Numerical Solution of Lundquist Equations of Magneto-hydrodynamics*

By R. L. Johnston and S. K. Pal

Abstract. A method of bicharacteristics [3] is used to derive a numerical method for solving multidimensional nonlinear Lundquist equations of magnetohydrodynamics. Actual numerical computations are carried out to solve two specific problems of magnetohydrodynamics—the magnetohydrodynamic initial-pressure problem and a problem of cylindrical waves in a transverse magnetic field due to a thin current-carrying wire perpendicular to the plane of the fluid.

1. Introduction. In this paper, we derive a method for the numerical solution of Lundquist equations which describe the flow of an electrically conducting fluid in the presence of an electromagnetic field. The method is derived from a method of bicharacteristics. In deriving the method, we have used the most general three-dimensional situation without linearization. The method is then used to solve two specific problems in magnetohydrodynamics—the magnetohydrodynamic initial-pressure problem and the problem of cylindrical waves in a transverse magnetic field due to a thin current-carrying wire perpendicular to the plane of the fluid. The exact solution of the initial-pressure problem in the presence of a uniform magnetic field was obtained by Friedlander [1] from the linearized version of the Lundquist equations. We compute solutions for both nonlinear and linearized equations.

2. The Lundquist Equations [2]. The equations of motion of magnetohydrodynamics consist of two groups. First, there are the equations of motion of an inviscid, electrically conducting fluid,

\[ \rho \left[ \frac{\partial V}{\partial t} + (V \cdot \nabla) V \right] + \nabla p - \rho j \times H = 0, \]

\[ \frac{\partial \rho}{\partial t} + (V \cdot \nabla) \rho + \rho \text{div} V = 0, \]

where \( p \) is the pressure, \( \rho \) the density, \( V \) the velocity, \( j \) the current, \( H \) the magnetic field and \( \mu \) the permeability. Secondly, one has Maxwell's equations

\[ \text{curl} \ H = 4\pi j, \quad \text{curl} \ E = -\mu \frac{\partial H}{\partial t}, \]

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where $E$ is the field strength and the displacement current has been neglected. Furthermore, assuming that the fluid is a perfect conductor,

$$ E + \mu V \times H = 0. $$

Eliminating $E$, one obtains

$$ \text{curl } H = 4\pi j, \quad \partial H/\partial t = \text{curl}(V \times H). $$

These equations must, as usual, be supplemented by $\text{div } H = 0$.

Finally, there is the energy equation. Since we have already neglected viscosity and taken the electrical conductivity to be infinite, we must, for the sake of consistency, also ignore heat conduction. Then the entropy of any fluid particle remains constant and this implies that

$$ \partial p/\partial t + (V \cdot \text{grad})p = C^2 \{ \partial p/\partial t + (V \cdot \text{grad})p \}, $$

where $C^2 = (\partial p/\partial \rho)^{1/2}$, evaluated for constant specific entropy, is the local velocity of sound. In this case, the pressure-density relation is

$$ p = A\rho^2, \quad A = \text{constant}. $$

Thus the equations for $p$, $V$ and $H$ are

(2.1) \[ U_i + A_1 U_z + A_2 U_x + A_3 U_y = 0 \]

where

(2.2) \[ U = [p, V_z, V_x, V_y, H_z, H_x, H_y]^T, \]

(2.3) \[ A_1 = \begin{bmatrix}
V_z & C^2 \rho & 0 & 0 & 0 & 0 & 0 \\
1/\rho & V_z & 0 & 0 & 0 & KH_y & KH_x \\
0 & 0 & V_z & 0 & 0 & -KH_x & 0 \\
0 & 0 & 0 & V_z & 0 & 0 & 0 \\
0 & H_x & -H_z & 0 & 0 & V_x & 0 \\
0 & H_x & 0 & -H_x & 0 & 0 & V_x \\
\end{bmatrix}, \]

(2.4) \[ A_2 = \begin{bmatrix}
V_y & 0 & C^2 \rho & 0 & 0 & 0 & 0 \\
0 & V_y & 0 & 0 & -KH_y & 0 & 0 \\
1/\rho & 0 & V_y & 0 & KH_z & 0 & KH_x \\
0 & 0 & 0 & V_y & 0 & 0 & -KH_y \\
0 & -H_v & H_x & 0 & V_y & 0 & 0 \\
0 & 0 & 0 & 0 & V_y & 0 & 0 \\
0 & 0 & H_x & -H_v & 0 & 0 & V_y \\
\end{bmatrix}. \]
where \( K = \mu/4\pi\rho \).

3. The Method. The method used for the Lundquist equations is the method of bicharacteristics developed by Johnston and Pal [3] for a hyperbolic system of partial differential equations. We are given a hyperbolic system

\[
U_i + \sum_{j=1}^{\infty} A_{ij} U_{x_j} = 0
\]

where \( U = [u_1, u_2, \cdots, u_n]^T \) and \( A_i \)'s are \( N \times N \) matrices. The bicharacteristics [2] of the system are given by

\[
\frac{dx_j}{dt} = \frac{\partial h_j}{\partial \lambda_i}, \quad 1 \leq j \leq N, 1 \leq i \leq m, \tag{3.2}
\]

\[
\frac{d\lambda_i}{dt} = -\frac{\partial h_i}{\partial x_j}, \quad 1 \leq j \leq N, 1 \leq i \leq m, \tag{3.3}
\]

where \(-h_i, 1 \leq j \leq N\), are the \( N \) real zeros of the characteristic polynomial

\[
H = \det \left( \lambda I + \sum_{i=1}^{m} A_i \lambda_i \right) \tag{3.4}
\]

for a given set \((\lambda_1, \lambda_2, \cdots, \lambda_m)\) of real numbers. Selecting a bicharacteristic and integrating along it, the system of given differential equations can be written as the following equivalent system:

\[
U(t + \Delta t, \xi) = U(t, \alpha) + \sum_{i=1}^{m} \int_{t}^{t+\Delta t} D_i U_{x_i} dt \tag{3.5}
\]

where \( D_i = -A_i + (\partial h/\partial \lambda_i)I \), \( h \) being an eigenvalue of the matrix \( \sum A_i \lambda_i \) and \( \alpha = (\alpha_1, \alpha_2, \cdots, \alpha_m) \) is given by

\[
\alpha_i = \xi_i - \int_{t}^{t+\Delta t} \frac{\partial h_i}{\partial \lambda_i} dt, \quad 1 \leq i \leq m. \tag{3.6}
\]

Approximating the integrals using \( \int_{t}^{t+\Delta t} f(x, s) ds \approx f(x, t)\Delta t \) and the derivatives \( U_{x_i} \) by

\[
U_{x_i}(t, \xi) \simeq (1/2\Delta x_i)[E_{x_i} - E_{x_i-1}] U(t, \xi), \tag{3.7}
\]

we get an explicit method.
Using the approximation

\[ \int_{t}^{t + \Delta t} f(x, s) \, ds \simeq \frac{1}{2} [f(x, t) + f(x, t + \Delta t)] \Delta t \]

for the integrals and the same approximations as in (3.7) for the derivatives \( U_{x_i} \), we have an implicit method

\[ U^{n+1}(\xi) = \left(1 - \sum_{i=1}^{m} \left( \frac{\partial h}{\partial \lambda_i} \right) i_{i} \right)_{q} U^{n}(\xi) + \frac{1}{2} \sum_{i=1}^{m} \left( -A_{i} + \left( \frac{\partial h}{\partial \lambda_i} \right) i_{i} \right)_{q} E_{+,i} U^{n}(\xi) \]

\[ + \frac{1}{4} \sum_{i=1}^{m} \left( -A_{i} + \left( \frac{\partial h}{\partial \lambda_i} \right) i_{i} \right)_{q} r_{i} [E_{+,i} - E_{-,i}] U^{n}(\xi) \]

\[ + \frac{1}{4} \sum_{i=1}^{m} \left( -A_{i} + \left( \frac{\partial h}{\partial \lambda_i} \right) i_{i} \right)_{q} r_{i} [E_{+,i} - E_{-,i}] U^{n+1}(\xi). \]

Here \( r_{i} = \Delta t/\Delta x_{i} \), \( Q \) is the point \((n \Delta t, a)\) and

\[ E_{+,i}(t, x) = f(t, x_{i}, x_{2}, \ldots, x_{n} \pm \Delta x_{i}, \ldots, x_{n}) \]

and \( E_{-,i} \) is understood to mean \( E_{+,i} \) when \((\partial h/\partial \lambda_{i})_{q} \leq 0\) and \( E_{-,i} \) when \((\partial h/\partial \lambda_{i})_{q} > 0\).

It is natural to ask if the choice of different bicharacteristics makes any significant difference in the solution obtained. The question is answered in [3] where it is shown that the discrepancy in the solutions obtained by using two different bicharacteristics is at most of the same order as the truncation error which is \( O(\Delta t^{2}) \).

In [3] it is also shown that the methods are stable provided that \( \lambda_{i} \)'s are chosen such that \( |\partial h/\partial \lambda_{i}| \leq \max_{j=1}^{m} |A_{j}|_{2} \leq R \) and \( r_{i} = \Delta t/\Delta x_{i} < \Omega/mR^{2}, 1 \leq j \leq m \), where \( \Omega = \min_{j}|\partial h/\partial \lambda_{i}|. \) The eigenvalues of \( A_{1} \lambda_{1} + A_{2} \lambda_{2} + A_{3} \lambda_{3} \) for the Lundquist equations are

1. \( V \lambda_{1} + V \lambda_{2} + V \lambda_{3} \)
2. \( V \lambda_{1} + V \lambda_{2} + V \lambda_{3} \pm c_{r} \cdot \lambda \),
   \[ c_{r}^{2} = \frac{1}{2}[c^{2} + b^{2}] + [(c^{2} + b^{2})^{2} - 4c^{2}b_{n}^{2}]^{1/2} \]
3. \( V \lambda_{1} + V \lambda_{2} + V \lambda_{3} \pm c_{s} \cdot \lambda \),
   \[ c_{s}^{2} = \frac{1}{2}[c^{2} + b^{2}] - [(c^{2} + b^{2})^{2} - 4c^{2}b_{n}^{2}]^{1/2} \]
4. \( V \lambda_{1} + V \lambda_{2} + V \lambda_{3} \pm b \cdot \lambda \),
   \[ \lambda^{2} = \lambda_{1}^{2} + \lambda_{2}^{2} + \lambda_{3}^{2}, \]
   \[ b^{2} = (\mu/4\pi \rho)(H_{x}^{2} + H_{y}^{2} + H_{z}^{2}), \quad b_{n} = (\mu/4\pi \rho)^{1/2}(H_{x} \lambda_{1} + H_{y} \lambda_{2} + H_{z} \lambda_{3})/\lambda, \]
   \[ H_{n} = (H_{x} \lambda_{1} + H_{y} \lambda_{2} + H_{z} \lambda_{3})/\lambda, \quad H = H_{x}^{2} + H_{y}^{2} + H_{z}^{2}. \]

Here the bicharacteristics corresponding to the eigenvalue \( h = V \lambda_{1} + V \lambda_{2} + V \lambda_{3} + c_{r} \cdot \lambda \) are determined by
\[
\frac{dx}{dt} = \frac{\partial h}{\partial \lambda_1} = V_x + c_1 \lambda_1 / \lambda - \frac{b^2 s (H_n / H)^2}{c_f C} (H_x - H_n \lambda_1 / \lambda),
\]
\[
\frac{dy}{dt} = \frac{\partial h}{\partial \lambda_2} = V_y + c_2 \lambda_2 / \lambda - \frac{b^2 s (H_n / H)^2}{c_f C} (H_y - H_n \lambda_2 / \lambda),
\]
\[
\frac{dz}{dt} = \frac{\partial h}{\partial \lambda_3} = V_z + c_3 \lambda_3 / \lambda - \frac{b^2 s (H_n / H)^2}{c_f C} (H_z - H_n \lambda_3 / \lambda),
\]

where
\[
s = c^2 / b^2, \quad C = [(1 + s)^2 - 4s b^2 / b^2]^{1/2}.
\]

Similarly, bicharacteristics corresponding to the other eigenvalues can be obtained. Numerical solution can now be obtained by using these values of \( \partial h / \partial \lambda_1, \partial h / \partial \lambda_2, \partial h / \partial \lambda_3 \) in either (3.8) or (3.9).

Here, it should be noted that in the derivation of the method no assumption was made about the strictly hyperbolic nature of the equations. Thus even if, in a given case, certain bicharacteristic rays are taken more than once, the method should be successful as is proved by the computational results obtained in the next section in the two degenerate cases where (1) \( c_1^2 = 0 \) and the wave-speed locus has a double point and (2) \( c_1 = b, -b, c_2 = b, -b \).

4. The Numerical Solutions.

(a) The Magnetohydrodynamic Initial-Pressure Problem. This problem, as mentioned before, was considered by Friedlander [1]. It is a problem in three space dimensions and concerns the propagation of small disturbances in a compressible fluid which is also a conductor of electricity in the presence of a magnetic field. Energy dissipation by viscosity, heat conduction and the Joule heat is neglected as is the displacement current. The equations governing the phenomenon are the Lundquist equations (2.1). We now consider departures from an equilibrium in which the medium is uniform. Let \( p_0, \rho_0 \) and \( H_0 \) be the constant equilibrium values of the pressure, density and the magnetic field respectively and put \( p = p_0 + p', \rho = \rho_0 + \rho', H = H_0 + H' \), where \( p', \rho' \) and \( H' \) are departures from the respective equilibrium values. Then the equations for \( p', \rho', \rho' \) are

\[
(4.1) \quad U_t + A_1 U_x + A_2 U_y + A_3 U_z = 0
\]

where

\[
(4.2) \quad U = [p', V_x, V_y, V_z, H'_x, H'_y, H'_z]^T,
\]

and \( A_1, A_2, A_3 \) are as defined in (2.3), (2.4) and (2.5). Assuming small departures, and by choosing the direction of \( H_0 \) as the x-axis, we can obtain an approximation to the system by the following linear system

\[
(4.3) \quad \frac{\partial p'}{\partial t} + c^2 \rho_0 \left( \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right) = 0,
\]
\[
(4.4) \quad \frac{\partial V_z}{\partial t} + \frac{1}{\rho_0} \frac{\partial p'}{\partial x} = 0.
\]
\begin{equation}
\frac{\partial V_x}{\partial t} + \frac{1}{\rho_0} \frac{\partial p'}{\partial y} + K_0 H_0 \left( \frac{\partial H'_y}{\partial y} - \frac{\partial H'_x}{\partial x} \right) = 0,
\end{equation}

\begin{equation}
\frac{\partial V_z}{\partial t} + \frac{1}{\rho} \frac{\partial p'}{\partial z} + K_0 H_0 \left( \frac{\partial H'_z}{\partial z} - \frac{\partial H'_x}{\partial x} \right) = 0,
\end{equation}

\begin{equation}
\frac{\partial H'_x}{\partial t} + H_0 \left( \frac{\partial V_x}{\partial y} + \frac{\partial V_z}{\partial z} \right) = 0,
\end{equation}

\begin{equation}
\frac{\partial H'_y}{\partial t} - H_0 \frac{\partial V_y}{\partial x} = 0,
\end{equation}

\begin{equation}
\frac{\partial H'_z}{\partial t} - H_0 \frac{\partial V_z}{\partial x} = 0,
\end{equation}

where \( p' = c^2 \rho' \), \( c \) being now the velocity of sound calculated with the equilibrium \( p_0 \) and \( \rho_0 \) and \( K_0 = \mu/4\pi p_0 \). These equations, of course, follow directly from the

**TABLE 1**

Solution of Initial-Pressure Problem at \( x = y = z = .4 \). 1 and 11 denote the exact and numerical solutions, respectively, of the linearized problem while 111 denotes the numerical solution of the nonlinear equations.

<table>
<thead>
<tr>
<th>No. of time-steps</th>
<th>Solution</th>
<th>( p' )</th>
<th>( V_x )</th>
<th>( V_y = V_z )</th>
<th>( H'_x )</th>
<th>( H'_y = H'_z )</th>
</tr>
</thead>
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**TABLE 2**

Solution of Initial-Pressure Problem at \( x = y = z = .4 \). This is the degenerate case when \( c^2 = 0 \). 1 and 11 denote the exact and numerical solutions, respectively, of the linearized problem while 111 denotes the numerical solutions of the nonlinear equation.

<table>
<thead>
<tr>
<th>No. of time-steps</th>
<th>Solution</th>
<th>( p' )</th>
<th>( V_x )</th>
<th>( V_y = V_z )</th>
<th>( H'_x )</th>
<th>( H'_y = H'_z )</th>
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TABLE 3

Solution of Initial-Pressure Problem at \( x = y = z = .4 \). This is the degenerate case when \( c_f = b, \ -b \) and \( c_s = b, -b \). 1 and 11 denote the exact and numerical solutions, respectively, of the linearized problem while 111 denotes the numerical solutions of the nonlinear equations.

<table>
<thead>
<tr>
<th>No. of time-steps</th>
<th>Solution</th>
<th>( p' )</th>
<th>( V_x )</th>
<th>( V_y = V_z )</th>
<th>( H_x' )</th>
<th>( H_y' = H_z' )</th>
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nonlinear system by noting that \( H_x = H_0 + H_x', H_y = H_y', H_z = H_z', p = p_0 + p', \)
\( \rho = \rho_0 + \rho' \) and putting the primed quantities and \( V_x, V_y, V_z \) in the matrices \( A_1, A_2, A_3 \) equal to zero.

In the numerical computation, the following initial conditions and values were used:

**Figure 1. Distribution of density in space at different times.**
Figure 2. Distribution of velocity in space at different times.

\[ p'(0, x, y, z) = \cos(x \cos \theta + y \sin \theta \cos \phi + z \sin \theta \sin \phi), \]

\[ V(0, x, y, z) = H'(0, x, y, z) = 0, \]

with the following values for the different parameters of the problem: \( H_0 = 5, \mu = 1, \rho_0 = 1, \theta = \phi = \pi/4, p = \rho^\gamma \text{ with } \gamma = 2. \)

Computation was done for the region \( 0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1. \) Boundary values were calculated by modifying the difference scheme as outlined in [5]. Mesh widths chosen are: \( \Delta x = \Delta y = \Delta z = .1, \Delta t/\Delta x = .25. \) The exact solution (1) and the numerical solution (11) for the linearized problem as well as the numerical solution (111) of the exact nonlinear equations are given in Table 1 for the point \( x = y = z = .4. \) The results for (11) are better than the ones reported in [4] because of finer meshes used here.

If we take \( \theta = \pi/2, \) then \( c,^2 = 0 \) in this case [1] and we have a case where two bicharacteristic rays are taken more than once. The results for this case are given in Table 2.

If \( c^2 = b^2 \) and \( \theta = 0, \) then we have \( c_r = b, -b \) and \( c, = b, -b. \) For achieving such a case in this problem, we chose

\[ \mu = 8\pi\rho_0/H_0^2 \text{ with } p = \rho^\gamma, \gamma = 2. \]
The results for this case are given in Table 3.

(b) Cylindrical Waves in Magnetohydrodynamics. Assume an inviscid, conducting gas with a transverse magnetic field due to a thin current-carrying wire perpendicular to the plane of the fluid. In this problem, the velocity has only the radial component \( q \) while the magnetic field has only the transverse component \( H \). Initially, the conducting fluid is assumed to be isothermal. The initial density distribution is assumed to be \( \rho_0 = 1 + 2e^{-4r^2} \) where \( r \) is the radial distance and the initial magnetic field is of the form

\[
H_0 = \begin{cases} 
\frac{B}{r}, & \text{for } r \neq 0, \\
0, & \text{for } r = 0,
\end{cases}
\]

where \( B \) is a constant. Briefly, the problem resembles that of the flow which results when compressed mass of conducting gas under a magnetic field, initially at rest, is suddenly released. The situation simulates, in simplified fashion, the conditions of a stellar explosion.

The equations governing the fluid are...
Figure 4. Distribution of density at centre.

\[
\frac{\partial q}{\partial t} + q \frac{\partial q}{\partial r} + \frac{\mu H^2}{4\pi \rho r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} - \frac{\mu H}{4\pi \rho} \frac{\partial H}{\partial r},
\]

\[
\frac{\partial p}{\partial t} + q \frac{\partial p}{\partial r} + \rho \frac{\partial q}{\partial r} + \frac{\rho q}{r} = 0,
\]

\[
\frac{\partial H}{\partial t} + q \frac{\partial H}{\partial r} + H \frac{\partial q}{\partial r} + \frac{H q}{r} = 0,
\]

\[
\left(\frac{\partial}{\partial t} + q \frac{\partial}{\partial r}\right)\left(\frac{p}{\rho}\right) = 0.
\]

At the centre \(r = 0\), we have, from considerations of symmetry, \(q = 0\), \(\partial p/\partial r = 0\), \(\partial p/\partial r = 0\). Also \(H = 0\) at \(r = 0\).

Numerical computations were performed with \(\gamma = 1.4\), \(B = 1\), \(\mu = 1\), \(\Delta r = .1\), \(\Delta t/\Delta r = .1\) over 300 time intervals \((t = 3)\). The results are shown in Figs. 1, 2, 3, 4.
Figure 5 gives the propagation of the wave front. The velocities of propagation of the wave front calculated from this curve at different times agree with the velocities calculated from the formula

$dr/dt - q = (c^2 + H^2/4)^{1/2}$

where $c$ is, as usual, the local speed of sound.

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