

# Fluid Dynamics Archives

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# Chapter 1

## Basic Definitions

### 1.1 Dynamic Variables

Name	Symbollic Representa- tion	Units	Description
Lift	L	N	Upward force experienced by the aircraft
Drag	D	N	Backward force experienced by the aircraft

### 1.2 Geometrical variables

Name	Symbollic Representa- tion	Units	Description
Angle of at- tack	$\alpha$	rad	How pitched up or down the wing or horizontal stabilizer is usually, could represent more than just wings or horizontal stabilizers though
Leading Edge	-	-	The front-most edge of the airfoil
Trailing Edge	-	-	The back-most edge of the airfoil
Chord length		m	Length of the chord line, wherein chord line is a line joining the leading edge and trailing edge
Span length		m	The sideways length of the wing. The distance between one wing tip to another wing tip
Mean Cam- ber line			
Chord line			

### 1.3 Processed Geometry

Name	Symbollic Representation	Units	Description
Aerodynamic Center		-	A specific point in the airfoil wherein the moments acting on the airfoil due to fluid pressures is unchanging with angle of attack
Center of Pressure		-	A specific point in the airfoil wherein the airfoil experiences no resultant moment about this point
Neutral Point			
Aspect Ratio			

### 1.4 Dimensionless Coefficients

Name	Symbollic Representation	Units	Description
Coefficient of Lift			
Coefficient of Drag			
Coefficient of Moments			

### 1.5 Definition of Processes

Name	Symbollic Representation	Description
Isothermal	<i>it</i>	Constant temperature
Isobaric	<i>ib</i>	Constant pressure
Isochoric	<i>ic</i>	Constant volume
Adiabatic	<i>ad</i>	No heat exchange with external system
Reversible	<i>rev</i>	No dissipative phenomena, no mass diffusion, no thermal conductivity, no viscosity
Isentropic	<i>ise</i>	Both Adiabatic and Reversible

## Chapter 2

# Reynold's Transport Theorem

One variation of Liebniz Rule applicable for volumetric integrals is shown below. for the variable  $T$  wherein  $T$  may represent a time dependent scalar, vector, or tensor.

$$\frac{d}{dt} \iiint_{R(t)} T dV_o = \iiint_{R(t)} \frac{\partial}{\partial t} [T] dV_o + \iint_{S(t)} T \bar{v}_s \bar{n} dS$$

wherein  $R(t)$  represents an arbitray region of space,  $V_o$  represents volume,  $S(t)$  represents the surface of the region defined by  $R(t)$ ,  $\bar{v}_s$  represents the velocity of the moving surface,  $\bar{n}$  represents normal vector of the surface. Depending on the variable type  $T$ , the operation  $T \bar{v}_s \bar{n}$  would depend on a case to case basis.

Using a change of variables,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \frac{d}{dt} \iiint_{\Gamma} \phi J dV_{o,i}$$

wherein  $V_s(t)$  represents a control mass region,  $\phi$  may represent some time changing scalar variable, but in general, could represent the elements of an arbitrary tensor as well.  $dV_o$  represents infinitesimal volume. Since the vector field is evolving with time, all the points inside  $V_s(t)$  is at some place initially at time  $t = 0$ . The region that contains all the points inside  $V_s(t)$  at time  $t = 0$  is considered to be  $\Gamma$ . Since we are considering the general case wherein volume may expand or contract, we declare  $dV_{o,i}$  to represent infinitesimal volume initially at time  $t = 0$ . The relationship between infinitesimal volume at the present time  $dV_o$  and infinitesimal volume initially,

$$dV_o = J dV_{o,i}$$

wherein  $J$  represents the Jacobian, which is the determinant of the velocity gradient tensor (more on this later). From all these information, the change of variables could be performed as shown above.  $\epsilon$  is a region that is not varying with time  $t$ . Since the bounds of integration is now unchanging with time, the time derivative operation is now commutative with the volumetric integral. Therefore,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{\Gamma} \frac{d}{dt} [\phi J] dV_{o,i}$$

Without loss of generality, assuming that  $\phi$  changes with coordinates  $x_i$  and time, the time derivative is equivalent to the substantive or material derivative. Therefore,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{\Gamma} \frac{D}{Dt} [\phi J] dV_{o,i}$$

Using product rule,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{\Gamma} \phi \frac{D}{Dt} [J] + J \frac{D}{Dt} [\phi] dV_{o,i}$$

By a tedious mathematical proof,

$$\frac{D}{Dt} [J] = (\nabla \cdot \bar{v}_s) J$$

wherein  $\bar{v}_s$  represents the velocity of the moving surface.  $\bar{v}_s$  is not to be confused with  $V_s$ .  $V_s$  represents the control mass region earlier meanwhile  $\bar{v}_s$  represents the velocity of the moving boundaries of  $V_s$ . Substituting,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{\Gamma} \phi (\nabla \cdot \bar{v}_s) J + J \frac{D}{Dt} [\phi] dV_{o,i}$$

Making a change of variables once again to revert back to the region  $V_s(t)$  from the initial positions  $\Gamma$ ,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{\Gamma} \left\{ \phi (\nabla \cdot \bar{v}_s) + \frac{D}{Dt} [\phi] \right\} J dV_{o,i}$$

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{V_s(t)} \phi (\nabla \cdot \bar{v}_s) + \frac{D}{Dt} [\phi] dV_o$$

Expanding the substantive derivative of  $\phi$  as  $\frac{D}{Dt} [\phi] = \frac{\partial}{\partial t} [\phi] + \bar{v}_s \cdot \nabla \phi$ ,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{V_s(t)} \phi (\nabla \cdot \bar{v}_s) + \frac{\partial}{\partial t} [\phi] + \bar{v}_s \cdot \nabla \phi dV_o$$

Using the divergence of scalar vector product identity,

$$\nabla \cdot (\phi \bar{v}_s) = \phi (\nabla \cdot \bar{v}_s) + \bar{v}_s \cdot \nabla \phi$$

Substituting,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{V_s(t)} \frac{\partial}{\partial t} [\phi] + \nabla \cdot (\phi \bar{v}_s) dV_o$$

Parsing out the integral,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{V_s(t)} \frac{\partial}{\partial t} [\phi] dV_o + \iiint_{V_s(t)} \nabla \cdot (\phi \bar{v}_s) dV_o$$

Using divergence theorem,  $\iiint_{V_s(t)} \nabla \cdot (\phi \bar{v}_s) dV_o = \iint_{S_s(t)} \phi \bar{v}_s \cdot \hat{n} dS$ . Substituting,

$$\frac{d}{dt} \iiint_{V_s(t)} \phi dV_o = \iiint_{V_s(t)} \frac{\partial}{\partial t} [\phi] dV_o + \iint_{S_s(t)} \phi \bar{v}_s \cdot \hat{n} dS$$

## 2.1 Substantive Derivative

Suppose a quantity  $b$  is dependent on the the variable time  $t$  and the typical cartesian coordinates  $x, y, z$ . Taking the derivative of variable  $b$  with respect to time yields the following based on chain rule,

$$\frac{d}{dt}[b] = \frac{\partial}{\partial t}[b] + \frac{\partial}{\partial x}[b] \times \frac{\partial}{\partial t}[x] + \frac{\partial}{\partial y}[b] \times \frac{\partial}{\partial t}[y] + \frac{\partial}{\partial z}[b] \times \frac{\partial}{\partial t}[z]$$

Taking note that the partial derivatives of the cartesian coordinates defines velocity in the cartesian coordinates. Therefore,

$$\frac{\partial}{\partial t}[x] = u \quad , \quad \frac{\partial}{\partial t}[y] = v \quad , \quad \frac{\partial}{\partial t}[z] = w$$

wherein  $u, v$ , and  $w$  typically represents velocity in the  $x, y$ , and  $z$  directions respectively.

Therefore, the derivative of  $y$  with respect to time  $t$  would take the form,

$$\frac{d}{dt}[b] = \frac{\partial}{\partial t}[b] + u \frac{\partial}{\partial x}[b] + v \frac{\partial}{\partial y}[b] + w \frac{\partial}{\partial z}[b]$$

If the  $\nabla$  operator is defined as

$$\nabla = \left( \frac{\partial}{\partial x} \quad \frac{\partial}{\partial y} \quad \frac{\partial}{\partial z} \right)^T$$

Therefore, the derivative of  $y$  with respect to time  $t$  would take the form

$$\frac{d}{dt}[b] = \frac{\partial}{\partial t}[b] + u \frac{\partial}{\partial x}[b] + v \frac{\partial}{\partial y}[b] + w \frac{\partial}{\partial z}[b]$$

Let the velocity vector be defined as

$$\bar{v} = \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

It follows that the derivative of  $b$  with respect to time  $t$  would take the form

$$\frac{d}{dt}[b] = \frac{\partial}{\partial t}[b] + \bar{v} \cdot \nabla b$$

## 2.2 Divergence Theorem

The Divergence Theorem is stated below. The variable  $\bar{F}$  must represent a vector in  $R^3$

$$\iiint_{R(t)} \nabla \cdot \bar{F} dV_o = \iint_{S(t)} \bar{F} \cdot \bar{n} dS$$

Alternately,

$$\iiint_{R(t)} \frac{\partial}{\partial x}[\bar{F}] + \frac{\partial}{\partial y}[\bar{F}] + \frac{\partial}{\partial z}[\bar{F}] dV_o = \iint_{S(t)} \bar{F} \cdot \bar{n} dS$$

wherein  $dV_o$  represents an infinitesimally small volume.  $S(t)$  is the surface encapsulating the region  $R(t)$ .  $\bar{n}$  is the normal vector of the control volume, and  $dS$  is an infinitesimal area of surface  $S(t)$ .



# Chapter 3

## Governing Equations

### 3.1 Governing Equation: Continuum Equation

The Governing Continuum Equation in its differential form:

$$0 = \frac{\partial}{\partial t}[\rho] + \nabla \cdot (\rho \bar{v}_f)$$

The Governing Continuum Equation in its integral form:

$$\frac{d}{dt}M(t) = \frac{d}{dt} \iiint_{R(t)} \rho dV_o = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho] dV_o + \iint_{S(t)} \rho \bar{v}_s \cdot \bar{n} dS$$

A more useful alternate form:

$$\frac{d}{dt}M(t) = \iint_{S(t)} \rho(\bar{v}_s - \bar{v}_f) \cdot \bar{n} dS$$

wherein  $M(t)$  represent mass contained in a control volume,  $\bar{v}_f$  represent the velocity of the fluid and  $\bar{v}_s$  represent the velocity of the deforming control volume  $R(t)$ .  $S(t)$  represents the surface that is encapsuating the control volume  $R(t)$ .

#### 3.1.1 Differential Continuity Proof

Starting with the definition of mass contained in the arbitrary control volume  $R(t)$ ,

$$M(t) = \iiint_{R(t)} \rho dV_o$$

Taking the derivative of the mass contained within the control volume with respect to time,

$$\frac{d}{dt}M(t) = \frac{d}{dt} \iiint_{R(t)} \rho dV_o$$

By application of Liebniz rule, substituting  $T$  with  $\rho$ ,

$$\frac{d}{dt} \iiint_{R(t)} T dV_o = \iiint_{R(t)} \frac{\partial}{\partial t}[T] dV_o + \iint_{S(t)} T \bar{v}_s \cdot \bar{n} dS$$

$$\frac{d}{dt}M(t) = \frac{d}{dt} \iiint_{R(t)} \rho dV_o = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho] dV_o + \iint_{S(t)} \rho \bar{v}_s \cdot \bar{n} dS$$

If the velocity of the surface expanding is equivalent to the velocity of the fluid at the boundary of the control volume ( $\bar{v}_s = \bar{v}_f$ ), then the amount of mass within the control volume must remain constant.

$$0 = \frac{d}{dt}M(t) = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho]dV_o + \iint_{S(t)} \rho \bar{v}_f \cdot \bar{n}dS$$

The second term of the expression above could be converted into a volumetric integral based on the divergence theorem by substituting  $F$  with  $\rho \bar{v}_f$ .

$$\begin{aligned} \iiint_{R(t)} \nabla \cdot \bar{F} dV_o &= \iint_{S(t)} \bar{F} \cdot \bar{n}dS \\ \iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f) dV_o &= \iint_{S(t)} (\rho \bar{v}_f) \cdot \bar{n}dS \end{aligned}$$

Therefore,

$$\begin{aligned} 0 &= \frac{d}{dt}M(t) = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho]dV_o + \iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f) dV_o \\ 0 &= \frac{d}{dt}M(t) = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho] + \nabla \cdot (\rho \bar{v}_f) dV_o \end{aligned}$$

Since the integration is zero for an arbitrary region the integrand must be zero everywhere. To prove this, simply choose the arbitray region to be infinitesimally small at all points in  $R^3$  and it could be seen that the integrand is always zero everywhere.

$$0 = \frac{\partial}{\partial t}[\rho] + \nabla \cdot (\rho \bar{v}_f)$$

### 3.1.2 Integral Continuity Proof

To prove the integral form for the Governing Continuum Equation, consider the time rate of change of a mass enclosed within the control volume:

$$\frac{d}{dt}M(t) = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho]dV_o + \iint_{S(t)} \rho \bar{v}_s \cdot \bar{n}dS$$

From the differential form of the Governing Continuum Equation,

$$0 = \frac{\partial}{\partial t}[\rho] + \nabla \cdot (\rho \bar{v}_f)$$

Therefore,

$$\frac{\partial}{\partial t}[\rho] = -\nabla \cdot (\rho \bar{v}_f)$$

Therefore,

$$\frac{d}{dt}M(t) = \iiint_{R(t)} \frac{\partial}{\partial t}[\rho]dV_o + \iint_{S(t)} \rho \bar{v}_s \cdot \bar{n}dS = - \iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f) dV_o + \iint_{S(t)} \rho \bar{v}_s \cdot \bar{n}dS$$

By applying the divergence theorem to convert the first term volumetric integral into a surface integral,

$$\iiint_{R(t)} \nabla \cdot \bar{F} dV_o = \iint_{S(t)} \bar{F} \cdot \bar{n}dS$$

$$\iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f) dV_o = \iint_{S(t)} \rho \bar{v}_f \cdot \bar{n} dS$$

$$\frac{d}{dt} M(t) = - \iint_{S(t)} \rho \bar{v}_f \cdot \bar{n} dS + \iint_{S(t)} \rho \bar{v}_s \cdot \bar{n} dS = \iint_{S(t)} \rho (\bar{v}_s - \bar{v}_f) \cdot \bar{n} dS$$

A more familiar form would yield,

$$0 = \frac{d}{dt} M(t) + \iint_{S(t)} \rho (\bar{v}_f - \bar{v}_s) \cdot \bar{n} dS$$

$$0 = \frac{d}{dt} \iiint_{R(t)} \rho dV_o + \iint_{S(t)} \rho (\bar{v}_f - \bar{v}_s) \cdot \bar{n} dS$$

## 3.2 Governing Equation: Momentum Equation

The Governing Momentum Equation in its differential form:

$$\frac{\partial}{\partial t} (\rho \bar{v}_f) + \nabla \cdot (\rho \bar{v}_f \bar{v}_f) = -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b$$

wherein  $\rho$  represents density,  $\bar{v}_f$  represents fluid velocity vector,  $P_r$  represents fluid pressure at a particular point,  $\tau$  represents viscous forces,  $\bar{F}_b$  represents body force experienced by the fluid inside the control volume. The Governing Momentum Equation in its integral form:

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = \iiint_{R(t)} \rho \bar{F}_b dV_o + \iint_{S(t)} \bar{F}_s \cdot \bar{n} dS = \iiint_{R(t)} \frac{\partial}{\partial t} (\rho \bar{v}_f) + \nabla \cdot (\rho \bar{v}_f \bar{v}_f) dV_o$$

wherein  $\bar{F}_s$  represents surface forces. Like in the previous proof,  $S(t)$  represents the surface binding the control volume region  $R(t)$ . An alternate form to the momentum governing equation exists. It is shown below,

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = \iint_{S(t)} \rho \bar{v}_f [(\bar{v}_s - \bar{v}_f) \cdot \bar{n}] dS + \iiint_{R(t)} -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b dV_o$$

### 3.2.1 Differential Momentum Proof

The total Momentum  $\bar{P}_m$  contained in a control volume,

$$\bar{P}_m = \iiint_{R(t)} \rho \bar{v}_f dV_o$$

The derivative of momentum with respect to time,

$$\frac{d}{dt} \bar{P}_m = \frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o$$

By applying Liebniz's rule, substituting  $T$  with  $\rho \bar{v}_f$

$$\frac{d}{dt} \iiint_{R(t)} T dV_o = \iiint_{R(t)} \frac{\partial}{\partial t} [T] dV_o + \iint_{S(t)} T \bar{v}_s \cdot \bar{n} dS$$

$$\frac{d}{dt} \bar{P}_m = \iiint_{R(t)} \frac{\partial}{\partial t} [\rho \bar{v}_f] dV_o + \iint_{S(t)} \rho \bar{v}_f \bar{v}_s \cdot \bar{n} dS$$

By applying Divergence Theorem substituting  $F$  with  $\rho \bar{v}_f \bar{v}_s$

$$\begin{aligned}\iiint_{R(t)} \nabla \cdot \bar{F} dV_o &= \iint_{S(t)} \bar{F} \cdot \bar{n} dS \\ \iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f \bar{v}_s) dV_o &= \iint_{S(t)} \rho \bar{v}_f \bar{v}_s \cdot \bar{n} dS\end{aligned}$$

By substituting the terms to the derivative of momentum with respect to time,

$$\begin{aligned}\frac{d}{dt} \bar{P}_m &= \iiint_{R(t)} \frac{\partial}{\partial t} [\rho \bar{v}_f] dV_o + \iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f \bar{v}_s) dV_o \\ \frac{d}{dt} \bar{P}_m &= \iiint_{R(t)} \frac{\partial}{\partial t} [\rho \bar{v}_f] + \nabla \cdot (\rho \bar{v}_f \bar{v}_s) dV_o\end{aligned}$$

Since the derivative of momentum with respect to time is the total force applied to the control volume,

$$\iiint_{R(t)} \rho \bar{F}_b dV_o + \iint_{S(t)} \bar{F}_s \cdot \bar{n} dS = \iiint_{R(t)} \frac{\partial}{\partial t} [\rho \bar{v}_f] + \nabla \cdot (\rho \bar{v}_f \bar{v}_s) dV$$

The first term in the expression above represents the total body force acting on the control volume meanwhile the second term in the expression represents the total surface force acting on the control volume. When the velocity of the surface is identical to the velocity of the fluid flow,  $\bar{v}_s = \bar{v}_f$ , the total force acting on the specific volume of region  $R_s(t)$ ,

$$\iiint_{R_s(t)} -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b dV_o = \iiint_{R_s(t)} \frac{\partial}{\partial t} [\rho \bar{v}_f] + \nabla \cdot (\rho \bar{v}_f \bar{v}_f) dV$$

Since the equation above is always true under the constraint that the surface velocity of the region is identical to the velocity of the fluid flow, one can simply choose smaller and smaller regions until  $R_s(t)$  is an infinitesimally small region. This process can be applied everywhere in the fluid. Therefore,

$$-\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b = \frac{\partial}{\partial t} [\rho \bar{v}_f] + \nabla \cdot (\rho \bar{v}_f \bar{v}_f)$$

The equation above is the differential formulation and is always true all throughout the fluid.

### 3.2.2 Integral Momentum Proof

To prove the alternate form of the momentum governing equation in integral form, the differential formulation of the momentum equation would be vital. Rearranging for the

$$\frac{\partial}{\partial t} (\rho \bar{v}_f) \text{ term,}$$

$$\frac{\partial}{\partial t} (\rho \bar{v}_f) + \nabla \cdot (\rho \bar{v}_f \bar{v}_f) = -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b$$

$$\frac{\partial}{\partial t} (\rho \bar{v}_f) = -\nabla \cdot (\rho \bar{v}_f \bar{v}_f) - \nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b$$

Referencing the previous equation for derivative of momentum within an arbitrary region  $R(t)$  with respect to time,

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = \iiint_{R(t)} \frac{\partial}{\partial t} [\rho \bar{v}_f] dV_o + \iint_{S(t)} \rho \bar{v}_f (\bar{v}_s \cdot \bar{n}) dS$$

Substituting the term,  $\frac{\partial}{\partial t}(\rho \bar{v}_f)$ ,

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = \iiint_{R(t)} -\nabla \cdot (\rho \bar{v}_f \bar{v}_f) - \nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b dV_o + \iint_{S(t)} \rho \bar{v}_f (\bar{v}_s \cdot \bar{n}) dS$$

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = - \iiint_{R(t)} \nabla \cdot (\rho \bar{v}_f \bar{v}_f) dV_o + \iint_{S(t)} \rho \bar{v}_f (\bar{v}_s \cdot \bar{n}) dS + \iiint_{R(t)} -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b dV_o$$

The applying the Divergence Theorem substituting  $F$  with  $\rho \bar{v}_f \bar{v}_f$

$$\iiint_{R(t)} \nabla \cdot \bar{F} dV_o = \iint_{S(t)} \bar{F} \cdot \bar{n} dS$$

$$\iiint_{R(t)} \nabla \cdot \rho \bar{v}_f \bar{v}_f dV_o = \iint_{S(t)} \rho \bar{v}_f (\bar{v}_f \cdot \bar{n}) dS$$

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = - \iint_{S(t)} \rho \bar{v}_f (\bar{v}_f \cdot \bar{n}) dS + \iint_{S(t)} \rho \bar{v}_f (\bar{v}_s \cdot \bar{n}) dS + \iiint_{R(t)} -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b dV_o$$

$$\frac{d}{dt} \iiint_{R(t)} \rho \bar{v}_f dV_o = \iint_{S(t)} \rho \bar{v}_f [(\bar{v}_s - \bar{v}_f) \cdot \bar{n}] dS + \iiint_{R(t)} -\nabla P_r + \nabla \cdot \tau + \rho \bar{F}_b dV_o$$

### 3.3 Governing Equation: Energy Equation

# Chapter 4

## Navier-Stokes Equations

The full set of the Navier-Stokes Equations are shown below. The three equations below correspond to the differential continuity, momentum, energy laws.

$$\frac{\partial}{\partial t}[\rho] + \bar{v}_f \cdot \nabla \rho = -\rho \nabla \cdot \bar{v}_f$$

$$\rho \left[ \frac{\partial}{\partial t}[\bar{v}_f] + (\bar{v}_f \cdot \nabla) \bar{v}_f \right] = -\nabla P_r + \rho \bar{F}_b + \mu \nabla^2 \bar{v}_f = -\nabla P_r + \rho \bar{F}_b - \frac{2}{3} \nabla(\mu \nabla \cdot \bar{v}_f) + 2 \nabla \cdot (\mu S)$$

$$\rho c_p \left[ \frac{\partial}{\partial t}(T) + \bar{v}_f \cdot \nabla T \right] = \nabla \cdot (k \nabla T) - \frac{2}{3} \mu (\nabla \cdot \bar{v}_f)^2 + 2 \mu S : S + \beta T \frac{D}{Dt} [P_r]$$

### 4.1 Hiemenz Flow

#### 4.1.1 Cartesian Coordinates

#### 4.1.2 Polar Coordinates

The continuity governing equation for incompressible fluids in cylindrical coordinates,

$$0 = \nabla \cdot \bar{v} = \frac{1}{r} \frac{\partial}{\partial r}[r v_r] + \frac{1}{r} \frac{\partial}{\partial \theta}[v_\theta] + \frac{\partial}{\partial z}[v_z]$$

In 3-dimensions, the fluid velocity has a radial component, an azimuthal (swirl) component and a  $z$  component. For this derivation, it is assumed that the fluid does not have swirl and that the flow is axis-symmetric. All quantities are not expected to vary in the  $\theta$  direction.

The flow is also assumed to be steady. Let the fluid velocity vector  $\bar{v}$  be defined below,

$$\bar{v} = \begin{bmatrix} v_r & v_\theta & v_z \end{bmatrix}^T$$

wherein the  $v_r$ ,  $v_\theta$  and  $v_z$  correspond to the fluid velocity components in the radial, azimuthal and  $z$ -direction respectively. The radial component of velocity for axis-symmetric potential flow is defined to be,

$$v_{r,i} = c r$$

Reiterating the continuity expression,

$$0 = \frac{1}{r} \frac{\partial}{\partial r}[r v_r] + \frac{\partial}{\partial z}[v_z]$$

Due to the axis-symmetric assumption,  $\frac{1}{r} \frac{\partial}{\partial \theta} [v_\theta] = 0$ . Substituting,

$$0 = \frac{1}{r} \frac{\partial}{\partial r} [rv_r] + \frac{\partial}{\partial z} [v_z]$$

Substituting the radial velocity for the inviscid flow into the continuity expression,

$$0 = \frac{1}{r} \frac{\partial}{\partial r} [r \times cr] + \frac{\partial}{\partial z} [v_z]$$

$$0 = \frac{1}{r} \frac{\partial}{\partial r} [cr^2] + \frac{\partial}{\partial z} [v_z]$$

$$0 = \frac{1}{r} \times 2cr + \frac{\partial}{\partial z} [v_z]$$

$$0 = 2c + \frac{\partial}{\partial z} [v_z]$$

$$-2c = \frac{\partial}{\partial z} [v_z]$$

$$-2cz + k = v_z$$

wherein  $k$  is some constant to satisfy some boundary condition. Stagnation point is defined to be a point in the fluid where there is no velocity. Since a stagnation point occurs at  $z = 0$ , then the  $v_z$  velocity must also be zero at said point. Substituting,

$$0 + k = 0$$

From applying the boundary condition of the stagnation point,  $k$  can be safely neglected. Hence, the fluid velocity in the  $z$ -direction for inviscid flows,

$$-2cz = v_{z,i}$$

To make an "intelligent" guess on the modification performed for the fluid flow, the stream function for the inviscid flow must first be determined. Assume that the  $\bar{A}$  is the velocity potential vector, whose components,

$$\bar{A} = \begin{bmatrix} A_r & A_\theta & A_z \end{bmatrix}^T$$

The relationship of the velocity vector field to the velocity potential vector,

$$\bar{v} = \begin{bmatrix} v_r \\ v_\theta \\ v_z \end{bmatrix} = \nabla \times \bar{A} = \begin{bmatrix} \frac{1}{r} \frac{\partial A_z}{\partial \theta} - \frac{\partial A_\theta}{\partial z} \\ \frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r} \\ \frac{1}{r} \frac{\partial}{\partial r} (r A_\theta) - \frac{1}{r} \frac{\partial A_r}{\partial \theta} \end{bmatrix}$$

Since the problem is assumed to be axis-symmetric, and also no swirl, then

$$0 = \frac{\partial A_r}{\partial z} \quad , \quad 0 = \frac{\partial A_z}{\partial r}$$

Therefore,

$$0 = A_r \quad , \quad 0 = A_z$$

Let  $A_\theta = \psi$  which would represent the stream function of this axis-symmetric fluid flow.

Substituting for the simplification,

$$v_r = -\frac{\partial A_\theta}{\partial z} \quad , \quad v_z = \frac{1}{r} \frac{\partial}{\partial r}(r A_\theta)$$

Substituting for  $\psi$ ,

$$v_r = -\frac{\partial \psi}{\partial z} \quad , \quad v_z = \frac{1}{r} \frac{\partial}{\partial r}(r \psi)$$

If  $\psi_i$  represents the stream function to the inviscid fluid flow,

$$v_{r,i} = -\frac{\partial \psi_i}{\partial z} \quad , \quad v_{z,i} = \frac{1}{r} \frac{\partial}{\partial r}(r \psi_i)$$

Substituting for the inviscid flow field that was determined earlier,

$$cr = -\frac{\partial \psi_i}{\partial z} \quad , \quad -2cz = \frac{1}{r} \frac{\partial}{\partial r}(r \psi_i)$$

Analyzing the velocity in the axis-direction,

$$-2cz = \frac{1}{r} \frac{\partial}{\partial r}(r \psi_i)$$

$$-2c z r = \frac{\partial}{\partial r}(r \psi_i)$$

$$-2cz \int r dr = \int \frac{\partial}{\partial r}(r \psi_i) dr$$

$$-2cz \times \frac{1}{2} r^2 = \int d(r \psi_i)$$

$$-cz \times r^2 = r \psi_i + k(z)$$

$$-cz r^2 = r \psi_i + k(z)$$

Analyzing the velocity in the radial direction,

$$cr = -\frac{\partial \psi_i}{\partial z}$$

$$-cr = \frac{\partial \psi_i}{\partial z}$$

Deriving the previous expression with respect to  $z$ ,

$$\frac{\partial}{\partial z}[-cz r^2] = \frac{\partial}{\partial z}[r \psi_i] + \frac{\partial}{\partial z}[k(z)]$$

$$-cr^2 = r \frac{\partial}{\partial z}[\psi_i] + k'(z)$$

Substituting for the derivative of  $\psi_i$  with respect to  $z$ ,

$$-cr^2 = r \times -cr + k'(z)$$



$$-cr^2 = -cr^2 + k'(z)$$

$$k'(z) = 0$$

Hence,  $k(z) = \text{constant}$ . This shows that some constant can be added to the stream function and the resulting fluid flow would still be identical. Let  $k(z) = 0$  purely for convenience,

$$-c zr^2 = r\psi_i + k(z) = r\psi_i$$

$$-c zr = \psi_i$$

This is the stream function for the inviscid flow. The stream function should be altered in order to satisfy the no-slip boundary condition on the walls. Making the minimum changes necessary to allow for this,  $z$  in the stream function of the inviscid flow is replaced with an arbitrary function  $f(z)$ .  $f$  is a function purely in  $z$ . Let  $\psi$  be the stream function to a fluid flow that satisfies the Navier-Stokes equations near a stagnation point,

$$\psi = -crf(z)$$

To simplify notation,

$$\psi = -crf$$

Finding the velocities with the modified stream function,

$$v_r = -\frac{\partial \psi}{\partial z} \quad , \quad v_z = \frac{1}{r} \frac{\partial}{\partial r}(r\psi)$$

$$v_r = -\frac{\partial}{\partial z}(\psi) \quad , \quad v_z = \frac{1}{r} \frac{\partial}{\partial r}(r\psi)$$

$$v_r = -\frac{\partial}{\partial z}(-crf) \quad , \quad v_z = \frac{1}{r} \frac{\partial}{\partial r}(-cr^2 f)$$

$$v_r = crf' \quad , \quad v_z = \frac{1}{r} \times (-2crf)$$

$$v_r = crf' \quad , \quad v_z = -2cf$$

Although the fluid velocity field that obeys the Navier-Stokes equation would be different than the inviscid flow field near the wall, the velocity field should be identical to the inviscid flow field very far from the wall. Hence,

$$\lim_{z \rightarrow \infty} [v_{r,i}] = \lim_{z \rightarrow \infty} [crf']$$

$$\lim_{z \rightarrow \infty} [cr] = \lim_{z \rightarrow \infty} [cr] \lim_{z \rightarrow \infty} [f']$$

$$1 = \lim_{z \rightarrow \infty} [f']$$

$$\lim_{z \rightarrow \infty} [v_{z,i}] = \lim_{z \rightarrow \infty} [-2cf]$$

$$\lim_{z \rightarrow \infty} [-2cz] = \lim_{z \rightarrow \infty} [-2cf]$$

$$\lim_{z \rightarrow \infty} [-2c] \lim_{z \rightarrow \infty} [z] = \lim_{z \rightarrow \infty} [-2c] \lim_{z \rightarrow \infty} [f]$$

$$\lim_{z \rightarrow \infty} [z] = \lim_{z \rightarrow \infty} [f]$$

To summarize the stream function of the flow field which is an exact-solution to the Navier-Stokes equation,

$$\psi = -crf$$

The resulting velocity components of the flow field with such a stream function,

$$v_r = crf' \quad , \quad v_z = -2cf$$

The limits of  $f$  such that the boundary conditions of the flow field matching with that of the inviscid fluid flow very far away from the wall,

$$1 = \lim_{z \rightarrow \infty} [f'] \quad , \quad \lim_{z \rightarrow \infty} [z] = \lim_{z \rightarrow \infty} [f]$$

The laplacian of an arbitrary vector  $v$  in polar coordinates,

$$\nabla^2 v = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial v}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 v}{\partial \theta^2} + \frac{\partial^2 v}{\partial z^2}$$

The momentum equation in the radial direction,

$$\rho \left[ \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z \frac{\partial v_r}{\partial z} \right] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{v_r}{r^2} - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} \right] + \rho g_r$$

Due to the steady state assumption,  $\frac{\partial v_r}{\partial t} = 0$ . Due to the axis-symmetric assumption,  $\frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} = 0$ . Assuming the flow field does not have any swirl,  $\frac{v_\theta^2}{r} = 0$  and  $-\frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} = 0$ . Neglecting any body force,  $\rho g_r = 0$ . Substituting,

$$\rho \left[ v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z} \right] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{v_r}{r^2} \right]$$

Substituting the definition of  $v_r$  from the stream-function analysis,

$$\rho \left[ crf' \frac{\partial}{\partial r} (crf') + v_z \frac{\partial}{\partial z} (crf') \right] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{crf'}{r^2} \right]$$

$$\rho [crf' \times cf' + v_z \times crf''] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{cf'}{r} \right]$$

$$\rho [c^2 r f'^2 + v_z \times crf''] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{cf'}{r} \right]$$

Substituting for the velocity  $v_z$ ,

$$\rho [c^2 r f'^2 - 2cf \times crf''] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{cf'}{r} \right]$$

$$\rho [c^2 r f'^2 - 2c^2 r f f''] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{cf'}{r} \right]$$

The laplacian of the radial velocity,

$$\nabla^2 v_r = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial v_r}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} + \frac{\partial^2 v_r}{\partial z^2}$$

Substituting for the radial velocity  $v_r$ .

$$\nabla^2 v_r = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial c r f'}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 c r f'}{\partial \theta^2} + \frac{\partial^2 c r f'}{\partial z^2}$$

Due to the axis-symmetric assumption

$$\nabla^2 v_r = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial c r f'}{\partial r} \right] + \frac{\partial^2 c r f'}{\partial z^2}$$

$$\nabla^2 v_r = \frac{1}{r} \frac{\partial}{\partial r} [c r f'] + \frac{\partial^2 c r f'}{\partial z^2}$$

$$\nabla^2 v_r = \frac{1}{r} \times c f' + c r f'''$$

$$\nabla^2 v_r = \frac{c f'}{r} + c r f'''$$

Reiterating where we left off with the radial momentum,

$$\rho [c^2 r f'^2 - 2c^2 r f f''] = -\frac{\partial p}{\partial r} + \mu \left[ \nabla^2 v_r - \frac{c f'}{r} \right]$$

Substituting the laplacian of radial velocity into the momentum equation in the radial direction,

$$\rho [c^2 r f'^2 - 2c^2 r f f''] = -\frac{\partial p}{\partial r} + \mu \left[ \frac{c f'}{r} + c r f''' - \frac{c f'}{r} \right]$$

$$\rho [c^2 r f'^2 - 2c^2 r f f''] = -\frac{\partial p}{\partial r} + \mu [c r f''']$$

The above is the first ordinary differential equation which describes  $f$ . Unfortunately, the term  $\frac{\partial p}{\partial r}$  cannot be ignored when considering the exact case because there is significant pressure changes in the fluid flow. If the exact solution of the Navier-Stokes mimics potential flow far away, and the inviscid solution does allow for significant pressure gradients, then pressure gradients must also be taken into account when considering the exact solution to the Navier-Stokes.

The momentum equation in the axial direction,

$$\rho \left[ \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right] = -\frac{\partial p}{\partial z} + \mu \nabla^2 v_z + \rho g_z$$

Just like before, due to the steady state assumption,  $\frac{\partial v_z}{\partial t} = 0$ . Due to the axis-symmetric

assumption,  $\frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} = 0$ . Neglecting any body force in the axial direction,  $\rho g_z = 0$ .

Substituting for these simplifications,

$$\rho \left[ v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} \right] = -\frac{\partial p}{\partial z} + \mu \nabla^2 v_z$$

Substituting for axial velocity  $v_z$  in terms of  $f$ ,

$$v_z = -2c f$$

$$\rho \left[ v_r \frac{\partial}{\partial r} (-2cf) - 2cf \frac{\partial}{\partial z} (-2cf) \right] = -\frac{\partial p}{\partial z} + \mu \nabla^2 v_z$$

Substituting for radial velocity,

$$v_r = crf'$$

$$\rho \left[ crf' \frac{\partial}{\partial r} (-2cf) - 2cf \frac{\partial}{\partial z} (-2cf) \right] = -\frac{\partial p}{\partial z} + \mu \nabla^2 v_z$$

$$\rho [-2cf \times -2cf'] = -\frac{\partial p}{\partial z} + \mu \nabla^2 v_z$$

$$\rho [4c^2 ff'] = -\frac{\partial p}{\partial z} + \mu \nabla^2 v_z$$

The laplacian of the axial velocity,

$$\nabla^2 v_z = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial v_z}{\partial r} \right] + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}$$

Due to the axis-symmetric assumption,  $\frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} = 0$

$$\nabla^2 v_z = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial v_z}{\partial r} \right] + \frac{\partial^2 v_z}{\partial z^2}$$

Substituting for radial velocity  $v_r$  and axial velocity  $v_z$ ,

$$\nabla^2 v_z = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial}{\partial r} (-2cf) \right] + \frac{\partial^2}{\partial z^2} (-2cf)$$

$$\nabla^2 v_z = -2cf''$$

Substituting laplacian of axial velocity into the axial momentum equation,

$$\rho [4c^2 ff'] = -\frac{\partial p}{\partial z} + \mu \times -2cf''$$

$$4\rho c^2 ff' = -\frac{\partial p}{\partial z} - 2\mu cf''$$

We now have 2 ordinary differential equations that describe  $f$  it is now possible to potentially solve the expressions by using differential equation 2 to determine pressure in terms of  $f$  and substituting into differential equation 1 to solve for  $f$ . Integrating differential equation 2,

$$4\rho c^2 \int ff' dz = - \int \frac{\partial p}{\partial z} dz - 2\mu c \int f'' dz$$

$$4\rho c^2 \int f \frac{df}{dz} dz = - \int dp - 2\mu c \int f'' dz$$

$$4\rho c^2 \int f df = - \int dp - 2\mu c \int f'' dz$$

$$4\rho c^2 \times \frac{1}{2} f^2 = -p - 2\mu cf' + k(r)$$

wherein  $k(r)$  is a function that is purely in terms of  $r$ . This function appears as a consequence of integrating with respect to  $z$ .

$$2\rho c^2 f^2 = -p - 2\mu cf' + k(r)$$

Making pressure the subject of the expression,

$$p = -2\mu c f' - 2\rho c^2 f^2 + k(r)$$

The exact solution to the Navier-Stokes equation should match the inviscid solution very far away from the wall. Implying that the pressure for the exact solution and the inviscid solution must match infinitely far away from the wall. Taking the limits as  $z$  approaches  $\infty$ ,

$$\lim_{z \rightarrow \infty} [p] = -2\mu c \lim_{z \rightarrow \infty} [f'] - 2\rho c^2 \lim_{z \rightarrow \infty} [f^2] + \lim_{z \rightarrow \infty} [k(r)]$$

Substituting the limits for  $f$  which was determined earlier,

$$1 = \lim_{z \rightarrow \infty} [f'] \quad , \quad \lim_{z \rightarrow \infty} [z] = \lim_{z \rightarrow \infty} [f]$$

$$\lim_{z \rightarrow \infty} [p] = -2\mu c - 2\rho c^2 \lim_{z \rightarrow \infty} [z^2] + \lim_{z \rightarrow \infty} [k(r)]$$

For values of  $z \rightarrow \infty$ ,

$$p = -2\mu c - 2\rho c^2 z^2 + k(r)$$

For the inviscid fluid flow, bernoulli's equation can be used to determine pressure,

$$p_0 = p + \frac{1}{2}\rho |\bar{v}_i|^2$$

wherein  $\bar{v}_i$  represents the local fluid velocity for inviscid flow. Considering that there is only radial and axial velocity in an axis-symmetric problem,

$$|\bar{v}_i|^2 = v_{r,i}^2 + v_{z,i}^2$$

Substituting,

$$p_0 = p + \frac{1}{2}\rho [v_{r,i}^2 + v_{z,i}^2]$$

Making pressure the subject of the expression,

$$p = p_0 - \frac{1}{2}\rho [v_{r,i}^2 + v_{z,i}^2]$$

Substituting for the inviscid radial and axial velocities,

$$p = p_0 - \frac{1}{2}\rho [(cr)^2 + (-2cz)^2]$$

$$p = p_0 - \frac{1}{2}\rho [c^2 r^2 + 4c^2 z^2]$$

$$p = p_0 - \frac{1}{2}\rho c^2 r^2 - 2\rho c^2 z^2$$

Matching the exact solution's pressure to the inviscid solution's pressure far away from the wall,

$$p = -2\mu c - 2\rho c^2 z^2 + k(r) = p_0 - \frac{1}{2}\rho c^2 r^2 - 2\rho c^2 z^2$$

$$-2\mu c + k(r) = p_0 - \frac{1}{2}\rho c^2 r^2$$

$$k(r) = p_0 - \frac{1}{2}\rho c^2 r^2 + 2\mu c$$

Substituting the function  $k$  into the expression for pressure in the exact solution,

$$p = -2\mu c - 2\rho c^2 z^2 + p_0 - \frac{1}{2}\rho c^2 r^2 + 2\mu c$$

$$p = -2\rho c^2 z^2 + p_0 - \frac{1}{2}\rho c^2 r^2$$

Taking the derivative with respect to  $r$ ,

$$\frac{\partial p}{\partial r} = -2\rho c^2 \frac{\partial}{\partial r}(z^2) + \frac{\partial p_0}{\partial r} - \frac{1}{2}\rho \frac{\partial}{\partial r}(c^2 r^2)$$

$$\frac{\partial p}{\partial r} = -\frac{1}{2}\rho \frac{\partial}{\partial r}(c^2 r^2)$$

$$\frac{\partial p}{\partial r} = -\frac{1}{2}\rho \times 2c^2 r$$

$$\frac{\partial p}{\partial r} = -\rho c^2 r$$

$$-\frac{\partial p}{\partial r} = \rho c^2 r$$

Substituting the gradient of pressure in  $r$  into differential equation 1,

$$\rho [c^2 r f'^2 - 2c^2 r f f''] = -\frac{\partial p}{\partial r} + \mu [c r f''']$$

$$\rho [c^2 r f'^2 - 2c^2 r f f''] = \rho c^2 r + \mu c r f'''$$

$$[c^2 r f'^2 - 2c^2 r f f''] = c^2 r + \frac{\mu}{\rho} c r f'''$$

$$r f'^2 - 2r f f'' = r + \frac{\mu}{\rho} \frac{1}{c} r f'''$$

The relation between kinematic and dynamic viscosity is shown below,

$$\nu = \frac{\mu}{\rho}$$

Substituting,

$$r f'^2 - 2r f f'' = r + \nu \frac{1}{c} r f'''$$

$$f'^2 - 2f f'' = 1 + \nu \frac{1}{c} f'''$$

$$-\frac{\nu}{c} f''' + f'^2 - 2f f'' - 1 = 0$$

Let the function  $\phi$  and variable  $\eta$  be defined below,

$$f = \left(\frac{2c}{\nu}\right)^{-1/2} \phi \quad , \quad \eta = \left(\frac{2c}{\nu}\right)^{1/2} z$$

By conjecture,

$$\frac{d^n}{dz^n} = \left[ \left(\frac{2c}{\nu}\right)^{1/2} \right]^n \frac{d^n}{d\eta^n}$$

$$\frac{d^n}{dz^n} = 2^{n/2} \left( \frac{c}{\nu} \right)^{n/2} \frac{d^n}{d\eta^n}$$

Consider when  $n = 1$ ,

$$\frac{d}{dz} = \frac{d}{d\eta} \times \frac{d\eta}{dz}$$

$$\frac{d}{dz} = \frac{d}{d\eta} \times \frac{d}{dz} \left[ \left( \frac{2c}{\nu} \right)^{1/2} z \right]$$

$$\frac{d}{dz} = 2^{1/2} \left( \frac{c}{\nu} \right)^{1/2} \frac{d}{d\eta}$$

Let  $n = k + 1$

$$\frac{d}{dz} \left[ \frac{d^k}{dz^k} \right] = 2^{(k+1)/2} \left( \frac{c}{\nu} \right)^{(k+1)/2} \frac{d^{k+1}}{d\eta^{k+1}}$$

Let  $LHS$  and  $RHS$  be defined,

$$LHS = \frac{d}{dz} \left[ \frac{d^k}{dz^k} \right], \quad RHS = 2^{(k+1)/2} \left( \frac{c}{\nu} \right)^{(k+1)/2} \frac{d^{k+1}}{d\eta^{k+1}}$$

$$LHS = \frac{d}{dz} \left[ 2^{k/2} \left( \frac{c}{\nu} \right)^{k/2} \frac{d^k}{d\eta^k} \right]$$

$$LHS = \frac{d}{d\eta} \left[ 2^{k/2} \left( \frac{c}{\nu} \right)^{k/2} \frac{d^k}{d\eta^k} \right] \times \frac{d\eta}{dz}$$

$$LHS = \frac{d}{d\eta} \left[ 2^{k/2} \left( \frac{c}{\nu} \right)^{k/2} \frac{d^k}{d\eta^k} \right] \times 2^{1/2} \left( \frac{c}{\nu} \right)^{1/2}$$

$$LHS = 2^{(k+1)/2} \left( \frac{c}{\nu} \right)^{(k+1)/2} \frac{d}{d\eta} \left[ \frac{d^k}{d\eta^k} \right]$$

Since  $LHS = RHS$ , by principle of mathematical induction, the formula is true. Applying to the exact solution,

$$-\frac{\nu}{c} f''' + f'^2 - 2ff'' - 1 = 0$$

$$-\frac{\nu}{c} f''' = -\frac{\nu}{c} \times 2^{3/2} \left( \frac{c}{\nu} \right)^{3/2} \frac{d^3}{d\eta^3} \left[ 2^{-1/2} \left( \frac{c}{\nu} \right)^{-1/2} \phi \right]$$

$$-\frac{\nu}{c} f''' = -2^{3/2-1-1/2} \left( \frac{c}{\nu} \right)^{3/2-1-1/2} \frac{d^3}{d\eta^3} [\phi]$$

$$-\frac{\nu}{c} f''' = -2 \frac{d^3}{d\eta^3} [\phi]$$

$$-\frac{\nu}{c} f''' = -2\phi'''$$

$$f'^2 = \left\{ 2^{1/2} \left( \frac{c}{\nu} \right)^{1/2} \frac{d}{d\eta} \left[ 2^{-1/2} \left( \frac{c}{\nu} \right)^{-1/2} \phi \right] \right\}^2$$

$$f'^2 = \left\{ \frac{d}{d\eta} [\phi] \right\}^2$$

$$f'^2 = \{\phi'\}^2$$

$$f'^2 = \phi'^2$$

$$-2ff'' = -(2)2^{-1/2} \left[ \left( \frac{c}{\nu} \right)^{-1/2} \phi \right] 2 \left( \frac{c}{\nu} \right) \frac{d^2}{d\eta^2} \left[ 2^{-1/2} \left( \frac{c}{\nu} \right)^{-1/2} \phi \right]$$

$$-2ff'' = -2^{1-1/2+1-1/2} \left[ \left( \frac{c}{\nu} \right)^{-1/2+1-1/2} \phi \right] \frac{d^2}{d\eta^2} [\phi]$$

$$-2ff'' = -2\phi\phi''$$

Substituting all the terms together,

$$-2\phi''' + \phi'^2 - 2\phi\phi'' - 1 = 0$$

$$-2\phi''' - 2\phi\phi'' + \phi'^2 - 1 = 0$$

$$\phi''' + \phi\phi'' - \frac{1}{2}\phi'^2 + \frac{1}{2} = 0$$

Reiterating the radial and axial velocities based on the modified stream function,

$$v_r = crf' \quad , \quad v_z = -2cf$$

At the stagnation point  $z = 0$  and since  $\eta$  is a linear function of  $z$ ,  $z = 0$ . The stagnation point is defined as a point in the fluid where fluid velocity is zero. Therefore,

$$0 = crf'(0) \quad , \quad 0 = -2cf(0)$$

$$0 = f'(0) \quad , \quad 0 = -f(0)$$

Both derivative and function  $f$  have linear scaling with  $\phi'$  and  $\phi$  respectively. Therefore,

$$\phi(0) = 0 \quad , \quad \phi'(0) = 0$$

Infinitely far away,

$$v_r = cr = crf'$$

$$1 = f'(\infty)$$

Taking the derivative of  $f$ ,

$$\frac{df}{dz} = \left( \frac{2c}{\nu} \right)^{1/2} \frac{d}{d\eta} \left[ \left( \frac{2c}{\nu} \right)^{-1/2} \phi \right]$$

$$\frac{df}{dz} = \phi'(\eta)$$

Substituting for infinite distance away,

$$\frac{df}{dz}_{z=\infty} = \phi'(\eta = \infty)$$

$$1 = \phi'(\infty)$$



## 4.2 Alternate Forms

### 4.2.1 Strain & Rotation

#### 4.2.1.1 Continuity: Index Notation

The continuity and momentum equations in vector form,

$$\nabla \cdot u = 0 \quad , \quad \frac{Du}{Dt} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 u$$

The continuity equation in index form,

$$0 = \frac{\partial u_j}{\partial x_j}$$

Simplifying the momentum equation in vector form,

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\frac{1}{\rho} \nabla p + \nu \nabla^2 u$$

Converting the momentum equation into index form,

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial}{\partial x_j} \frac{\partial}{\partial x_j} (u_i)$$

#### 4.2.1.2 Momentum: Velocity Gradient

Renaming the dummy indices in the index momentum equation  $j \rightarrow k$ ,

$$\frac{\partial u_i}{\partial t} + u_k \frac{\partial u_i}{\partial x_k} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (u_i)$$

Taking the derivative of the index momentum equation with respect to  $x_j$ ,

$$\frac{\partial}{\partial x_j} \frac{\partial}{\partial t} (u_i) + \frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = -\frac{1}{\rho} \frac{\partial}{\partial x_j} \frac{\partial}{\partial x_i} (p) + \nu \frac{\partial}{\partial x_j} \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (u_i)$$

Here, the fluid is assumed to be incompressible, hence  $\rho$  is a simple known fluid property.

Since the partial derivative operator is commutative,

$$\frac{\partial}{\partial t} \frac{\partial}{\partial x_j} (u_i) + \frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) + \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_j} (u_i)$$

$$\text{Substituting } e_{ij} = \frac{\partial u_i}{\partial x_j},$$

$$\frac{\partial}{\partial t} e_{ij} + \frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) + \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} e_{ij}$$

Simplifying the convective acceleration term by applying chain rule,

$$\frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = u_k \frac{\partial}{\partial x_j} \left[ \frac{\partial u_i}{\partial x_k} \right] + \frac{\partial u_i}{\partial x_k} \frac{\partial}{\partial x_j} [u_k]$$

Due to the partial derivative operator being commutative,

$$\frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = u_k \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_j} (u_i) + \frac{\partial u_i}{\partial x_k} \frac{\partial}{\partial x_j} [u_k]$$

$$\text{Substituting } e_{ij} = \frac{\partial u_i}{\partial x_j},$$

$$\frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = u_k \frac{\partial}{\partial x_k} e_{ij} + \frac{\partial u_i}{\partial x_k} \frac{\partial}{\partial x_j} [u_k]$$

Based on the definition of  $e_{ij}$ ,

$$e_{ik} = \frac{\partial u_i}{\partial x_k} \quad , \quad e_{kj} = \frac{\partial u_k}{\partial x_j}$$

$$\frac{\partial}{\partial x_j} \left[ u_k \frac{\partial u_i}{\partial x_k} \right] = u_k \frac{\partial}{\partial x_k} e_{ij} + e_{ik} e_{kj}$$

Substituting the convective acceleration into the momentum equation,

$$\frac{\partial}{\partial t} e_{ij} + u_k \frac{\partial}{\partial x_k} e_{ij} + e_{ik} e_{kj} = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) + \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} e_{ij}$$

Manipulating the equation further,

$$\frac{\partial}{\partial t} e_{ij} + u_k \frac{\partial}{\partial x_k} e_{ij} = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - e_{ik} e_{kj} + \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} e_{ij}$$

$$\frac{\partial}{\partial t} (e_{ij}) + u_k \frac{\partial}{\partial x_k} (e_{ij}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ij}) = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - e_{ik} e_{kj}$$

#### 4.2.1.3 Strain Rate Form

Reiterating the momentum equation in index form,

$$\frac{\partial}{\partial t} (e_{ij}) + u_k \frac{\partial}{\partial x_k} (e_{ij}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ij}) = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - e_{ik} e_{kj}$$

Renaming the indices,  $i \rightarrow j$ , and  $j \rightarrow i$ ,

$$\frac{\partial}{\partial t} (e_{ji}) + u_k \frac{\partial}{\partial x_k} (e_{ji}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ji}) = -\frac{1}{\rho} \frac{\partial^2}{\partial x_i \partial x_j} (p) - e_{jk} e_{ki}$$

Adding the 2 equations above together and taking into account that  $\frac{\partial^2}{\partial x_i \partial x_j} (p) = \frac{\partial^2}{\partial x_j \partial x_i} (p)$ ,

$$\frac{\partial}{\partial t} (e_{ij} + e_{ji}) + u_k \frac{\partial}{\partial x_k} (e_{ij} + e_{ji}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ij} + e_{ji}) = -\frac{2}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - e_{ik} e_{kj} - e_{jk} e_{ki}$$

$$\frac{\partial}{\partial t} (e_{ij} + e_{ji}) + u_k \frac{\partial}{\partial x_k} (e_{ij} + e_{ji}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ij} + e_{ji}) = -\frac{2}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - (e_{ik} e_{kj} + e_{jk} e_{ki})$$

Multiplying both sides by half,

$$\frac{\partial}{\partial t} \left[ \frac{1}{2} (e_{ij} + e_{ji}) \right] + u_k \frac{\partial}{\partial x_k} \left[ \frac{1}{2} (e_{ij} + e_{ji}) \right] - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} \left[ \frac{1}{2} (e_{ij} + e_{ji}) \right] = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - \frac{1}{2} (e_{ik} e_{kj} + e_{jk} e_{ki})$$

The symmetric strain rate tensor is defined as,  $S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$ . Expressing the symmetric strain rate tensor in terms of  $e_{ij}$  and  $e_{ji}$ ,  $S_{ij} = \frac{1}{2} (e_{ij} + e_{ji})$ . Substituting for the symmetric strain rate tensor into the momentum equation,

$$\frac{\partial}{\partial t} [S_{ij}] + u_k \frac{\partial}{\partial x_k} [S_{ij}] - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} [S_{ij}] = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - \frac{1}{2} (e_{ik} e_{kj} + e_{jk} e_{ki})$$

Simplifying further,

$$\left\{ \frac{\partial}{\partial t} + u_k \frac{\partial}{\partial x_k} - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} \right\} S_{ij} = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - \frac{1}{2} (e_{ik} e_{kj} + e_{jk} e_{ki})$$

$\frac{\partial}{\partial t} + u_k \frac{\partial}{\partial x_k}$  represents the substantive derivative in index notation meanwhile

$\frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k}$  represents the laplacian in index notation. **4.2.1.4 Rotation Rate Form**

Performing the same steps as the previous part but instead of adding 2 equations together, the equations are subtracted off each other,

$$\frac{\partial}{\partial t} (e_{ij} - e_{ji}) + u_k \frac{\partial}{\partial x_k} (e_{ij} - e_{ji}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ij} - e_{ji}) = -\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) + \frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) - e_{ik} e_{kj} + e_{jk} e_{ki}$$

Since the partial differential operators are commutative,  $-\frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) + \frac{1}{\rho} \frac{\partial^2}{\partial x_j \partial x_i} (p) = 0$ .

Substituting,

$$\frac{\partial}{\partial t} (e_{ij} - e_{ji}) + u_k \frac{\partial}{\partial x_k} (e_{ij} - e_{ji}) - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} (e_{ij} - e_{ji}) = -e_{ik} e_{kj} + e_{jk} e_{ki}$$

Multiplying both sides by half,

$$\frac{\partial}{\partial t} \left[ \frac{1}{2} (e_{ij} - e_{ji}) \right] + u_k \frac{\partial}{\partial x_k} \left[ \frac{1}{2} (e_{ij} - e_{ji}) \right] - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} \left[ \frac{1}{2} (e_{ij} - e_{ji}) \right] = -\frac{1}{2} [e_{ik} e_{kj} - e_{jk} e_{ki}]$$

The rotation rate tensor is defined as  $\Omega_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right)$ . Substituting for  $e_{ij} = \frac{\partial u_i}{\partial x_j}$  and

$e_{ji} = \frac{\partial u_j}{\partial x_i}$ ,  $\Omega_{ij} = \frac{1}{2} (e_{ij} - e_{ji})$  Substituting the rotation rate tensor,

$$\frac{\partial}{\partial t} [\Omega_{ij}] + u_k \frac{\partial}{\partial x_k} [\Omega_{ij}] - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} [\Omega_{ij}] = -\frac{1}{2} [e_{ik} e_{kj} - e_{jk} e_{ki}]$$

$$\left\{ \frac{\partial}{\partial t} + u_k \frac{\partial}{\partial x_k} - \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} \right\} \Omega_{ij} = -\frac{1}{2} [e_{ik} e_{kj} - e_{jk} e_{ki}]$$

Just as before,  $\frac{\partial}{\partial t} + u_k \frac{\partial}{\partial x_k}$  represents the substantive derivative in index notation meanwhile

$\frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k}$  represents the laplacian in index notation. Interestingly, here the expression is independent of the pressure gradient tensor since the pressure gradient tensor is symmetric.

## 4.2.2 Vorticity Equation

### 4.2.2.1 Derivation

The substantive derivative of fluid velocity  $\bar{v}_f$  appears in the non-conservative form of the momentum equation. The substantive derivative of fluid velocity  $\bar{v}_f$  in vector form,

$$\frac{D\bar{v}_f}{Dt} = \frac{\partial \bar{v}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{v}_f$$

By conjecture,

$$\bar{v}_f \cdot \nabla \bar{v}_f = \bar{\omega}_f \times \bar{v}_f + \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right)$$

Let,

$$LHS = \bar{v}_f \cdot \nabla \bar{v}_f \quad , \quad RHS = \bar{\omega}_f \times \bar{v}_f + \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right)$$

wherein  $\bar{\omega}_f$  represents the fluid vorticity. Fluid vorticity is defined as the curl of fluid velocity,

$$\bar{\omega}_f = \nabla \times \bar{v}_f.$$

Expressing  $LHS$  in index notation,

$$LHS_i = v_j \frac{\partial v_i}{\partial x_j}$$

wherein  $v_i$  represents the  $i^{th}$  component of the velocity vector  $\bar{v}_f$ .

Expressing  $RHS$  in index notation,

$$RHS_i = \epsilon_{ijk} \omega_j v_k + \frac{\partial}{\partial x_i} \left[ \frac{1}{2} v_j v_j \right]$$

wherein  $\omega_j$  represents the  $j^{th}$  component of fluid vorticity vector  $\bar{\omega}_f$ . Expressing the definition of vorticity as curl of fluid velocity in index notation,

$$\omega_j = \epsilon_{jlm} \frac{\partial v_m}{\partial x_l}$$

Substituting  $\omega_j$  into  $RHS_i$ ,

$$RHS_i = \epsilon_{ijk} \epsilon_{jlm} \frac{\partial v_m}{\partial x_l} v_k + \frac{\partial}{\partial x_i} \left[ \frac{1}{2} v_j v_j \right] = \epsilon_{ijk} \epsilon_{jlm} v_k \frac{\partial v_m}{\partial x_l} + \frac{\partial}{\partial x_i} \left[ \frac{1}{2} v_j v_j \right]$$

Based on the cyclic permutation properties of the permutation tensors  $\epsilon_{ijk}$ ,  $\epsilon_{ijk} = \epsilon_{jki}$ .

Therefore,

$$\epsilon_{ijk} \epsilon_{jlm} = \epsilon_{jki} \epsilon_{jlm}$$

Based on the double permutation tensor identity,

$$\epsilon_{ijk} \epsilon_{jlm} = \epsilon_{jki} \epsilon_{jlm} = \delta_{kl} \delta_{im} - \delta_{km} \delta_{il}$$

Substituting into  $RHS_i$ ,

$$RHS_i = [\delta_{kl} \delta_{im} - \delta_{km} \delta_{il}] v_k \frac{\partial v_m}{\partial x_l} + \frac{\partial}{\partial x_i} \left[ \frac{1}{2} v_j v_j \right] = \delta_{kl} \delta_{im} v_k \frac{\partial v_m}{\partial x_l} - \delta_{km} \delta_{il} v_k \frac{\partial v_m}{\partial x_l} + \frac{\partial}{\partial x_i} \left[ \frac{1}{2} v_j v_j \right]$$

$$RHS_i = v_l \frac{\partial v_i}{\partial x_l} - v_k \frac{\partial v_k}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \frac{1}{2} v_j v_j \right] = v_l \frac{\partial v_i}{\partial x_l} - v_k \frac{\partial v_k}{\partial x_i} + \frac{1}{2} \frac{\partial}{\partial x_i} [v_j v_j]$$

$$RHS_i = v_l \frac{\partial v_i}{\partial x_l} - v_k \frac{\partial v_k}{\partial x_i} + \frac{1}{2} \left[ v_j \frac{\partial}{\partial x_i} (v_j) + v_j \frac{\partial}{\partial x_i} (v_j) \right] = v_l \frac{\partial v_i}{\partial x_l} - v_k \frac{\partial v_k}{\partial x_i} + v_j \frac{\partial v_j}{\partial x_i} = v_l \frac{\partial v_i}{\partial x_l}$$

Renaming the dummy index  $l \rightarrow j$ ,

$$RHS_i = v_j \frac{\partial v_i}{\partial x_j}$$

Since  $LHS_i = RHS_i$ , then the conjecture shown below must be true,

$$\bar{v}_f \cdot \nabla \bar{v}_f = \bar{\omega}_f \times \bar{v}_f + \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right)$$

Substituting into the substantive derivative of fluid velocity,

$$\frac{D\bar{v}_f}{Dt} = \frac{\partial \bar{v}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{v}_f = \frac{\partial \bar{v}_f}{\partial t} + \bar{\omega}_f \times \bar{v}_f + \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right)$$

Taking the curl of the substantive derivative of fluid velocity,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \nabla \times \left( \frac{\partial \bar{v}_f}{\partial t} \right) + \nabla \times (\bar{\omega}_f \times \bar{v}_f) + \nabla \times \left[ \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right) \right]$$

The curl operations and the partial derivative operations are commutative. Therefore,

$$\nabla \times \left( \frac{\partial \bar{v}_f}{\partial t} \right) = \frac{\partial}{\partial t} (\nabla \times \bar{v}_f)$$

Substituting for the definition of fluid vorticity  $\bar{\omega}_f = \nabla \times \bar{v}_f$ ,

$$\nabla \times \left( \frac{\partial \bar{v}_f}{\partial t} \right) = \frac{\partial}{\partial t} (\bar{\omega}_f) = \frac{\partial \bar{\omega}_f}{\partial t}$$

Substituting into the curl of fluid velocity substantive derivative,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{\partial \bar{\omega}_f}{\partial t} + \nabla \times (\bar{\omega}_f \times \bar{v}_f) + \nabla \times \left[ \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right) \right]$$

$\bar{v}_f \cdot \bar{v}_f$  is a scalar. The curl of a scalar gradient is zero. Therefore,

$$0 = \nabla \times \left[ \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right) \right]$$

Neglecting the  $\nabla \times \left[ \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right) \right]$  term,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{\partial \bar{\omega}_f}{\partial t} + \nabla \times (\bar{\omega}_f \times \bar{v}_f)$$

This is a vector identity,

$$\nabla \times (\bar{A} \times \bar{B}) = \bar{B} \cdot \nabla \bar{A} + \bar{A} \nabla \cdot \bar{B} - \bar{A} \cdot \nabla \bar{B} - \bar{B} \nabla \cdot \bar{A}$$

Let  $\bar{A} = \bar{\omega}_f$  and  $\bar{B} = \bar{v}_f$ ,

$$\nabla \times (\bar{\omega}_f \times \bar{v}_f) = \bar{v}_f \cdot \nabla \bar{\omega}_f + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f - \bar{v}_f \nabla \cdot \bar{\omega}_f$$

Based on the definition of fluid vorticity  $\bar{\omega}_f = \nabla \times \bar{v}_f$ ,

$$\bar{v}_f \nabla \cdot \bar{\omega}_f = \bar{v}_f \nabla \cdot (\nabla \times \bar{v}_f)$$

Since the divergence of a vector field curl is zero,  $\nabla \cdot (\nabla \times \bar{v}_f) = 0$ . Therefore,

$$0 = \bar{v}_f \nabla \cdot \bar{\omega}_f$$

Neglecting the  $\bar{v}_f \nabla \cdot \bar{\omega}_f$  term,

$$\nabla \times (\bar{\omega}_f \times \bar{v}_f) = \bar{v}_f \cdot \nabla \bar{\omega}_f + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f$$

Substituting  $\nabla \times (\bar{\omega}_f \times \bar{v}_f)$ , into the substantive derivative of vorticity,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{\partial \bar{\omega}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{\omega}_f + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f$$

The definition of substantive derivative of vorticity is shown below,

$$\frac{D\bar{\omega}_f}{Dt} = \frac{\partial \bar{\omega}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{\omega}_f$$

Substituting for the substantive derivative of vorticity into the curl of fluid velocity substantive derivative,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{D\bar{\omega}_f}{Dt} + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f$$

The symmetric strain rate tensor is defined as,

$$S_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

The symmetric strain rate tensor is symmetric.

The rotation rate tensor is defined as,

$$\Omega_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i} \right)$$

The rotation rate tensor is anti-symmetric.

The summation of the strain rate tensor and the rotation rate tensor,

$$S_{ij} + \Omega_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) + \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i} \right) = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i} \right) = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_i}{\partial x_j} \right)$$

$$S_{ij} + \Omega_{ij} = \frac{\partial v_i}{\partial x_j}$$

Therefore, this shows that the fluid velocity gradient tensor  $\frac{\partial v_i}{\partial x_j}$  can be decomposed into an

algebraic sum of a symmetric tensor  $S_{ij}$  and an anti-symmetric tensor  $\Omega_{ij}$ .

The rotation rate tensor is somewhat related to the fluid vorticity vector. Consider  $i^{th}$  component of the fluid vorticity vector the  $i^{th}$  component of fluid velocity curl,

$$\omega_i = \epsilon_{ijk} \frac{\partial v_k}{\partial x_j}$$

Using the fluid vorticity to contract the permutation tensor on along its third dimension,

$$\epsilon_{lmi}\omega_i = \epsilon_{lmi}\epsilon_{ijk}\frac{\partial v_k}{\partial x_j}$$

Due to the permutation cyclic property,  $\epsilon_{lmi} = \epsilon_{ilm}$ . Therefore,

$$\epsilon_{lmi}\epsilon_{ijk} = \epsilon_{ilm}\epsilon_{ijk} = \delta_{lj}\delta_{mk} - \delta_{lk}\delta_{mj}$$

Substituting into the permutation tensor contraction,

$$\epsilon_{lmi}\omega_i = \epsilon_{lmi}\epsilon_{ijk}\frac{\partial v_k}{\partial x_j} = [\delta_{lj}\delta_{mk} - \delta_{lk}\delta_{mj}]\frac{\partial v_k}{\partial x_j} = \delta_{lj}\delta_{mk}\frac{\partial v_k}{\partial x_j} - \delta_{lk}\delta_{mj}\frac{\partial v_k}{\partial x_j} = \delta_{mk}\frac{\partial v_k}{\partial x_l} - \delta_{mj}\frac{\partial v_l}{\partial x_j}$$

$$\epsilon_{lmi}\omega_i = \frac{\partial v_m}{\partial x_l} - \frac{\partial v_l}{\partial x_m}$$

Under an index variable change  $l \rightarrow i, m \rightarrow j, i \rightarrow k$ ,

$$\epsilon_{ijk}\omega_k = \frac{\partial v_j}{\partial x_i} - \frac{\partial v_i}{\partial x_j}$$

This form is already similar to the rotation rate tensor. In essence, contracting the permutation tensor along any dimension would allow the usage of the double permutation tensor identity. The third dimension was chosen in order to obtain the 'alternating' pattern similar to the rotation rate tensor. Minor algebraic manipulations can then be performed to match  $\epsilon_{ijk}\omega_k$  to the rotation rate tensor,

$$\begin{aligned} -\epsilon_{ijk}\omega_k &= \frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i} \\ -\frac{1}{2}\epsilon_{ijk}\omega_k &= \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i}\right) \end{aligned}$$

The *RHS* matches the rotation rate tensor. Therefore,

$$-\frac{1}{2}\epsilon_{ijk}\omega_k = \Omega_{ij}$$

By conjecture, using the fluid vorticity vector  $\bar{\omega}_f$  to contract the rotation rate tensor along the second dimension would yield zero. This claim is expressed in index notation,

$$0 = \omega_j\Omega_{ij}$$

Let

$$LHS_i = 0 \quad , \quad RHS_i = \omega_j\Omega_{ij}$$

Substituting the definition of the rotation rate tensor in terms of the fluid vorticity vector,

$$RHS_i = \omega_j\Omega_{ij} = -\frac{1}{2}\epsilon_{ijk}\omega_j\omega_k$$

Since  $\epsilon_{ijk}$  is an anti-symmetric tensor, and  $\omega_j\omega_k$  is a symmetric tensor due to multiplication being a commutative operation,

$$RHS_i = \omega_j\Omega_{ij} = -\frac{1}{2}\epsilon_{ijk}\omega_j\omega_k = 0$$

Therefore, the claim is proven to be true.  
 Reiterating the last form of the curl of fluid velocity substantive derivative,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{D\bar{\omega}_f}{Dt} + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f$$

Converting the last term in *RHS* into index notation,

$$(\bar{\omega}_f \cdot \nabla \bar{v}_f)_i = \omega_j \frac{\partial v_i}{\partial x_j}$$

Expressing the velocity gradient tensor  $\frac{\partial v_i}{\partial x_j}$  in terms of its symmetric and anti-symmetric components,

$$(\bar{\omega}_f \cdot \nabla \bar{v}_f)_i = \omega_j \frac{\partial v_i}{\partial x_j} = \omega_j [S_{ij} + \Omega_{ij}] = \omega_j S_{ij} + \omega_j \Omega_{ij}$$

Based on previous work, the contraction of the rotation tensor on the second index using the fluid vorticity vector yields zero,

$$0 = \omega_j \Omega_{ij}$$

Neglecting the  $\omega_j \Omega_{ij}$  term,

$$(\bar{\omega}_f \cdot \nabla \bar{v}_f)_i = \omega_j S_{ij}$$

Converting into vector notation,

$$\bar{\omega}_f \cdot \nabla \bar{v}_f = \bar{\omega}_f \cdot \bar{\bar{S}}_f$$

wherein  $\bar{\bar{S}}_f$  represents the symmetric strain rate tensor for the fluid velocity vector field.  
 Substituting into the curl of fluid velocity substantive derivative,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{D\bar{\omega}_f}{Dt} + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \bar{\bar{S}}_f$$

The differential continuity equation is shown below,

$$0 = \frac{\partial}{\partial t}[\rho] + \nabla \cdot (\rho \bar{v}_f)$$

Converting the differential continuity equation into tensor index notation,

$$0 = \frac{\partial}{\partial t}[\rho] + \frac{\partial}{\partial x_j}(\rho v_j)$$

Using chain rule,

$$0 = \frac{\partial}{\partial t}[\rho] + \rho \frac{\partial}{\partial x_j}(v_j) + v_j \frac{\partial}{\partial x_j}(\rho)$$

Manipulating further,

$$\rho \frac{\partial}{\partial x_j}(v_j) = -\frac{\partial}{\partial t}[\rho] - v_j \frac{\partial}{\partial x_j}(\rho)$$



$$\frac{\partial}{\partial x_j}(v_j) = -\frac{1}{\rho} \left[ \frac{\partial}{\partial t}(\rho) + v_j \frac{\partial}{\partial x_j}(\rho) \right]$$

The substantive derivative of fluid density  $\rho$  in vector notation,

$$\frac{D}{Dt}(\rho) = \frac{\partial}{\partial t}(\rho) + \bar{v}_f \cdot \nabla \rho$$

Converting the substanttive derivative of fluid density into index notation,

$$\left[ \frac{D}{Dt}(\rho) \right]_i = \frac{\partial}{\partial t}(\rho) + v_j \frac{\partial}{\partial x_j}(\rho)$$

Substituting,

$$\frac{\partial}{\partial x_j}(v_j) = -\frac{1}{\rho} \left[ \frac{D}{Dt}(\rho) \right]_i$$

Converting into vector index notation,

$$\nabla \cdot \bar{v}_f = -\frac{1}{\rho} \frac{D}{Dt}(\rho)$$

Substituting the divergence of fluid velocity  $\bar{v}_f$  into the fluid velocity substantive derivative,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{D\bar{\omega}_f}{Dt} - \frac{\bar{\omega}_f}{\rho} \frac{D}{Dt}(\rho) - \bar{\omega}_f \cdot \bar{\bar{S}}_f$$

By conjecture,

$$\rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] = \frac{D\bar{\omega}_f}{Dt} - \frac{\bar{\omega}_f}{\rho} \frac{D}{Dt}(\rho)$$

Let

$$LHS = \rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] \quad , \quad RHS = \frac{D\bar{\omega}_f}{Dt} - \frac{\bar{\omega}_f}{\rho} \frac{D}{Dt}(\rho)$$

Using quotient rule,

$$LHS = \rho \times \frac{1}{\rho^2} \left\{ \rho \frac{D}{Dt} [\bar{\omega}_f] - \bar{\omega}_f \frac{D}{Dt} [\rho] \right\} = \frac{1}{\rho} \left\{ \rho \frac{D}{Dt} [\bar{\omega}_f] - \bar{\omega}_f \frac{D}{Dt} [\rho] \right\} = \frac{1}{\rho} \rho \frac{D}{Dt} [\bar{\omega}_f] - \frac{1}{\rho} \bar{\omega}_f \frac{D}{Dt} [\rho]$$

$$LHS = \frac{D}{Dt} [\bar{\omega}_f] - \frac{\bar{\omega}_f}{\rho} \frac{D}{Dt} [\rho]$$

Since  $LHS = RHS$ , the claim is proven.

Substituting for this simplification,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] - \bar{\omega}_f \cdot \bar{\bar{S}}_f$$

The non-conservative form of the momentum equation,

$$\rho \frac{D\bar{v}_f}{Dt} = \nabla \cdot \bar{T}_f + \bar{g}_b$$

Making the substantive derivative of fluid velocity the subject of the equation,

$$\frac{D\bar{v}_f}{Dt} = \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f + \frac{1}{\rho} \bar{g}_b$$

Taking the curl of the resulting expression so that it might be substituted into the main equation,

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f + \frac{1}{\rho} \bar{g}_b \right] = \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] + \nabla \times \left[ \frac{1}{\rho} \bar{g}_b \right]$$

Substituting the complete stress tensor and external acceleration into the main equation,

$$\begin{aligned} \nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) &= \rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] - \bar{\omega}_f \cdot \bar{\bar{S}}_f = \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] + \nabla \times \left[ \frac{1}{\rho} \bar{g}_b \right] \\ \rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] - \bar{\omega}_f \cdot \bar{\bar{S}}_f &= \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] + \nabla \times \left[ \frac{1}{\rho} \bar{g}_b \right] \end{aligned}$$

Hence, the 'basic' vorticity equation,

$$\rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] = \bar{\omega}_f \cdot \bar{\bar{S}}_f + \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] + \nabla \times \left[ \frac{1}{\rho} \bar{g}_b \right]$$

The complete stress tensor  $\bar{\bar{T}}_f$  defined in index notation,

$$T_{ij} = -P_r \delta_{ij} + \mu \left[ \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right] + \lambda \frac{\partial v_k}{\partial x_k} \delta_{ij}$$

wherein  $\left( \bar{\bar{T}}_f \right)_{ij} = T_{ij}$ ,  $\mu$  is the dynamic viscosity and  $\lambda$  is the second coefficient of viscosity.

The viscous stress tensor  $\bar{\bar{\tau}}_f$  has a rank of 2 and its  $ij$  component is referred as  $\tau_{ij}$ . The viscous stress tensor components in index form is defined to be,

$$\tau_{ij} = \mu \left[ \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right] + \lambda \frac{\partial v_k}{\partial x_k} \delta_{ij}$$

Therefore, the complete stress tensor can be expressed in terms of the viscous stress tensor,

$$T_{ij} = -P_r \delta_{ij} + \tau_{ij}$$

Expressing the complete stress tensor term in index notation,

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (T_{ml}) \right]$$

Renaming the indices  $i \rightarrow m$   $j \rightarrow l$ ,

$$T_{ml} = -P_r \delta_{ml} + \tau_{ml}$$

Substituting for the complete stress tensor,

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (-P_r \delta_{ml} + \tau_{ml}) \right]$$

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (-P_r \delta_{ml}) \right] + \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (\tau_{ml}) \right]$$

By applying the kronecker-delta contraction,

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = -\epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial P_r}{\partial x_l} \right] + \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (\tau_{ml}) \right]$$

By applying product rule on the pressure-related term,

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = -\epsilon_{ijl} \frac{1}{\rho} \frac{\partial}{\partial x_j} \left[ \frac{\partial P_r}{\partial x_l} \right] - \epsilon_{ijl} \frac{\partial P_r}{\partial x_l} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \right] + \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (\tau_{ml}) \right]$$

Due to the partial derivative operations being commutative  $\frac{\partial}{\partial x_j} \left[ \frac{\partial P_r}{\partial x_l} \right]$  is a symmetric tensor of rank 2. Since the permutation tensor  $\epsilon_{ijl}$  is anti-symmetric,

$$0 = -\epsilon_{ijl} \frac{1}{\rho} \frac{\partial}{\partial x_j} \left[ \frac{\partial P_r}{\partial x_l} \right]$$

Neglecting the term,

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = -\epsilon_{ijl} \frac{\partial P_r}{\partial x_l} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \right] + \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (\tau_{ml}) \right]$$

Applying chain rule,  $\frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \right] = -\frac{1}{\rho^2} \frac{\partial \rho}{\partial x_j}$ . Substituting,

$$\left\{ \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] \right\}_i = \epsilon_{ijl} \frac{\partial P_r}{\partial x_l} \frac{1}{\rho^2} \frac{\partial \rho}{\partial x_j} + \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (\tau_{ml}) \right] = \epsilon_{ijl} \frac{1}{\rho^2} \frac{\partial \rho}{\partial x_j} \frac{\partial P_r}{\partial x_l} + \epsilon_{ijl} \frac{\partial}{\partial x_j} \left[ \frac{1}{\rho} \frac{\partial}{\partial x_m} (\tau_{ml}) \right]$$

Converting into index notation,

$$\nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] = \frac{1}{\rho^2} \nabla \rho \times \nabla P_r + \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right]$$

Substituting into the basic vorticity equation,

$$\rho \frac{D}{Dt} \left[ \frac{\bar{\omega}_f}{\rho} \right] = \bar{\omega}_f \cdot \bar{\bar{S}}_f + \frac{1}{\rho^2} \nabla \rho \times \nabla P_r + \nabla \times \left[ \frac{1}{\rho} \nabla \cdot \bar{\bar{T}}_f \right] + \nabla \times \left[ \frac{1}{\rho} \bar{g}_b \right]$$

#### 4.2.2.2 Summary

Basic Substantive derivative of fluid velocity

$$\frac{D\bar{v}_f}{Dt} = \frac{\partial \bar{v}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{v}_f$$

Kinematic Relations

Intermediate derivative kinetic energy form

$$\frac{D\bar{v}_f}{Dt} = \frac{\partial \bar{v}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{v}_f = \frac{\partial \bar{v}_f}{\partial t} + \bar{\omega}_f \times \bar{v}_f + \nabla \left( \frac{1}{2} \bar{v}_f \cdot \bar{v}_f \right)$$

Double  $\epsilon\epsilon$  Identity

$$\nabla \times \nabla \phi = 0, \quad \nabla \cdot (\nabla \times v) = 0$$

Vorticity 1<sup>st</sup> relation

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{\partial \bar{\omega}_f}{\partial t} + \bar{v}_f \cdot \nabla \bar{\omega}_f + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f$$

Definition of material derivative

3 term equation part 1

$$\nabla \times \left( \frac{D\bar{v}_f}{Dt} \right) = \frac{D\bar{\omega}_f}{Dt} + \bar{\omega}_f \nabla \cdot \bar{v}_f - \bar{\omega}_f \cdot \nabla \bar{v}_f$$



# Chapter 5

## Potential Flows

Potential and inviscid flows are flows wherein the effects of viscosity is neglected. The degeneracy from the general Navier Stokes equation is shown below,

Consider the continuity differential governing equation,

$$0 = \frac{\partial}{\partial t}[\rho] + \nabla \cdot (\rho \bar{v}_f)$$

For a steady-state flow,  $\frac{\partial}{\partial t}[\rho] = 0$ . Substituting to the continuity differential governing equation,

$$0 = \nabla \cdot (\rho \bar{v}_f)$$

### 5.1 Compressible Potential Flow

For the compressible potential flow, let the potential function  $\psi_c$  be defined as,

$$\rho \bar{v}_f = \nabla \psi_c$$

Substituting the definition of the potential function into the steady state continuity differential governing equation,

$$0 = \nabla \cdot (\nabla \psi_c) = \nabla^2 \psi_c$$

In cartesian coordinates, this yields,

$$0 = \frac{\partial^2}{\partial x^2}[\psi_c] + \frac{\partial^2}{\partial y^2}[\psi_c] + \frac{\partial^2}{\partial z^2}[\psi_c]$$

### 5.2 Incompressible Potential Flow

Due to the nature of the fluid, the density could be considered a scalar constant. The  $\frac{\partial}{\partial t}[\rho]$  term in this case is evaluates to zero under two conditions: steady state means that the gradient is unchanging, but also since density is non-changing, this particular term also evaluates to zero. Therefore, for for incompressible flows, the potential flow function would still be applicable for non-steady fluid states.

$$0 = \nabla \cdot (\rho \bar{v}_f) = \rho \nabla \cdot (\bar{v}_f)$$

Division of both sides by  $\rho$ ,

$$0 = \nabla \cdot (\bar{v}_f)$$

For the incompressible potential flow, let the potential function  $\psi_i$  be defined as,

$$\bar{v}_f = \nabla \psi_i$$

By substituting the fluid velocity field into the continuity degenerate differential form,

$$0 = \nabla \cdot (\nabla \psi_i) = \nabla^2 \psi_i = \frac{\partial^2}{\partial x^2}[\psi_i] + \frac{\partial^2}{\partial y^2}[\psi_i] + \frac{\partial^2}{\partial z^2}[\psi_i]$$

# Chapter 6

## Numerical Methods: Potential Flows

### 6.1 Potential Flow

#### 6.1.1 Gauss-Siedel Grid Method

The Taylor expansion series for an arbitrary function  $f(t)$  is defined as the following,

$$f(t) = \sum_{n=0}^{\infty} \left\{ \frac{1}{n!} \frac{d^n}{dx^n} [f(a)] (x-a)^n \right\}$$

Let the control volume be split up into infinitesimally small grids. Each grid will have horizontal width of  $dx$  and a vertical height of  $dy$ . Let  $\psi_{i,j}$  represent the  $i^{th}$  column and the  $j^{th}$  row value of the stream function. Columns are defined as the vertical edges of the infinitesimally small grids meanwhile rows are defined as the horizontal edges of the infinitesimally small grids. Therefore, the analysis performed occurs at the edges of the infinitesimally small grids. Indexing starts from the bottom left corner of the control volume, at the origin of the declared coordinate system. Indices start at 0 and progress by increments of 1 along the  $x$  and  $y$  axes. Analyzing the Taylor Expansion series horizontally in the  $x$ -direction,

$$\psi_{i+1,j} = \sum_{n=0}^{\infty} \left\{ \frac{1}{n!} \frac{d^n}{dx^n} [\psi_{i,j}] (\Delta x)^n \right\}$$

For the  $i-1^{th}$  term,

$$\psi_{i-1,j} = \sum_{n=0}^{\infty} \left\{ \frac{1}{n!} \frac{d^n}{dx^n} [\psi_{i,j}] (-\Delta x)^n \right\}$$

Taking the second order approximation, and neglecting the higher order terms,

$$\sum_{n=3}^{\infty} \left\{ \frac{1}{n!} \frac{d^n}{dx^n} [\psi_{i,j}] (\Delta x)^n \right\} \approx \sum_{n=3}^{\infty} \left\{ \frac{1}{n!} \frac{d^n}{dx^n} [\psi_{i,j}] (-\Delta x)^n \right\} \approx 0$$

Therefore, for the  $i+1^{th}$  term and the  $i-1^{th}$  term respectively,

$$\psi_{i+1,j} \approx \psi_{i,j} + \frac{d\psi_{i,j}}{dx} \Delta x + \frac{1}{2} \frac{d^2\psi_{i,j}}{dx^2} (\Delta x)^2 \quad , \quad \psi_{i-1,j} \approx \psi_{i,j} - \frac{d\psi_{i,j}}{dx} \Delta x + \frac{1}{2} \frac{d^2\psi_{i,j}}{dx^2} (\Delta x)^2$$

Adding the terms together and manipulating the equation to isolate the  $\frac{d^2\psi_{i,j}}{dx^2}$  term,

$$\psi_{i+1,j} + \psi_{i-1,j} \approx \psi_{i,j} + \frac{d\psi_{i,j}}{dx} \Delta x + \frac{1}{2} \frac{d^2\psi_{i,j}}{dx^2} (\Delta x)^2 + \psi_{i,j} - \frac{d\psi_{i,j}}{dx} \Delta x + \frac{1}{2} \frac{d^2\psi_{i,j}}{dx^2} (\Delta x)^2$$

$$\psi_{i+1,j} + \psi_{i-1,j} \approx 2\psi_{i,j} + \frac{d^2\psi_{i,j}}{dx^2}(\Delta x)^2$$

$$\frac{d^2\psi_{i,j}}{dx^2}(\Delta x)^2 \approx \psi_{i+1,j} + \psi_{i-1,j} - 2\psi_{i,j}$$

$$\frac{d^2\psi_{i,j}}{dx^2} \approx \frac{\psi_{i+1,j} + \psi_{i-1,j} - 2\psi_{i,j}}{(\Delta x)^2}$$

Using the same process in the  $y$ -direction,

$$\frac{d^2\psi_{i,j}}{dy^2} \approx \frac{\psi_{i,j+1} + \psi_{i,j-1} - 2\psi_{i,j}}{(\Delta y)^2}$$

Substituting the relevant terms into the governing equation,

$$\frac{\partial^2}{\partial x^2}[\psi] + \frac{\partial^2}{\partial y^2}[\psi] = 0$$

$$\frac{\psi_{i+1,j} + \psi_{i-1,j} - 2\psi_{i,j}}{(\Delta x)^2} + \frac{\psi_{i,j+1} + \psi_{i,j-1} - 2\psi_{i,j}}{(\Delta y)^2} = 0$$

Making  $\psi_{i,j}$  the subject of the equation above,

$$(\psi_{i+1,j} + \psi_{i-1,j} - 2\psi_{i,j})(\Delta y)^2 + (\psi_{i,j+1} + \psi_{i,j-1} - 2\psi_{i,j})(\Delta x)^2 = 0$$

$$(\psi_{i+1,j} + \psi_{i-1,j})(\Delta y)^2 + (\psi_{i,j+1} + \psi_{i,j-1})(\Delta x)^2 = 2\psi_{i,j}(\Delta y)^2 + 2\psi_{i,j}(\Delta x)^2$$

$$(\psi_{i+1,j} + \psi_{i-1,j})(\Delta y)^2 + (\psi_{i,j+1} + \psi_{i,j-1})(\Delta x)^2 = 2[(\Delta y)^2 + (\Delta x)^2](\psi_{i,j})$$

$$\psi_{i,j} = \frac{(\psi_{i+1,j} + \psi_{i-1,j})(\Delta y)^2 + (\psi_{i,j+1} + \psi_{i,j-1})(\Delta x)^2}{2[(\Delta y)^2 + (\Delta x)^2]}$$

The relative error  $\epsilon$  of the stream function for the mesh corners are defined as

$$\left| \frac{\psi_{i,j}^{p+1} - \psi_{i,j}^p}{\psi_{i,j}^{p+1}} \right| = \epsilon$$

wherein  $\psi_{i,j}^{p+1}$  represents the  $p + 1^{th}$  iteration of  $\psi_{i,j}$  formulated through the Gauss-Seidel method. The relative error for the control volume would likewise be defined as

$$\frac{1}{k} \sqrt{\sum_{i=1}^{n-1} \sum_{j=1}^{m-1} \left( \frac{\psi_{i,j}^{p+1} - \psi_{i,j}^p}{\psi_{i,j}^{p+1}} \right)^2} = \epsilon_t \quad , \quad k = (n-1)(m-1)$$

The value of the error  $\epsilon$  would represent the error tolerance and a direct numerical simulation of the potential flow algorithm should keep running until the error tolerance would be low enough. The values of  $n$  and  $m$  would be shown analytically below,

$$m = \frac{H}{dy} \quad , \quad n = \frac{L}{dx}$$



## 6.2 Unsteady Diffusion

Consider the grid definition shown below,

Consider the general form the of the unsteady diffusion problem shown below,

$$\frac{\partial}{\partial t}(\rho\phi) + \nabla \cdot (\rho u\phi) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi$$

$\frac{\partial}{\partial t}(\rho\phi)$  represents the unsteady term,  $\nabla \cdot (\rho u\phi)$  represents the convection term,  $\nabla \cdot (\Gamma \nabla \phi)$  represents the diffusion term and  $S_\phi$  represents the source term. If the convection term is neglected,  $\nabla \cdot (\rho u\phi) = 0$ . Substituting for this,

$$\frac{\partial}{\partial t}(\rho\phi) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi$$

Integrating the unsteady diffusion equation over a small time step  $\Delta t$  as well as over the control volume  $CV$ ,

$$\int_t^{t+\Delta t} \int_{CV} \frac{\partial}{\partial t}(\rho\phi) dV_o dt = \int_t^{t+\Delta t} \int_{CV} \nabla \cdot (\Gamma \nabla \phi) + S_\phi dV_o dt$$

For the 1-dimensional case  $\nabla \phi = \frac{\partial}{\partial x}(\phi)$ . Substituting for the gradient of  $\phi$ ,

$$\nabla \cdot \nabla \phi = \frac{\partial^2}{\partial x^2}(\phi). \text{ Substituting for this,}$$

$$\int_t^{t+\Delta t} \int_{CV} \frac{\partial}{\partial t}(\rho\phi) dV_o dt = \int_t^{t+\Delta t} \int_{CV} \frac{\partial}{\partial x} \left[ \Gamma \frac{\partial}{\partial x}(\phi) \right] + S_\phi dV_o dt$$

The order of integration is commutative for the independent spatial and time variables.

Therefore,

$$\begin{aligned} \int_{CV} \int_t^{t+\Delta t} \frac{\partial}{\partial t}(\rho\phi) dt dV_o &= \int_t^{t+\Delta t} \int_{CV} \frac{\partial}{\partial x} \left[ \Gamma \frac{\partial}{\partial x}(\phi) \right] + S_\phi dV_o dt \\ \int_{CV} \int_t^{t+\Delta t} \frac{\partial}{\partial t}(\rho\phi) dt dV_o &= \int_t^{t+\Delta t} \int_{CV} \frac{\partial}{\partial x} \left[ \Gamma \frac{\partial}{\partial x}(\phi) \right] dV_o dt + \int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt \end{aligned}$$

The differential for volume  $dV_o = A dx$ . Substituting for this,

$$\int_{CV} \int_t^{t+\Delta t} \frac{\partial}{\partial t}(\rho\phi) dt dV_o = \int_t^{t+\Delta t} \int_{CV} \frac{\partial}{\partial x} \left[ \Gamma \frac{\partial}{\partial x}(\phi) \right] A dx dt + \int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt$$

Due to the exact differential simplification for  $dx$ ,

$$\int_{CV} \int_t^{t+\Delta t} \frac{\partial}{\partial t}(\rho\phi) dt dV_o = \int_t^{t+\Delta t} \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_w^e dt + \int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt$$

Due to the exact differential simplification for  $dt$ ,

$$\begin{aligned} \int_{CV} [\rho\phi]_t^{t+\Delta t} dV_o &= \int_t^{t+\Delta t} \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_w dt + \int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt \\ \int_{CV} [\rho\phi]_{t+\Delta t} - [\rho\phi]_t dV_o &= \int_t^{t+\Delta t} \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_w dt + \int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt \end{aligned}$$

Assuming that the value of  $\phi_P$  is the value of  $\phi$  throughout the entirety of a single cell, then  $\phi$  would be a constant with respect to the volumetric integral. Substituting for this,

$$\left\{ [\rho\phi]_{t+\Delta t} - [\rho\phi]_t \right\} \Delta V_o = \int_t^{t+\Delta t} \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_w dt + \int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt$$

Assuming uniformity throughout the grid, that  $\rho$ ,  $A$  and  $\Gamma$  is constant from one cell to the next,

$$\left\{ [\rho\phi]_{t+\Delta t} - [\rho\phi]_t \right\} \Delta V_o = \rho [\phi_{t+\Delta t} - \phi_t] \Delta V_o$$

With a slight abuse of notation, let  $\phi_t$  be represented as  $\phi_{t,o}$  and  $\phi_{t+\Delta t}$  be represented as  $\phi_t$ . Substituting for this,

$$\left\{ [\rho\phi]_{t+\Delta t} - [\rho\phi]_t \right\} \Delta V_o = \rho \Delta V_o [\phi_t - \phi_{t,o}]$$

With the uniformity assumption,

$$\left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \Gamma A \frac{\partial}{\partial x}(\phi) \right]_w = \Gamma A \left[ \frac{\partial}{\partial x}(\phi) \right]_e - \Gamma A \left[ \frac{\partial}{\partial x}(\phi) \right]_w = \Gamma A \left\{ \left[ \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \frac{\partial}{\partial x}(\phi) \right]_w \right\}$$

The source term is assumed to be uniform throughout a single grid much like  $\phi$  and is then simplified to,

$$\int_t^{t+\Delta t} \int_{CV} S_\phi dV_o dt = \int_t^{t+\Delta t} S_\phi \Delta V_o dt$$

Substituting for all of these simplifications,

$$\rho [\phi_{t+\Delta t} - \phi_t] \Delta V_o = \int_t^{t+\Delta t} \Gamma A \left\{ \left[ \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \frac{\partial}{\partial x}(\phi) \right]_w \right\} dt + \int_t^{t+\Delta t} S_\phi \Delta V_o dt$$

$$\rho [\phi_{t+\Delta t} - \phi_t] \Delta V_o = \Gamma A \int_t^{t+\Delta t} \left[ \frac{\partial}{\partial x}(\phi) \right]_e - \left[ \frac{\partial}{\partial x}(\phi) \right]_w dt + \Delta V_o \int_t^{t+\Delta t} S_\phi dt$$

#### 6.2.0.1 Interior Cells

For the interior cells, the spatial derivative  $\frac{\partial}{\partial x}(\phi)$  is computed using central differencing. Therefore,

$$\left[ \frac{\partial}{\partial x}(\phi) \right]_e = \frac{\phi_E - \phi_P}{\delta x_{EP}} \quad , \quad \left[ \frac{\partial}{\partial x}(\phi) \right]_w = \frac{\phi_P - \phi_W}{\delta x_{PW}}$$

Substituting for the definitions of these spatial derivatives,

$$\rho [\phi_{t+\Delta t} - \phi_t] \Delta V_o = \Gamma A \int_t^{t+\Delta t} \frac{\phi_E - \phi_P}{\delta x_{EP}} - \frac{\phi_P - \phi_W}{\delta x_{PW}} dt + \Delta V_o \int_t^{t+\Delta t} S_\phi dt$$

Re-arranging the equation,

$$\rho [\phi_{t+\Delta t} - \phi_t] \Delta V_o = \Gamma A \int_t^{t+\Delta t} \frac{1}{\delta x_{EP}} \phi_E - \frac{1}{\delta x_{EP}} \phi_P - \frac{1}{\delta x_{PW}} \phi_P + \frac{1}{\delta x_{PW}} \phi_W dt + \Delta V_o \int_t^{t+\Delta t} S_\phi dt$$

$$\rho [\phi_{t+\Delta t} - \phi_t] \Delta V_o = \Gamma A \int_t^{t+\Delta t} \frac{1}{\delta x_{EP}} \phi_E - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] \phi_P + \frac{1}{\delta x_{PW}} \phi_W dt + \Delta V_o \int_t^{t+\Delta t} S_\phi dt$$

The time integration approximation for  $\phi$  with respect to time is shown below,

$$\int_t^{t+\Delta t} \phi dt = [\theta \phi_{t+\Delta t} + (1 - \theta) \phi_t] \Delta t$$

Using a change of notation,

$$\int_t^{t+\Delta t} \phi_i dt = [\theta \phi_i + (1 - \theta) \phi_{i,o}] \Delta t$$

wherein the subscript  $i$  would represent some point in the grids,  $\phi_i$  represents the value of  $\phi$  at the new time step meanwhile  $\phi_{i,o}$  represents the value of  $\phi$  at the old time step.

Substituting for the integration scheme,

$$\begin{aligned} \rho [\phi_t - \phi_{t,o}] \Delta V_o = & \Gamma A \Delta t \left\{ \frac{1}{\delta x_{EP}} [\theta \phi_E + (1 - \theta) \phi_{E,o}] - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] [\theta \phi_P + (1 - \theta) \phi_{P,o}] \right. \\ & \left. + \frac{1}{\delta x_{PW}} [\theta \phi_W + (1 - \theta) \phi_{W,o}] \right\} + \Delta V_o \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

The finite volume could be expressed in terms of area  $A$  and grid size,  $\Delta V_o = A \delta_{ew}$ .

Substituting for this,

$$\begin{aligned} \rho [\phi_t - \phi_{t,o}] A \delta_{ew} = & \Gamma A \Delta t \left\{ \frac{1}{\delta x_{EP}} [\theta \phi_E + (1 - \theta) \phi_{E,o}] - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] [\theta \phi_P + (1 - \theta) \phi_{P,o}] \right. \\ & \left. + \frac{1}{\delta x_{PW}} [\theta \phi_W + (1 - \theta) \phi_{W,o}] \right\} + A \delta_{ew} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Dividing both sides by  $A \Delta t$ ,

$$\begin{aligned} \rho [\phi_t - \phi_{t,o}] \frac{\delta_{ew}}{\Delta t} = & \Gamma \left\{ \frac{1}{\delta x_{EP}} [\theta \phi_E + (1 - \theta) \phi_{E,o}] - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] [\theta \phi_P + (1 - \theta) \phi_{P,o}] \right. \\ & \left. + \frac{1}{\delta x_{PW}} [\theta \phi_W + (1 - \theta) \phi_{W,o}] \right\} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Re-arranging the equation,

$$\begin{aligned} \frac{\rho \delta_{ew}}{\Delta t} \phi_t - \frac{\rho \delta_{ew}}{\Delta t} \phi_{t,o} = & \Gamma \left\{ \frac{1}{\delta x_{EP}} [\theta \phi_E + (1 - \theta) \phi_{E,o}] - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] [\theta \phi_P + (1 - \theta) \phi_{P,o}] \right. \\ & \left. + \frac{1}{\delta x_{PW}} [\theta \phi_W + (1 - \theta) \phi_{W,o}] \right\} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

$$\begin{aligned} \frac{\rho \delta_{ew}}{\Delta t} \phi_t - \frac{\rho \delta_{ew}}{\Delta t} \phi_{t,o} + \left[ \frac{\Gamma}{\delta x_{EP}} + \frac{\Gamma}{\delta x_{PW}} \right] [\theta \phi_P] = & \Gamma \left\{ \frac{1}{\delta x_{EP}} [\theta \phi_E + (1 - \theta) \phi_{E,o}] \right. \\ & - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] [(1 - \theta) \phi_{P,o}] \\ & \left. + \frac{1}{\delta x_{PW}} [\theta \phi_W + (1 - \theta) \phi_{W,o}] \right\} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Here  $\phi_t$  represents  $\phi_P$ , because the value of  $\phi$  is assumed to be uniform throughout the cell.

$$\begin{aligned} \frac{\rho\delta_{ew}}{\Delta t}\phi_P + \left[ \frac{\Gamma}{\delta x_{EP}} + \frac{\Gamma}{\delta x_{PW}} \right] [\theta\phi_P] = & \Gamma \left\{ \frac{1}{\delta x_{EP}} [\theta\phi_E + (1-\theta)\phi_{E,o}] \right. \\ & - \left[ \frac{1}{\delta x_{EP}} + \frac{1}{\delta x_{PW}} \right] [(1-\theta)\phi_{P,o}] \\ & \left. + \frac{1}{\delta x_{PW}} [\theta\phi_W + (1-\theta)\phi_{W,o}] \right\} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt + \frac{\rho\delta_{ew}}{\Delta t}\phi_{P,o} \end{aligned}$$

$$\begin{aligned} \frac{\rho\delta_{ew}}{\Delta t}\phi_P + \left[ \frac{\Gamma}{\delta x_{EP}} + \frac{\Gamma}{\delta x_{PW}} \right] [\theta\phi_P] = & \left\{ \frac{\Gamma}{\delta x_{EP}} [\theta\phi_E + (1-\theta)\phi_{E,o}] \right. \\ & - \left[ \frac{\Gamma}{\delta x_{EP}} + \frac{\Gamma}{\delta x_{PW}} \right] [(1-\theta)\phi_{P,o}] \\ & \left. + \frac{\Gamma}{\delta x_{PW}} [\theta\phi_W + (1-\theta)\phi_{W,o}] \right\} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt + \frac{\rho\delta_{ew}}{\Delta t}\phi_{P,o} \end{aligned}$$

$$\begin{aligned} \left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{EP}}\theta + \frac{\Gamma}{\delta x_{PW}}\theta \right] [\phi_P] = & \frac{\Gamma}{\delta x_{EP}} [\theta\phi_E + (1-\theta)\phi_{E,o}] \\ & + \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{EP}}(1-\theta) - \frac{\Gamma}{\delta x_{PW}}(1-\theta) \right] [\phi_{P,o}] \\ & + \frac{\Gamma}{\delta x_{PW}} [\theta\phi_W + (1-\theta)\phi_{W,o}] + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Let

$$a_W = \frac{\Gamma}{\delta x_{PW}} \quad , \quad a_E = \frac{\Gamma}{\delta x_{EP}} \quad , \quad a_{P,0} = \frac{\rho\delta_{ew}}{\Delta t} \quad , \quad a_P = a_{P,0} + a_E\theta + a_W\theta$$

Under the substitutions above, the expression becomes,

$$\begin{aligned} a_P\phi_P = & a_E[\theta\phi_E + (1-\theta)\phi_{E,o}] + [a_{P,0} - a_E(1-\theta) - a_W(1-\theta)] [\phi_{P,o}] \\ & + a_W[\theta\phi_W + (1-\theta)\phi_{W,o}] + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

When evaluating  $\phi$  at the new time step, the old time step would be considered a known quantity. Re-arranging the equation to place all of the known variables on *LHS* and the unknown variables at the *RHS*,

$$\begin{aligned} a_P\phi_P = & a_E\theta\phi_E + a_E(1-\theta)\phi_{E,o} + [a_{P,0} - a_E(1-\theta) - a_W(1-\theta)] [\phi_{P,o}] \\ & + a_W\theta\phi_W + a_W(1-\theta)\phi_{W,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \\ -a_E\theta\phi_E + a_P\phi_P - a_W\theta\phi_W = & a_E(1-\theta)\phi_{E,o} + [a_{P,0} - a_E(1-\theta) - a_W(1-\theta)] [\phi_{P,o}] \\ & + a_W(1-\theta)\phi_{W,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

### 6.2.0.2 Dirichlet Western Boundary Conditions

The expression for the interior cells before the declaration of definitions of  $a_W$ ,  $a_E$  and substitution is shown below,

$$\begin{aligned} \left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{EP}}\theta + \frac{\Gamma}{\delta x_{PW}}\theta \right] [\phi_P] &= \frac{\Gamma}{\delta x_{EP}}[\theta\phi_E + (1-\theta)\phi_{E,o}] \\ &+ \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{EP}}(1-\theta) - \frac{\Gamma}{\delta x_{PW}}(1-\theta) \right] [\phi_{P,o}] \\ &+ \frac{\Gamma}{\delta x_{PW}}[\theta\phi_W + (1-\theta)\phi_{W,o}] + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

When applying dirichlet boundary conditions to the cell that is closest to the origin of the coordinate system, several modifications must be made to the expression for the interior cells. Finite difference instead of central differencing is used at the left boundary of the first cell. This would mean the following change of variables to allow the formulation to be suitable at the boundaries,

$$\delta x_{PW} \rightarrow \delta x_{Pw} \quad , \quad \phi_W \rightarrow \phi_A \quad , \quad \phi_{W,o} \rightarrow \phi_{A,o}$$

The first change is to accomodate for the one-sided finite differencing at the west face, the second change is to accomodate for the boundary condition of  $\phi_A$  at the wall at the new time step and the third change is to accomodate for the boundary condition of  $\phi_{A,o}$  at the wall for the old time step. Substituting these changes into the expression,

$$\begin{aligned} \left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{EP}}\theta + \frac{\Gamma}{\delta x_{Pw}}\theta \right] [\phi_P] &= \frac{\Gamma}{\delta x_{EP}}[\theta\phi_E + (1-\theta)\phi_{E,o}] \\ &+ \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{EP}}(1-\theta) - \frac{\Gamma}{\delta x_{Pw}}(1-\theta) \right] [\phi_{P,o}] \\ &+ \frac{\Gamma}{\delta x_{Pw}}[\theta\phi_A + (1-\theta)\phi_{A,o}] + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Placing the unknown variables to the *LHS* and the known variables to *RHS*,

$$\begin{aligned} \left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{EP}}\theta + \frac{\Gamma}{\delta x_{Pw}}\theta \right] [\phi_P] &= \frac{\Gamma}{\delta x_{EP}}\theta\phi_E + \frac{\Gamma}{\delta x_{EP}}(1-\theta)\phi_{E,o} \\ &+ \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{EP}}(1-\theta) - \frac{\Gamma}{\delta x_{Pw}}(1-\theta) \right] [\phi_{P,o}] \\ &+ \frac{\Gamma}{\delta x_{Pw}}\theta\phi_A + \frac{\Gamma}{\delta x_{Pw}}(1-\theta)\phi_{A,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \\ \left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{EP}}\theta + \frac{\Gamma}{\delta x_{Pw}}\theta \right] [\phi_P] - \frac{\Gamma}{\delta x_{EP}}\theta\phi_E &= \frac{\Gamma}{\delta x_{EP}}(1-\theta)\phi_{E,o} \\ &+ \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{EP}}(1-\theta) - \frac{\Gamma}{\delta x_{Pw}}(1-\theta) \right] [\phi_{P,o}] \\ &+ \frac{\Gamma}{\delta x_{Pw}}\theta\phi_A + \frac{\Gamma}{\delta x_{Pw}}(1-\theta)\phi_{A,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Let

$$a_W = 0 \quad , \quad a_E = \frac{\Gamma}{\delta x_{EP}} \quad , \quad a_{P,0} = \frac{\rho\delta_{ew}}{\Delta t} \quad , \quad S_P = -\frac{\Gamma}{\delta x_{Pw}} \quad , \quad a_P = a_{P,0} + \theta(a_E + a_W - S_P)$$

Substituting these variables into the expression above,

$$-a_E\theta\phi_E + a_P\phi_P - a_W\phi_W = a_E(1-\theta)\phi_{E,o} + [a_{P,0} - a_E(1-\theta) + S_P(1-\theta)]\phi_{P,o} \\ - S_P\theta\phi_A - S_P(1-\theta)\phi_{A,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt$$

### 6.2.0.3 Dirichlet Eastern Boundary Conditions

The expression for the interior cells before the declaration of definitions of  $a_W$ ,  $a_E$  and substitution is shown below,

$$\left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{EP}}\theta + \frac{\Gamma}{\delta x_{PW}}\theta \right] [\phi_P] = \frac{\Gamma}{\delta x_{EP}} [\theta\phi_E + (1-\theta)\phi_{E,o}] \\ + \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{EP}}(1-\theta) - \frac{\Gamma}{\delta x_{PW}}(1-\theta) \right] [\phi_{P,o}] \\ + \frac{\Gamma}{\delta x_{PW}} [\theta\phi_W + (1-\theta)\phi_{W,o}] + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt$$

Much like in determining the eastern boundary condition, one-sided finite difference is employed to find the approximate derivative of  $\phi$  with respect to displacement  $x$  at the boundary. For the eastern boundary, the unknown boundary would be at the east face of the last cell. The change of variables would then be,

$$\delta x_{EP} \rightarrow \delta x_{eP} \quad , \quad \phi_E = \phi_B \quad , \quad \phi_{E,o} = \phi_{B,o}$$

The first change of variable is to accomodate for the one-sided finite difference wherein the distance between the node point  $P$  and the eastern face is  $\delta x_{eP}$  instead of the previous case wherein the distance between the node point  $P$  and the eastern node is  $\delta x_{EP}$ . The second change of variable is to accomodate for the boundary condition wherein the value of  $\phi$  at the right face of the last cell is  $\phi_B$ .  $\phi_B$  represents the value of  $\phi$  at the new time step meanwhile  $\phi_{B,o}$  represents the value of  $\phi$  at the old time step at the right boundary of the last cell. Substituting these change of variables to modify the interior cell formulation for the right boundary condition,

$$\left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{eP}}\theta + \frac{\Gamma}{\delta x_{PW}}\theta \right] [\phi_P] = \frac{\Gamma}{\delta x_{eP}} [\theta\phi_B + (1-\theta)\phi_{B,o}] \\ + \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{eP}}(1-\theta) - \frac{\Gamma}{\delta x_{PW}}(1-\theta) \right] [\phi_{P,o}] \\ + \frac{\Gamma}{\delta x_{PW}} [\theta\phi_W + (1-\theta)\phi_{W,o}] + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt$$

$$\left[ \frac{\rho\delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{eP}}\theta + \frac{\Gamma}{\delta x_{PW}}\theta \right] [\phi_P] = \frac{\Gamma}{\delta x_{eP}} [\theta\phi_B + (1-\theta)\phi_{B,o}] \\ + \left[ \frac{\rho\delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{eP}}(1-\theta) - \frac{\Gamma}{\delta x_{PW}}(1-\theta) \right] [\phi_{P,o}] \\ + \frac{\Gamma}{\delta x_{PW}}\theta\phi_W + \frac{\Gamma}{\delta x_{PW}}(1-\theta)\phi_{W,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt$$

Placing the unknown variables at *LHS* and the known variables at *RHS*,

$$\begin{aligned} \left[ \frac{\rho \delta_{ew}}{\Delta t} + \frac{\Gamma}{\delta x_{eP}} \theta + \frac{\Gamma}{\delta x_{PW}} \theta \right] [\phi_P] - \frac{\Gamma}{\delta x_{PW}} \theta \phi_W = & \frac{\Gamma}{\delta x_{eP}} [\theta \phi_B + (1 - \theta) \phi_{B,o}] \\ & + \left[ \frac{\rho \delta_{ew}}{\Delta t} - \frac{\Gamma}{\delta x_{eP}} (1 - \theta) - \frac{\Gamma}{\delta x_{PW}} (1 - \theta) \right] [\phi_{P,o}] \\ & + \frac{\Gamma}{\delta x_{PW}} (1 - \theta) \phi_{W,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

Let

$$\begin{aligned} a_W = \frac{\Gamma}{\delta x_{PW}} \quad , \quad a_E = 0 \quad , \quad a_{P,0} = \frac{\rho \delta_{ew}}{\Delta t} \quad , \quad S_P = -\frac{\Gamma}{\delta x_{eP}} \quad , \quad a_P = a_{P,0} + \theta(a_E + a_W - S_P) \\ -a_E \theta \phi_E + a_P \phi_P - a_W \theta \phi_W = -S_P [\theta \phi_B + (1 - \theta) \phi_{B,o}] + [a_{P,0} + S_P (1 - \theta) - a_W (1 - \theta)] [\phi_{P,o}] \\ + a_W (1 - \theta) \phi_{W,o} + \frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt \end{aligned}$$

### 6.2.1 Part c

The workings in the previous section is performed with the arbitray scalar function  $\phi$ , and the arbitrary variables  $\rho$  and  $\Gamma$ . The source term  $\int_t^{t+\Delta t} S_\phi dt$  has not been specified. In this section, the arbitrary variables will be mapped to the problem variables to apply all the formulations to the fortran program.

Geometrically, the variable  $x$  could be re-interpreted in this problem to be vertical displacement  $y$ . This would set the western boundary condition of the arbitray  $\phi$  case to be the bottom boundary condition in the momentum diffusion problem. The eastern boundary condition of the arbitrary  $\phi$  case would be set to the top boundary condition in the momentum diffusion problem. Let positive direction of  $y$  then also be interpreted going "up" in the vertical direction. The top wall of the channel would be at positive  $H$   $y$ -value. The unsteady momentum governing equation for this problem is shown below,

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} - \frac{1}{\rho} \frac{\partial p}{\partial x}$$

wherein  $\rho$  represents density and  $\nu$  represents viscosity. The unsteady diffusion equation that is the basis of the previous formulation is shown below,

$$\frac{\partial}{\partial t}(\rho \phi) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi$$

Under the 1-dimensional assumption and uniformity of  $\rho$  as well as  $\Gamma$ ,

$$\begin{aligned} \rho \frac{\partial}{\partial t}(\phi) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi = \frac{\partial}{\partial x} \left[ \Gamma \frac{\partial}{\partial x}(\phi) \right] + S_\phi = \Gamma \frac{\partial^2}{\partial x^2}(\phi) + S_\phi \\ \frac{\partial}{\partial t}(\phi) = \frac{\Gamma}{\rho} \frac{\partial^2}{\partial x^2}(\phi) + \frac{S_\phi}{\rho} \end{aligned}$$

By comparing the differential forms of the unsteady diffusion equation and unsteady momentum governing equation,

$$\phi = u \quad , \quad x = y \quad , \quad \frac{\Gamma}{\rho \phi} = \nu \quad , \quad \frac{S_\phi}{\rho \phi} = -\frac{1}{\rho_{prob}} \frac{\partial p}{\partial x}$$

Distinction has been made between  $\rho_\phi$  and  $\rho_{prob}$ .  $\rho_\phi$  represents the value of the arbitrary variable  $\rho$  in the general unsteady diffusion equation meanwhile  $\rho_{prob}$  represents the fluid density in the momentum diffusion problem. Since  $\phi$  is a scalar field, and velocity  $u$  is typically a scalar, here  $u$  is assumed to be the magnitude of the horizontal velocity of the fluid, so that it could be represented by  $\phi$ . In the momentum diffusion problem, the density of the fluid is assumed to remain constant and the derivative of pressure along the horizontal distance of the channel is assumed to be constant. Therefore,  $S_\phi$  must also be a constant,

$$\frac{S_\phi}{\rho_\phi} = -\frac{1}{\rho_{prob}} \frac{\partial p}{\partial x}$$

$$S_\phi = -\frac{\rho_\phi}{\rho_{prob}} \frac{\partial p}{\partial x}$$

Given that  $S_\phi$  is some constant that could be determined by the momentum diffusion problem definition,

$$\frac{\delta_{ew}}{\Delta t} \int_t^{t+\Delta t} S_\phi dt = \frac{\delta_{ew}}{\Delta t} S_\phi [t]_t^{t+\Delta t} = \frac{\delta_{ew}}{\Delta t} S_\phi [(t + \Delta t) - (t)] = \frac{\delta_{ew}}{\Delta t} S_\phi \Delta t = \delta_{ew} S_\phi$$

There exists a non-unique way to choose the variable mappings for  $\rho_\phi$ ,  $\Gamma$ . For a simple implementation of the general diffusion problem into the momentum diffusion, let  $\rho_\phi = 1$ . Therefore,

$$\phi = u \quad , \quad x = y \quad , \quad \Gamma = \nu \quad , \quad S_\phi = -\frac{1}{\rho_{prob}} \frac{\partial p}{\partial x}$$

The code was modified to simulate unsteady diffusion of momentum and given a few additional features. The modified fortran code is shown below,

## 6.3 Fourier Stability Analysis

### 6.3.1 Discretization of Wave Equation

The one-dimensional wave equation is shown below,

$$0 = \frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x}$$

Integrating with time and space,

$$0 = \int_t^{t+\Delta t} \int_{CV} \frac{\partial \phi}{\partial t} dV dt + u \int_t^{t+\Delta t} \int_{CV} \frac{\partial \phi}{\partial x} dV dt$$

Switching the order of integration in order to form exact differentials,

$$0 = \int_{CV} \int_t^{t+\Delta t} \frac{\partial \phi}{\partial t} dt dV + u \int_t^{t+\Delta t} \int_{CV} \frac{\partial \phi}{\partial x} dV dt$$

$$0 = \int_{CV} [\phi]_t^{t+\Delta t} dV + u \int_t^{t+\Delta t} A [\phi]_{CV} dt$$

$$0 = [\phi]_t^{t+\Delta t} \Delta V + u \int_t^{t+\Delta t} A \phi_e - A \phi_w dt$$



Substituting for the infinitesimally small volume  $\Delta V = A dx$ ,

$$0 = [\phi]_t^{t+\Delta t} A dx + u \int_t^{t+\Delta t} A \phi_e - A \phi_w dt$$

Assuming uniform area throughout the grids,

$$0 = [\phi]_t^{t+\Delta t} dx + u \int_t^{t+\Delta t} \phi_e - \phi_w dt$$

Assuming that the value of  $\phi$  is constant within a single cell,

$$0 = [\phi_P - \phi_{P,o}] dx + u \int_t^{t+\Delta t} \phi_e - \phi_w dt$$

Using the generalized time integration scheme,

$$\int_t^{t+\Delta t} \phi dt = [\theta \phi_{t+\Delta t} + (1 - \theta) \phi_t] \Delta t$$

Substituting the time integration scheme,

$$0 = [\phi_P - \phi_{P,o}] dx + u \{ \theta \phi_e + (1 - \theta) \phi_{e,o} - \theta \phi_w - (1 - \theta) \phi_{w,o} \} dt$$

Factoring for the CFL number,

$$0 = [\phi_P - \phi_{P,o}] \frac{dx}{u dt} + \{ \theta \phi_e + (1 - \theta) \phi_{e,o} - \theta \phi_w - (1 - \theta) \phi_{w,o} \}$$

$$0 = [\phi_P - \phi_{P,o}] \frac{\Delta x}{u \Delta t} + \theta \phi_e + (1 - \theta) \phi_{e,o} - \theta \phi_w - (1 - \theta) \phi_{w,o}$$

Let

$$\gamma = \frac{1}{CFL} = \frac{\Delta x}{u \Delta t}$$

$$0 = \gamma \phi_P - \gamma \phi_{P,o} + \theta \phi_e + (1 - \theta) \phi_{e,o} - \theta \phi_w - (1 - \theta) \phi_{w,o}$$

Placing the new time step quantities on *LHS* and the old time step quantities on *RHS*,

$$-\gamma \phi_P + \theta \phi_w - \theta \phi_e = -\gamma \phi_{P,o} + (1 - \theta) \phi_{e,o} - (1 - \theta) \phi_{w,o}$$

### 6.3.2 Cubic Polynomial Spatial Scheme

The discretization of the pure convection problem with a generalized time advancement scheme and a cubic polynomial spatial advancement scheme is shown below,

$$\begin{aligned} 0 = & \frac{\phi_P - \phi_{P,o}}{\Delta t} + \frac{u}{\Delta x} \left[ \theta \left( \frac{1}{16} \phi_{WW} - \frac{5}{16} \phi_W + \frac{15}{16} \phi_P + \frac{5}{16} \phi_E \right) \right. \\ & + (1 - \theta) \left( \frac{1}{16} \phi_{WW,o} - \frac{5}{16} \phi_{W,o} + \frac{15}{16} \phi_{P,o} + \frac{5}{16} \phi_{E,o} \right) \\ & - \theta \left( \frac{1}{16} \phi_{WWW} - \frac{5}{16} \phi_{WW} + \frac{15}{16} \phi_W + \frac{5}{16} \phi_P \right) \\ & \left. - (1 - \theta) \left( \frac{1}{16} \phi_{WWW,o} - \frac{5}{16} \phi_{WW,o} + \frac{15}{16} \phi_{W,o} + \frac{5}{16} \phi_{P,o} \right) \right] \end{aligned}$$

Assuming that the solution  $\phi(x, t)$  is a product of a time component  $\hat{\phi}(t)$  and a spatial component  $e^{ikx}$ , the solution  $\phi(x, t)$  could be rewritten as,

$$\phi(x, t) = \hat{\phi}(t)e^{ikx}$$

Points at the future time step would be given the time component shown below,

$$\hat{\phi}(t + \Delta t) = \hat{\phi}$$

Points at the old time step would be given the time component shown below,

$$\hat{\phi}(t) = \hat{\phi}_o$$

Following convention, the coordinate system considers eastern direction of the grid points to be positive  $x$  and western direction of the grid points to be negative  $x$ . The point of interest  $P$  would be given a spatial component  $e^{ikx}$ . Following the coordinate system definition, the west point would be given spatial component  $e^{ik(x-\Delta x)}$ . The east point would be given spatial component  $e^{ik(x+\Delta x)}$ . The diagram below summarizes the coordinate system used in this derivation, Uniform grid spacing is assumed in the following derivation. Parsing the original expression into several parts. For the discrete derivative of  $\phi$  with respect to time,

$$\frac{\phi_P - \phi_{P,o}}{\Delta t} = \frac{1}{\Delta t} [\phi_P - \phi_{P,o}] = \frac{1}{\Delta t} [\hat{\phi}e^{ikx} - \hat{\phi}_oe^{ikx}] = \frac{e^{ikx}}{\Delta t} [\hat{\phi} - \hat{\phi}_o]$$

For the first part of *RHS*,

$$\begin{aligned} \frac{1}{16}\phi_{WW} - \frac{5}{16}\phi_W + \frac{15}{16}\phi_P + \frac{5}{16}\phi_E &= \frac{1}{16}\hat{\phi}e^{ik(x-2\Delta x)} - \frac{5}{16}\hat{\phi}e^{ik(x-\Delta x)} \\ &\quad + \frac{15}{16}\hat{\phi}e^{ikx} + \frac{5}{16}\hat{\phi}e^{ik(x+\Delta x)} \end{aligned}$$

$$\begin{aligned} \frac{1}{16}\phi_{WW} - \frac{5}{16}\phi_W + \frac{15}{16}\phi_P + \frac{5}{16}\phi_E &= \frac{1}{16}\hat{\phi}e^{ikx-2ik\Delta x} - \frac{5}{16}\hat{\phi}e^{ikx-ik\Delta x} \\ &\quad + \frac{15}{16}\hat{\phi}e^{ikx} + \frac{5}{16}\hat{\phi}e^{ikx+ik\Delta x} \end{aligned}$$

$$\begin{aligned} \frac{1}{16}\phi_{WW} - \frac{5}{16}\phi_W + \frac{15}{16}\phi_P + \frac{5}{16}\phi_E &= \frac{1}{16}\hat{\phi}e^{ikx}e^{-2ik\Delta x} - \frac{5}{16}\hat{\phi}e^{ikx}e^{-ik\Delta x} \\ &\quad + \frac{15}{16}\hat{\phi}e^{ikx} + \frac{5}{16}\hat{\phi}e^{ikx}e^{ik\Delta x} \end{aligned}$$

$$\frac{1}{16}\phi_{WW} - \frac{5}{16}\phi_W + \frac{15}{16}\phi_P + \frac{5}{16}\phi_E = \hat{\phi}e^{ikx} \left[ \frac{1}{16}e^{-2ik\Delta x} - \frac{5}{16}e^{-ik\Delta x} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} \right]$$

Performing similar operations for the second part of *RHS*,

$$\frac{1}{16}\phi_{WW,o} - \frac{5}{16}\phi_{W,o} + \frac{15}{16}\phi_{P,o} + \frac{5}{16}\phi_{E,o} = \hat{\phi}_oe^{ikx} \left[ \frac{1}{16}e^{-2ik\Delta x} - \frac{5}{16}e^{-ik\Delta x} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} \right]$$

Performing similar operations for the third part of *RHS*,

$$\frac{1}{16}\phi_{WWW} - \frac{5}{16}\phi_{WW} + \frac{15}{16}\phi_W + \frac{5}{16}\phi_P = \hat{\phi}e^{ikx} \left[ \frac{1}{16}e^{-3ik\Delta x} - \frac{5}{16}e^{-2ik\Delta x} + \frac{15}{16}e^{-ik\Delta x} + \frac{5}{16} \right]$$

Performing similar operations for the fourth part of *RHS*,

$$\frac{1}{16}\phi_{WWW,o} - \frac{5}{16}\phi_{WW,o} + \frac{15}{16}\phi_{W,o} + \frac{5}{16}\phi_{P,o} = \hat{\phi}_oe^{ikx} \left[ \frac{1}{16}e^{-3ik\Delta x} - \frac{5}{16}e^{-2ik\Delta x} + \frac{15}{16}e^{-ik\Delta x} + \frac{5}{16} \right]$$

Let

$$A = \frac{1}{16}e^{-2ik\Delta x} - \frac{5}{16}e^{-ik\Delta x} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} \quad , \quad B = \frac{1}{16}e^{-3ik\Delta x} - \frac{5}{16}e^{-2ik\Delta x} + \frac{15}{16}e^{-ik\Delta x} + \frac{5}{16}$$

Substituting for  $A$  and  $B$  shortens the expressions,

$$\begin{aligned} \frac{1}{16}\phi_{WW} - \frac{5}{16}\phi_W + \frac{15}{16}\phi_P + \frac{5}{16}\phi_E &= \hat{\phi}e^{ikx}A \\ \frac{1}{16}\phi_{WW,o} - \frac{5}{16}\phi_{W,o} + \frac{15}{16}\phi_{P,o} + \frac{5}{16}\phi_{E,o} &= \hat{\phi}_oe^{ikx}A \\ \frac{1}{16}\phi_{WWW} - \frac{5}{16}\phi_{WW} + \frac{15}{16}\phi_W + \frac{5}{16}\phi_P &= \hat{\phi}e^{ikx}B \\ \frac{1}{16}\phi_{WWW,o} - \frac{5}{16}\phi_{WW,o} + \frac{15}{16}\phi_{W,o} + \frac{5}{16}\phi_{P,o} &= \hat{\phi}_oe^{ikx}B \end{aligned}$$

Substituting the simplified parts into the original expression,

$$\begin{aligned} 0 &= \frac{e^{ikx}}{\Delta t} [\hat{\phi} - \hat{\phi}_o] + \frac{u}{\Delta x} \left[ \theta (\hat{\phi}e^{ikx}A) + (1-\theta) (\hat{\phi}_oe^{ikx}A) - \theta (\hat{\phi}e^{ikx}B) - (1-\theta) (\hat{\phi}_oe^{ikx}B) \right] \\ 0 &= \frac{e^{ikx}}{\Delta t} [\hat{\phi} - \hat{\phi}_o] + \frac{u}{\Delta x} [\theta \hat{\phi}e^{ikx}A + (1-\theta)\hat{\phi}_oe^{ikx}A - \theta \hat{\phi}e^{ikx}B - (1-\theta)\hat{\phi}_oe^{ikx}B] \end{aligned}$$

Since  $e^{ikx} \neq 0$ ,

$$\begin{aligned} 0 &= \frac{1}{\Delta t} [\hat{\phi} - \hat{\phi}_o] + \frac{u}{\Delta x} [\theta \hat{\phi}A + (1-\theta)\hat{\phi}_oA - \theta \hat{\phi}B - (1-\theta)\hat{\phi}_oB] \\ 0 &= \frac{\Delta x}{u \Delta t} [\hat{\phi} - \hat{\phi}_o] + \theta \hat{\phi}A + (1-\theta)\hat{\phi}_oA - \theta \hat{\phi}B - (1-\theta)\hat{\phi}_oB \end{aligned}$$

Let

$$\gamma = \frac{1}{CFL} = \frac{\Delta x}{u \Delta t}$$

Substituting for the parameter  $\gamma$ ,

$$\begin{aligned} 0 &= \gamma \hat{\phi} - \gamma \hat{\phi}_o + \theta \hat{\phi}A + (1-\theta)\hat{\phi}_oA - \theta \hat{\phi}B - (1-\theta)\hat{\phi}_oB \\ \gamma \hat{\phi}_o - (1-\theta)\hat{\phi}_oA + (1-\theta)\hat{\phi}_oB &= \gamma \hat{\phi} + \theta \hat{\phi}A - \theta \hat{\phi}B \\ \hat{\phi} [\gamma + \theta A - \theta B] &= \hat{\phi}_o [\gamma - (1-\theta)A + (1-\theta)B] \\ \frac{\hat{\phi}}{\hat{\phi}_o} &= \frac{[\gamma - (1-\theta)A + (1-\theta)B]}{[\gamma + \theta A - \theta B]} = \frac{\gamma + (\theta-1)A + (1-\theta)B}{\gamma + \theta A - \theta B} = \frac{\gamma + \theta A - A + B - \theta B}{\gamma + \theta A - \theta B} \\ \frac{\hat{\phi}}{\hat{\phi}_o} &= \frac{\gamma - A + B + \theta A - \theta B}{\gamma + \theta A - \theta B} = \frac{\gamma - (A-B) + \theta(A-B)}{\gamma + \theta(A-B)} \end{aligned}$$

Let  $\alpha = A - B$ . Simplifying,

$$\begin{aligned} \alpha &= \frac{1}{16}e^{-2ik\Delta x} - \frac{5}{16}e^{-ik\Delta x} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} - \left( \frac{1}{16}e^{-3ik\Delta x} - \frac{5}{16}e^{-2ik\Delta x} + \frac{15}{16}e^{-ik\Delta x} + \frac{5}{16} \right) \\ \alpha &= \frac{1}{16}e^{-2ik\Delta x} - \frac{5}{16}e^{-ik\Delta x} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} - \frac{1}{16}e^{-3ik\Delta x} + \frac{5}{16}e^{-2ik\Delta x} - \frac{15}{16}e^{-ik\Delta x} - \frac{5}{16} \end{aligned}$$

$$\begin{aligned}
\alpha &= -\frac{1}{16}e^{-3ik\Delta x} + \frac{1}{16}e^{-2ik\Delta x} + \frac{5}{16}e^{-2ik\Delta x} - \frac{5}{16}e^{-ik\Delta x} - \frac{15}{16}e^{-ik\Delta x} - \frac{5}{16} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} \\
\alpha &= -\frac{1}{16}e^{-3ik\Delta x} + \left[\frac{1}{16} + \frac{5}{16}\right]e^{-2ik\Delta x} - \left[\frac{5}{16} + \frac{15}{16}\right]e^{-ik\Delta x} - \frac{5}{16} + \frac{15}{16} + \frac{5}{16}e^{ik\Delta x} \\
\alpha &= -\frac{1}{16}e^{-3ik\Delta x} + \left[\frac{6}{16}\right]e^{-2ik\Delta x} - \left[\frac{20}{16}\right]e^{-ik\Delta x} + \frac{10}{16} + \frac{5}{16}e^{ik\Delta x} \\
\alpha &= -\frac{1}{16}e^{-3ik\Delta x} + \frac{6}{16}e^{-2ik\Delta x} - \frac{20}{16}e^{-ik\Delta x} + \frac{10}{16} + \frac{5}{16}e^{ik\Delta x}
\end{aligned}$$

Substituting for  $\alpha$ ,

$$\frac{\hat{\phi}}{\hat{\phi}_o} = \frac{\gamma - \alpha + \theta\alpha}{\gamma + \theta\alpha}$$

### 6.3.3 Upwind Differencing Scheme

The theoretical section shows that discretizing the 1-dimensional wave equation yields the following expression,

$$-\gamma\phi_P + \theta\phi_w - \theta\phi_e = -\gamma\phi_{P,o} + (1 - \theta)\phi_{e,o} - (1 - \theta)\phi_{w,o}$$

Assuming upwing differencing,

$$\phi_w = \phi_W \quad , \quad \phi_e = \phi_P$$

Substituting for this,

$$-\gamma\phi_P + \theta\phi_W - \theta\phi_P = -\gamma\phi_{P,o} + (1 - \theta)\phi_{P,o} - (1 - \theta)\phi_{W,o}$$

Simplifying,

$$\phi_P [-\gamma - \theta] + \theta\phi_W = \phi_{P,o} [-\gamma + (1 - \theta)] - (1 - \theta)\phi_{W,o}$$

Substituting the Fourier representaiton of the solution,  $\phi = \hat{\phi}e^{ikx}$ ,

$$\begin{aligned}
\hat{\phi}e^{ikx} [-\gamma - \theta] + \theta\hat{\phi}e^{ik(x-\Delta x)} &= \hat{\phi}_oe^{ikx} [-\gamma + (1 - \theta)] - (1 - \theta)\hat{\phi}_oe^{ik(x-\Delta x)} \\
\hat{\phi}e^{ikx} [-\gamma - \theta] + \theta\hat{\phi}e^{ikx-ik\Delta x} &= \hat{\phi}_oe^{ikx} [-\gamma + (1 - \theta)] - (1 - \theta)\hat{\phi}_oe^{ikx-ik\Delta x} \\
\hat{\phi}e^{ikx} [-\gamma - \theta] + \theta\hat{\phi}e^{ikx}e^{-ik\Delta x} &= \hat{\phi}_oe^{ikx} [-\gamma + (1 - \theta)] - (1 - \theta)\hat{\phi}_oe^{ikx}e^{-ik\Delta x} \\
\hat{\phi}e^{ikx} \left\{ [-\gamma - \theta] + \theta e^{-ik\Delta x} \right\} &= \hat{\phi}_oe^{ikx} \left\{ [-\gamma + (1 - \theta)] - (1 - \theta)e^{-ik\Delta x} \right\}
\end{aligned}$$

Since  $e^{ikx} \neq 0$  for all values of  $x$ ,

$$\hat{\phi} \left\{ [-\gamma - \theta] + \theta e^{-ik\Delta x} \right\} = \hat{\phi}_o \left\{ [-\gamma + (1 - \theta)] - (1 - \theta)e^{-ik\Delta x} \right\}$$

$$\begin{aligned}
\frac{\hat{\phi}}{\hat{\phi}_o} &= \frac{\left\{ [-\gamma + (1 - \theta)] - (1 - \theta)e^{-ik\Delta x} \right\}}{\left\{ [-\gamma - \theta] + \theta e^{-ik\Delta x} \right\}} \\
\frac{\hat{\phi}}{\hat{\phi}_o} &= \frac{\left\{ [\gamma - (1 - \theta)] + (1 - \theta)e^{-ik\Delta x} \right\}}{\left\{ [\gamma + \theta] - \theta e^{-ik\Delta x} \right\}}
\end{aligned}$$

$$\frac{\hat{\phi}}{\hat{\phi}_o} = \frac{\{\gamma - 1 + \theta + (1 - \theta)e^{-ik\Delta x}\}}{\{\gamma + \theta - \theta e^{-ik\Delta x}\}}$$

$$\frac{\hat{\phi}}{\hat{\phi}_o} = \frac{\gamma - 1 + \theta + (1 - \theta)e^{-ik\Delta x}}{\gamma + \theta (1 - e^{-ik\Delta x})}$$

The amplification factor for the polynomial interpolation as well as the upwind differencing is implemented into the Matlab script. The matlab script was modified to accomodate multiple plots in a single figure and write the maximum amplification factor to a file. The matlab script is shown below,

# Chapter 7

## Inviscid Incompressible Flow

### 7.1 Thin Airfoil Theory

An infinitely long wing could be considered a 2-dimensional problem. The thin airfoil theory also incorporates all vortices generated by the viscous boundary layer as a line of free-stream vortices on the mean camber line of the airfoil. The vortices extend parallel in the spanwise direction. The thin airfoil theory differentiates between different geometries of an airfoil.

#### 7.1.1 Derivation and Theorem-Specific Coefficients

A coordinate change is used in this theorem to express  $x$  in terms of  $\theta_d$  wherein  $x$  represents the horizontal distance from the leading edge of the airfoil and  $\theta_d$  is the change of coordinates variable that is used to represent  $x$ . Here,  $c$  represents the chord length of the airfoil. The relationship between  $x$  and  $\theta_d$  is shown below,

$$x = \frac{c}{2}[1 - \cos(\theta_d)] \quad , \quad 0 \leq \theta_d \leq \pi$$

Conversely  $\theta_d$  in terms of  $x$ ,

$$\frac{2x}{c} = 1 - \cos(\theta_d)$$

$$\cos(\theta_d) = 1 - \frac{2x}{c}$$

$$\theta_d = \arccos \left[ 1 - \frac{2x}{c} \right] \quad , \quad 0 \leq x \leq c$$

The coefficients  $A_0$  and  $A_n$  are shown below,

$$A_0 = \alpha - \frac{1}{\pi} \int_0^\pi \frac{dz}{dx} d\theta_d \quad , \quad A_n = \frac{2}{\pi} \int_0^\pi \frac{dz}{dx} \cos(n\theta_d) d\theta_d$$

wherein  $\alpha$  represents angle of attack of the specific airfoil.

#### 7.1.2 Lift

The equation for the coefficient of lift  $C_L$  is shown below,

$$C_L = 2\pi \left( A_0 + \frac{A_1}{2} \right) = 2\pi (\alpha - \alpha_0)$$

wherein  $\alpha_0$  represents the angle of attack for the airfoil when lift is zero.

### 7.1.3 Moments

The moments about the aerodynamic center of the airfoil,

$$C_{M,ac} = C_{M,c/4} = \frac{\pi}{4}(A_2 - A_1)$$

wherein  $C_M$  represent the moments coefficient and the subscript  $ac$  represents at the aerodynamic center. Since the aerodynamic center is assumed to be quarter chord of the airfoil, the coefficients of moments at the aerodynamic center is identical to the coefficient of moments at the quarter chord of the airfoil. The coefficients  $A_1$  and  $a_2$  are obtainable via the equations above.

### 7.1.4 Limitations

The thin airfoil theory fails at thicker airfoils, also, could not predict drag. The theory also fails to predict stall since the airflow is assumed to be inviscid. The theorem can only be used to find lift and pitching coefficient.

### 7.1.5 Other Implications

## 7.2 Lifting Line Theory

An early attempt at describing the behaviours of a finite wing. Uniquely the lifting line theory incorporates free-stream vortices in a 'u'-shape. Firstly in the configuration of a horse-shoe vortex, and in more advanced interpretation, as a bunch of horse-shoe vortices superimposed on top of each other along the 'lifting-line'. The lifting line theory differentiates could only take into account the total effect of airfoil twist, geometry and perhaps deployed flaps instead of each individual effect. The total factor of those effects affect the free-stream vortex distribution along the 'lifting-line'.

### 7.2.1 Lift

Based on the Kutta-Joukowski theorem,

$$\frac{dL}{dy} = \rho_{\infty} v_{\infty} \Gamma(y)$$

wherein  $\rho_{\infty}$  represents the free stream density of the airflow,  $v_{\infty}$  represents free stream velocity and  $\Gamma(y)$  represents the vortex strength at some point along the wing. Integrating the expression above,

$$L = \rho_{\infty} v_{\infty} \int_{-b/2}^{b/2} \Gamma(y) dy$$

wherein  $b$  represents the full wingspan. The coordinate as per usual is nested on the root of the wing at the leading edge of the main wing. The  $x$ -direction is parallel to the chord line, the  $y$ -direction is parallel to the span length, and  $z$ -direction is vertical.

### 7.2.2 Drag

Since the fluid is inviscid, there is no drag due to viscosity, or flow separation. In the lifting line theory, then the drag is purely induced drag. Induced drag is caused by the "downwash"

of the wing causing a slightly altered angle of attack. This causes the lift force to tilt backwards slightly, contributing to drag. Since this phenomenon only exists due to the existence of downwash which in turn is due to lift generation, induced drag is also known as lift-induced drag. The formula for induced drag is below,

$$D_i = \rho_\infty v_\infty \int_{-b/2}^{b/2} \Gamma(y) \alpha_i(y) dy$$

wherein the induced angle of attack  $\alpha_i$  is determined by the downwash and free stream velocity. The downwash in turn is determined by integrating the vortex distribution via biot-savart law.

$$\alpha_i(y) = \arctan \left[ \frac{-w(y)}{v_\infty} \right]$$

Due to the small angle approximation or taking the first order taylor approximation,  $\lim_{x \rightarrow 0} [\tan(x)] = x$ . By the small angle, approximation, then,

$$\alpha_i(y) \approx -\frac{w(y)}{v_\infty}$$

Substituting for the definition of downwash  $w(y)$ ,

$$w(y) = -\frac{1}{4\pi} \int_{-b/2}^{b/2} \frac{1}{y - y_d} \frac{d\Gamma}{dy} dy_d$$

wherein  $y_d$  represents a dummy variable that is used for integration purposes only.

$$\alpha_i(y) \approx \frac{1}{4\pi v_\infty} \int_{-b/2}^{b/2} \frac{1}{y - y_d} \frac{d\Gamma}{dy} dy_d$$

### 7.2.3 Elliptical Vortex Distribution Wing

By using the vortex distribution,

$$\Gamma(y) = \Gamma_0 \sqrt{1 - \left( \frac{2y}{b} \right)^2}$$

The results of performing the steps above and performing the relevant substitutions,

$$\alpha_i = \frac{\Gamma_0}{2bv_\infty} \quad , \quad C_L = \alpha_i \pi A_R \quad , \quad C_{Di} = \frac{C_L^2}{\pi A_R}$$

wherein  $A_R$  represents aspect ratio, and  $b$  represents total wingspan.

## 7.3 Static Longitudinal Stability

The coefficient of moments about the center of mass  $C_{M,cm}$  is shown below,

$$C_{M,cm} = C_{M,0} + C_{M,\alpha} \alpha_a$$

wherein  $C_{M,0}$  represents the coefficeint of moments about the center of mass when the absolute angle of attack is zero.  $\alpha_a$  represents the absolute angle of attack, which is the angle of attack of the airfoil starting at zero from the airfoil producing zero lift.  $C_{M,\alpha}$  represents the derivative of  $C_{M,cm}$  with respect to the absolute angle of attack  $\alpha_a$ . There are only 2 conditions for static longitudinal stability:



1.  $C_{M,0}$  must be a positive value
2.  $C_{M,\alpha}$  must be a negative value

# Chapter 8

## Inviscid Compressible Flow

### 8.1 Thermodynamic Relations

For an ideal gas,

$$p = \rho RT$$

wherein  $p$  represents pressure,  $\rho$  represents density, and  $T$  represents temperature in Kelvins. To compute the  $c_v$  and  $c_p$  constants,

$$c_p = \frac{\gamma R}{\gamma - 1} \quad , \quad c_v = \frac{R}{\gamma - 1}$$

wherein  $\gamma = \frac{c_p}{c_v}$ . The expression for enthalpy  $h$ ,

$$h = e + pv$$

Under the assumption that  $c_v$  and  $c_p$  as are constants,

$$e = c_v T \quad , \quad h = c_p T$$

Assuming no entropy generation via diffusion and that the coefficients  $c_v$  and  $c_p$  are constant,

$$s_2 - s_1 = c_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{p_2}{p_1} \right) \quad , \quad s_2 - s_1 = c_v \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{v_2}{v_1} \right)$$

wherein the subscript denotes the state of the fluid, and  $v$  represents specific volume, the reciprocal of density. Only for isentropic processes, the following is true,

$$\frac{p_2}{p_1} = \left( \frac{\rho_2}{\rho_1} \right)^\gamma = \left( \frac{T_2}{T_1} \right)^{\gamma/(\gamma-1)}$$

For flow that is steady, adiabatic, and inviscid, the following equation holds true,

$$h_0 = h + \frac{1}{2} v_f^2$$

wherein  $h_0$  represents stagnation enthalpy,  $h$  represents current enthalpy, and  $v_f$  represents fluid velocity. The equation above holds true for any two points in a single streamline that follows the conditions stated above.

## 8.2 Shock Relations

### 8.2.1 Normal Shocks

For normal shocks, there are 3 governing equations and 2 thermodynamical relationships that is applicable. For continuity, momentum and energy,

$$\rho_1 u_1 = \rho_2 u_2 \quad , \quad p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2 \quad , \quad h_1 + \frac{1}{2}u_1^2 = h_2 + \frac{1}{2}u_2^2$$

The thermodynamic relations,

$$h_2 = c_p T_2 \quad , \quad p_2 = \rho_2 R T_2$$

The speed of sound  $a$  as well as the Mach number  $M$  is given by the following equations,

$$a = \sqrt{\frac{\gamma p}{\rho}} = \sqrt{\gamma R T} \quad , \quad M = \frac{v_f}{a}$$

The 0 subscript is often used to symbolize stagnation conditions, wherein the small element of fluid is brought to rest adiabatically, the \* subscript is used to represent sonic conditions, wherein the small element of fluid is brought to sonic conditions. The equation relating speed of sound and the relationship between speed of sound and sonic speed of sound, as well as Mach and sonic Mach number,

$$\frac{a^2}{\gamma - 1} + \frac{1}{2}u^2 = \frac{\gamma + 1}{2(\gamma - 1)}a_*^2 \quad , \quad M_*^2 = \frac{(\gamma + 1)M^2}{2 + (\gamma - 1)M^2}$$

For calorically perfect gases, which is the assumption that  $c_v$  and  $c_p$  remain as constants, the general relations between temperature, pressure and density to their respective stagnation conditions,

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2}M^2 \quad , \quad \frac{p_0}{p} = \left[1 + \frac{\gamma - 1}{2}M^2\right]^{\gamma/(\gamma - 1)} \quad , \quad \frac{\rho_0}{\rho} = \left[1 + \frac{\gamma - 1}{2}M^2\right]^{1/(\gamma - 1)}$$

The temperature, pressure and density relations between sonic conditions and stagnant conditions,

$$\frac{T_*}{T_0} = \frac{2}{\gamma + 1} \quad , \quad \frac{p_*}{p_0} = \left[\frac{2}{\gamma + 1}\right]^{\gamma/(\gamma - 1)} \quad , \quad \frac{\rho_*}{\rho_0} = \left[\frac{2}{\gamma + 1}\right]^{1/(\gamma - 1)}$$

The Mach number before and after shock,

$$M_2^2 = \frac{1 + [(\gamma - 1)/2]M_1^2}{\gamma M_1^2 - (\gamma - 1)/2}$$

The density, velocity, and pressure relations before and after shock,

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma + 1)M_1^2}{2 + (\gamma - 1)M_1^2} \quad , \quad \frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1)$$

wherein the subscript 1 is used to represent quantities before the shock and 2 is after the shock. The relations for temperature and enthalpy,

$$\frac{T_2}{T_1} = \frac{h_2}{h_1} = \left[1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1)\right] \left[\frac{2 + (\gamma - 1)M_1^2}{(\gamma + 1)M_1^2}\right]$$

For the stagnation temperature and pressure before and after the shock,

$$T_{0,1} = T_{0,2} \quad , \quad \frac{p_{0,2}}{p_{0,1}} = e^{-(s_2-s_1)/R} = \left[ 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \right]^{-1/(\gamma-1)} \left[ \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \right]^{\gamma/(\gamma-1)}$$

The ratio of nozzle cross-section at any arbitrary point of the nozzle to the nozzle cross-section at sonic conditions as a function of Mach number,

$$\left( \frac{A}{A_*} \right)^2 = \frac{1}{M^2} \left[ \frac{2}{\gamma+1} \left( 1 + \frac{\gamma-1}{2} M^2 \right) \right]^{(\gamma+1)/(\gamma-1)}$$

For choked flows, the exit Mach number  $M_e$  with or without shock,

$$M_e^2 = \frac{1}{(\gamma-1)} \left\{ -1 + \left[ 1 + 2(\gamma-1) \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left( \frac{p_{0,1}A_t}{p_eA_e} \right) \right]^{1/2} \right\}$$

### 8.2.2 Oblique Shocks

The mathematical expression used relating Mach number,  $\theta$  and  $\beta$  is shown below,

$$\tan(\theta) = 2 \cot(\beta) \left\{ \frac{M_1^2 \sin^2(\beta) - 1}{M_1^2 [\gamma + \cos(2\beta)] + 2} \right\}$$

Reiterating the relation shown in the previous problem,

$$M_{n,1} = M_1 \sin \beta \quad , \quad M_{n,2} = M_2 \sin(\beta - \theta)$$

The relationship of the quantities between at  $M_{n,1}$  and  $M_{n,2}$  could be found using the relations at the normal shock relations. The only minor modification is that the stagnant relations for the normal shocks are no longer applicable to oblique shocks due to the tangential velocity of the fluid being conserved across the oblique shock.

## 8.3 Prandtl-Meyer Expansion Theory

An interesting property of the Prandtl Meyer function  $\nu(M)$  wherein  $M$  represents Mach number,

$$\theta = \nu(M_2) - \nu(M_1)$$

wherein  $M_2$  represents Mach number after expansion meanwhile  $M_1$  represents Mach number before expansion. Manipulating this relation for convenience,

$$\nu(M_2) = \theta + \nu(M_1)$$

## 8.4 Shock-Expansion Theory

The coefficient of lift  $c_L$  and coefficient of drag  $c_D$  in terms of coefficient of pressures  $c_{p3}$  and  $c_{p2}$  is shown below,

$$c_L = (c_{p3} - c_{p2}) \cos \alpha \quad , \quad c_D = (c_{p3} - c_{p2}) \sin \alpha$$

The coefficient of pressure by definition,

$$c_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty U_\infty^2} = \frac{2(p - p_\infty)}{\rho_\infty U_\infty^2} = \frac{2p_\infty}{\rho_\infty U_\infty^2} \left( \frac{p}{p_\infty} - 1 \right)$$

wherein  $U_\infty$  is used to indicate velocity infinitely far away from the wing. Other relations for Mach number and speed of sound,

$$M = \frac{U}{a} \quad , \quad a = \sqrt{\gamma RT} \quad , \quad p = \rho RT$$

Manipulating the Mach number relation and the ideal gas relation,

$$M_\infty a_\infty = U_\infty \quad , \quad \frac{p_\infty}{RT_\infty} = \rho_\infty$$

Substituting both relations into each other,

$$\rho_\infty U_\infty^2 = \frac{p_\infty}{RT_\infty} \times M_\infty^2 a_\infty^2$$

Substituting for the speed of sound  $a_\infty$  in terms of temperature and ratio of specific heats,

$$\rho_\infty U_\infty^2 = \frac{p_\infty}{RT_\infty} \times M_\infty^2 \gamma RT_\infty = p_\infty M_\infty^2 \gamma$$

Substituting into the expression for coefficient of pressures,

$$c_p = \frac{2p_\infty}{p_\infty \gamma M_\infty^2} \left( \frac{p}{p_\infty} - 1 \right) = \frac{2}{\gamma M_\infty^2} \left( \frac{p}{p_\infty} - 1 \right)$$

## 8.5 Linear Theory

### 8.5.1 Supersonic

The coefficient of pressure in supersonic linear theory is shown below,

$$c_{p,u} = -\frac{2\theta}{\sqrt{M_\infty^2 - 1}} \quad , \quad c_{p,l} = \frac{2\theta}{\sqrt{M_\infty^2 - 1}}$$

The important equations for the coefficients in supersonic linear theory are listed below,

$$c_L = \frac{4(\alpha + \Delta\alpha)}{\sqrt{M_\infty^2 - 1}} \quad , \quad c_D = \frac{4}{\sqrt{M_\infty^2 - 1}} [(\alpha + \Delta\alpha)^2 + K_2 + K_3]$$

$$c_{m,le} = \frac{4}{\sqrt{M_\infty^2 - 1}} \left[ -\frac{1}{2}\alpha + K_1 \right] \quad , \quad c_{m,ac} = \frac{4}{\sqrt{M_\infty^2 - 1}} \left[ K_1 + \frac{\Delta\alpha}{2} \right]$$

wherein the various constants  $K$  as well as  $\Delta\alpha$ ,

$$K_1 = \int_0^1 \left( \frac{d\hat{y}_c}{d\hat{x}} \right) \hat{x} d\hat{x} \quad , \quad K_2 = \int_0^1 \left( \frac{d\hat{y}_c}{d\hat{x}} \right)^2 d\hat{x} \quad , \quad K_3 = \int_0^1 \left( \frac{d\hat{y}_t}{d\hat{x}} \right)^2 d\hat{x}$$

$$\Delta\alpha = - \int_0^1 \frac{d\hat{y}_c}{d\hat{x}} d\hat{x} = -(\hat{y}_{te} - \hat{y}_{le})$$

wherein the various  $y$ -values are further expressed below,

$$y_c = \frac{1}{2}[y_u(x) + y_l(x)] \quad , \quad y_t = \frac{1}{2}[y_u(x) - y_l(x)]$$

The aerodynamic centers and variables of integration are shown below,

$$\hat{x} = \frac{x}{c} \quad , \quad \hat{y} = \frac{y}{c} \quad , \quad \frac{x_{ac}}{x} = \frac{1}{2}$$

### 8.5.2 Subsonic

Based on the Prandtl-Glauert Rule

$$c_L = \frac{c_{L,0}}{\beta} \quad , \quad c_{m,le} = \frac{c_{m,le,0}}{\beta} \quad , \quad c_D = 0$$

wherein the variable  $\beta = \sqrt{1 - M_\infty^2}$ . Let  $c_p$  represent coefficient of pressure in compressible flow meanwhile  $c_{p0}$  represent the corresponding coefficient of pressure in the incompressible flow. The Prandtl-Glauert rule relating  $c_p$  to  $c_{p0}$ ,

$$c_p = \frac{c_{p0}}{\sqrt{1 - M^2}}$$

The Karman-Tsien rule relating  $c_p$  to  $c_{p0}$ ,

$$c_p = \frac{c_{p0}}{\sqrt{1 - M^2} + \left( \frac{M^2}{1 + \sqrt{1 - M^2}} \right) \left( \frac{c_{p0}}{2} \right)}$$

The Laitone's rule relating  $c_p$  to  $c_{p0}$ ,

$$c_p = \frac{c_{p0}}{\sqrt{1 - M^2} + c_{p0} M^2 \left[ 1 + \left( \frac{\gamma - 1}{2} \right) M^2 \right] \left[ \frac{\sqrt{1 - M^2}}{2} \right]}$$

The equation for critical Mach number  $M_{cr}$  is shown below,

$$c_{p,cr} = \frac{2}{\gamma M_{cr}^2} \left\{ \left[ \frac{1 + \left( \frac{\gamma - 1}{2} \right) M_{cr}^2}{\frac{\gamma + 1}{2}} \right]^{\gamma/(\gamma-1)} - 1 \right\}$$

The minimum coefficient of pressure at critical Mach number could then be expressed by the Prandtl-Glauert rule shown below,

$$c_{p,cr} = \frac{c_{p0,min}}{\sqrt{1 - M_{cr}^2}}$$

Other rules could potentially be used such as the Laitone or the Karman-Tsien for the expression of  $c_{p,cr}$ . Equating  $c_{p,cr}$  would produce an equation whose solution of  $M_{cr}$  represents the critical Mach number.

# Chapter 9

## Creeping Flows

Creeping Flows are the opposite of Potential Flows. The effects of viscosity are important but the inertial effects of the fluid is negligible. The degeneracy from the general Navier Stokes equation is shown below,

### 9.1 Cartesian Parallel Flows

The continuum governing equation for incompressible fluids in cartesian coordinates are shown below,

$$0 = \nabla \cdot \bar{v}_f = \frac{\partial}{\partial x}[\bar{v}_f] + \frac{\partial}{\partial y}[\bar{v}_f] + \frac{\partial}{\partial z}[\bar{v}_f]$$

Ignoring the  $y$ -direction degenerates this problem to a 2-dimensional case and evaluates the term  $\frac{\partial}{\partial y}[\bar{v}_f]$  to zero. It is known that this case is a parallel flow case, therefore, the velocity in the  $z$ -direction is also non-existent. Therefore, the term  $\frac{\partial}{\partial z}[\bar{v}_f]$  evaluates to zero as well.

$$0 = \frac{\partial}{\partial x}[\bar{v}_f]$$

Since this is a 2-dimensional problem, then the velocity is also independent in the thickness  $y$ -direction. This also means that the fluid velocity is identical to just the horizontal velocity  $\bar{v}_f = \bar{v}_x$ . Therefore,

$$0 = \frac{\partial}{\partial x}[\bar{v}_f] = \frac{\partial}{\partial x}[\bar{v}_x]$$

This equation shows that the velocity is independent in the  $x$ -direction. An alternate version of the Navier-Stokes momentum equation,

$$\rho \left[ \frac{\partial \bar{v}_f}{\partial t} + (\bar{v}_f \cdot \nabla) \bar{v}_f \right] = \rho \bar{g} - \nabla P_r + \mu \nabla^2 \bar{v}_f$$

wherein  $\nabla^2 \bar{v}_f = (\nabla \cdot \nabla) \bar{v}_f$  in this case. Evaluating the Navier-Stokes momentum equation in the  $x$ -direction,

$$\rho \left[ \frac{\partial \bar{v}_x}{\partial t} + \bar{v}_x \frac{\partial}{\partial x}[\bar{v}_x] + \bar{v}_y \frac{\partial}{\partial y}[\bar{v}_x] + \bar{v}_z \frac{\partial}{\partial z}[\bar{v}_x] \right] = -\frac{\partial}{\partial x}[P_r] + \mu \left[ \frac{\partial^2}{\partial x^2}[\bar{v}_x] + \frac{\partial^2}{\partial y^2}[\bar{v}_x] + \frac{\partial^2}{\partial z^2}[\bar{v}_x] \right]$$

If analysis is performed on a steady state fluid flow, the term  $\frac{\partial \bar{v}_x}{\partial t}$  evaluates to zero. Using the previous finding after applying the continuity governing equation, the term  $\bar{v}_x \frac{\partial}{\partial x} [\bar{v}_x]$  evaluates to zero. Due to the 2-dimensional nature of the problem, the term  $\bar{v}_y \frac{\partial}{\partial y} [\bar{v}_x]$  evaluates to zero. Since there is no velocity in the vertical  $z$ -direction due to the parallel nature of the flow, the term  $\bar{v}_z \frac{\partial}{\partial z} [\bar{v}_x]$  evaluates to zero. Consistent with the previous findings, since the velocity is not a function of horizontal displacement  $x$ , the term  $\frac{\partial^2}{\partial x^2} [\bar{v}_x]$  evaluates to zero. Due to the 2-dimensional nature of the problem, the term  $\frac{\partial^2}{\partial y^2} [\bar{v}_x]$  evaluates to zero. Therefore,

$$0 = -\frac{\partial}{\partial x} [P_r] + \mu \frac{\partial^2}{\partial z^2} [\bar{v}_x]$$

$$\frac{\partial}{\partial x} [P_r] = \mu \frac{\partial^2}{\partial z^2} [\bar{v}_x]$$

Evaluating the Navier-Stokes momentum equation in the  $z$ -direction,

$$\rho \left[ \frac{\partial \bar{v}_z}{\partial t} + \bar{v}_x \frac{\partial}{\partial x} [\bar{v}_z] + \bar{v}_y \frac{\partial}{\partial y} [\bar{v}_z] + \bar{v}_z \frac{\partial}{\partial z} [\bar{v}_z] \right] = -\rho g - \frac{\partial}{\partial z} [P_r] + \mu \left[ \frac{\partial^2}{\partial x^2} [\bar{v}_z] + \frac{\partial^2}{\partial y^2} [\bar{v}_z] + \frac{\partial^2}{\partial z^2} [\bar{v}_z] \right]$$

Since the the vertical velocities are zero, then,

$$\frac{\partial \bar{v}_z}{\partial t} = \bar{v}_x \frac{\partial}{\partial x} [\bar{v}_z] = \bar{v}_y \frac{\partial}{\partial y} [\bar{v}_z] = \bar{v}_z \frac{\partial}{\partial z} [\bar{v}_z] = \frac{\partial^2}{\partial x^2} [\bar{v}_z] = \frac{\partial^2}{\partial y^2} [\bar{v}_z] = \frac{\partial^2}{\partial z^2} [\bar{v}_z] = 0$$

Therefore,

$$0 = -\rho g - \frac{\partial}{\partial z} [P_r]$$

Suppose one were to attempt to find the pressure function,

$$-\rho g \int dz = \int dP_r$$

$$-\rho g z + f(x) = P_r$$

wherein  $f(x)$  is a function purely in terms of  $x$ . Taking the second conclusion we obtained from applying the Navier-Stokes momentum equation in the  $x$ -direction,

$$\frac{\partial}{\partial x} [-\rho g z + f(x)] = \mu \frac{\partial^2}{\partial z^2} [\bar{v}_x]$$

$$f'(x) = \mu \frac{\partial^2}{\partial z^2} [\bar{v}_x]$$

The velocity  $\bar{v}_x$  is only dependent on the  $z$ -direction. Therefore, the second order partial derivative term,  $\mu \frac{\partial^2}{\partial z^2} [\bar{v}_x]$  must also be fully dependent on the  $z$ -direction. This means that the function  $f'(x)$  is a constant function  $f'(x) = c_1$ , therefore,  $f(x)$ . Firstly this computes the pressure function,

$$P_r = -\rho g z + c_1 x + \alpha$$



wherein both  $c_1$  and  $\alpha$  are arbitrary constants. Secondly, the implications for the velocity profile,

$$\begin{aligned} f'(x) &= c_1 = \mu \frac{\partial^2}{\partial z^2} [\bar{v}_x] \\ \frac{1}{\mu} \int c_1 dz &= \frac{c_1}{\mu} z + c_2 = \frac{\partial}{\partial z} [\bar{v}_x] \\ \frac{c_1}{\mu} \int z dz + \int c_2 dz &= \bar{v}_x \\ \frac{c_1}{2\mu} z^2 + c_2 z + c_3 &= \bar{v}_x \end{aligned}$$

## 9.2 Radial Parallel Flows

The continuum governing equation is shown below,

$$0 = \nabla \cdot \bar{v}_f = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \frac{\partial v_r}{\partial r} + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z}$$

The Navier-Stokes Equation is shown below,

$$\rho \left[ \frac{\partial \bar{v}_f}{\partial t} + (\bar{v}_f \cdot \nabla) \bar{v}_f \right] = \rho \bar{g} - \nabla P + \mu \nabla^2 \bar{v}_f$$

### 9.2.1 Velocity Profile

To find the velocity profile of the fluid in the radial direction, the continuum governing equation is applied first in polar coordinates.

$$0 = \nabla \cdot \bar{v}_f = \frac{\partial v_r}{\partial r} + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z}$$

Ignoring the  $z$ -axis,

$$0 = \frac{\partial v_r}{\partial r} + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta}$$

By inspection it could be seen that the radial velocity is zero, and  $v_r = 0$ . Therefore,

$$0 = \frac{\partial v_\theta}{\partial \theta} \quad , \quad 0 = \frac{\partial^2 v_\theta}{\partial \theta^2}$$

This shows that the tangential velocity is purely a function of radius and not a function of  $\theta$ .

It is Assumed that gravity acts on the  $z$ -direction and is largely ignored. Evaluating the expression in the radial direction,

$$\rho \left[ \frac{dv_r}{dt} + v_r \frac{\partial v_r}{\partial r} + v_\theta \frac{1}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} \right] = -\frac{\partial P}{\partial r} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_r}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} - \frac{v_r}{r^2} - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} \right]$$

Since radial velocity is always zero,  $\frac{dv_r}{dt} = v_r \frac{\partial v_r}{\partial r} = v_\theta \frac{1}{r} \frac{\partial v_r}{\partial \theta} = \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} = \frac{v_r}{r^2} = 0$ . Since tangential velocity is not a function of  $\theta$ ,  $\frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} = 0$

$$-\frac{\rho v_\theta^2}{r} = -\frac{\partial P}{\partial r}$$

$$\frac{\rho v_\theta^2}{r} = \frac{\partial P}{\partial r}$$

Evaluating the expression in the tangential direction,

$$\rho \left[ \frac{dv_\theta}{dt} + v_r \frac{\partial v_\theta}{\partial r} + v_\theta \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} \right] = -\frac{1}{r} \frac{\partial P}{\partial \theta} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_\theta}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} - \frac{v_\theta}{r^2} + \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} \right]$$

$\frac{dv_\theta}{dt} = 0$  because it is assumed that the system is already in a steady state.  
 $v_r \frac{\partial v_\theta}{\partial r} = \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} = \frac{v_r v_\theta}{r} = 0$  because  $v_r = 0$  as the previous assumption. Since tangential velocity is purely a function of radius,  $\frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} = v_\theta \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} = 0$ . Therefore, the equation degenerates into,

$$0 = -\frac{1}{r} \frac{\partial P}{\partial \theta} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_\theta}{\partial r} \right) - \frac{v_\theta}{r^2} \right]$$

By a separate mathematical proof,

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_\theta}{\partial r} \right) - \frac{v_\theta}{r^2} = \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial}{\partial r} (r v_\theta) \right]$$

Therefore,

$$0 = -\frac{1}{r} \frac{\partial P}{\partial \theta} + \mu \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial}{\partial r} (r v_\theta) \right]$$

By the relation found by applying the Incompressible Navier-Stokes on the radial direction, it could be seen that pressure  $P$  is dependent on tangential velocity  $v_\theta$  and  $r$ . However, since tangential velocity is only dependent on  $r$  from the relation found by applying continuity, then it follows that pressure must only be dependent on  $r$ . Therefore,  $\frac{\partial P}{\partial r} = 0$ . Therefore, the Navier-Stokes applied on the tangential direction further degenerates into,

$$0 = \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial}{\partial r} (r v_\theta) \right]$$

Solving for tangential velocity as a function of radius,

$$c_\alpha = \frac{1}{r} \frac{\partial}{\partial r} (r v_\theta)$$

$$\int_{r=R_1}^r r c_\alpha dr = \int_{r=R_1, v_\theta=\omega_1 R_1}^{r, v_\theta} dr v_\theta$$

$$\frac{1}{2} c_\alpha [r^2]_{r=R_1}^r = [r v_\theta]_{r=R_1, v_\theta=\omega_1 R_1}^{r, v_\theta}$$

$$\frac{1}{2} c_\alpha [r^2 - R_1^2] = [r v_\theta - \omega_1 R_1^2]$$

When  $r = R_2$ ,  $v_\theta = \omega_2 R_2$ . Therefore,

$$\frac{1}{2} c_\alpha [R_2^2 - R_1^2] = [R_2 \omega_2 R_2 - \omega_1 R_1^2]$$

$$c_\alpha [R_2^2 - R_1^2] = 2 [\omega_2 R_2^2 - \omega_1 R_1^2]$$

$$c_\alpha = \frac{2 [\omega_2 R_2^2 - \omega_1 R_1^2]}{[R_2^2 - R_1^2]}$$

By substituting the newly found definition for the constant  $c_\alpha$ ,

$$\frac{[\omega_2 R_2^2 - \omega_1 R_1^2]}{[R_2^2 - R_1^2]} [r^2 - R_1^2] = r v_\theta - \omega_1 R_1^2$$

$$\frac{[\omega_2 R_2^2 - \omega_1 R_1^2]}{[R_2^2 - R_1^2]} \left[ r - \frac{R_1^2}{r} \right] + \frac{\omega_1 R_1^2}{r} = v_\theta$$

$$\frac{[\omega_2 R_2^2 - \omega_1 R_1^2]}{[R_2^2 - R_1^2]} \left[ r - \frac{R_1^2}{r} \right] + \frac{\omega_1 R_1^2 [R_2^2 - R_1^2]}{r [R_2^2 - R_1^2]} = v_\theta$$

$$\frac{[\omega_2 R_2^2 - \omega_1 R_1^2]}{[R_2^2 - R_1^2]} \left[ r - \frac{R_1^2}{r} \right] + \frac{[\omega_1 R_1^2 R_2^2 - \omega_1 R_1^4]}{r [R_2^2 - R_1^2]} = v_\theta$$

$$\frac{1}{[R_2^2 - R_1^2]} \left[ r (\omega_2 R_2^2 - \omega_1 R_1^2) - \frac{R_1^2 (\omega_2 R_2^2 - \omega_1 R_1^2) - [\omega_1 R_1^2 R_2^2 - \omega_1 R_1^4]}{r} \right] = v_\theta$$

$$\frac{1}{[R_2^2 - R_1^2]} \left[ r (\omega_2 R_2^2 - \omega_1 R_1^2) - \frac{\omega_2 R_1^2 R_2^2 - \omega_1 R_1^4 - \omega_1 R_1^2 R_2^2 + \omega_1 R_1^4}{r} \right] = v_\theta$$

$$v_\theta = \frac{1}{[R_2^2 - R_1^2]} \left[ r (\omega_2 R_2^2 - \omega_1 R_1^2) - \frac{R_1^2 R_2^2 [\omega_2 - \omega_1]}{r} \right]$$

### 9.2.2 Scalar Pressure Field

To find the pressure field of the fluid, the two relations that are obtained from applying the incompressible Navier-Stokes equation on the radial and tangential direction is used,

$$\frac{\rho v_\theta^2}{r} = \frac{\partial P}{\partial r} \quad , \quad 0 = \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial}{\partial r} (r v_\theta) \right]$$

The second relation when further operated on gives the function of tangential velocity  $v_\theta$  with respect to radius  $r$ . Integrating the first relation with respect to  $r$  and applying the boundary conditions yields,

$$P = P_1 + \frac{\rho}{(R_2^2 - R_1^2)^2} \left[ (\omega_2 R_2^2 - \omega_1 R_1^2)^2 \left( \frac{r^2 - R_1^2}{2} \right) \right. \\ \left. - 2 R_1^2 R_2^2 (\omega_2 - \omega_1) (\omega_2 R_2^2 - \omega_1 R_1^2) \ln \frac{r}{R_1} - \frac{R_1^4 R_2^4}{2} (\omega_2 - \omega_1)^2 \left( \frac{1}{r^2} - \frac{1}{R_1^2} \right) \right]$$

### 9.2.3 Induced Torque

Suppose the outer cylinder is rotating and the inner cylinder is held at rest, the equation for torque exerted on the inner cylinder must be

$$\Gamma = 2\pi\mu\omega_2 R_1^2 \left[ \frac{R_2 H}{R_2 - R_1} + \frac{R_1^2}{4b} \right]$$

wherein  $b$  represents the gap between the two cylindrical surfaces and  $\Gamma$  is the torque exerted on the inner cylinder. Since this is typically ignored,

$$\Gamma = 2\pi\mu\omega_2 R_1^2 \left[ \frac{R_2 H}{R_2 - R_1} \right]$$

The torque per unit width length,

$$\Gamma_H = 2\pi\mu\omega_2 R_1^2 \left[ \frac{R_2}{R_2 - R_1} \right]$$

This is very useful to test for the viscosity of a specific fluid.