

# MMAE 320: Thermofluid Dynamics — Reference Material

## Illinois Institute of Technology

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# A Complex Numbers

Complex numbers are numbers that have both a real part and an imaginary part.

$$z = a \pm bi \quad (\text{A.1})$$

where

$$i = \sqrt{-1} \quad (\text{A.2})$$

*Remark* ( $i$  vs.  $j$  for Imaginary Numbers). Complex numbers are generally denoted with either  $i$  or  $j$ . Since this is an appendix section, I will denote complex numbers with  $i$ , to make it more general. However, electrical engineering regularly makes use of  $j$  as the imaginary value. This is because alternating current  $i$  is already taken, so  $j$  is used as the imaginary value instead.

$$Ae^{-ix} = A [\cos(x) + i \sin(x)] \quad (\text{A.3})$$

## A.1 Complex Conjugates

If we have a complex number as shown below,

$$z = a \pm bi$$

then, the conjugate is denoted and calculated as shown below.

$$\bar{z} = a \mp bi \quad (\text{A.4})$$

**Defn A.1.1** (Complex Conjugate). The conjugate of a complex number is called its *complex conjugate*. The complex conjugate of a complex number is the number with an equal real part and an imaginary part equal in magnitude but opposite in sign.

The complex conjugate can also be denoted with an asterisk (\*). This is generally done for complex functions, rather than single variables.

$$z^* = \bar{z} \quad (\text{A.5})$$

### A.1.1 Complex Conjugates of Exponentials

$$\overline{e^z} = e^{\bar{z}} \quad (\text{A.6})$$

$$\overline{\log(z)} = \log(\bar{z}) \quad (\text{A.7})$$

### A.1.2 Complex Conjugates of Sinusoids

Since sinusoids can be represented by complex exponentials, as shown in Appendix B.2, we could calculate their complex conjugate.

$$\begin{aligned} \overline{\cos(x)} &= \cos(x) \\ &= \frac{1}{2} (e^{ix} + e^{-ix}) \end{aligned} \quad (\text{A.8})$$

$$\begin{aligned} \overline{\sin(x)} &= \sin(x) \\ &= \frac{1}{2i} (e^{ix} - e^{-ix}) \end{aligned} \quad (\text{A.9})$$

## B Trigonometry

### B.1 Trigonometric Formulas

$$\sin(\alpha) \pm \sin(\beta) = 2 \sin\left(\frac{\alpha \pm \beta}{2}\right) \cos\left(\frac{\alpha \mp \beta}{2}\right) \quad (\text{B.1})$$

$$\cos(\theta) \sin(\theta) = \frac{1}{2} \sin(2\theta) \quad (\text{B.2})$$

### B.2 Euler Equivalents of Trigonometric Functions

$$e^{\pm j\alpha} = \cos(\alpha) \pm j \sin(\alpha) \quad (\text{B.3})$$

$$\cos(x) = \frac{e^{jx} + e^{-jx}}{2} \quad (\text{B.4})$$

$$\sin(x) = \frac{e^{jx} - e^{-jx}}{2j} \quad (\text{B.5})$$

$$\sinh(x) = \frac{e^x - e^{-x}}{2} \quad (\text{B.6})$$

$$\cosh(x) = \frac{e^x + e^{-x}}{2} \quad (\text{B.7})$$

### B.3 Angle Sum and Difference Identities

$$\sin(\alpha \pm \beta) = \sin(\alpha) \cos(\beta) \pm \cos(\alpha) \sin(\beta) \quad (\text{B.8})$$

$$\cos(\alpha \pm \beta) = \cos(\alpha) \cos(\beta) \mp \sin(\alpha) \sin(\beta) \quad (\text{B.9})$$

### B.4 Double-Angle Formulae

$$\sin(2\alpha) = 2 \sin(\alpha) \cos(\alpha) \quad (\text{B.10})$$

$$\cos(2\alpha) = \cos^2(\alpha) - \sin^2(\alpha) \quad (\text{B.11})$$

### B.5 Half-Angle Formulae

$$\sin\left(\frac{\alpha}{2}\right) = \sqrt{\frac{1 - \cos(\alpha)}{2}} \quad (\text{B.12})$$

$$\cos\left(\frac{\alpha}{2}\right) = \sqrt{\frac{1 + \cos(\alpha)}{2}} \quad (\text{B.13})$$

### B.6 Exponent Reduction Formulae

$$\sin^2(\alpha) = (\sin(\alpha))^2 = \frac{1 - \cos(2\alpha)}{2} \quad (\text{B.14})$$

$$\cos^2(\alpha) = (\cos(\alpha))^2 = \frac{1 + \cos(2\alpha)}{2} \quad (\text{B.15})$$

### B.7 Product-to-Sum Identities

$$2 \cos(\alpha) \cos(\beta) = \cos(\alpha - \beta) + \cos(\alpha + \beta) \quad (\text{B.16})$$

$$2 \sin(\alpha) \sin(\beta) = \cos(\alpha - \beta) - \cos(\alpha + \beta) \quad (\text{B.17})$$

$$2 \sin(\alpha) \cos(\beta) = \sin(\alpha + \beta) + \sin(\alpha - \beta) \quad (\text{B.18})$$

$$2 \cos(\alpha) \sin(\beta) = \sin(\alpha + \beta) - \sin(\alpha - \beta) \quad (\text{B.19})$$

## B.8 Sum-to-Product Identities

$$\sin(\alpha) \pm \sin(\beta) = 2 \sin\left(\frac{\alpha \pm \beta}{2}\right) \cos\left(\frac{\alpha \mp \beta}{2}\right) \quad (\text{B.20})$$

$$\cos(\alpha) + \cos(\beta) = 2 \cos\left(\frac{\alpha + \beta}{2}\right) \cos\left(\frac{\alpha - \beta}{2}\right) \quad (\text{B.21})$$

$$\cos(\alpha) - \cos(\beta) = -2 \sin\left(\frac{\alpha + \beta}{2}\right) \sin\left(\frac{\alpha - \beta}{2}\right) \quad (\text{B.22})$$

## B.9 Pythagorean Theorem for Trig

$$\cos^2(\alpha) + \sin^2(\alpha) = 1^2 \quad (\text{B.23})$$

## B.10 Rectangular to Polar

$$a + jb = \sqrt{a^2 + b^2} e^{j\theta} = r e^{j\theta} \quad (\text{B.24})$$

$$\theta = \begin{cases} \arctan\left(\frac{b}{a}\right) & a > 0 \\ \pi - \arctan\left(\frac{b}{a}\right) & a < 0 \end{cases} \quad (\text{B.25})$$

## B.11 Polar to Rectangular

$$r e^{j\theta} = r \cos(\theta) + j r \sin(\theta) \quad (\text{B.26})$$

## C Calculus

### C.1 L'Hopital's Rule

L'Hopital's Rule can be used to simplify and solve expressions regarding limits that yield irreconcilable results.

**Lemma C.0.1** (L'Hopital's Rule). *If the equation*

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \begin{cases} \frac{0}{0} \\ \frac{\infty}{\infty} \end{cases}$$

*then Equation (C.1) holds.*

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)} \quad (\text{C.1})$$

### C.2 Fundamental Theorems of Calculus

**Defn C.2.1** (First Fundamental Theorem of Calculus). The *first fundamental theorem of calculus* states that, if  $f$  is continuous on the closed interval  $[a, b]$  and  $F$  is the indefinite integral of  $f$  on  $[a, b]$ , then

$$\int_a^b f(x) dx = F(b) - F(a) \quad (\text{C.2})$$

**Defn C.2.2** (Second Fundamental Theorem of Calculus). The *second fundamental theorem of calculus* holds for  $f$  a continuous function on an open interval  $I$  and  $a$  any point in  $I$ , and states that if  $F$  is defined by

$$F(x) = \int_a^x f(t) dt,$$

then

$$\begin{aligned} \frac{d}{dx} \int_a^x f(t) dt &= f(x) \\ F'(x) &= f(x) \end{aligned} \quad (\text{C.3})$$

**Defn C.2.3** (argmax). The arguments to the *argmax* function are to be maximized by using their derivatives. You must take the derivative of the function, find critical points, then determine if that critical point is a global maxima. This is denoted as

$$\operatorname{argmax}_x$$

### C.3 Rules of Calculus

#### C.3.1 Chain Rule

**Defn C.3.1** (Chain Rule). The *chain rule* is a way to differentiate a function that has 2 functions multiplied together.

If

$$f(x) = g(x) \cdot h(x)$$

then,

$$\begin{aligned} f'(x) &= g'(x) \cdot h(x) + g(x) \cdot h'(x) \\ \frac{df(x)}{dx} &= \frac{dg(x)}{dx} \cdot h(x) + g(x) \cdot \frac{dh(x)}{dx} \end{aligned} \quad (\text{C.4})$$

### C.4 Useful Integrals

$$\int \cos(x) dx = \sin(x) \quad (\text{C.5})$$

$$\int \sin(x) dx = -\cos(x) \quad (\text{C.6})$$

$$\int x \cos(x) dx = \cos(x) + x \sin(x) \quad (\text{C.7})$$

Equation (C.7) simplified with Integration by Parts.

$$\int x \sin(x) dx = \sin(x) - x \cos(x) \quad (\text{C.8})$$

Equation (C.8) simplified with Integration by Parts.

$$\int x^2 \cos(x) dx = 2x \cos(x) + (x^2 - 2) \sin(x) \quad (\text{C.9})$$

Equation (C.9) simplified by using Integration by Parts twice.

$$\int x^2 \sin(x) dx = 2x \sin(x) - (x^2 - 2) \cos(x) \quad (\text{C.10})$$

Equation (C.10) simplified by using Integration by Parts twice.

$$\int e^{\alpha x} \cos(\beta x) dx = \frac{e^{\alpha x} (\alpha \cos(\beta x) + \beta \sin(\beta x))}{\alpha^2 + \beta^2} + C \quad (\text{C.11})$$

$$\int e^{\alpha x} \sin(\beta x) dx = \frac{e^{\alpha x} (\alpha \sin(\beta x) - \beta \cos(\beta x))}{\alpha^2 + \beta^2} + C \quad (\text{C.12})$$

$$\int e^{\alpha x} dx = \frac{e^{\alpha x}}{\alpha} \quad (\text{C.13})$$

$$\int x e^{\alpha x} dx = e^{\alpha x} \left( \frac{x}{\alpha} - \frac{1}{\alpha^2} \right) \quad (\text{C.14})$$

Equation (C.14) simplified with Integration by Parts.

$$\int \frac{dx}{\alpha + \beta x} = \int \frac{1}{\alpha + \beta x} dx = \frac{1}{\beta} \ln(\alpha + \beta x) \quad (\text{C.15})$$

$$\int \frac{dx}{\alpha^2 + \beta^2 x^2} = \int \frac{1}{\alpha^2 + \beta^2 x^2} dx = \frac{1}{\alpha \beta} \arctan \left( \frac{\beta x}{\alpha} \right) \quad (\text{C.16})$$

$$\int \alpha^x dx = \frac{\alpha^x}{\ln(\alpha)} \quad (\text{C.17})$$

$$\frac{d}{dx} \alpha^x = \frac{d\alpha^x}{dx} = \alpha^x \ln(\alpha) \quad (\text{C.18})$$

## C.5 Leibnitz's Rule

**Lemma C.0.2** (Leibnitz's Rule). *Given*

$$g(t) = \int_{a(t)}^{b(t)} f(x, t) dx$$

*with  $a(t)$  and  $b(t)$  differentiable in  $t$  and  $\frac{\partial f(x, t)}{\partial t}$  continuous in both  $t$  and  $x$ , then*

$$\frac{d}{dt} g(t) = \frac{dg(t)}{dt} = \int_{a(t)}^{b(t)} \frac{\partial f(x, t)}{\partial t} dx + f[b(t), t] \frac{db(t)}{dt} - f[a(t), t] \frac{da(t)}{dt} \quad (\text{C.19})$$

## D Laplace Transform

### D.1 Laplace Transform

**Defn D.1.1** (Laplace Transform). The *Laplace transformation* operation is denoted as  $\mathcal{L}\{x(t)\}$  and is defined as

$$X(s) = \int_{-\infty}^{\infty} x(t)e^{-st} dt \quad (\text{D.1})$$

### D.2 Inverse Laplace Transform

**Defn D.2.1** (Inverse Laplace Transform). The *inverse Laplace transformation* operation is denoted as  $\mathcal{L}^{-1}\{X(s)\}$  and is defined as

$$x(t) = \frac{1}{2j\pi} \int_{\sigma-\infty}^{\sigma+\infty} X(s)e^{st} ds \quad (\text{D.2})$$

### D.3 Properties of the Laplace Transform

#### D.3.1 Linearity

The Laplace Transform is a linear operation, meaning it obeys the laws of linearity. This means Equation (D.3) must hold.

$$x(t) = \alpha_1 x_1(t) + \alpha_2 x_2(t) \quad (\text{D.3a})$$

$$X(s) = \alpha_1 X_1(s) + \alpha_2 X_2(s) \quad (\text{D.3b})$$

#### D.3.2 Time Scaling

Scaling in the time domain (expanding or contracting) yields a slightly different transform. However, this only makes sense for  $\alpha > 0$  in this case. This is seen in Equation (D.4).

$$\mathcal{L}\{x(\alpha t)\} = \frac{1}{\alpha} X\left(\frac{s}{\alpha}\right) \quad (\text{D.4})$$

#### D.3.3 Time Shift

Shifting in the time domain means to change the point at which we consider  $t = 0$ . Equation (D.5) below holds for shifting both forward in time and backward.

$$\mathcal{L}\{x(t-a)\} = X(s)e^{-as} \quad (\text{D.5})$$

#### D.3.4 Frequency Shift

Shifting in the frequency domain means to change the complex exponential in the time domain.

$$\mathcal{L}^{-1}\{X(s-a)\} = x(t)e^{at} \quad (\text{D.6})$$

#### D.3.5 Integration in Time

Integrating in time is equivalent to scaling in the frequency domain.

$$\mathcal{L}\left\{\int_0^t x(\lambda) d\lambda\right\} = \frac{1}{s} X(s) \quad (\text{D.7})$$

#### D.3.6 Frequency Multiplication

Multiplication of two signals in the frequency domain is equivalent to a convolution of the signals in the time domain.

$$\mathcal{L}\{x(t) * v(t)\} = X(s)V(s) \quad (\text{D.8})$$

#### D.3.7 Relation to Fourier Transform

The Fourier transform looks and behaves very similarly to the Laplace transform. In fact, if  $X(\omega)$  exists, then Equation (D.9) holds.

$$X(s) = X(\omega)|_{\omega=\frac{s}{j}} \quad (\text{D.9})$$



## D.4 Theorems

There are 2 theorems that are most useful here:

1. Initial Value Theorem
2. Final Value Theorem

**Theorem D.1** (Initial Value Theorem). *The Initial Value Theorem states that when the signal is treated at its starting time, i.e.  $t = 0^+$ , it is the same as taking the limit of the signal in the frequency domain.*

$$x(0^+) = \lim_{s \rightarrow \infty} sX(s)$$

**Theorem D.2** (Final Value Theorem). *The Final Value Theorem states that when taking a signal in time to infinity, it is equivalent to taking the signal in frequency to zero.*

$$\lim_{t \rightarrow \infty} x(t) = \lim_{s \rightarrow 0} sX(s)$$

## D.5 Laplace Transform Pairs

Time Domain	Frequency Domain
$x(t)$	$X(s)$
$\delta(t)$	1
$\delta(t - T_0)$	$e^{-sT_0}$
$\mathcal{U}(t)$	$\frac{1}{s}$
$t^n \mathcal{U}(t)$	$\frac{n!}{s^{n+1}}$
$\mathcal{U}(t - T_0)$	$\frac{e^{-sT_0}}{s}$
$e^{at} \mathcal{U}(t)$	$\frac{1}{s-a}$
$t^n e^{at} \mathcal{U}(t)$	$\frac{n!}{(s-a)^{n+1}}$
$\cos(bt) \mathcal{U}(t)$	$\frac{s}{s^2+b^2}$
$\sin(bt) \mathcal{U}(t)$	$\frac{b}{s^2+b^2}$
$e^{-at} \cos(bt) \mathcal{U}(t)$	$\frac{s+a}{(s+a)^2+b^2}$
$e^{-at} \sin(bt) \mathcal{U}(t)$	$\frac{b}{(s+a)^2+b^2}$
$re^{-at} \cos(bt + \theta) \mathcal{U}(t)$	$\begin{cases} a : \frac{sr \cos(\theta) + ar \cos(\theta) - br \sin(\theta)}{s^2 + 2as + (a^2 + b^2)} \\ b : \frac{1}{2} \left( \frac{re^{j\theta}}{s+a-jb} + \frac{re^{-j\theta}}{s+a+jb} \right) \\ c : \frac{As+B}{s^2+2as+c} \begin{cases} r = \sqrt{\frac{A^2c+B^2-2ABa}{c-a^2}} \\ \theta = \arctan\left(\frac{Aa-B}{A\sqrt{c-a^2}}\right) \end{cases} \end{cases}$
$e^{-at} \left( A \cos(\sqrt{c-a^2}t) + \frac{B-Aa}{\sqrt{c-a^2}} \sin(\sqrt{c-a^2}t) \right) \mathcal{U}(t)$	$\frac{As+B}{s^2+2as+c}$

## D.6 Higher-Order Transforms

Time Domain	Frequency Domain
$x(t)$	$X(s)$
$x(t) \sin(\omega_0 t)$	$\frac{j}{2} (X(s + j\omega_0) - X(s - j\omega_0))$
$x(t) \cos(\omega_0 t)$	$\frac{1}{2} (X(s + j\omega_0) + X(s - j\omega_0))$
$t^n x(t)$	$(-1)^n \frac{d^n}{ds^n} X(s) \quad n \in \mathbb{N}$
$\frac{d^n}{dt^n} x(t)$	$s^n X(s) - \sum_{i=0}^{n-1} s^{n-1-i} \frac{d^i}{dt^i} x(t) _{t=0^-} \quad n \in \mathbb{N}$