

BSc, MSci and MSc EXAMINATIONS (MATHEMATICS)
May 2024

This paper is also taken for the relevant examination for the
Associateship of the Royal College of Science

Applied Complex Analysis

Date: Wednesday, May 15, 2024

Time: 14:00 – 16:30 (BST)

Time Allowed: 2.5 hours

This paper has 5 Questions.

Please Answer All Questions in 1 Answer Booklet

Candidates should start their solutions to each question on a new sheet of paper.

Supplementary books may only be used after the relevant main book(s) are full.

Any required additional material(s) will be provided.

Allow margins for marking.

Credit will be given for all questions attempted.

Each question carries equal weight.

DO NOT OPEN THIS PAPER UNTIL THE INVIGILATOR TELLS YOU TO

1. (a) Define the Cauchy and Hilbert transforms for a complex function $f(z)$ over a smooth contour $\gamma \in \mathbb{C}$. (2 marks)
- (b) Write down the Plemelj formulae satisfied by $f(z)$ on the path γ . (2 marks)
- (c) Verify that the Plemelj formulae hold in the case where $f(z) = z$ and $\gamma = [-1, 1]$. [Note: you may use the fact that the multi-valued function

$$\log \left(\frac{z-1}{z+1} \right) = \log \left(\frac{r_1}{r_2} \right) + i(\theta_1 - \theta_2),$$

where $r_1 = |z-1|$, $r_2 = |z+1|$, $\theta_1 = \arg\{z-1\}$, $\theta_2 = \arg\{z+1\}$, and that we can make this function single-valued by introducing a branch-cut along $[-1, 1]$ and restricting $-\pi \leq \theta_1, \theta_2 \leq \pi$.] (9 marks)

- (d) The function $f(x)$, integrable over the interval $[-1, 1]$, satisfies the integral equation

$$\frac{1}{\pi} \int_{-1}^1 f(t) \log |t-x| dt = \sqrt{1-x^2}, \quad -1 < x < 1.$$

Determine $f(x)$, expressing the final result in terms of the integral

$$I_0 = \frac{2}{\pi^2} \int_0^1 \frac{\log t}{\sqrt{1-t^2}} \left[t \log \left(\frac{1-t}{1+t} \right) \right] dt.$$

You may use the result from lectures that

$$\int_{-1}^1 \frac{\log |t|}{\sqrt{1-t^2}} dt = -\pi \log 2.$$

(7 marks)

[The Hilbert inversion formula

$$f(x) = -\frac{1}{\pi\sqrt{1-x^2}} \oint_{-1}^1 \frac{g(t)\sqrt{1-t^2}}{t-x} dt + \frac{A}{\sqrt{1-x^2}},$$

for the singular integral equation

$$\frac{1}{\pi} \oint_{-1}^1 \frac{f(t)}{t-x} dt = g(x), \quad -1 < x < 1,$$

may be quoted without proof. Here A is an arbitrary constant and \oint represents the principal value integral.]

(Total: 20 marks)

2. The Gamma function $\Gamma(z)$ is defined for $\operatorname{Re}\{z\} > 0$ by

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt.$$

(a) (i) Show that for $\operatorname{Re}\{z\} > 0$ we can write

$$\Gamma(z) = 2 \int_0^\infty x^{2z-1} e^{-x^2} dx,$$

and hence that, for $\lambda \in [0, 1]$

$$\Gamma(\lambda)\Gamma(1-\lambda) = 4 \int_0^\infty \int_0^\infty \left(\frac{x}{y}\right)^{2\lambda-1} e^{-(x^2+y^2)} dx dy.$$

(3 marks)

(ii) Further, by introducing polar coordinates, show that

$$\Gamma(\lambda)\Gamma(1-\lambda) = 2 \int_0^\infty \frac{u^{2\lambda-1}}{1+u^2} du.$$

(4 marks)

(iii) Hence show that, for all z

$$\Gamma(z)\Gamma(1-z) = \frac{\pi}{\sin(\pi z)}.$$

(9 marks)

For $|z| < 1$ and c not equal to zero or a negative integer, the hypergeometric series $F(a, b; c; z)$ may be represented as

$$F(a, b; c; z) = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{n! (c)_n} z^n, \quad \text{where } (a)_n = \prod_{k=0}^{n-1} (a+k),$$

is the Pochhammer symbol.

(b) Show that

$$F(1, 2; 1; z) = \frac{1}{(1-z)^2}.$$

(4 marks)

(Total: 20 marks)

3. (a) Give a heuristic argument that if a mapping $\zeta = f(z)$ from the complex z -plane to the complex ζ -plane is **conformal** at a point z_0 , then it preserves the angle between any two arcs passing through z_0 . (5 marks)

Figure 1 shows the unbounded region, extending to infinity in the upper-half z -plane, exterior to a semi-circular protrusion of unit radius on the real axis, centred at the origin. The region is shaded in grey and labelled A in the figure.

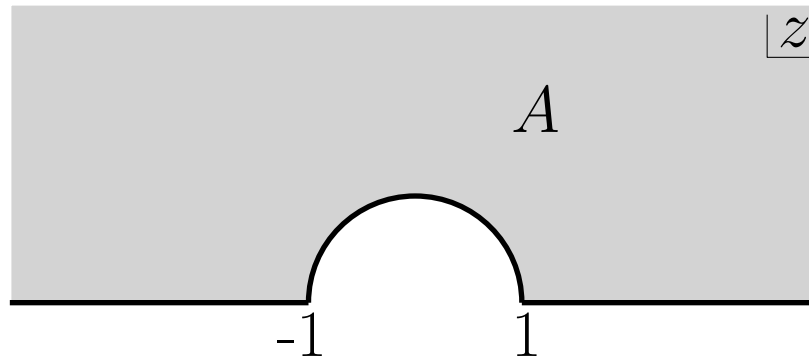


Figure 1: The region exterior to a semi-circular ‘bump’ on the real axis.

- (b) Show that the transformation $\zeta = z + \frac{1}{z}$ maps region A to the upper-half ζ -plane. (5 marks)

A company that manufactures radiator devices wishes to construct a heater whose shape is to follow the boundary of the shaded region in figure 1. The straight boundaries along the real axis are to be maintained at a constant temperature T_1 , with the curved semi-circular boundary kept at a constant temperature T_2 . The shaded region A represents the ambient medium to be heated within which the company wishes to determine the steady-state temperature distribution.

- (c) Assuming that everywhere inside region A the temperature, $T(x, y)$, satisfies Laplace’s equation $\nabla^2 T = 0$, show that

$$T(r, \theta) = \frac{(T_2 - T_1)}{\pi} \left[\tan^{-1} \left(\frac{(r^2 - 1) \sin \theta}{(r^2 + 1) \cos \theta - 2r} \right) - \tan^{-1} \left(\frac{(r^2 - 1) \sin \theta}{(r^2 + 1) \cos \theta + 2r} \right) \right] + T_1,$$

where r and θ are the polar variables of points inside A , i.e. $z = re^{i\theta}$ with $r > 1$ and $0 < \theta < \pi$. (Note: in this question you may apply the inverse tangent function without concern over the details involved in selecting the appropriate branch cuts to ensure the function is single-valued.)

(10 marks)

(Total: 20 marks)

4. The function $f(x)$ satisfies the integral equation

$$f(x) + \frac{5}{4} \int_0^\infty f(y) e^{-2|x-y|} dy = \frac{9}{2},$$

for $x \geq 0$.

- (a) Using the Wiener-Hopf method, and taking the strip of analyticity to be $\{s : \alpha < \operatorname{Im}\{s\} < \beta\}$, for values $\alpha, \beta > 0$ which you should define carefully, show that for $\operatorname{Im}\{s\} > \alpha$ the right-sided Fourier transform $F_+(s) \equiv \int_0^\infty f(x) e^{isx} dx$ is given by

$$F_+(s) = \frac{3i(s+2i)}{s(s+3i)}.$$

(16 marks)

- (b) Hence show that for $x \geq 0$

$$f(x) = 2 + e^{-3x}.$$

(4 marks)

(Total: 20 marks)

5. Consider two-dimensional Stokes flow in the complex z -plane with streamfunction ψ , which can be represented as

$$\psi = \text{Im}\{\bar{z}f(z) + g(z)\},$$

where $f(z)$ and $g(z)$ are analytic functions known as the Goursat functions and the bar represents the complex conjugate. The velocity field of the flow, (u, v) , is known to satisfy

$$u - iv = -\overline{f'(z)} + \bar{z}f''(z) + g'(z),$$

where the dash represents the derivative with respect to the function argument.

- (a) Find the Goursat functions describing a stagnation point flow over the plane with velocity field given by $(u, v) = (kx, -ky)$, where $k > 0 \in \mathbb{R}$. (4 marks)

Consider now an infinitely thin rod of length 2 centred at the point $z = i$ making an angle of 0 with the real axis (i.e aligned horizontally) positioned in the same stagnation point flow over the z -plane as discussed in part (a). A schematic of the setup is shown in figure 2.

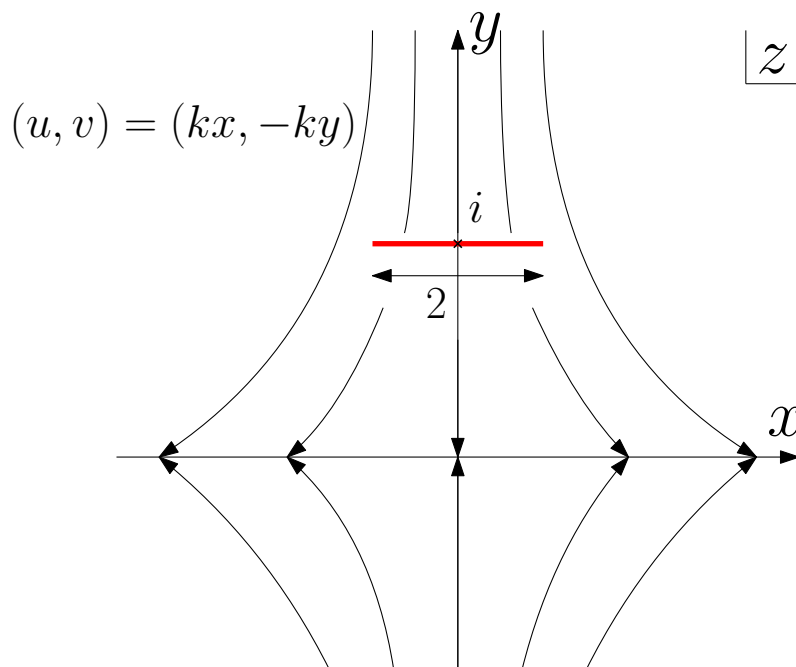


Figure 2: A thin rod of length 2 in Stokes flow with a background stagnation point flow in the z -plane.

- (b) Briefly explain why, or show that, the conformal mapping

$$z(\zeta) = i + \frac{1}{2} \left(\zeta + \frac{1}{\zeta} \right),$$

maps from the interior of the unit disc in the complex ζ -plane, to the region exterior to the rod in the z -plane. (2 marks)

We now represent the Goursat functions in the form $F(\zeta) = f(z(\zeta))$ and $G(\zeta) = g'(z(\zeta))$ and proceed to work in the unit disc in the complex ζ -plane.

- (c) The rod moves according to the effects of its induced velocity and solid body rotation. This means that $u - iv = \bar{U} - i\Omega(\bar{z} + i)$ on the rod. Here $U = U_{\text{rod}} + iV_{\text{rod}}$ where $U_{\text{rod}}, V_{\text{rod}} \in \mathbb{R}$ represent the horizontal and vertical velocity of the rod respectively and $\Omega \in \mathbb{R}$ represents the rod's angular velocity. These are unknown quantities that we will determine. Show that this boundary condition can be written in the form

$$-\bar{F}\left(\frac{1}{\zeta}\right) + \frac{\zeta(\zeta^2 - 2i\zeta + 1)}{(\zeta^2 - 1)}F'(\zeta) + G(\zeta) = \bar{U} - \frac{i\Omega}{2}\left(\zeta + \frac{1}{\zeta}\right),$$

in terms of ζ . (4 marks)

- (d) Given that $F(\zeta)$ takes the form

$$F(\zeta) = \frac{A}{\zeta} + B + C\zeta,$$

for unknown constants A, B and $C \in \mathbb{C}$, show that $G(\zeta)$ must take the form

$$G(\zeta) = \left(-A + \bar{C} - \frac{i\Omega}{2}\right)\frac{1}{\zeta} + (\bar{B} + \bar{U} + 2iA) + \left(\bar{A} - 2A + C - \frac{i\Omega}{2}\right)\zeta + O(\zeta^2),$$

as $\zeta \rightarrow 0$. (3 marks)

- (e) Far away from the rod, the fluid moves according to the background stagnation point flow. Noting this; deduce that

$$A = \frac{1}{2}, \quad B = i, \quad C = \frac{k + 1 - i\Omega}{2} \quad \text{and} \quad U = -ki.$$

(3 marks)

The torque acting on the rod can be calculated via the formula

$$\text{Torque} = -2\text{Re}\left\{\oint_{|\zeta|=1} G(\zeta)z'(\zeta)d\zeta\right\},$$

where $\text{Re}\{\}$ denotes the real part of the expression within the parenthesis and the integration is taken in the positive (anti-clockwise) orientation.

- (f) Given that there is **no-torque** on the rod (i.e. Torque = 0), deduce the value of Ω . (3 marks)
- (g) Describe the instantaneous motion of the rod. (1 mark)

(Total: 20 marks)

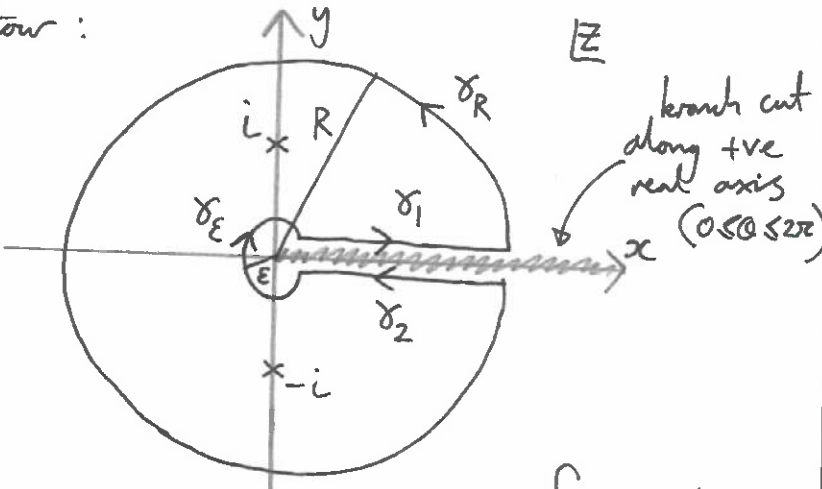
	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 1	Topic SINGULAR INTEGRAL EQUATIONS	Marks & seen/unseen
Parts	<p>(a). The Cauchy transform of $f(z)$ over $\gamma \in \mathbb{C}$ is:</p> $C(z) = \frac{1}{2\pi i} \int_{\gamma} \frac{f(\xi)}{\xi - z} d\xi.$ <p>The Hilbert transform of $f(z)$ over $\gamma \in \mathbb{C}$ is:</p> $H(z) = \frac{1}{2\pi i} \oint_{\gamma} \frac{f(\xi)}{\xi - z} d\xi.$ <p>(b). Plemelj formulae:</p> $C_+(z) + C_-(z) = 2H(z),$ $C_+(z) - C_-(z) = f(z),$ <p>for z not an end point of γ. Here $C_{\pm}(z_0)$ represents the limiting value of $C(z)$ as $z \rightarrow z_0$ from the left/right of γ (facing in the direction of integration).</p> <p>(c). When $f(z) = z$, $\gamma = [-1, 1]$, then:</p> $C(z) = \frac{1}{2\pi i} \int_{-1}^1 \frac{\xi}{\xi - z} d\xi,$ <p style="text-align: right;">①</p> <p>but $\frac{\xi}{\xi - z} = \frac{\xi - z}{\xi - z} + \frac{z}{\xi - z} = 1 + \frac{z}{\xi - z},$</p>	<p>} 1 A seen</p> <p>} 1 A seen</p> <p>} 2 A seen</p> <p>[Part (c) seen example $f(z)=1$ in lectures]</p> <p>} 1 A seen similar</p>
	Setter's initials SJB Checker's initials	Page number 1

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 1	Topic SINGULAR INTEGRAL EQUATIONS	Marks & seen/unseen
Parts (c). (continued).	<p>so that:</p> $C(z) = \frac{1}{2\pi i} \int_{-1}^1 \left(1 + \frac{z}{\xi - z} \right) d\xi$ $= \frac{1}{2\pi i} \left(\left[\xi \right]_{-1}^1 + z \left[\log(\xi - z) \right]_{-1}^1 \right)$ $= \frac{1}{\pi i} + \frac{1}{2\pi i} z \log \left(\frac{z-1}{z+1} \right).$ $= \frac{1}{\pi i} + \frac{1}{2\pi i} z \left(\log \left(\frac{r_1}{r_2} \right) + i(\theta_1 - \theta_2) \right),$ <p>using the given fact. Now, taking $x \in \gamma$ (not an end point), we have: $r_1 = 1-x$, $r_2 = 1+x$, and as we approach x from <u>above</u> (left): $\theta_1 = \pi$, $\theta_2 = 0$, but as we approach x from <u>below</u> (left): $\theta_1 = -\pi$, $\theta_2 = 0$, which gives:</p> $C_+(x) = \frac{1}{\pi i} + \frac{1}{2\pi i} x \log \left(\frac{1-x}{1+x} \right) + \frac{x}{2},$ $C_-(x) = \frac{1}{\pi i} + \frac{1}{2\pi i} x \log \left(\frac{1-x}{1+x} \right) - \frac{x}{2}.$ <p>Now, calculating the Hilbert transform:</p> $H(x) = \frac{1}{2\pi i} \int_{-1}^1 \frac{\xi}{\xi - x} d\xi$	<p>1 A seen similar</p> <p>1 A use result</p> <p>3 C seen similar</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question <u>1</u>	Topic SINGULAR INTEGRAL EQUATIONS	Marks & seen/unseen
Parts (c). (continued).	$= \frac{1}{2\pi i} \left(\int_{-1}^1 d\xi + x \int_{-1}^1 \frac{1}{\xi - x} d\xi \right), \text{ using } \textcircled{1}$ $= \frac{1}{\pi i} + \frac{1}{2\pi i} x \log \left(\frac{1-x}{1+x} \right)$ <p>Hence, for $x \in \gamma$ (not an end point):</p> $C_+(x) + C_-(x) = \frac{2}{\pi i} + \frac{1}{\pi i} x \log \left(\frac{1-x}{1+x} \right) = 2H(x)$ $C_+(x) - C_-(x) = x = f(x)$ <p>(d). Differentiate both sides w.r.t x:</p> $\frac{1}{\pi} \int_{-1}^1 \frac{f(t)}{t-x} dt = (-1) \cdot \frac{1}{2} \cdot (-2x) \cdot (1-x^2)^{-\frac{1}{2}}$ $= \frac{x}{\sqrt{1-x^2}}$ <p>Apply Hilbert inversion:</p> $f(x) = \frac{-1}{\pi \sqrt{1-x^2}} \int_{-1}^1 \frac{t}{t-x} dt + \frac{A}{\sqrt{1-x^2}}$	<p>B 2 seen similar</p> <p>A 1 seen similar</p> <p>B 2 seen similar</p> <p>B 1 seen similar</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 1	Topic SINGULAR INTEGRAL EQUATIONS	Marks & seen/unseen
Parts (d). (continued.)	$\Rightarrow f(x) = \frac{-1}{\pi\sqrt{1-x^2}} \left(2 + x \log \left(\frac{1-x}{1+x} \right) \right) + \frac{A}{\sqrt{1-x^2}},$ <p style="text-align: right;">from (c).</p> $\Rightarrow f(x) = \frac{(A\pi - 2 - x \log \left(\frac{1-x}{1+x} \right))}{\pi\sqrt{1-x^2}} \quad (2)$ <p>To determine A, plug (2) into original equation:</p> $\frac{1}{\pi} \int_{-1}^1 \frac{(A\pi - 2 - t \log \left(\frac{1-t}{1+t} \right))}{\pi\sqrt{1-t^2}} \log t-x dt = \sqrt{1-x^2},$ <p>and set $x=0$:</p> $\frac{A}{\pi} \int_{-1}^1 \frac{\log t }{\sqrt{1-t^2}} dt - \frac{2}{\pi^2} \int_{-1}^1 \frac{\log t }{\sqrt{1-t^2}} dt$ $- \frac{1}{\pi^2} \int_{-1}^1 \frac{\log t }{\sqrt{1-t^2}} \left(t \log \left(\frac{1-t}{1+t} \right) \right) dt = 1$ $\Rightarrow \left(\frac{A}{\pi} - \frac{2}{\pi^2} \right) (-\pi \log 2) - I_0 = 1, \text{ since the third integral above is even so can be written as } I_0.$	<div style="text-align: right;"> <div style="border: 1px solid red; padding: 2px; display: inline-block;">D</div> 1 unseen </div> <div style="text-align: right;"> <div style="border: 1px solid red; padding: 2px; display: inline-block;">D</div> 1 seen similar </div>
	Setter's initials SJB	Checker's initials Page number 4

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question <u>1</u>	Topic SINGULAR INTEGRAL EQUATIONS	Marks & seen/unseen
Parts (d). (continued.)	$\Rightarrow -A \log 2 + \frac{2}{\pi} \log 2 - I_0 = 1$ $\Rightarrow A = \frac{1 + I_0 - \frac{2}{\pi} \log 2}{-\log 2} = \underline{\underline{\frac{2}{\pi} - \frac{1 + I_0}{\log 2}}}$ <p>Hence:</p> $f(x) = \underline{\underline{\frac{-\left(\frac{(1 + I_0)\pi}{\log 2} + x \log \left(\frac{1-x}{1+x}\right)\right)}{\pi \sqrt{1-x^2}}}}$	<div style="border: 1px solid red; padding: 5px; display: inline-block;"> D </div> 2 unseen Q1 Total (20)
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		Page number 5

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question <u>2</u>	Topic SPECIAL FUNCTIONS	Marks & seen/unseen
Parts (a). (ii). (continued.)	<p>Then: $T(\lambda)T(1-\lambda) = 2 \int_0^{\infty} \frac{u^{2\lambda-1}}{1+u^2} du.$</p> <p>(iii). Since $0 < \lambda < 1$ the remaining integral has a multi-valued function $z^{2\lambda-1}$ in the integrand. Hence, we introduce the contour:</p>  <p>Let $\gamma = \gamma_R + \gamma_E + \gamma_1 + \gamma_2$ and consider: $\oint_{\gamma} q(z) dz,$ where $q(z) = \frac{z^{2\lambda-1}}{1+z^2} = \frac{z^{2\lambda-1} \gamma}{(z+i)(z-i)}.$</p> <p>By the residue theorem:</p> $\oint_{\gamma} q(z) dz = 2\pi i \left(\text{Res} \{ q, i \} + \text{Res} \{ q, -i \} \right)$ $= 2\pi i \left(\frac{(e^{i\frac{\pi}{2}})^{2\lambda-1}}{2i} + \frac{(e^{\frac{3\pi i}{2}})^{2\lambda-1}}{-2i} \right)$	<p>2 A seen</p> <p>1 A - contour</p> <p>2 B - locate poles - branch cut seen similar</p>
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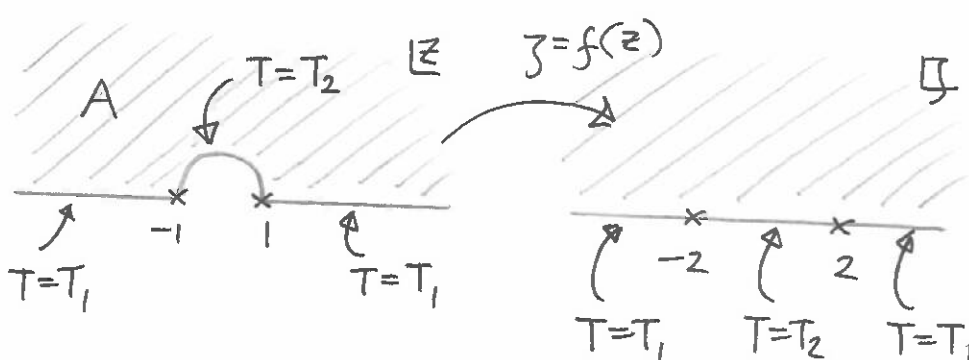
	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 2	Topic SPECIAL FUNCTIONS	Marks & seen/unseen
Parts (a). (iii). (continued.)	$= \pi (e^{\pi i \lambda} (-i) - e^{3\pi i \lambda} (i))$ $= -\pi i (e^{\pi i \lambda} + e^{3\pi i \lambda}).$ <p>The contours \int_{γ_R} and $\int_{\gamma_\epsilon} \rightarrow 0$ as $R \rightarrow \infty$ and $\epsilon \rightarrow 0$ respectively.</p> <p>Now, letting $I = \int_0^\infty \frac{u^{2\lambda-1}}{1+u^2} du$, then:</p> $\int_{\gamma_1} q(z) dz = I, \text{ and}$ $\int_{\gamma_2} q(z) dz = \int_\infty^0 \frac{(ue^{2\pi i})^{2\lambda-1}}{u^2+1} du = -e^{4\pi i \lambda} \int_0^\infty \frac{u^{2\lambda-1}}{1+u^2} du$ $= -e^{4\pi i \lambda} I.$ <p>Hence, putting everything together:</p> $T(\lambda)T(1-\lambda) = \frac{2(-\pi i (e^{\pi i \lambda} + e^{3\pi i \lambda}))}{1 - e^{4\pi i \lambda}} \times \frac{e^{-2\pi i \lambda}}{e^{-2\pi i \lambda}}$ $= \frac{-2\pi i (e^{-\pi i \lambda} + e^{\pi i \lambda})}{e^{-2\pi i \lambda} - e^{2\pi i \lambda}}$	<p>1 B -residue at i</p> <p>1 C -residue at -i seen Similar</p> <p>2 D Seen Similar</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 2	Topic SPECIAL FUNCTIONS	Marks & seen/unseen
Parts (a). (iii). (continued.)	$= \frac{2\pi \cos(\pi\lambda)}{\sin(2\pi\lambda)}$ $= \frac{2\pi \cos(\pi\lambda)}{2 \cos(\pi\lambda) \sin(\pi\lambda)}$ $= \frac{\pi}{\sin(\pi\lambda)}$ <p>Hence, by <u>analytic continuation</u> to all of z, we deduce the result:</p> $\boxed{T(z)T(1-z) = \frac{\pi}{\sin(\pi z)}, \quad \forall z.}$ <p>(b). $F(1,2;1;z) = \sum_{n=0}^{\infty} \frac{(1)_n (2)_n}{n! (1)_n} z^n$, for $z < 1$</p> <p>Now $(2)_n = \prod_{k=0}^{n-1} (2+k) = 2 \times 3 \times \dots \times (n+1) = (n+1)!$</p> <p>So we have:</p> $F(1,2;1;z) = \sum_{n=0}^{\infty} \frac{(n+1)!}{n!} z^n, \text{ for } z < 1$ $= \sum_{n=0}^{\infty} (n+1) z^n, \text{ for } z < 1.$	<p>1 C unseen</p> <p>1 C seen</p> <p>2 B seen similar</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 2	Topic SPECIAL FUNCTIONS	Marks & seen/unseen
Parts (b). (continued).	<p>But note that $(1-z)^{-1} = 1+z+z^2+\dots$, for $z <1$, so differentiating both sides wrt z:</p> $(1-z)^{-2} = 1+2z+3z^2+\dots, \text{ for } z <1$ $= \sum_{n=0}^{\infty} (n+1)z^n, \text{ for } z <1.$ <p>Hence: $F(1,2;1;z) = \frac{1}{(1-z)^2}$, which holds for all z by analytic continuation ($z \neq 1$).</p>	<div style="border: 1px solid red; padding: 5px; display: inline-block;"> D </div> 2 unseen Q2 Total: 20
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 3	Topic CONFORMAL MAPPING	Marks & seen/unseen
Parts	<p>(a). Suppose $f(z)$ is analytic <u>conformal</u> at z_0. This means that $f(z)$ is <u>analytic</u> at z_0 and that $f'(z_0) \neq 0$. Thus, we have:</p> $f'(z_0) = \lim_{\Delta z \rightarrow 0} \frac{f(z_0 + \Delta z) - f(z_0)}{\Delta z},$ <p>or, for <u>small</u> Δz, approximately:</p> $\Delta z f'(z_0) \approx f(z_0 + \Delta z) - f(z_0),$ <p>and denoting $z = z_0 + \Delta z$ gives:</p> $z = f(z) \approx \underbrace{f'(z_0)}_a z + \underbrace{(f(z_0) - f'(z_0)z_0)}_b,$ <p>so that, locally, $z = f(z)$ behaves like the linear mapping $z = az + b$ ($a, b \in \mathbb{C}$), where $a = f'(z_0) \neq 0$. Since $f(z)$ is conformal so that $f'(z_0) \neq 0$.</p> <p>We argue from lectures that linear mappings preserve the angle between any two arcs passing through z_0, but this is straightforward to show.</p> <p>Thus $z = f(z)$ conformal at $z_0 \Rightarrow$ angles through z_0 preserved.</p>	<p>2 A -deg. of conformal seen</p> <p>2 A seen</p> <p>1 A seen</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 3	Topic CONFORMAL MAPPING	Marks & seen/unseen
Parts	<p>(b). Denote $z = re^{i\theta}$. Then we have:</p> $\begin{aligned} \zeta &= z + \frac{1}{z} = re^{i\theta} + \frac{1}{r}e^{-i\theta} \\ &= r\cos\theta + \frac{1}{r}\cos\theta + i(r\sin\theta - \frac{1}{r}\sin\theta) \\ &= (r + \frac{1}{r})\cos\theta + i(r - \frac{1}{r})\sin\theta. \end{aligned}$ <p>On ①: $\theta = 0, r = x \geq 1$ $\Rightarrow \zeta = x + \frac{1}{x}, x \geq 1$. This is clearly part of the positive real axis (in fact one can show $x + \frac{1}{x} \geq 2$ as shown in the diagram).</p> <p>On ②: $r = 1, 0 \leq \theta \leq \pi$ $\Rightarrow \zeta = 2\cos\theta, 0 \leq \theta \leq \pi$ $\Rightarrow \zeta \in [-2, 2]$, so maps to this section of the real axis, as shown in the diagram.</p> <p>Similarly to ①, on ③: $\theta = \pi, r = x \geq 1$ $\Rightarrow \zeta = -x - \frac{1}{x}$, so is negative the section ①.</p> <p>Lastly, check a point: $z = 2i \Rightarrow \zeta = 2i + \frac{1}{2i} = \frac{3}{2}i$, so indeed we have the UHζ-plane.</p>	<p>unseen</p> <p>1 B</p> <p>$x + \frac{1}{x} \geq 2$</p> <p>3 A</p> <p>seen Similar</p> <p>seen similar</p> <p>1 B</p> <p>- check point</p>
	Setter's initials SJB <div style="margin-left: 100px;">Checker's initials</div>	Page number 12

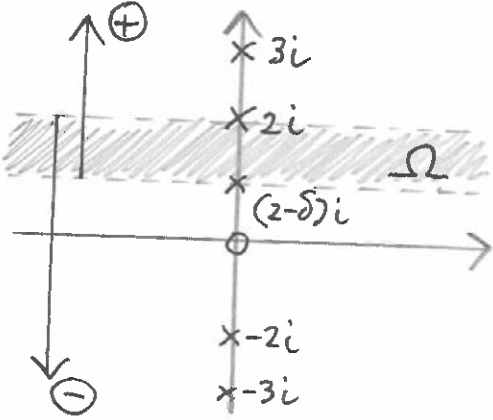
	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 3	Topic CONFORMAL MAPPING	Marks & seen/unseen
Parts (c).	 <p>First, employ the conformal transformation $z = \zeta + \frac{1}{\zeta}$ to map region A to the Uz-plane. The boundary conditions on each section map over according to the diagram above. Now, working in the z-plane, we make the following ansatz for the complex potential</p> $w(z) = W(z(\zeta)) = T(x, y) + i\psi(x, y):$ $W(z) = -a i \log(z-2) - b i \log(z+2) + c,$ <p>where $a, b, c \in \mathbb{R}$. So then:</p> $T = \operatorname{Re} \{ W(z) \} = a \cdot \arg \{ z-2 \} + b \cdot \arg \{ z+2 \} + c.$ <p>Now we use the boundary conditions:</p> <ul style="list-style-type: none"> $T = T_1$ when $\arg \{ z-2 \} = \arg \{ z+2 \} = \pi$ $\Rightarrow \pi(a+b) + c = T_1 \quad (1)$	<div style="border: 1px solid red; padding: 5px; display: inline-block;">B</div> 2 Seen similar <div style="border: 1px solid red; padding: 5px; display: inline-block;">D</div> 2 unseen <div style="border: 1px solid red; padding: 5px; display: inline-block;">Students have seen one log term in an example in lectures</div>
	Setter's initials STB	Checker's initials Page number 13

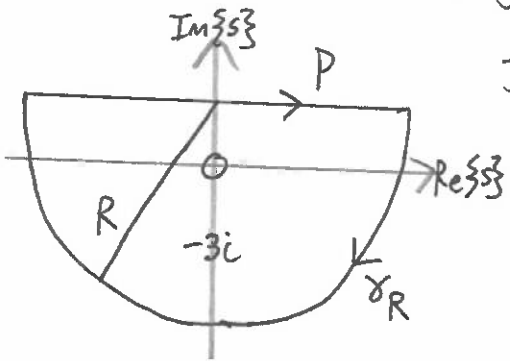
	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 3	Topic CONFORMAL MAPPING	Marks & seen/unseen
Parts (c). (continued.)	<p>• $T = T_1$ when $\arg\{z-2\} = \arg\{z+2\} = 0$ $\Rightarrow \underline{C = T_1}$, so ① gives: $\underline{a = -b}$ ②</p> <p>• $T = T_2$ when $\arg\{z-2\} = \pi$, $\arg\{z+2\} = 0$ $\Rightarrow a\pi + T_1 = T_2 \Rightarrow \underline{a = \frac{T_2 - T_1}{\pi}}$, so using ②: $\underline{b = \frac{T_1 - T_2}{\pi}}$.</p> <p>Hence we have: $w(z) = -\left(\frac{T_2 - T_1}{\pi}\right) i \log(z-2) + \left(\frac{T_2 - T_1}{\pi}\right) i \log(z+2) + T_1,$</p> <p>thus: $T(x,y) = \operatorname{Re}\{w(z)\}$ $= \left(\frac{T_2 - T_1}{\pi}\right) [\arg\{z-2\} - \arg\{z+2\}] + T_1,$</p> <p>but: $z-2 = z + \frac{1}{z} - 2 = re^{i\theta} + \frac{1}{r}e^{-i\theta} - 2$ $= \left(r + \frac{1}{r}\right)\cos\theta - 2 + i\left(r - \frac{1}{r}\right)\sin\theta$ $\Rightarrow \arg\{z-2\} = \tan^{-1}\left(\frac{\left(r - \frac{1}{r}\right)\sin\theta}{\left(r + \frac{1}{r}\right)\cos\theta - 2}\right),$</p>	<div style="text-align: right;"> <div style="border: 1px solid red; padding: 2px; display: inline-block;">C</div> 3 unseen </div> <div style="text-align: right;"> <div style="border: 1px solid red; padding: 2px; display: inline-block;">D</div> 2 unseen </div>
	Setter's initials SJB <div style="margin-left: 100px;">Checker's initials</div>	Page number 14

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 3	Topic CONFORMAL MAPPING	Marks & seen/unseen
Parts (c). (Continued).	<p>and similarly: $\arg\{z+2\} = \tan^{-1}\left(\frac{(r-\frac{1}{r})\sin\theta}{(r+\frac{1}{r})\cos\theta+2}\right)$</p> <p>Thus:</p> $T(r,\theta) = \left(\frac{T_2-T_1}{\pi}\right) \left[\tan^{-1}\left(\frac{(r^2-1)\sin\theta}{(r^2+1)\cos\theta-2r}\right) - \tan^{-1}\left(\frac{(r^2-1)\sin\theta}{(r^2+1)\cos\theta+2r}\right) \right] + T_1,$ <p>as required upon multiplying by $\frac{r}{r}$ within each \tan^{-1} function.</p>	<p>1</p> <p>B</p> <p>Seen similar</p> <p>Q3 Total: (20)</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 4	Topic WIENER-HOPF METHOD	Marks & seen/unseen
Parts (a).	<p>Let $k(x) = \frac{5}{4} e^{-2 x }$ and $p(x) = \frac{9}{2}$. Introduce:</p> $f_+(x) = \begin{cases} f(x), & x \geq 0 \\ 0, & x < 0 \end{cases}$ $p_+(x) = \begin{cases} p(x), & x \geq 0 \\ 0, & x < 0 \end{cases}$ $g_-(x) = \begin{cases} 0, & x \geq 0 \\ \int_0^\infty f(y) k(x-y) dy, & x < 0. \end{cases}$ <p>Then, we have the equation:</p> $\frac{5}{4} \int_0^\infty f(y) e^{-2 x-y } dy = -f_+(x) + p_+(x) + g_-(x), \quad (1)$ <p>valid for $-\infty < x < \infty$. Taking the Fourier transform of both sides of (1) gives:</p> $\hat{K}(s) F_+(s) = -F_+(s) + P_+(s) + G_-(s), \text{ or}$ $K(s) F_+(s) + G_-(s) = -P_+(s), \quad (2)$ <p>where $K(s) = -\hat{K}(s) - 1$ and where $F_+(s)$ denotes the right-sided FT of $f_+(x)$, $P_+(s)$ the right-sided FT of $p_+(x)$, $G_-(s)$ the left-sided FT of $g_-(x)$ and $\hat{K}(s)$ the ordinary FT of $k(x)$.</p>	<p>1 A seen</p> <p>1 A seen</p>
	Setter's initials STB <div style="margin-left: 100px;">Checker's initials</div>	Page number 16

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 4	Topic WIENER-HOPF METHOD	Marks & seen/unseen
Parts (a). (continued).	<p>One can either show, or use the result from problem sheets, that: $\hat{K}(s) = \frac{5}{s^2+4}$.</p> <p>For $P_+(s)$ we calculate:</p> $P_+(s) = \frac{q}{2} \int_0^{\infty} e^{isx} dx = \frac{q}{2} \left[\frac{e^{isx}}{is} \right]_0^{\infty} = -\frac{q}{2is} = \frac{qi}{2s}$ <p>It follows that:</p> $K(s) = -\hat{K}(s) - 1 = -\frac{(s^2+4) - 5}{s^2+4} = -\frac{(s^2+9)}{(s^2+4)}$ <p>• We require, from lectures: $f_+(x) < A e^{(2-\delta)x}$ as $x \rightarrow \infty$, for some $\delta > 0$ (A constant).</p> <p>$\Rightarrow F_+(s)$ analytic in $\{s: \text{Im}\{s\} > 2-\delta\}$.</p> <p>• Similarly, for $G_-(s)$, from lectures we can show that $g_-(x) = B e^{2x}$ (B constant).</p> <p>$\Rightarrow G_-(s)$ analytic in $\{s: \text{Im}\{s\} < 2\}$.</p> <p>We thus take \oplus and \ominus regions desired to be:</p> <p>$\oplus = \{s: \text{Im}\{s\} > 2-\delta\}$, $\ominus = \{s: \text{Im}\{s\} < 2\}$, where $0 < \delta < 2$. Hence the strip of analyticity where \oplus and \ominus overlap is the region: $\underbrace{2-\delta}_{\alpha} < \text{Im}\{s\} < \underbrace{2}_{\beta}$.</p>	<p>$\left. \begin{array}{l} \boxed{A} \\ 1 \end{array} \right\}$ seen</p> <p>$\left. \begin{array}{l} \boxed{P_+ A} \\ 1 \end{array} \right\}$ seen similar</p> <p>$\left. \begin{array}{l} \boxed{K A} \\ 1 \end{array} \right\}$ seen similar</p> <p>$\left. \begin{array}{l} \alpha/\beta \boxed{A} \\ 2 \end{array} \right\}$ seen similar</p>
	Setter's initials SJB <div>Checker's initials</div>	Page number 17

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 4	Topic WIENER-HOPF METHOD	Marks & seen/unseen
Parts (a). (continued).	 <p> $K(s)$ analytic provided $s \neq \pm 2i$ ✓ $K(s)$ non-zero provided $s \neq \pm 3i$ ✓ $P_+(s)$ analytic provided $s \neq 0$ ✓ </p> <p>We decompose $K(s)$ as $K(s) = K_+(s)K_-(s)$, where:</p> $K_+(s) = \frac{(s+3i)}{(s+2i)}, \quad K_-(s) = -\frac{(s-3i)}{(s-2i)},$ <p>then ② gives:</p> $K_+(s)F_+(s) + \frac{G_-(s)}{K_-(s)} = -\frac{P_+(s)}{K_-(s)} = \frac{9i(s-2i)}{2s(s-3i)} = R(s)$ <p>Now observe that we can write $R(s) = R_+(s) + R_-(s)$, where:</p> $R_+(s) = \frac{3i}{s}, \quad R_-(s) = \frac{3i}{2(s-3i)},$ <p>the constants found from a partial fraction decomposition.</p> <p>Now we have:</p> $\underbrace{K_+(s)F_+(s)}_{\text{analytic in } \oplus} - \underbrace{R_+(s)}_{\text{analytic in } \ominus} = \underbrace{-\frac{G_-(s)}{K_-(s)} + R_-(s)}_{K_-(s)} \quad s \in \Omega$	<p>K decomp. D</p> <p>2 seen similar</p> <p>R decomp. D</p> <p>2 seen similar</p>
	Setter's initials STB	Page number 18

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 4	Topic WIENER-HOPF METHOD	Marks & seen/unseen
Parts (a). (continued.)	<p>Since \oplus, \ominus overlap in Ω, then:</p> $E(s) = \begin{cases} F_+(s)K_+(s) - R_+(s), & s \in \oplus \\ -\frac{G_-(s)}{K_-(s)} + R_-(s), & s \in \ominus, \text{ is entire.} \end{cases}$ <p>Consider now $s \rightarrow \infty$ in \oplus:</p> $F_+(s)K_+(s) - R_+(s) \sim \left[\underbrace{\frac{if(0)}{s} + O\left(\frac{1}{s^2}\right)}_{\text{from lectures}} \right] \cdot \left(1 + O\left(\frac{1}{s}\right)\right) - O\left(\frac{1}{s}\right)$ $\sim O\left(\frac{1}{s}\right) \rightarrow 0 \text{ as } s \rightarrow \infty.$ <p>Hence, by <u>Liouville's theorem</u>: $E(s) \equiv 0$ <u>for all</u> s.</p> <p>Therefore: $F_+(s)K_+(s) - R_+(s) = 0$</p> $\Rightarrow F_+(s) = \frac{R_+(s)}{K_+(s)} = \frac{3i(s+2i)}{s(s+3i)},$ <p style="text-align: right;">as required.</p> <p>(b). To retrieve $f_+(x)$, we apply the inversion formula:</p> $f_+(x) = \frac{1}{2\pi i} \int F_+(s) e^{-isx} ds,$  <p>where P is a horizontal line in the \oplus region.</p>	<p>B</p> <p>1 E(s) entire. Seen</p> <p>C</p> <p>2 expand. Seen similar</p> <p>C</p> <p>1 Liouville. Seen</p> <p>A</p> <p>1 result. Seen similar</p> <p>B</p> <p>1 Seen</p>
	Setter's initials STB	Checker's initials
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 4	Topic <u>WIENER-HOPF METHOD</u>	Marks & seen/unseen
Parts (b). (Continued).	<p>• For $x < 0$, from lectures; $f_+(x) = 0$ as expected.</p> <p>• For $x > 0$, we close P with a semi-circle γ_R below P of radius R and take $R \rightarrow \infty$.</p> <p>Denoting $\gamma = P + \gamma_R$, we have by the <u>residue theorem</u>:</p> <p>$\oint_{\gamma} \frac{3i(s+2i)}{s(s+3i)} e^{-isx} ds = -2\pi i (\text{Res}\{0\} + \text{Res}\{-3i\})$ \because clockwise integration.</p> <p>$= -2\pi i \left(\frac{3i \cdot 2i}{3i} \cdot e^0 + \frac{3i \cdot (-i)}{-3i} \cdot e^{-3x} \right)$ \swarrow both simple poles</p> <p>$= 4\pi + 2\pi e^{-3x}$</p> <p>Now in the limit as $R \rightarrow \infty$, $\int_{\gamma_R} \rightarrow 0$ (from lectures), hence:</p> <p>$f_+(x) = \frac{1}{2\pi} (4\pi + 2\pi e^{-3x})$</p> <p>$\Rightarrow \boxed{f(x) = 2 + e^{-3x}}, \quad x > 0.$</p>	<div style="text-align: right;"> <div style="border: 1px solid black; padding: 2px; display: inline-block;">B</div> 2 seen similar </div> <div style="text-align: right; margin-top: 20px;"> <div style="border: 1px solid black; padding: 2px; display: inline-block;">B</div> 1 seen similar </div> <div style="text-align: right; margin-top: 20px;"> Q4 Total (20) </div>
	Setter's initials STB	Checker's initials
		Page number 20

	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 5	Topic COMPLEX METHODS FOR BIHARMONIC EQUATION	Marks & seen/unseen
Parts	<p>(a). We have $(u, v) = (kx, -ky)$, so:</p> $u - iv = kx + ky i = -\overline{f(z)} + \overline{z} f'(z) + g'(z)$ $\Rightarrow k z = -\overline{f(z)} + \overline{z} f'(z) + g'(z), \text{ so, comparing both sides; we must have:}$ $f'(z) = \text{constant} = A \in \mathbb{C}$ $g'(z) = k z$ $\Rightarrow A \overline{z} = (\overline{A} \overline{z} + \overline{B}), \text{ upon integrating } f'(z), \text{ so we conclude } B = 0 \text{ and } A = 1, \text{ giving:}$ <div style="border: 1px solid black; padding: 5px; display: inline-block;"> $f(z) = z, g'(z) = k z$ </div> <p>(Note: a real constant may be added to each and this is also correct - it is the degree of freedom we have prescribing background pressures).</p> <p>(b). The mapping $z(\zeta) = \frac{1}{2}(\zeta + \frac{1}{\zeta})$ is the Joukowski mapping studied in lectures. This maps the <u>interior</u> of the <u>unit ζ-disc</u> to the region around a slit from -1 to 1 on the positive real axis in the z-plane. Adding i to this mapping then simply translates the slit so that it is centred at $z = i$ in the z-plane, as required.</p>	<p>} 1 seen</p> <p>} 2 seen</p> <p>} 1 seen</p> <p>} 1 seen</p> <p>} 1 seen</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 5	Topic COMPLEX METHODS FOR BIHARMONIC EQUATION	Marks & seen/unseen
Parts (c).	<p>we have:</p> $u - iv = -f(z) + \bar{z}f'(z) + g'(z) = \bar{U} - i\Omega(\bar{z} + i),$ <p>writing this in terms of ζ: on the rod.</p> $-\overline{F(\zeta)} + \overline{z(\zeta)} \frac{d\zeta}{dz} F'(\zeta) + G(\zeta) = \bar{U} - i\Omega(\overline{z(\zeta)} + i),$ <p style="text-align: right;">on the rod.</p> <p>Now we have:</p> $z(\zeta) = i + \frac{1}{2}\left(\zeta + \frac{1}{\zeta}\right), \text{ so } \overline{z(\zeta)} = -i + \frac{1}{2}\left(\bar{\zeta} + \frac{1}{\bar{\zeta}}\right).$ <p>But, on the rod (which is the <u>boundary</u> of the unit ζ-disc), we have $\bar{\zeta} = \frac{1}{\zeta}$, so this means:</p> $\overline{z(\zeta)} = -i + \frac{1}{2}\left(\zeta + \frac{1}{\zeta}\right).$ <p>Now $z'(\zeta) = \frac{1}{2}\left(1 - \frac{1}{\zeta^2}\right)$; so this means that:</p> $\overline{z(\zeta)} \frac{d\zeta}{dz} = \left(-i + \frac{1}{2}\left(\zeta + \frac{1}{\zeta}\right)\right) \cdot \frac{2}{\left(1 - \frac{1}{\zeta^2}\right)}$ $= \frac{\zeta(\zeta^2 - 2i\zeta + 1)}{(\zeta^2 - 1)}.$ <p>Putting everything together:</p> $-\overline{F\left(\frac{1}{\zeta}\right)} + \frac{\zeta(\zeta^2 - 2i\zeta + 1)}{(\zeta^2 - 1)} F'(\zeta) + G(\zeta) = \bar{U} - \frac{i\Omega}{2}\left(\zeta + \frac{1}{\zeta}\right),$ <p style="text-align: right;">as required.</p>	<p>1 seen similar</p> <p>1 seen similar</p> <p>2 seen similar</p>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 5	Topic COMPLEX METHODS FOR BIHARMONIC EQUATION	Marks & seen/unseen
Parts	<p>(d). We plug $F(z) = \frac{A}{z} + B + Cz$ into the boundary condition from part (c):</p> $-\left(\bar{A}z + \bar{B} + \frac{\bar{C}}{z}\right) + \frac{z(z^2 - 2iz + 1)}{(z^2 - 1)} \left[C - \frac{A}{z^2}\right] + G(z)$ $= \bar{U} - \frac{i\Omega}{2}\left(z + \frac{1}{z}\right)$ <div style="border: 1px solid black; border-radius: 50%; padding: 10px; display: inline-block; margin: 10px;"> $= \frac{1}{z^2 - 1} = -(1 - z^2)^{-1}$ $= -[1 + z^2 + z^4 + O(z^6)]$ <p style="text-align: right;">as $z \rightarrow 0$.</p> </div> <p>\Rightarrow</p> $G(z) = \frac{1}{z} \left(\bar{C} - A - \frac{i\Omega}{2} \right) + \left(\bar{B} + 2Ai + \bar{U} \right)$ $+ \left(\bar{A} - 2A + C - \frac{i\Omega}{2} \right) z + O(z^2),$ <p style="text-align: right;">as $z \rightarrow 0$</p> <p>(e). In the far-field, we know:</p> $f(z) \sim z, \text{ as } z \rightarrow \infty \text{ (from (a).)}$ $g'(z) \sim kz, \text{ as } z \rightarrow \infty \text{ (from (a).)}$ <p>In terms of z, these become:</p> $F(z) \sim \left(i + \frac{1}{2}\left(z + \frac{1}{z}\right) \right) \text{ as } z \rightarrow 0$ $\sim \frac{1}{2z} + i \text{ as } z \rightarrow 0$ $G(z) \sim \frac{k}{2z} + ki \text{ as } z \rightarrow 0$	<div style="display: flex; align-items: center; justify-content: center;"> } <div> <p>1 unseen</p> <p>1 unseen</p> <p>1 unseen</p> <p>1 unseen</p> <p>1 unseen</p> <p>1 unseen</p> </div> </div>
	Setter's initials <div style="border: 1px solid black; padding: 2px; display: inline-block;">SJB</div>	Checker's initials <div style="border: 1px solid black; padding: 2px; display: inline-block;"></div>
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	EXAMINATION SOLUTION 23 - 24	Course: Applied Complex Analysis
Question 5	Topic COMPLEX METHODS FOR BIHARMONIC EQUATION	Marks & seen/unseen
Parts (e). (Continued).	<p>Comparing these forms with $F(z) = \frac{A}{z} + B + Cz$ and the form of $G(z)$ from (d). leads to:</p> <p><u>$A = \frac{1}{2}$</u>, <u>$B = i$</u> (comparing $F(z)$)</p> <p>and:</p> <p>$(-\frac{1}{2} + \bar{C} - \frac{i\Omega}{2}) = \frac{k}{2} \Rightarrow \underline{\underline{C = \frac{k+1-i\Omega}{2}}}$</p> <p>$(-i + \bar{U} + i) = ki \Rightarrow \underline{\underline{U = -ki}}$ (comparing $G(z)$).</p> <p>(f). $\oint_{ z =1} G(z) z'(z) dz = \oint_{ z =1} \left(\frac{k}{2} \frac{1}{z} + ki + \left(\frac{k}{2} - i\Omega \right) z + \dots \right) \times \frac{1}{2} \left(1 - \frac{1}{z^2} \right) dz$</p> <p>$= \oint_{ z =1} \left(\dots + \left(\frac{k}{4} - \frac{k}{4} + \frac{\Omega i}{2} \right) \frac{1}{z} + \dots \right) dz$</p> <p>$= 2\pi i \cdot \left(\frac{\Omega i}{2} \right) = -\Omega\pi$, by the residue theorem.</p> <p>Hence, torque = 0 $\Rightarrow -2 \cdot \text{Re} \{ -\Omega\pi \} = 0$ $\Rightarrow \underline{\underline{\Omega = 0}}$</p> <p>(g). $U = U_{\text{rod}} + iV_{\text{rod}} = -ki \Rightarrow \boxed{U_{\text{rod}} = 0, V_{\text{rod}} = -k, \Omega = 0}$</p>	<p>1 unseen</p> <p>2 unseen</p> <p>1 unseen</p> <p>1 unseen</p> <p>1 total: 20</p>
	Setter's initials STB <div> Checker's initials i.e. The rod moves vertically down at speed k and doesn't rotate. </div>	Page number 24