

1 Basic Equations

The so-called Stokes stream function, used in axisymmetric situations, is given by

$$\mathbf{u} = \begin{bmatrix} \frac{1}{r} \partial_z \psi \hat{\mathbf{r}} \\ u_\phi \hat{\phi} \\ -\frac{1}{r} \partial_r \psi \hat{\mathbf{z}} \end{bmatrix}; \quad (1)$$

here we define A in the same way.

Using the definitions in

$$\begin{aligned} \partial_t \left[\frac{1}{r} \left(\nabla^2 \psi - \frac{2\partial_r \psi}{r} \right) \right] + \frac{1}{r^2} J(\psi, \nabla^2 A - \frac{2\partial_r \psi}{r}) &= \frac{\partial_z A}{r^3} \left(\nabla^2 A - \frac{2\partial_r A}{r} \right) \\ &+ \frac{1}{r} J \left(A, \frac{1}{r} \left(\nabla^2 A - \frac{2\partial_r A}{r} \right) \right) - \frac{2B_\phi \partial_z B_\phi}{r} \\ &+ \nu \left\{ \nabla^2 \left[\frac{1}{r} \left(\nabla^2 \psi - \frac{2\partial_r \psi}{r} \right) \right] - \frac{1}{r^2} \left(\nabla^2 \psi - \frac{2\partial_r \psi}{r} \right) \right\} \end{aligned} \quad (2)$$

For the expanded form of the Ψ equation, Susan gets:

$$\partial_t u_\phi + \frac{J(\psi, u_\phi)}{r} + \frac{u_\phi \partial_z \psi}{r^2} = \frac{J(A, B_\phi)}{r} + \frac{B_\phi \partial_z A}{r^2} + \nu \left(\nabla^2 u_\phi - \frac{u_\phi}{r} \right) \quad (3)$$

$$\partial_t A = \frac{1}{r} J(A, \psi) + \frac{1}{\text{Rm}} \left(\nabla^2 A - \frac{2\partial_r A}{r} \right) \quad (4)$$

$$\begin{aligned} \partial_t B_\phi &= \frac{1}{r} J(A, u_\phi) + \frac{1}{r} J(B_\phi, \psi) \\ &+ \frac{1}{r^2} B_\phi \partial_z \psi - \frac{1}{r^2} u_\phi \partial_z A + \eta \left(\nabla^2 B_\phi - \frac{1}{r^2} B_\phi \right) \end{aligned} \quad (5)$$

2 Detailed Derivation of Ψ Equation

The Ψ equation, governing the x- and z-components of the velocity, is particularly tricky to derive so I will write out the steps here.

1. Find $\hat{\mathbf{r}}$ and $\hat{\mathbf{z}}$ components of the momentum equation, i.e.:

$$\partial_t u_z + [u \cdot \nabla u]_z = [(\nabla \times B) \times B]_z + \frac{1}{\text{Re}} [\nabla^2 u]_z \quad (6)$$

We sub in our stream/flux function notation and expand the operators in cylindrical coordinates. Then take ∂_r of the resulting equation to obtain:

$$\begin{aligned}
& \frac{1}{r^2} \partial_t \partial_r \Psi - \frac{1}{r} \partial_t \partial_r^2 \Psi - \frac{3}{r^4} \partial_z \Psi \partial_r \Psi + \frac{1}{r^3} \partial_r (\partial_z \Psi \partial_r \Psi) + \frac{2}{r^3} \partial_z \Psi \partial_r^2 \Psi - \frac{1}{r^2} \partial_r (\partial_z \Psi \partial_r^2 \Psi) \\
& \quad - \frac{2}{r^3} \partial_r \Psi \partial_r \partial_z \Psi + \frac{1}{r^2} \partial_r (\partial_r \Psi \partial_r \partial_z \Psi) = \\
& \partial_r (B_\phi \partial_z B_\phi) + \frac{2}{r^3} \partial_z^2 A \partial_z A - \frac{1}{r^2} \partial_r (\partial_z^2 A \partial_z A) + \frac{3}{r^4} \partial_z A \partial_r A - \frac{1}{r^3} \partial_r (\partial_z A \partial_r A) - \frac{2}{r^3} \partial_z A \partial_r^2 A \\
& \quad + \frac{1}{r^2} \partial_r (\partial_z A \partial_r^2 A) + \frac{1}{\text{Re}} \left[\frac{3}{r^4} \partial_r \Psi - \frac{3}{r^3} \partial_r^2 \Psi + \frac{2}{r^2} \partial_r^3 \Psi - \frac{1}{r} \partial_r^4 \Psi \right] \quad (7)
\end{aligned}$$

Repeat this process for the $\hat{\mathbf{r}}$ component of the momentum equation,

$$\partial_t u_r + [u \cdot \nabla u]_r = [(\nabla \times B) \times B]_r + \frac{1}{\text{Re}} [\nabla^2 u]_r \quad (8)$$

and take ∂_z of the expanded equation to obtain

$$\begin{aligned}
& \frac{1}{r} \partial_t \partial_z^2 \Psi - \frac{1}{r^3} \partial_z (\partial_z \Psi \partial_z \Psi) + \frac{1}{r^2} \partial_z (\partial_z \Psi \partial_z \partial_r \Psi) - \frac{1}{r^2} \partial_z (\partial_r \Psi \partial_z^2 \Psi) - \frac{1}{r} 2u_\phi \partial_z u_\phi \\
& = -\frac{1}{r^2} \partial_z^3 A \partial_r A - \frac{1}{r^2} \partial_z^2 A \partial_r \partial_z A + \frac{2}{r^3} \partial_r \partial_z A \partial_r A - \frac{1}{r^2} \partial_r^2 \partial_z A \partial_r A - \frac{1}{r^2} \partial_r^2 A \partial_r \partial_z A \\
& \quad + \frac{1}{\text{Re}} \left[-\frac{1}{r^2} \partial_z^2 \partial_r \Psi + \frac{1}{r} \partial_z^2 \partial_r^2 \Psi + \frac{1}{r} \partial_z^4 \Psi \right] \quad (9)
\end{aligned}$$

It is clear from the ∂_t terms that we must combine these equations by subtracting the $\hat{\mathbf{z}}$ equation from the $\hat{\mathbf{r}}$ equation.

When we do, we can simplify the LHS of the equation to:

$$\frac{1}{r} \partial_t \left(\nabla^2 \Psi - \frac{2}{r} \partial_r \Psi \right) + J \left(\Psi, \frac{1}{r^2} \left(\nabla^2 \Psi - \frac{2}{r} \partial_r \Psi \right) \right) - \frac{1}{r} 2u_\phi \partial_z u_\phi \quad (10)$$

Note that the relevant quantity appears to be $\nabla^2 \Psi - \frac{2}{r} \partial_r \Psi$, and that the $\frac{1}{r^2}$ in the second term cannot come out of the Jacobian (a point of disagreement with Jeff's equation above). Also I'm confused why Jeff's has no u_ϕ term. The RHS of this equation is significantly more complicated.

RHS viscous term:

$$\frac{1}{\text{Re}} \left[\nabla^2 \left(\frac{1}{r} \nabla^2 \Psi \right) - \frac{1}{r^3} \partial_r^2 \Psi - \frac{1}{r^4} \partial_r \Psi \right] \quad (11)$$

Full Ψ equation according to Susan:

$$\begin{aligned}
& \frac{1}{r} \partial_t \left(\nabla^2 \Psi - \frac{2}{r} \partial_r \Psi \right) + J \left(\Psi, \frac{1}{r^2} \left(\nabla^2 \Psi - \frac{2}{r} \partial_r \Psi \right) \right) - \frac{1}{r} 2u_\phi \partial_z u_\phi \\
& = J \left(A, \frac{1}{r^2} \left(\nabla^2 A - \frac{2}{r} \partial_r A \right) \right) - \frac{2}{r} B_\phi \partial_z B_\phi \\
& \quad + \frac{1}{\text{Re}} \left[\nabla^2 \left(\frac{1}{r} \nabla^2 \Psi \right) - \frac{1}{r^3} \partial_r^2 \Psi - \frac{1}{r^4} \partial_r \Psi \right] \quad (12)
\end{aligned}$$

Note that this is actually beautifully symmetric. Except the viscous term which still seems clunky....

The derivation of the non-viscous term on the righthand side of the momentum equation ($\mathbf{J} \times \mathbf{B}$) is as follows.

$$\partial_z ([(\nabla \times B) \times B]_r) - \partial_r ([(\nabla \times B) \times B]_z) \quad (13)$$

$$\begin{aligned}
& = \partial_z \left(\left[(\partial_z B_r - \partial_r B_z) B_z - \left(\frac{1}{r} \partial_r (r B_\phi) \right) B_\phi \right] \right) - \partial_r \left([(-\partial_z B_\phi) B_\phi - (\partial_z B_r - \partial_r B_z) B_r] \right) \\
& \quad (14)
\end{aligned}$$

$$\begin{aligned}
& = -\frac{1}{r^2} \partial_z^3 A \partial_r A + \frac{1}{r^3} \partial_r \partial_z A \partial_r A - \frac{1}{r^2} \partial_r^2 \partial_z A \partial_r A - \frac{2}{r^3} \partial_z^2 A \partial_z A \\
& \quad + \frac{1}{r^2} \partial_z^2 \partial_r A \partial_z A + \frac{3}{r^4} \partial_r A \partial_z A - \frac{3}{r^3} \partial_r^2 A \partial_z A + \frac{1}{r^2} \partial_r^3 A \partial_z A - \frac{2}{r} B_\phi \partial_z B_\phi \quad (15)
\end{aligned}$$

This simplifies to

$$J \left(A, \frac{1}{r^2} \left(\nabla^2 A - \frac{2}{r} \partial_r A \right) \right) - \frac{2}{r} B_\phi \partial_z B_\phi \quad (16)$$

Full derivation of viscous term:

$$\partial_z \left(\frac{1}{\text{Re}} [\nabla^2 u]_r \right) - \partial_r \left(\frac{1}{\text{Re}} [\nabla^2 u]_z \right) \quad (17)$$

$$= \frac{1}{\text{Re}} \left[\partial_z \left(\nabla^2 u_r - \frac{1}{r^2} u_r \right) - \partial_r \left(\nabla^2 u_z \right) \right] \quad (18)$$

$$\begin{aligned}
& = \frac{1}{\text{Re}} \left[-\frac{2}{r^2} \partial_z^2 \partial_r \Psi + \frac{2}{r} \partial_z^2 \partial_r^2 \Psi + \frac{1}{r} \partial_z^4 \Psi - \frac{3}{r^4} \partial_r \Psi + \frac{3}{r^3} \partial_r^2 \Psi - \frac{2}{r^2} \partial_r^3 \Psi + \frac{1}{r} \partial_r^4 \Psi \right] \\
& \quad (19)
\end{aligned}$$

3 Recovery of Narrow Gap Equations

4 Nondimensionalization

The momentum equation must be nondimensionalized. Here are the definitions of all of the dimensional components:

$$\begin{aligned}
 \tilde{u} &= \Omega_0 r_0 \delta u \\
 \tilde{x} &= \delta r_0 x \\
 \tilde{\nabla} &= \frac{\nabla}{\delta r_0} \\
 \tilde{t} &= \frac{t}{\Omega_0} \\
 \tilde{B} &= B_0 B \\
 \tilde{P} &= P_0 P \\
 \tilde{\rho} &= \rho_0 \rho
 \end{aligned} \tag{20}$$

If we define the velocity scale v_0 as the local sound speed scale ($c_{s0} \equiv \sqrt{\frac{P_0}{\rho_0}}$), then $\Omega_0 r_0 \delta = \sqrt{\frac{P_0}{\rho_0}}$.

Nondimensionalizing the momentum equation and dividing by a factor of $\Omega_0^2 r_0 \delta$ yields

$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = \frac{1}{4\pi\rho} \frac{B_0^2}{\Omega_0^2 r_0^2 \delta^2} (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{\text{Re}} \nabla^2 \mathbf{u} - 2\boldsymbol{\Omega} \times \mathbf{u} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r}) \tag{21}$$

If we define

$$\beta \equiv \frac{P}{P_{mag}} = \frac{\rho_0 \Omega_0^2 r_0^2 8\pi}{B_0^2} \tag{22}$$

where $P_{mag} = \frac{B_0^2}{8\pi}$, then the factor in front of $(\nabla \times \mathbf{B}) \times \mathbf{B}$ should be $\frac{2}{\beta}$. Agreed?

5 Perturbed Equations

We perturb the wide gap equations according to

$$\mathbf{B} = B_0 \hat{z} + \mathbf{B}_1, \tag{23}$$

which is the same perturbation we used in the thin-gap construction. But wait! We perturbed the thin-gap equations according to

$$\mathbf{u} = -q\Omega_0 r \hat{\phi} + \mathbf{u}_1 \tag{24}$$

but I don't think this is valid in the wide-gap case. To be sure, I'm going to perturb instead by

$$\mathbf{u} = r\Omega(r)\hat{\phi} + \mathbf{u}_1 \quad (25)$$

where $\Omega(r) = \Omega_0 \left(\frac{r}{r_0}\right)^{-q} = \Omega_0(r)^{-q}$ in dimensionless coordinates (but keeping Ω_0 to flag a rotational term...) Agreed?

We also add the Coriolis and centrifugal terms $-2\boldsymbol{\Omega} \times \mathbf{u} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r})$ which expand as follows:

$$-2\Omega(r)\hat{\mathbf{z}} \times (\mathbf{u}_1 + r\Omega(r)\hat{\phi}) = -2\Omega(r)u_r\hat{\phi} + 2\Omega(r)u_\phi\hat{\mathbf{r}} + 2r\Omega(r)^2\hat{\mathbf{r}} \quad (26)$$

$$-\Omega(r)\hat{\mathbf{z}} \times (\Omega(r)\hat{\mathbf{z}} \times r\hat{\mathbf{r}}) = +\Omega(r)^2r\hat{\mathbf{r}} \quad (27)$$

The $\hat{\mathbf{r}}$ terms will have ∂_z applied to them, which will destroy the $3\Omega(r)^2r\hat{\mathbf{r}}$ term and so the righthand side of the Ψ equation will ultimately gain only the term $2\Omega(r)\partial_z u_\phi\hat{\mathbf{r}}$. The $\hat{\phi}$ equation gains the term $-\frac{2}{r}\Omega(r)\partial_z\Psi$ on the righthand side.

The Ψ equation becomes

$$\begin{aligned} \frac{1}{r}\partial_t \left(\nabla^2\Psi - \frac{2}{r}\partial_r\Psi \right) + J \left(\Psi, \frac{1}{r^2} \left(\nabla^2\Psi - \frac{2}{r}\partial_r\Psi \right) \right) - \frac{1}{r}2u_\phi\partial_z u_\phi - \partial_z(u_\phi\Omega(r)) \\ = \frac{2}{\beta}J \left(A, \frac{1}{r^2} \left(\nabla^2 A - \frac{2}{r}\partial_r A \right) \right) - \frac{2}{\beta}\frac{2}{r}B_\phi\partial_z B_\phi + 2\Omega(r)\partial_z u_\phi \\ + \frac{1}{\text{Re}} \left[\nabla^2 \left(\frac{1}{r}\nabla^2\Psi \right) - \frac{1}{r^3}\partial_r^2\Psi - \frac{1}{r^4}\partial_r\Psi \right] + \frac{2}{\beta}\frac{1}{r}B_0\partial_z \left(\nabla^2 A - \frac{2}{r}\partial_r A \right) \end{aligned} \quad (28)$$

Note that one of the terms gained from the base state in the $(\mathbf{u} \cdot \nabla)\mathbf{u}$ term can be combined with the term gained from the Coriolis term, but here I write them separately so we can check the equation. Equation 3 becomes

$$\begin{aligned} \partial_t u_\phi + \frac{J(\psi, u_\phi)}{r} + \frac{u_\phi\partial_z\psi}{r^2} + \partial_z\Psi \left(\frac{2}{r}\Omega(r) + \partial_r\Omega(r) \right) = \\ \frac{2}{\beta}\frac{J(A, B_\phi)}{r} + \frac{2}{\beta}\frac{B_\phi\partial_z A}{r^2} + \frac{1}{\text{Re}} \left(\nabla^2 u_\phi - \frac{u_\phi}{r} \right) + \frac{2}{\beta}B_0\partial_z B_\phi - \frac{2}{r}\Omega(r)\partial_z\Psi \end{aligned} \quad (29)$$

Equation 4 picks up $+\Omega(r)B_\phi$ from the term $-(u_0\hat{\phi} \cdot \nabla)\mathbf{B}_1$ and $-\Omega(r)B_\phi$ from the term $+(\mathbf{B}_1 \cdot \nabla)\hat{\phi}$ and, so those cancel and the equation becomes

$$\partial_t A = \frac{1}{r}J(A, \psi) + \frac{1}{\text{Rm}} \left(\nabla^2 A - \frac{2\partial_r A}{r} \right) + B_0\partial_z\Psi \quad (30)$$

Note that this is perfectly analogous to the thin-gap version of this equation.

The $\hat{\phi}$ component of the induction equation, Equation 5, becomes

$$\begin{aligned} \partial_t B_\phi &= \frac{1}{r} J(A, u_\phi) + \frac{1}{r} J(B_\phi, \psi) \\ &+ \frac{1}{r^2} B_\phi \partial_z \psi - \frac{1}{r^2} u_\phi \partial_z A + \frac{1}{\text{Rm}} \left(\nabla^2 B_\phi - \frac{1}{r^2} B_\phi \right) + B_0 \partial_z u_\phi + \partial_z A \left(\frac{2}{r} \Omega(r) + \partial_r \Omega(r) \right) \end{aligned} \quad (31)$$

6 Matrix Formulation

This is all pending a rigorous check of Equations 28 - 31, which Jeff is working on, but I'll start putting this into a matrix construction.

First, the nonlinear vector, on the lefthand side of the equation, is

$$\mathbf{N} = \begin{bmatrix} J\left(\Psi, \frac{1}{r^2} (\nabla^2 \Psi - \frac{2}{r} \partial_r \Psi)\right) - \frac{2}{\beta} J\left(A, \frac{1}{r^2} (\nabla^2 A - \frac{2}{r} \partial_r A)\right) - \frac{2}{\beta} u_\phi \partial_z u_\phi + \frac{2}{\beta} \frac{2}{r} B_\phi \partial_z B_\phi \\ \frac{1}{r} J(\Psi, u_\phi) - \frac{1}{r} \frac{2}{\beta} J(A, B_\phi) + \frac{1}{r^2} u_\phi \partial_z \Psi - \frac{2}{\beta} \frac{1}{r^2} B_\phi \partial_z A \\ - \frac{1}{r} J(A, \Psi) \\ - \frac{1}{r} J(A, u_\phi) - \frac{1}{r} J(B_\phi, \Psi) - \frac{1}{r^2} B_\phi \partial_z \Psi + \frac{1}{r^2} u_\phi \partial_z A \end{bmatrix} \quad (32)$$

Note that these differ from the thin-gap nonlinear terms not only because of the curvature terms in the Jacobians, but also because of the additional advective terms in all but the \mathbf{A} equation.

The ∂_t terms are grouped together into

$$\partial_t D = \partial_t \begin{bmatrix} \frac{1}{r} \nabla^2 - \frac{2}{r^2} \partial_r & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (33)$$

For the righthand side of the equation, I'll follow the same process that I did with the thin-gap. That is I'll first separate the matrices by physical meaning, and then regroup terms based on z -dependence. The RHS can be described by three matrices: one representing the rotational terms, one representing the background field terms, and one representing the viscous/resistive terms.

$$\begin{aligned} RHS &= \begin{bmatrix} 3\Omega(r) \partial_z u_\phi \\ -\frac{4}{r} \Omega(r) \partial_z \Psi - \partial_r \Omega(r) \partial_z \Psi \\ 0 \\ \frac{2}{r} \Omega(r) \partial_z A + \partial_r \Omega(r) \partial_z A \end{bmatrix} + \begin{bmatrix} \frac{2}{\beta} \frac{1}{r} B_0 \partial_z (\nabla^2 A - \frac{2}{r} \partial_r A) \\ \frac{2}{\beta} B_0 \partial_z B_\phi \\ B_0 \partial_z \Psi \\ B_0 \partial_z u_\phi \end{bmatrix} + \begin{bmatrix} \frac{1}{\text{Re}} \left[\nabla^2 \left(\frac{1}{r} \nabla^2 \Psi \right) - \frac{1}{r^3} \partial_r^2 \Psi - \frac{1}{r^4} \partial_r \Psi \right] \\ \frac{1}{\text{Re}} \left(\nabla^2 u_\phi - \frac{1}{r} \partial_r u_\phi \right) \\ \frac{1}{\text{Re}} \left(\nabla^2 A - \frac{2}{r} \partial_r A \right) \\ \frac{1}{\text{Re}} \left(\nabla^2 B_\phi - \frac{1}{r^2} B_\phi \right) \end{bmatrix} \\ &= \quad (34) \end{aligned}$$

A Cylindrical derivatives

Everything here follows <http://farside.ph.utexas.edu/teaching/336L/Fluidhtml/node177.html#scyl1>.

For a scalar field ψ ,

$$\nabla\psi = \frac{\partial\psi}{\partial r}\hat{\mathbf{r}} + \frac{1}{r}\frac{\partial\psi}{\partial\phi}\hat{\phi} + \frac{\partial\psi}{\partial z}\hat{\mathbf{z}}. \quad (35)$$

However, for a *vector* field \mathbf{u} ,

$$\nabla \cdot \mathbf{u} = \frac{1}{r}\frac{\partial(ru_r)}{\partial r} + \frac{1}{r}\frac{\partial u_\phi}{\partial\phi} + \frac{\partial u_z}{\partial z} \quad (36)$$

and

$$\nabla \times \mathbf{u} = \left(\frac{1}{r}\frac{\partial u_z}{\partial\phi} - \frac{\partial u_\phi}{\partial z}\right)\hat{\mathbf{r}} + \left(\frac{\partial u_r}{\partial z} - \frac{\partial u_z}{\partial r}\right)\hat{\phi} + \left(\frac{1}{r}\frac{\partial(ru_\phi)}{\partial r} - \frac{1}{r}\frac{\partial u_r}{\partial\phi}\right)\hat{\mathbf{z}}. \quad (37)$$

We also need the ϕ component of the convective derivative $\mathbf{u} \cdot \nabla \mathbf{u}$,

$$[\mathbf{u} \cdot \nabla \mathbf{u}]_\phi = \mathbf{u} \cdot \nabla u_\phi + \frac{u_r u_\phi}{r}, \quad (38)$$

and finally, the vector Laplacian,

$$(\nabla^2 \mathbf{u})_r = \nabla^2 u_r - \frac{u_r}{r^2} - \frac{2}{r^2} \frac{\partial u_\phi}{\partial\phi} \quad (39)$$

$$(\nabla^2 \mathbf{u})_\phi = \nabla^2 u_\phi + \frac{2}{r^2} \frac{\partial u_r}{\partial\phi} - \frac{u_\phi}{r^2} \quad (40)$$

$$(\nabla^2 \mathbf{u})_z = \nabla^2 u_z, \quad (41)$$

where ∇ on the vector components is given by equation (35).

Note that, expanding the definition of the vector Laplacian, where the cylindrical scalar Laplacian is substituted in for $\nabla^2 u_r$ and $\nabla^2 u_z$