

MATH-281

Complex Variables

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1 Complex Numbers

1.1 Definition

Definition 1.1.1: Complex Numbers

A complex number is a number that can be expressed in the form $a + bi$, where a and b are real numbers, and i is a solution of the equation $x^2 = -1$, or simply, $i = \sqrt{-1}$. Because no real number satisfies this equation, i is called an imaginary number. For the complex number $a + bi$, a is called the real part, and b is called the imaginary part.

- The set of all complex numbers is denoted by \mathbb{C} .
- The set of all real numbers is denoted by \mathbb{R} .

Definition 1.1.2: Modulus and Amplitude

Let $z = a + bi$ be a complex number. The modulus of z is the non-negative real number $|z| = \sqrt{a^2 + b^2}$. The amplitude of z is the angle θ such that $\cos(\theta) = \frac{a}{|z|}$ and $\sin(\theta) = \frac{b}{|z|}$.

If the polar form of the point (a, b) be (r, θ) , then $a = r \cos \theta$ and $b = r \sin \theta$.

$$r = |z| = \sqrt{a^2 + b^2} \quad \text{and} \quad \theta = \arctan\left(\frac{b}{a}\right) \quad (1.1.1)$$

Here, r is the modulus of z and θ is the amplitude of z .

In symbols, we write

$$r = \text{mod}(z) = |a + ib| \quad \text{and} \quad \theta = \arg(z) = \tan^{-1}\left(\frac{b}{a}\right) \quad (1.1.2)$$

1.2 De Moivre's Theorem

Theorem 1.2.1 (De Moivre's Theorem): Let $z = r(\cos \theta + i \sin \theta)$ be a complex number. Then, for any positive integer n ,

$$z^n = r^n(\cos n\theta + i \sin n\theta) \quad (1.2.1)$$

Proof:

Case 1: $n \in \mathbb{Z}_+$

We have,

$$\begin{aligned} z_1 z_2 \dots z_n &= (\cos \theta_1 + i \sin \theta_1)(\cos \theta_2 + i \sin \theta_2) \dots (\cos \theta_n + i \sin \theta_n) \\ &= \{\cos(\theta_1 + \theta_2) + i \sin(\theta_1 + \theta_2)\} \dots (\cos \theta_n + i \sin \theta_n) \\ &= \cos(\theta_1 + \theta_2 + \dots + \theta_n) + i \sin(\theta_1 + \theta_2 + \dots + \theta_n) \end{aligned}$$

Hence, we get

$$z^n = (\cos n\theta + i \sin n\theta) \quad \square$$

Case 2: $n \in \mathbb{Z}_-$

Let $n = -m$. We have,

$$\begin{aligned} z^n &= (\cos \theta + i \sin \theta)^{-m} \\ &= \frac{1}{(\cos \theta + i \sin \theta)^m} \\ &= \frac{1}{\cos m\theta + i \sin m\theta} \\ &= \frac{\cos m\theta - i \sin m\theta}{\cos^2 m\theta + \sin^2 m\theta} \\ &= \cos m\theta - i \sin m\theta \\ &= \cos n\theta + i \sin n\theta \end{aligned}$$

Hence, we get

$$z^n = (\cos n\theta + i \sin n\theta) \quad \square$$

Case 3: $n \in \mathbb{Q}$, i.e. $n = \frac{p}{q}$, where $p, q \in \mathbb{Z}$ and $q \neq 0$.

Now,

$$\begin{aligned} \left(\cos \frac{p}{q}\theta + i \sin \frac{p}{q}\theta \right)^q &= \cos \left(q \cdot \frac{p}{q}\theta \right) + i \sin \left(q \cdot \frac{p}{q}\theta \right) \\ &= \cos p\theta + i \sin p\theta \\ &= (\cos \theta + i \sin \theta)^p \end{aligned}$$

Taking the q^{th} root of both sides, we get

$$\cos \frac{p}{q}\theta + i \sin \frac{p}{q}\theta = (\cos \theta + i \sin \theta)^{\frac{p}{q}} \quad \square$$

Note:-

Some Important Results:

- (i) $1 = e^{i2n\pi} = \cos 2n\pi + i \sin 2n\pi$
- (ii) $-1 = \cos \pi + i \sin \pi = e^{i\pi}$
- (iii) $i = \cos \frac{\pi}{2} + i \sin \frac{\pi}{2} = e^{i\frac{\pi}{2}}$
- (iv) $-i = \cos \frac{\pi}{2} - i \sin \frac{\pi}{2} = e^{-i\frac{\pi}{2}}$

2 Analytic Functions

2.1 Definitions

Definition 2.1.1: Complex variable

A **complex variable** is a variable that can take on complex values. A complex variable is usually denoted by z .

If x and y are real variables, then $z = x + iy$ is a complex variable, where i is the imaginary unit.

Definition 2.1.2: Complex Function

A **complex function** is a function that takes complex variables as input and returns complex values. A complex function is usually denoted by $f(z)$.

If $z = x + iy$ and $w = u + iv$ are complex variables, then $f(z) = u(x, y) + iv(x, y)$ is a complex function, where $u(x, y)$ and $v(x, y)$ are real functions.

Definition 2.1.3: Single-valued Function

A **single-valued function** is a function that returns a unique value for each input.

A complex function $f(z)$ is single-valued if and only if $f(z_1) = f(z_2)$ implies $z_1 = z_2$. In other words, if $z_1 \neq z_2$, then $f(z_1) \neq f(z_2)$.

$$\forall z_1, z_2 \in \mathbb{C} \quad \text{s.t.} \quad z_1 \neq z_2 \quad \text{implies} \quad f(z_1) \neq f(z_2)$$

Definition 2.1.4: Multiple-valued Function

A **multiple-valued function** is a function that returns multiple values for each input.

A complex function $f(z)$ is multiple-valued if and only if $f(z_1) = f(z_2)$ for some $z_1 \neq z_2$.

$$\exists z_1, z_2 \in \mathbb{C} \quad \text{s.t.} \quad z_1 \neq z_2 \quad \text{and} \quad f(z_1) = f(z_2)$$

Definition 2.1.5: Derivative

The **derivative** of a complex function $f(z)$ is defined as

$$f'(z) = \lim_{\Delta z \rightarrow 0} \frac{f(z + \Delta z) - f(z)}{\Delta z}$$

where Δz is a complex number.

If the limit exists, then $f(z)$ is said to be **differentiable** at z . If $f(z)$ is differentiable at every point in a region R , then $f(z)$ is said to be **analytic** in R .

Definition 2.1.6: Analytic Function

A complex function $f(z)$ is **analytic** in a region R if it is differentiable at every point in R .

If $f(z)$ is analytic in a region R , then $f(z)$ is also said to be **regular** or **holomorphic** in R .

2.2 Necessary Conditions for Analyticity

Let $f(z) = u(x, y) + iv(x, y)$ be an analytic function in a region R .

That means, $f(z)$ is differentiable at every point in R .

$$\Rightarrow f'(z) = \lim_{\Delta z \rightarrow 0} \frac{f(z + \Delta z) - f(z)}{\Delta z} \text{ exists at every point in } R.$$

Now, let $z = x + iy$ and $\Delta z = \Delta x + i\Delta y$.

$$z + \Delta z = (x + \Delta x) + i(y + \Delta y)$$

Then,

$$\begin{aligned} f'(z) &= \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \frac{f(x + \Delta x + i(y + \Delta y)) - f(x + iy)}{\Delta x + i\Delta y} \\ &= \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \frac{u(x + \Delta x, y + \Delta y) + iv(x + \Delta x, y + \Delta y) - u(x, y) - iv(x, y)}{\Delta x + i\Delta y} \\ &= \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \frac{u(x + \Delta x, y + \Delta y) - u(x, y)}{\Delta x + i\Delta y} + i \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \frac{v(x + \Delta x, y + \Delta y) - v(x, y)}{\Delta x + i\Delta y} \end{aligned}$$

Along the real axis, $\Delta y = 0$. Hence, the limit is

$$\begin{aligned} f'(z) &= \lim_{\Delta x \rightarrow 0} \frac{u(x + \Delta x, y) - u(x, y)}{\Delta x} + i \lim_{\Delta x \rightarrow 0} \frac{v(x + \Delta x, y) - v(x, y)}{\Delta x} \\ f'(z) &= \frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} \end{aligned} \tag{2.2.1}$$

Along the imaginary axis, $\Delta x = 0$. Hence, the limit is

$$\begin{aligned} f'(z) &= \lim_{\Delta y \rightarrow 0} \frac{u(x, y + \Delta y) - u(x, y)}{i\Delta y} + i \lim_{\Delta y \rightarrow 0} \frac{v(x, y + \Delta y) - v(x, y)}{i\Delta y} \\ f'(z) &= -i \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} \end{aligned} \tag{2.2.2}$$

2.3 Cauchy-Riemann Equations

Since $f'(z)$ exists, (2.2.4) and (2.2.5) must be equal.

$$\frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} = \frac{\partial v}{\partial y} - i \frac{\partial u}{\partial y} \quad (2.3.1)$$

Comparing real and imaginary parts,

$$\boxed{\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}} \quad \text{and} \quad \boxed{\frac{\partial v}{\partial x} = -\frac{\partial u}{\partial y}} \quad (2.3.2)$$

These are called the **Cauchy-Riemann equations**.

2.4 Cauchy-Riemann Equations in Polar Form

Let

$$z = re^{i\theta}$$

$$f(z) = u(r, \theta) + iv(r, \theta)$$

Then

$$f(re^{i\theta}) = u(r, \theta) + iv(r, \theta) \quad (2.4.1)$$

Differentiating (2.4.1) with respect to r , we get

$$e^{i\theta} f'(re^{i\theta}) = \frac{\partial u}{\partial r} + i \frac{\partial v}{\partial r} \quad (2.4.2)$$

Differentiating (2.4.1) with respect to θ , we get

$$ire^{i\theta} f'(re^{i\theta}) = \frac{\partial u}{\partial \theta} + i \frac{\partial v}{\partial \theta} \quad (2.4.3)$$

Now, from (2.4.2) and (2.4.3),

$$\begin{aligned} \frac{\partial u}{\partial r} + i \frac{\partial v}{\partial r} &= \frac{1}{ir} \left(\frac{\partial u}{\partial \theta} + i \frac{\partial v}{\partial \theta} \right) \\ \frac{\partial u}{\partial r} + i \frac{\partial v}{\partial r} &= \frac{1}{ir} \frac{\partial u}{\partial \theta} + \frac{1}{r} \frac{\partial v}{\partial \theta} \\ \frac{\partial u}{\partial r} + i \frac{\partial v}{\partial r} &= -\frac{i}{r} \frac{\partial u}{\partial \theta} + \frac{1}{r} \frac{\partial v}{\partial \theta} \end{aligned}$$

Equating the real and imaginary parts, we get

$$\boxed{\frac{\partial u}{\partial r} = \frac{1}{r} \frac{\partial v}{\partial \theta}} \quad \text{and} \quad \boxed{\frac{\partial v}{\partial r} = -\frac{1}{r} \frac{\partial u}{\partial \theta}} \quad (2.4.4)$$

These are the **Cauchy-Riemann equations in polar form**.

3 Harmonic Function

3.1 Laplace's Equation

Definition 3.1.1: Laplace's Equation

An equation of the form

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \quad \text{or} \quad \nabla^2 \phi = 0 \quad (3.1.1)$$

is called **Laplace's equation** (in two dimensions).

Here, ∇^2 is the Laplacian operator.

3.2 Harmonic Function

Definition 3.2.1: Harmonic Function

A function $\phi(x, y)$ is called **harmonic** if it satisfies Laplace's equation

$$\nabla^2 \phi = 0 \quad (3.2.1)$$

where ∇^2 is the Laplacian operator.

Theorem 3.2.2: If $f(z) = u + iv$ is an analytic function, then u and v are both harmonic functions.

Proof:

Since $f(z)$ is analytic, it satisfies the Cauchy-Riemann equations

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} \quad (3.2.2)$$

$$\frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x} \quad (3.2.3)$$

Differentiating (3.2.2) w.r.t. x and (3.2.3) w.r.t. y , we get

$$\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 v}{\partial x \partial y} \quad (3.2.4)$$

$$\frac{\partial^2 u}{\partial y^2} = -\frac{\partial^2 v}{\partial y \partial x} \quad (3.2.5)$$

Adding (3.2.4) and (3.2.5), we get

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0 \quad (3.2.6)$$

Similarly,

$$\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} = 0 \quad (3.2.7)$$

Hence, both u and v are harmonic functions. \square

Definition 3.2.3: Conjugate Harmonic Function

Any two functions ϕ and ψ such that $f(z) = \phi + i\psi$ is analytic, are called **Conjugate Harmonic Functions**.

3.3 Velocity Potential

Consider a two-dimensional flow of an incompressible fluid. The velocity of the fluid at a point (x, y) is given by the vector

$$\mathbf{v} = v_x \hat{\mathbf{i}} + v_y \hat{\mathbf{j}} \quad (3.3.1)$$

Here, v is called the stream function.

The **velocity potential** $\phi(x, y)$ is defined as the scalar function such that

$$\mathbf{V} = \nabla\phi = \left(\hat{\mathbf{i}} \frac{\partial}{\partial x} + \hat{\mathbf{j}} \frac{\partial}{\partial y} \right) \phi = \hat{\mathbf{i}} \frac{\partial\phi}{\partial x} + \hat{\mathbf{j}} \frac{\partial\phi}{\partial y} \quad (3.3.2)$$

Comparing (3.3.1) and (3.3.2), we get

$$v_x = \frac{\partial\phi}{\partial x} \quad \text{and} \quad v_y = \frac{\partial\phi}{\partial y} \quad (3.3.3)$$

The scalar function $\phi(x, y)$ gives the velocity components.
Since the fluid is incompressible,

$$\begin{aligned} \nabla v &= 0 \\ \left(\hat{\mathbf{i}} \frac{\partial}{\partial x} + \hat{\mathbf{j}} \frac{\partial}{\partial y} \right) (\hat{\mathbf{i}} v_x + \hat{\mathbf{j}} v_y) &= 0 \\ \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} &= 0 \end{aligned}$$

Putting the values of v_x and v_y from (3.3.3),

$$\begin{aligned} \frac{\partial}{\partial x} \left(\frac{\partial\phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial\phi}{\partial y} \right) &= 0 \\ \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} &= 0 \end{aligned}$$

This is Laplace's equation. Hence, the velocity potential $\phi(x, y)$ is a harmonic function and is a real part of the analytic function

$$f(z) = \phi + i\psi$$

3.4 Method for Finding Conjugate Harmonic Function

A Method 1: Real or Imaginary Part of an Analytic Function is Given

If $f(z) = u + iv$ and u is known

We know that

$$dv = \frac{\partial v}{\partial x}dx + \frac{\partial v}{\partial y}dy$$

Using C-R equations,

$$\begin{aligned} dv &= -\frac{\partial u}{\partial y}dx + \frac{\partial u}{\partial x}dy \\ v &= -\int \frac{\partial u}{\partial y}dx + \int \frac{\partial u}{\partial x}dy + C \end{aligned}$$

Since u is known, v can be found using the above method.

If v is known, then u can be found using the same method.

B Method 2: Milne's Method/ Milne Thomson Method

By this method, $f(z)$ is directly constructed without finding v .

Since

$$\begin{aligned} z &= x + iy \quad \text{and} \quad \bar{z} = x - iy \\ x &= \frac{z + \bar{z}}{2} \quad \text{and} \quad y = \frac{z - \bar{z}}{2i} \end{aligned}$$

Thus,

$$\boxed{f(z) = u\left(\frac{z + \bar{z}}{2}, \frac{z - \bar{z}}{2i}\right) + iv\left(\frac{z + \bar{z}}{2}, \frac{z - \bar{z}}{2i}\right)} \quad (3.4.1)$$

Case 1: u is given

Let $f(z) = u + iv$ be an analytic function and u is given.

Then,

$$\frac{\partial u}{\partial x} = u_1(x, y) \quad \text{and} \quad \frac{\partial u}{\partial y} = u_2(x, y)$$

By Milne's method, we get

$$f'(z) = u_1(z, 0) - iu_2(z, 0) \quad (3.4.2)$$

Integrating (3.4.1) w.r.t. z , we get

$$f(z) = \int [u_1(z, 0) - iu_2(z, 0)] dz + C_1 \quad (3.4.3)$$

Case 2: v is given

If v is given, then

$$\frac{\partial v}{\partial y} = v_1(x, y) \quad \text{and} \quad \frac{\partial v}{\partial x} = v_2(x, y)$$

By Milne's method, we get

$$f'(z) = v_1(z, 0) + iv_2(z, 0) \quad (3.4.4)$$

Integrating (3.4.3) w.r.t. z , we get

$$f(z) = \int [v_1(z, 0) + iv_2(z, 0)] dz + C_2 \quad (3.4.5)$$