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Complex Analysis Notes

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1 Prelim : The Exponential Function and Hyperbolic Functions

1.1 Exponential Function

Derivative

$$\frac{d}{dt}(e^{at}) = a e^{at}$$

Integral

$$\int e^{at} dt = \frac{1}{a} e^{at} + C$$

1.2 Hyperbolic Functions

Definitions:

$$\sinh(at) = \frac{e^{at} - e^{-at}}{2} \quad \bigg| \quad \cosh(at) = \frac{e^{at} + e^{-at}}{2} \quad \bigg| \quad \tanh(at) = \frac{\sinh(at)}{\cosh(at)}.$$

Derivatives

$$\frac{d}{dt}(\sinh(at)) = a \cosh(at), \quad \bigg| \quad \frac{d}{dt}(\cosh(at)) = a \sinh(at), \quad \bigg| \quad \frac{d}{dt}(\tanh(at)) = a \operatorname{sech}^2(at).$$

Integrals

$$\begin{aligned} \int \sinh(at) dt &= \frac{1}{a} \cosh(at) + C \\ \int \cosh(at) dt &= \frac{1}{a} \sinh(at) + C, \\ \int \tanh(at) dt &= \frac{1}{a} \ln|\cosh(at)| + C. \end{aligned}$$

Common Identities

$$\begin{aligned} \cosh^2 x - \sinh^2 x &= 1, \\ \sinh(2x) &= 2 \sinh x \cosh x, \\ \cosh(2x) &= \cosh^2 x + \sinh^2 x, \\ \tanh(2x) &= \frac{2 \tanh x}{1 + \tanh^2 x}. \end{aligned}$$

1.3 Partial Fraction Decomposition

Unrepeated Linear Factors: A linear factor is of form $(ax + b)$

$$\frac{s+1}{s(s-2)(s+3)} = \frac{A}{s} + \frac{B}{s-2} + \frac{C}{s+3}$$

Repeated Linear Factors:

$$\frac{3}{(s+2)^2(s-3)} = \frac{A}{s+2} + \frac{B}{(s+2)^2} + \frac{C}{s-3}$$

Unrepeated Quadratic Factors with complex roots: Where the discriminant $(b^2 - 4ac)$ is negative (complex roots) but the factor is not repeated

$$\frac{3}{(s^2 - s + 1)(s + 2)} = \frac{As + B}{s^2 - s + 1} + \frac{C}{s + 2}$$

Repeated Quadratic Factors with complex roots:

$$\frac{1}{(s^2 + 1)^2(s - 1)} = \frac{As + B}{(s^2 + 1)^2} + \frac{Cs + D}{s^2 + 1} + \frac{E}{s - 1}$$

2 Laplace Transforms

2.1 What is a Laplace Transform?

The Laplace Transform, defined for $t \geq 0$, is given by

$$L\{f(t)\}(s) = F(s) = \int_0^{\infty} e^{-st} dt$$

2.2 Common Laplace Transforms

Example Find the Laplace Transform of $f(t) = 1$

We have:

$$L\{1\} = \int_0^{\infty} 1 \cdot e^{-st} dt = \lim_{R \rightarrow \infty} \int_0^R e^{-st} dt$$

This integral is equal to:

$$\int_0^R e^{-st} dt = \left. \frac{e^{-st}}{-s} \right|_{t=0}^{t=R} = -\frac{1}{s} [e^{-sR} - 1] = \frac{1 - e^{-sR}}{s}$$

Taking the limit as $R \rightarrow \infty$ gives:

$$L\{1\} = \lim_{R \rightarrow \infty} \frac{1 - e^{-sR}}{s} = \frac{1}{s}$$

Example Find the Laplace Transform of $f(t) = e^{2t}$

$$\begin{aligned} L\{e^{2t}\} &= \int_0^{\infty} e^{2t} e^{-st} dt = \int_0^{\infty} e^{-(s-2)t} dt \\ &= \lim_{R \rightarrow \infty} \int_0^R e^{-(s-2)t} dt \\ &= \lim_{R \rightarrow \infty} \left[\frac{e^{-(s-2)t}}{-(s-2)} \right]_{t=0}^{t=R} \\ &= \lim_{R \rightarrow \infty} \left(\frac{e^{-(s-2)R} - e^0}{-(s-2)} \right) = \lim_{R \rightarrow \infty} \left(\frac{e^{-(s-2)R} - 1}{-(s-2)} \right) \\ &= \frac{1}{s-2} \quad (\text{since } e^{-(s-2)R} \rightarrow 0 \text{ as } R \rightarrow \infty \text{ provided } s > 2) \end{aligned}$$

Example Find the Laplace Transform of $f(t) = \cosh(at)$

We have:

$$\begin{aligned} L\{\cosh(at)\} &= L\left\{ \frac{e^{at} + e^{-at}}{2} \right\} \quad \text{from the definition of } \cosh(at) \\ &= \frac{1}{2} L\{e^{at}\} + \frac{1}{2} L\{e^{-at}\} \quad \text{by linearity of the Laplace Transform} \\ &= \frac{1}{2} \left(\frac{1}{s-a} \right) + \frac{1}{2} \left(\frac{1}{s+a} \right) \end{aligned}$$

Hence:

$$L\{\cosh(at)\} = \frac{s}{s^2 - a^2}$$

Noting that $\sinh(at) = (e^{at} - e^{-at})/2$, we can find that:

$$L\{\sinh(at)\} = \frac{a}{(s^2 - a^2)}$$

Example Find the Laplace Transform of $\cos(wt)$ and $\sin(wt)$ where w is a constant.

We first compute the Laplace Transform of e^{iwt} using its definition:

$$L\{e^{iwt}\} = \int_0^{\infty} e^{-st} e^{iwt} dt = \int_0^{\infty} e^{-(s-iw)t} dt = \frac{1}{s-iw}, \quad \text{for } \Re(s) > 0.$$

To express this in terms of real and imaginary parts, we multiply the numerator and denominator by the complex conjugate of the denominator:

$$\frac{1}{s-iw} = \frac{s+iw}{(s-iw)(s+iw)} = \frac{s+iw}{s^2+w^2}.$$

Since Euler's formula gives:

$$e^{iwt} = \cos(wt) + i\sin(wt),$$

the linearity of the Laplace Transform yields:

$$L\{e^{iwt}\} = L\{\cos(wt)\} + iL\{\sin(wt)\}.$$

Equating the two representations of $L\{e^{iwt}\}$, we have:

$$L\{\cos(wt)\} + iL\{\sin(wt)\} = \frac{s+iw}{s^2+w^2}.$$

Since the equality must hold for both the real and imaginary parts, we equate them separately:

$$L\{\cos(wt)\} = \frac{s}{s^2+w^2} \quad \text{and} \quad L\{\sin(wt)\} = \frac{w}{s^2+w^2}.$$

2.3 Linearity of the Laplace Transform

The Laplace Transform is a linear operator, i.e. for any constants a and b :

$$L\{af(t) + bg(t)\} = aL\{f(t)\} + bL\{g(t)\}$$

Proof

$$\begin{aligned} L\{af(t) + bg(t)\} &= \int_0^{\infty} e^{-st}(af(t) + bg(t)) dt \\ &= a \int_0^{\infty} e^{-st}f(t) dt + b \int_0^{\infty} e^{-st}g(t) dt \\ &= aL\{f(t)\} + bL\{g(t)\} \end{aligned}$$

2.4 The First Shift Theorem

Theorem First Shift Theorem

If $f(t)$ has a Laplace Transform, $F(s)$, defined for $s > k$, then $e^{at} f(t)$ has a Laplace Transform, $F(s - a)$ defined for $s - a > k$ and is given by:

$$L\{e^{at} f(t)\} = F(s - a)$$

or, taking the inverse Laplace Transform of both sides:

$$e^{at} f(t) = L^{-1}\{F(s - a)\}$$

Example Find the Laplace Transform of $e^{at} \cos(wt)$, where a, w are constants.

We know that $L\{\cos(wt)\} = \frac{s}{s^2 + w^2}$, so by the First Shift Theorem:

$$\begin{aligned} L\{e^{at} \cos(wt)\} &= \frac{s - a}{(s - a)^2 + w^2} \\ &= \frac{s - a}{s^2 - 2as + a^2 + w^2} \end{aligned}$$

2.5 Existence of the Laplace Transform

Existence of a Laplace transform is not always guaranteed because we're integrating over an infinite integral. For a Laplace Transform to exist for a given s , then the integral must exist:

$$\int_0^\infty e^{-st} f(t) dt$$

Theorem Existence Theorem of Laplace Transforms

Suppose $f(t)$ is a piecewise continuous function on $[0, \infty)$. If $f(t)$ satisfies:

$$|f(t)| \leq Me^{kt} \quad (0 \leq t < \infty)$$

for some constants, M, k , then the Laplace Transform of $f(t)$ exists for $s > k$. In other words, the Laplace Transform of $f(t)$ exists if $f(t)$ is bounded by an exponential function.

Proof

If $s > k$, then from the equation above, we have:

$$|F(s)| = \left| \int_0^\infty f(t) e^{-st} dt \right| \leq \int_0^\infty |f(t)| e^{-st} dt \leq \int_0^\infty M e^{(k-s)t} dt = \frac{M}{s - k}$$

2.6 Integration by Parts

Starting with the product rule:

$$\frac{d}{dx}[uv] = u'v + uv',$$

we can express this in differential form as:

$$d(uv) = u dv + v du.$$

Integrate both sides with respect to x :

$$\int d(uv) = \int_a^b u dv + \int_a^b v du.$$

The Fundamental Theorem of Calculus tells us that the left-hand side is simply:

$$uv = \int_a^b u dv + \int_a^b v du.$$

Rearrange to solve for the desired integral:

$$\int_a^b u dv = uv - \int_a^b v du,$$

Example Use integration by parts to find the Laplace of $f(t) = t$

$$L\{t\} = \int_0^\infty te^{-st} dt$$

We integrate by parts by setting:

$$u = t, \quad dv = e^{-st}, \quad du = 1, \quad v = -\frac{e^{-st}}{s}$$

Then integrating by parts gives:

$$\begin{aligned} L\{t\} &= \left[-\frac{te^{-st}}{s} \right]_0^\infty + \frac{1}{s} \int_0^\infty e^{-st} dt \\ &= 0 + \frac{1}{s} \left[-\frac{e^{-st}}{s} \right]_0^\infty \end{aligned}$$

Hence:

$$L\{t\} = \frac{1}{s^2}$$

Example Use integration by parts to find the Laplace of $f(t) = \cos(t)$

Let:

$$u = e^{-st}, \quad du = -se^{-st}, \quad dv = \cos(t), \quad v = \sin(t)$$

Then:

$$\int_0^\infty e^{-st} \cos(t) dt = \left[e^{-st} \sin(t) \right]_0^\infty + \int_0^\infty \sin(t) \cdot se^{-st} dt = 0 + s \int_0^\infty e^{-st} \sin(t) dt$$

Considering the sin part :

$$u = e^{-st}, \quad du = -se^{-st}, \quad dv = \sin(t), \quad v = -\cos(t)$$

$$\int_0^\infty e^{-st} \sin(t) dt = 1 - s \int_0^\infty e^{-st} \cos(t) dt$$

Substituting this back into the original integral gives:

$$\int_0^\infty e^{-st} \cos(t) dt = 1 - s \int_0^\infty e^{-st} \cos(t) dt = s - s^2 \int_0^\infty e^{-st} \cos(t) dt$$

$$L\{\cos(t)\} = \frac{s}{1 + s^2}$$

2.7 Table of Laplace Transforms

$f(t)$	$L\{f(t)\}$
1	$\frac{1}{s}, s > 0$
t	$\frac{1}{s^2}, s > 0$
$t^n, n = 0, 1, 2, 3$	$\frac{n!}{s^{n+1}}, s > 0$
e^{at}	$\frac{1}{s-a}, s > a$
$\cos(\omega t)$	$\frac{s}{s^2 + \omega^2}$
$\sin(\omega t)$	$\frac{\omega}{s^2 + \omega^2}$
$\cosh(at)$	$\frac{s}{s^2 - a^2}, s > a \geq 0$
$\sinh(at)$	$\frac{a}{s^2 - a^2}, s > a \geq 0$
$e^{at} \cos(\omega t)$	$\frac{s-a}{(s-a)^2 + \omega^2}$
$e^{at} \sin(\omega t)$	$\frac{\omega}{(s-a)^2 + \omega^2}$
$e^{at} f(t)$	$F(s-a)$

2.8 Laplace Transforms of Derivatives

Theorem Laplace Transform of Derivatives

Suppose that $f(t)$ and $f'(t)$ are continuous and that $|f(t)| \leq Me^{kt}, \forall t \geq 0$ and for constants M, k . Then the Laplace Transform of $f'(t)$ exists for $s > k$ and is given by:

$$L\left\{\frac{df}{dt}\right\} = sL\{f\} - f(0) \quad \text{for } s > k$$

We can easily extend this to higher order derivatives. Assume the Laplace Transform of $f^{(n)}(t)$ exists for $s > k$ and is given by:

$$L\left\{\frac{d^n f}{dt^n}\right\} = s^n L\{f\} - s^{n-1}f(0) - s^{n-2}f'(0) - \dots - f^{(n-1)}(0) \quad \text{for } s > k$$

Example Find $L\{t^2\}$ using the fact $L\{s\} = 1/s$ for $s > 0$

$$L\{f''\} = s^2 L\{f\} - sf(0) - f'(0)$$

With $f(t) = t^2$. Since $f'(t) = 2t$, $f''(t) = 2$, $f'(0) = 0$, $f(0) = 0$, gives:

$$L\{2\} = s^2 L\{t^2\} - s \cdot 0 - 0$$

So that:

$$L\{t^2\} = \frac{L\{2\}}{s^2} = \frac{2}{s^3}$$

Example Find $L\{\sin(t)\}$ and $L\{\cos(t)\}$

We again use the equation:

$$L\{f''\} = s^2 L\{f\} - sf(0) - f'(0)$$

With $f(t) = \sin(t)$, $f'(t) = \cos(t)$, $f''(t) = -\sin(t)$, $\sin(0) = 0$, $\cos(0) = 1$. This gives:

$$L\{-\sin(t)\} = s^2 L\{\sin(t)\} - s \cdot 0 - 1$$

So that:

$$L\{\sin(t)\} = \frac{1}{s^2 + 1}$$

Similarly, we can find:

$$L\{\cos(t)\} = \frac{s}{s^2 + 1}$$

2.9 Solving Initial Value Problems

Consider an example from mechanics: A particle of mass $m > 0$ lies on rough table, attached to a spring of stiffness $k > 0$. At any time $t > 0$, the mass is a distance $x(t)$ from the equilibrium position O , and $x(t)$ is much less than the length of the spring.

The mass is subject to a driving force $F_d(t)$, from Newton's second law, we have:

$$F_d(t) - kx - \gamma \frac{dx}{dt} = m \frac{dx^2}{dt^2}$$

Where $\gamma > 0$ is the **damping constant** and the term $\gamma \frac{dx}{dt}$ models the **friction due to roughness** of the table, which opposes direction of motion. The **restoring force** due to the spring is $-kx$; and always points towards O . The term $m \frac{dx^2}{dt^2}$ is the **acceleration of the mass**. We can rewrite this as:

$$F_d(t) = m \frac{dx^2}{dt^2} + \gamma \frac{dx}{dt} + kx$$

In order to solve this, we also need initial displacement $v_0 = x(0)$ and initial velocity $v_0 = \frac{dx}{dt}(0)$.

Example

$$\frac{dx^2}{dt^2} = 3 \frac{dx}{dt} + 2x = 0, \quad x(0) = 0, \quad \frac{dx}{dt}(0) = 1$$

1. Take Laplace of governing equation:

$$L \left\{ \frac{dx^2}{dt^2} \right\} = s^2 L\{x\} - sx(0) - x'(0) = s^2 L\{x\} - 1$$

$$L \left\{ \frac{dx}{dt} \right\} = sL\{x\} - x(0) = sLx$$

Hence:

$$s^2 L\{x\} - 1 + 3sL\{x\} + 2L\{x\} = 0$$

This is known as the **subsidiary equation**. Rearranging:

$$(s^2 + 3s + 2)L\{x\} = 1$$

2. Solve the subsidiary equation:

$$L\{x\} = \frac{1}{s^2 + 3s + 2}$$

3. Find the inverse Laplace Transform:

$$x(t) = L^{-1} \left\{ \frac{1}{s^2 + 3s + 2} \right\} = L^{-1} \left\{ \frac{1}{(s+1)(s+2)} \right\}$$

$$\frac{1}{(s+1)(s+2)} = \frac{A}{s+1} + \frac{B}{s+2} = \frac{A(s+2) + B(s+1)}{(s+1)(s+2)}$$

Hence:

$$A(s+2) + B(s+1) = 1 \rightarrow A = 1, B = -1$$

Thus:

$$x = L^{-1} \left\{ \frac{1}{s+1} - \frac{1}{s+2} \right\} = L^{-1} \left\{ \frac{1}{s+1} \right\} - L^{-1} \left\{ \frac{1}{s+2} \right\} = e^{-t} - e^{-2t}$$