\mu = e\tau_e/m_e \qquad (4)$$

where e and m_e denote the electron charge and mass and τ_e is the average time between collisions randomizing the electron velocity. The last term of Eq. (3) represents the Hall effect. Its magnitude is given my the dimensionless Hall parameter μB which is of the order unity for most practical MHD power concepts.

The electric field due to the electron pressure gradient

$$\underline{E}_e = -\frac{1}{en_e}\, \text{grad}\, p_e \qquad (5)$$

has been neglected in Eq. (3) implying for equal and uniform gas and electron temperatures a constant electron density n_e and consequently constant scalar electron conductivity

$$\sigma = en_e\mu \qquad (6)$$

The ion current, usually denoted ion-slip, has not been taken account of in Eq. (3), however, this may simply be done with good approximation by replacing σ and μB in Eq. (3) by $\sigma/(1 + \mu\mu_i B_m^2)$ and $\mu B/(1 + \mu\mu_i B_m^2)$ where the ion mobility μ_i is given by an equation similar to (4) but instead containing the ion quantities m_i and τ_i. B_m is a mean value of the magnetic field strength.

For the plane case with $\underline{B}$ perpendicular to $\underline{V}$ and $\underline{j}$ Eq. (3) proves that $\underline{E}$ is perpendicular also to $\underline{B}$. Further, Eq. (3) can be written so as to yield an explicit expressions for $\underline{j}$

$$\underline{j}(1 + \mu^2 B^2) = \sigma(\underline{E}' + \mu \underline{E}' \times \underline{B}) \tag{7}$$

where $\underline{E}$ is the electric field strength in the fluid frame

$$\underline{E}' = \underline{E} + \underline{V} \times \underline{B} \tag{8}$$

The pertinent Maxwell equations are the following

$$\text{curl}\, \underline{E} = 0 \tag{9}$$

$$\text{curl}\, \underline{B} = \mu_o \underline{j} \tag{10}$$

$$\text{div}\, \underline{B} = 0 \tag{11}$$

Eq. (9) proves that $\underline{E}$ can be derived from a potential U

$$\underline{E} = -\,\text{grad}\, U \tag{12}$$

The magnetic field strength $\underline{B}$ is the sum of two parts,

$$\underline{B} = \underline{B}_o + \underline{B}_i \tag{13}$$

where the externally applied field $\underline{B}_o$ is irrotational as it originates from currents outside the plasma. Eq. (10) then takes a form involving only the induced part $\underline{B}_i$

$$\text{curl}\, \underline{B}_i = \mu_o \underline{j} \tag{14}$$

where μ_o is the permeability of free space.

Finally, conservation of electrical charge is expressed as

$$\text{div}\, \underline{j} = 0 \tag{15}$$

3. The coupling between the fluid motion and the magnetic field

By using Eq. (10) the equation of motion, Eq. (2), can be written as

$$\text{grad}(B^2/(2\mu_o) + p) - \rho\nu\Delta\underline{V} = 0 \tag{16}$$

proving that the Lorentz force is irrotational and that only the viscosity will impart vorticity to the fluid. The further simplified case when viscosity and Hall effect is negligible has been discussed by Lur'e (1962) who pointed out the the Eqs. (1) and (16) together with boundary conditions will suffice to give solutions to the hydrodynamical aspects of the flow like the pressure and the velocity distributions. The magnetic field can then be determined separately when the velocity is found.

Our neglect of ion slip means that the ions are assumed to be closely coupled to the neutral gas. When $\mu_i B << 1$ the magnetic effect on the ions is very small and the viscosity ν can be considered as unaffected by the magnetic field.

It will be shown that also in the viscous and tensor conductivity case knowledge of the velocity $V(y)$ makes it possible to determine the magnetic field strength distribution provided that its values on the boundaries are known. Consider the simplified generalized Ohm's law, Eq. (3) when the current density $\underline{j}$ has been substituted by μ_o^{-1} curl $\underline{B}$, Eq. (10). By applying the operator curl the following equation is obtained

$$\Delta\underline{B} = -\mu_o\sigma(\underline{B}\cdot\underline{\nabla})\underline{V} + \mu_o\sigma(\underline{V}\cdot\underline{\nabla})\underline{B} - \mu[(\underline{B}\cdot\underline{\nabla})\mathrm{curl}\,\underline{B} - (\mathrm{curl}\,\underline{B}\cdot\underline{\nabla})\underline{B}] \quad (17)$$

whereby the Eqs. (1), (9) and (11) have been used. The first right hand side term vanishes in the present case where the component of $\underline{V}$ in the direction of B is a constant equal to zero. The two terms in the square bracket both vanish in case of a current distribution perpendicular to a magnetic field of constant direction but of variable strength. The pertinent component of Eq. (17) can be written as homogenous linear equation for B

$$\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2} - \mu_o\sigma V(y)\frac{\partial B}{\partial x} = 0 \quad (18)$$

and when the externally applied field distribution $B_o(x,y)$ is known, as the following non-homogenous equation for B_i

$$\frac{\partial^2 B_i}{\partial x^2} + \frac{\partial^2 B_i}{\partial y^2} - \mu_o\sigma V(y)\frac{\partial B_i}{\partial x} = \mu_o\sigma V(y)\frac{\partial B_o}{\partial x} \quad (19)$$

4. The magnetic field distribution

A solution to Eq. (19) also gives by Eq. (14) the current distribution and quantities like ohmic power dissipation and flow power can readily be evaluated. However, the following facts should be noted:

i. Solutions to Eq. (19) will be influenced by the Hall effect only through the boundary conditions which usually are given as specifications of the normal current density j_n . Eq. (14) proves that the induced field B_i does not vary along an insulating boundary. On the other hand, the distribution of j_n to a conducting boundary is very non-uniform (Hurwitz, Jr et al. 1961) and it depends upon the conductor size and the Hall effect in a complicated way (Dzung 1965) so that a prescription of B_i there becomes difficult.

ii. In case the flow boundaries are all insulators there will exist only eddy currents. The simple boundary conditions in such a case make calculations not too difficult (Witalis IV).

iii. The ratio B_i/B_o is approximately given by the magnetic Reynold's number R_m

$$R_m = \mu_o \sigma V_o a \tag{20}$$

where V_o is the mean flow velocity and a is a characteristic length of the system. R_m is here taken to be arbitrary but a small value of it will simplify the solution as Eq. (19) then becomes the Laplace equation and further, the shape of the flow velocity profile becomes irrelevant.

iv. The basic conditions of two-dimensionality, $\frac{\partial}{\partial z} = 0$, may not be easily satisfied in practical cases. This especially applies to MHD power generators and accelerators where the currents in both the plasma and the external conductors modify the applied field. This influence is generally of the order R_m or less, still it may be important (Haines and Thompson 1962).

Two types of segmented generator electrode arrangements are shown schematically in Fig. 1. The applied magnetic field inside generator a is decreased by the field from the circulating currents and it is approximately two-dimensional. Generator b is series-segmented and it is of the one-load type (Witalis II, 1965). The doubling of short-circuiting conductors has been shown to reduce the interaction between the plasma and the generator top and bottom walls (Witalis III). Only at the plane $B_i = 0$ is the magnetic field transverse to the flow and nowhere is the condition $\frac{\partial}{\partial z} = 0$ fulfilled.

5. The potential distributions

Basically, the above determination of current flow pattern from the induced magnetic field derives from Eq. (15) that proves the existence of a stream function $\underline{B}_i/\mu_o$ which can be obtained from Eq. (19) together with boundary conditions. Using Eq. (3) or (7) the current density may instead be found from the electrostatic potential, Eq. (12). Applying Eq. (15) to Eq. (3) it is found that:

$$\sigma\Delta U = \sigma(\underline{B} \cdot \mathrm{curl}\,\underline{V} - \mu_o \underline{V} \cdot \underline{j}) + \mu\, \mathrm{div}(\underline{j} \times \underline{B}) \qquad (21)$$

where the Maxwell equations (11) and (14) have been used. In order to estimate the right hand side terms the current density as expressed by Eq. (3) is inserted in Eq. (21). The divergence term is then expanded whereby use is made of Eqs. (1), (9), (11), (12), (14), (15), and the power form of Eq. (3).

$$- \underline{V} \cdot (\underline{j} \times \underline{B}) = - \underline{E} \cdot \underline{j} + j^2/\sigma \qquad (22)$$

The result turns out

$$\Delta U - \mu_o \sigma \underline{V} \cdot \mathrm{grad}\, U = \underline{B} \cdot \mathrm{curl}\, \underline{V} - \mu\mu_o j^2/\sigma \qquad (23)$$

The practical applicability of Eq. (23) seems to be limited to inviscid, i.e. irrotational flow and in that case it will be shown that the last term may be large even when R_m is small. However, the main difficulty concerns boundary conditions which specify normal current density. They lead by Eq. (7) to relations involving both components of the potential gradient as well as the induced field strength.

The fact that the current density is proportional to the moving fluid frame field suggests that a potential U' may instead be associated with $\underline{E}'$, Eq. (8). This requires $\underline{E}'$ to be irrotational. It is readily found that both $\underline{B}$ and $\underline{V}$ may then be allowed to vary in the y-direction but not to be functions of the flow direction co-ordinate x. Proceeding like before the equations for U' becomes

$$\Delta U' = - \mu\mu_o [j^2/\sigma - \underline{V} \cdot (\underline{j} \times \underline{B})] \qquad (24)$$

In case of power generation the terms within the square bracket are both positive and they represent ohmic dissipation and flow power respectively. For the little perturbed flow of the channel center the order of magnitude of the right hand side can be shown to be given by

$$\mu B R_m (\Delta U')_{average} = \mu B R_m VB/a \tag{25}$$

and when $R_m << 1$ the Laplace approximation of Eq. (24)

$$\Delta U' = 0 \tag{26}$$

is valid.

Theoretical investigations (Hurwitz, Jr et al. 1961, Witalis I, 1965, Dzung, 1965) based on Eq. (26) have shown that the Hall effect will lead to an infinitely strong current density concentration at transitions between a conducting and an insulating boundary. This apparent contradiction can be removed when, more realistically, consideration is given to the flow velocity variation there. It is then found that the flow power term of Eq. (22) can not attain a very large value, a fact that then also applies to the two right hand side terms. Consequently, Eq. (26) can still be expected to be valid near boundaries.

6. Previous works

The special confirmal technique for solving Eq. (26) was first used in the pioneering work by Hurwitz, Jr et al. (1961). There is little reason to describe it here as it is now well known and extended in a number of theoretical works on MHD power generator design. Thus Witalis (II, 1965) and Dzung (1965) have independently found the favourable positions, shapes and connections of the generator electrodes. Podolsky and Sherman (1962), Dzung (1962) and Sutton (1963) have investigated generator end effects by the same conformal mapping technique. As shown first by Crown (1961), Eq. (26) and its associated mixed boundary conditions are susceptible also to numerical solutions. The fact that Eq. (26) also applies to non-uniform velocity profiles was pointed out by Yeh and Sutton (1963).

There does not seem to be any previous investigations based on an analysis of the induced magnetic field distribution as given here. In the works by Dzung (1962) and Sutton (1963) a stream function for $\underline{j}$ is derived from the equation of charge conservation, Eq. (15). By assuming a constant applied magnetic field and further, by stating the current density to be irrotational, which actually was an approximation, they obtained the

Laplace form of Eq. (19). However, the simplification did not affect the results presented as R_m was assumed to be small.

Recently, Witalis (IV) has investigated the action of a transverse step magnetic field on an incompressible flow with tensor conductivity by studying the induced magnetic field distribution. Limitations on μB or R_m are then not necessary.

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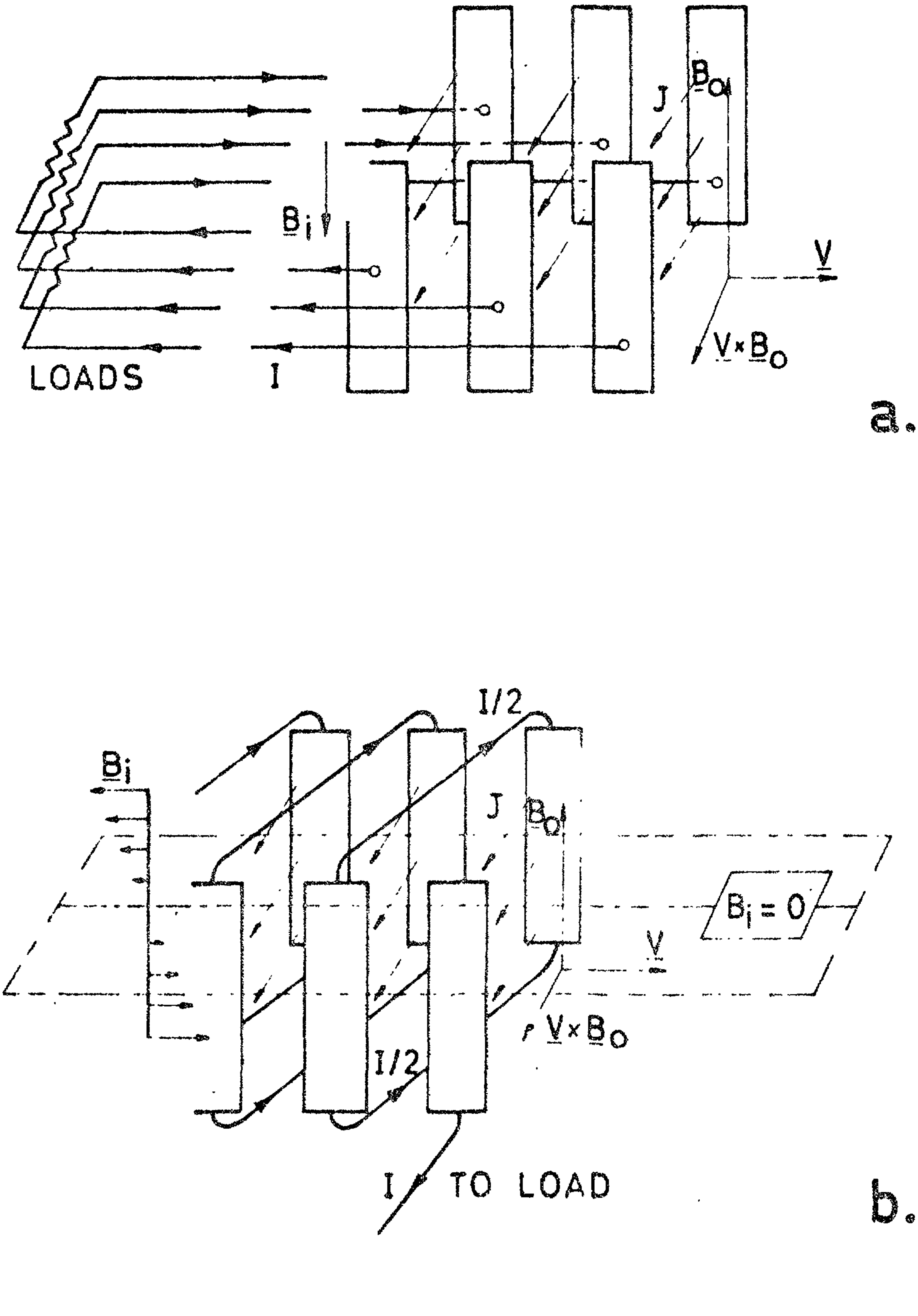

Fig. 1 Two generator configurations described in text.

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