

## Exam in Transform Theory

93MA54/STN1 2023-06-03

You are permitted to use:

- Transformteori - Sammanfattning, Formler & Lexikon (from MAI);
- Table of Formulæ (by Johan Thim). This one is included at the end of the exam.
- A calculator (with cleared memories).

Swedish version of the exam comes after the English version. You may answer in Swedish or English.

Each problem is worth 5 points (for a total of 35 points). No half-points will be awarded in the grading. A solution is deemed good if the question is awarded at least 3 points out of 5. For grade  $n$ , you need at least  $n$  good answers.

ERASMUS students will have their grades marked according to the scale: A = grade 5, B = grade 4, C = grade 3.

Grading (sufficient limit): 15 points for grade 3. Your solutions need to be complete, well motivated, carefully written and concluded with a clear answer. Be very careful with motivations since these are a huge part of your solutions. Make sure to point out that conditions in theorems you are using hold. Assumptions you make need to be explicit. The exercises are not necessarily in order of difficulty.

Solutions can be found on the homepage a couple of hours after the finished exam.

1. For each of these statements, prove or disprove the claims. For each correct answer, you get 1 p and for each incorrect answer, you get 0 p.

- (a) If  $u: [0, \infty[ \rightarrow \mathbf{C}$  is of exponential growth and has the unilateral Laplace transform  $U(s)$ , then  $\mathcal{L}(u(-t)) = U(-s)$ .
- (b) For any function  $u \in G(\mathbf{R})$ , there is a constant  $C > 0$  such that  $|\mathcal{F}u(\omega)| \leq C$  for all  $\omega \in \mathbf{R}$ .
- (c) The function defined by  $U(\omega) = \arctan(\omega^{-1})$ ,  $\omega \neq 0$ , and  $U(0) = \pi/2$ , is the Fourier transform of some  $u \in G(\mathbf{R})$ .
- (d) The Fourier series for the periodic function  $u$  defined by  $u(x) = \arcsin(x/\pi)$ , where  $-\pi \leq x < \pi$ , converges uniformly on  $\mathbf{R}$ .
- (e) Let  $u[k] = 2^{2^k}$  for  $k = 0, 1, 2, \dots$ . Then  $\mathcal{Z}(u[k]) = \frac{z}{z-4}$  for  $|z| > 4$ .

2. Solve the difference equation

$$u[k+2] - u[k] = 4(-1)^k, \quad u[0] = u[1] = 1, \quad k = 0, 1, 2, 3, \dots$$

3. Let

$$u(x) = \begin{cases} 1 - |x|, & -1 \leq x \leq 1, \\ 0, & 1 < |x| \leq \pi, \end{cases}$$

and extend  $u$  periodically. Find the Fourier series for  $u(x)$  and show what the Fourier series converges to for  $x \in \mathbf{R}$ . Is the convergence uniform? Show that

$$\sum_{k=1}^{\infty} \frac{1 - \cos k}{k^2} = \frac{\pi}{2} - \frac{1}{4}.$$

4. Find a solution  $f \in G(\mathbf{R})$  to  $\int_{-\infty}^{\infty} \frac{f(\tau) d\tau}{(t-\tau)^2 + 4} = \frac{1}{(t+1)^2 + 25}$ ,  $t \in \mathbf{R}$ .

5. (a) Let  $u(x) = 1$ ,  $|x| < 3$  and  $u(x) = 0$ ,  $|x| \geq 3$ . Derive the Fourier transform of  $u(x)$ . (1p)

(b) Calculate the limit  $\lim_{t \rightarrow \infty} \int_{-t}^t \frac{\sin(3\omega)}{\omega} e^{i\omega x} d\omega$ ,  $x \in \mathbf{R}$ . (2p)

(c) Calculate  $\int_{-\infty}^{\infty} \frac{\sin^2 \omega}{\omega^2} d\omega$ . (2p)

6. (a) Let  $u$  be a periodic function such that  $u(t) = -1$ ,  $0 \leq t < 1$  and  $u(t) = 1$ ,  $1 \leq t < 2$ , with period 2. Find the Laplace transform of  $u$ . (3p)

(b) Prove that if  $U(s) = \mathcal{L}(u(t))$ , then  $\mathcal{L}(u(at)) = a^{-1}U(s/a)$  if  $a > 0$ . (2p)

7. Show that  $u(x) = \sum_{k=1}^{\infty} \frac{1}{3x^4 + 5k^4}$  defines a function  $u \in C^1$  for all  $x \in \mathbf{R}$ .

# Svensk översättning av uppgifterna

1. För varje påstående, bevisa eller motbevisa påståendet. Du får 1 p för varje rätt och 0 p för varje fel.

- (a) Om  $u: [0, \infty[ \rightarrow \mathbf{C}$  är exponentiellt begränsad och har den enkelsidiga Laplacetransformen  $U(s)$ , så gäller att  $\mathcal{L}(u(-t)) = U(-s)$ .
- (b) För alla  $u \in G(\mathbf{R})$ , så finns det en konstant  $C > 0$  så att  $|\mathcal{F}u(\omega)| \leq C$  för alla  $\omega \in \mathbf{R}$ .
- (c) Funktionen definierad av  $U(\omega) = \arctan(\omega^{-1})$ ,  $\omega \neq 0$ , och  $U(0) = \pi/2$ , är Fouriertransformen av en funktion  $u \in G(\mathbf{R})$ .
- (d) Fourierserien för den periodiska funktionen  $u$  definierad av  $u(x) = \arcsin(x/\pi)$ ,  $-\pi \leq x < \pi$ , konvergerar likformigt på  $\mathbf{R}$ .
- (e) Låt  $u[k] = 2^{2^k}$  för  $k = 0, 1, 2, \dots$ . Då är  $\mathcal{Z}(u[k]) = \frac{z}{z-4}$  för  $|z| > 4$ .

2. Lös differensekvationen

$$u[k+2] - u[k] = 4(-1)^k, \quad u[0] = u[1] = 1, \quad k = 0, 1, 2, 3, \dots$$

3. Låt

$$u(x) = \begin{cases} 1 - |x|, & -1 \leq x \leq 1, \\ 0, & 1 < |x| \leq \pi, \end{cases}$$

och utvidga  $u$  periodiskt. Bestäm Fourierserien för  $u(x)$  och visa vad Fourierserien konvergerar till för  $x \in \mathbf{R}$ . Är konvergensen likformig? Visa även att

$$\sum_{k=1}^{\infty} \frac{1 - \cos k}{k^2} = \frac{\pi}{2} - \frac{1}{4}.$$

4. Hitta en lösning  $f \in G(\mathbf{R})$  till  $\int_{-\infty}^{\infty} \frac{f(\tau) d\tau}{(t-\tau)^2 + 4} = \frac{1}{(t+1)^2 + 25}$ ,  $t \in \mathbf{R}$ .

5. (a) Låt  $u(x) = 1$ ,  $|x| < 3$  och  $u(x) = 0$ ,  $|x| \geq 3$ . Härled Fouriertransformen för  $u(x)$ . (1p)

(b) Finn gränsvärdet  $\lim_{t \rightarrow \infty} \int_{-t}^t \frac{\sin(3\omega)}{\omega} e^{i\omega x} d\omega$ ,  $x \in \mathbf{R}$ . (2p)

(c) Beräkna  $\int_{-\infty}^{\infty} \frac{\sin^2 \omega}{\omega^2} d\omega$ . (2p)

6. (a) Låt  $u$  vara en periodisk funktion så att  $u(t) = -1$ ,  $0 \leq t < 1$  och  $u(t) = 1$ ,  $1 \leq t < 2$ , med perioden 2. Bestäm Laplacetransformen för  $u$ . (3p)

(b) Bevisa att om  $U(s) = \mathcal{L}(u(t))$ , så gäller  $\mathcal{L}(u(at)) = a^{-1}U(s/a)$  om  $a > 0$ . (2p)

7. Visa att  $u(x) = \sum_{k=1}^{\infty} \frac{1}{3x^4 + 5k^4}$  definierar en funktion  $u \in C^1$  för alla  $x \in \mathbf{R}$ .

# Table of formulæ

Johan Thim (johan.thim@liu.se)

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## 1 Notation and Definitions

- $\mathbf{R}$  is the set of all real numbers.
- $\mathbf{Q}$  is the set of all rational numbers.
- $\mathbf{C}$  is the set of all complex numbers.
- $\mathbf{Z}$  is the set of all integers.
- $\mathbf{N} = \{0, 1, 2, \dots\}$  is the set of all natural numbers (including 0).

For  $z = x + iy \in \mathbf{C}$ ,  $x, y \in \mathbf{R}$ ,

$$\operatorname{Re} z = x, \quad \operatorname{Im} z = y, \quad |z| = \sqrt{x^2 + y^2}.$$

### 1.1 Continuity and Differentiability

- One-sided limits:
- One-sided derivatives:
- $C(I)$ : The set of all continuous functions on a set  $I$ .
- $C^m(I)$ : The set of all continuously differentiable (up to order  $m$ ) functions on a set  $I$ .

A function  $u: I \rightarrow \mathbf{C}$  on an interval  $I$  is called piecewise continuous if...

- $I$  is finite and there are a finite number of points such that  $u$  is continuous everywhere on  $I$  except for at these points. Moreover, if  $c \in I$  is a point where  $u$  is discontinuous, the limits
- $\lim_{I \ni x \rightarrow c^-} u(x)$  and  $\lim_{I \ni x \rightarrow c^+} u(x)$  if points on the boundary of  $I$ .
- $I$  is infinite and there are a finite number of exception points (as in the finite case) in each finite sub-interval of  $I$ .

## 1.2 Function Spaces

A normed linear space is a linear space  $V$  endowed with a norm  $\|\cdot\|: V \rightarrow [0, \infty[$  such that

- (i)  $\|u\| \geq 0$
  - (ii)  $\|\alpha u\| = |\alpha| \|u\|$ ,  $\alpha \in \mathbf{C}$
  - (iii)  $\|u + v\| \leq \|u\| + \|v\|$ .
- An inner product  $\langle \cdot, \cdot \rangle: V \times V \rightarrow \mathbf{C}$  on a vector space  $V$  satisfies
- (i)  $\langle u, v \rangle = \overline{\langle v, u \rangle}$
  - (ii)  $\langle u + v, w \rangle = \langle u, w \rangle + \langle v, w \rangle$
  - (iii)  $\langle \alpha u, v \rangle = \alpha \langle u, v \rangle$
  - (iv)  $\langle u, u \rangle \geq 0$
  - (v)  $\langle u, u \rangle = 0 \iff u = 0$ .

In an inner product space, we use  $\|u\| = \sqrt{\langle u, u \rangle}$  as the norm.

### Sequence Spaces

The sequence spaces  $l^p$ ,  $1 \leq p \leq \infty$ , consists of sequences  $(x_0, x_1, x_2, x_3, \dots)$ ,  $x_i \in \mathbf{C}$ , such that the norm

$$\|x\|_p = \left( \sum_{k=0}^{\infty} |x_k|^p \right)^{1/p} < \infty, \quad 1 \leq p < \infty,$$

or

$$\|x\|_{l^\infty} = \sup_{k \geq 0} |x_k| < \infty, \quad p = \infty.$$

Sometimes we write  $l^p(\mathbf{N})$ . The spaces  $l^p(\mathbf{Z})$  are defined analogously. Only  $l^2$  is an inner product space with

$$\langle x, y \rangle = \sum_{k=0}^{\infty} x_k \overline{y_k}, \quad x, y \in l^2.$$

### Lebesgue Spaces (integrable functions)

The space  $L^1(a, b)$  of absolutely integrable functions  $u: ]a, b[ \rightarrow \mathbf{C}$  with norm

$$\|f\|_{L^1(a,b)} = \int_a^b |f(x)| dx < \infty.$$

The space  $L^2(a, b)$  consists of all “square integrable” functions with the norm

$$\|f\|_{L^2(a,b)} = \left( \int_a^b |f(x)|^2 dx \right)^{1/2} < \infty,$$

which is an inner product space with

$$\langle f, g \rangle = \int_a^b f(x) \overline{g(x)} dx.$$

The space  $L^\infty(a, b)$  of bounded functions with norm

$$\|f\|_{L^\infty(a,b)} = \sup_{a \leq x \leq b} |f(x)| < \infty.$$

Note that  $a = -\infty$  and/or  $b = \infty$  is allowed (so we might write  $L^p(\mathbf{R})$ ). Sometimes we write  $\|f\|_p$  instead of  $\|f\|_{L^p(a,b)}$ .

### Spaces of Piecewise Functions

- $E[a, b]$  (or  $E$ ): The linear space of all piecewise continuous functions on an interval  $[a, b]$ .
- $E^+[a, b]$  (or  $E^+$ ): The linear space of those  $u \in E[a, b]$  such that  $D^-u(x)$  exists for  $a < x \leq b$  and that  $D^+u(x)$  exists for  $a \leq x < b$ .
- $G(\mathbf{R})$  (or  $G$ ): The linear space of all piecewise continuous functions on  $\mathbf{R}$  that are absolutely integrable on  $\mathbf{R}$ .

### 1.3 Special Functions

- **Heaviside function:**
- **Signum function:**

$$H(x) = \begin{cases} 0, & x < 0, \\ 1, & x \geq 0. \end{cases}$$

$$\operatorname{sgn}(x) = \begin{cases} -1, & x < 0, \\ 0, & x = 0, \\ 1, & x > 0. \end{cases}$$

### Discrete Functions

- **Discrete Heaviside function:**
- **Discrete impulse function:**
- **Binomial coefficient functions:**

$$\binom{n}{k} = \begin{cases} \frac{n!}{(n-k)!k!}, & k = 0, 1, 2, \dots, \\ 0, & k > n. \end{cases}$$

### Convolutions (on $\mathbf{R}$ )

The convolution  $u * v : \mathbf{R} \rightarrow \mathbf{C}$  of two functions  $u : \mathbf{R} \rightarrow \mathbf{C}$  and  $v : \mathbf{R} \rightarrow \mathbf{C}$  is defined by

$$(u * v)(x) = \int_{-\infty}^{\infty} u(t)v(x-t)dt, \quad x \in \mathbf{R},$$

whenever this integral exists. If  $u, v \in L^1(\mathbf{R})$ , then  $u * v \in L^1(\mathbf{R})$ . If one function is also bounded, then  $u * v$  is continuous and bounded. Suppose that  $u, v, w \in G(\mathbf{R})$  and one function in each convolution is bounded. Then the convolution has the following properties.

- Associative:  $((u * v) * w)(x) = (u * (v * w))(x)$ .
- Distributive:  $((u + v) * w)(x) = (u * w)(x) + (v * w)(x)$ .
- Commutative:  $(u * v)(x) = (v * u)(x)$ .

### Convolutions (on $\mathbf{Z}$ )

- For  $u, v : \mathbf{Z} \rightarrow \mathbf{C}$ , the **discrete convolution**  $u * v$  is

$$(u * v)[n] = \sum_{k=-\infty}^{\infty} u[k]v[n-k], \quad n \in \mathbf{Z},$$

whenever this series exists.

- For  $u, v : \mathbf{N} \rightarrow \mathbf{C}$ , the **unilateral (or one-sided) discrete convolution**  $u * v$  is

$$(u * v)[n] = \sum_{k=0}^n u[k]v[n-k], \quad n = 0, 1, 2, \dots$$

### 1.4 Inequalities

- **The Cauchy-Schwarz inequality:** If  $u, v \in V$  and  $V$  is an inner product space, then
- **Bessel's inequality:** Let  $V$  be an inner product space, let  $v \in V$  and let  $\{e_1, e_2, \dots\}$  be an ON system in  $V$ . Then

$$|\langle u, v \rangle| \leq \|u\|\|v\|.$$

$$\sum_{k=1}^{\infty} |\langle v, e_k \rangle|^2 \leq \|v\|^2.$$

This implies the **Riemann-Lebesgue lemma** for inner product spaces:

$$\lim_{n \rightarrow \infty} \langle v, e_n \rangle = 0.$$

- **The triangle inequality:** In a normed space  $V$ ,
- **Young's inequality** ( $r = p = q = 1$ ):

$$\| \|u\| - \|v\| \| \leq \|u + v\| \leq \|u\| + \|v\|.$$

$$\|u * v\|_{L^1(\mathbf{R})} \leq \|u\|_{L^1(\mathbf{R})}\|v\|_{L^1(\mathbf{R})}.$$

and

$$\|u * v\|_{L^1(\mathbf{Z})} \leq \|u\|_{L^1(\mathbf{Z})}\|v\|_{L^1(\mathbf{Z})}.$$

### 1.5 Convergence of Sequences

Let  $u_1, u_2, \dots$  be a sequence in a normed space  $V$ . We say that  $u_n \rightarrow u$  for some  $u \in V$  if  $\|u_n - u\| \rightarrow 0$  as  $n \rightarrow \infty$ . This is called **strong convergence** or **convergence in norm**.

### Convergence of Functions

- **Pointwise convergence:** We say that  $u_k \rightarrow u$  pointwise on  $I$  as  $k \rightarrow \infty$  if

$$\lim_{k \rightarrow \infty} u_k(x) = u(x)$$

for every  $x \in I$ . We often refer to  $u$  as the *limiting function*.

- **Uniform convergence:** We say that  $u_k \rightarrow u$  uniformly on  $[a, b]$  as  $k \rightarrow \infty$  if

$$\lim_{k \rightarrow \infty} \|u_k - u\|_{L^\infty(a,b)} = 0.$$

**Weierstrass' M-test:** If  $I \subset \mathbf{R}$  and  $M_k$ ,  $k = 1, 2, \dots$ , are constants such that  $|u_k(x)| \leq M_k$  for  $x \in I$ , then

$$\sum_{k=1}^{\infty} M_k < \infty \Rightarrow \sum_{k=1}^{\infty} u_k(x) \text{ converges uniformly on } I.$$

If:

- $u_0, u_1, u_2, \dots$  are continuous functions on  $[a, b]$
- and  $u(x) = \sum_{k=0}^{\infty} u_k(x)$  is uniformly convergent for  $x \in [a, b]$ ,

then

- the series  $u$  is a continuous function on  $[a, b]$ ,
- we can exchange the order of summation and integration:

$$\int_c^d u(x) dx = \int_c^d \left( \sum_{k=0}^{\infty} u_k(x) \right) dx = \sum_{k=0}^{\infty} \int_c^d u_k(x) dx, \quad \text{for } a \leq c < d \leq b,$$

- and if in addition  $\sum_{k=0}^{\infty} u'_k(x)$  converges uniformly on  $[a, b]$ , then

$$u'(x) = \frac{d}{dx} \left( \sum_{k=0}^{\infty} u_k(x) dx \right) = \sum_{k=0}^{\infty} \frac{d}{dx} u_k(x) = \sum_{k=0}^{\infty} u'_k(x), \quad x \in [a, b].$$

### 1.6 Integration Theory

The **principal value** integral is defined by

$$\text{P. V. } \int_{-\infty}^{\infty} u(x) dx = \lim_{R \rightarrow \infty} \int_{-R}^R u(x) dx.$$

- If  $F(x) = \int_{-\infty}^x f(x, y) dy$  exists for every  $x \in I$  and

$$\sup_{x \in I} \left| \int_{-R}^R f(x, y) dy - F(x) \right| \rightarrow 0, \quad \text{as } R \rightarrow \infty,$$

then we call the integral defining  $F(x)$  uniformly convergent on  $I$ .

- **Dominated convergence:**

If:

- $f : \mathbf{R}^2 \rightarrow \mathbf{C}$ ,
- $F(x) = \int_{-\infty}^{\infty} f(x, y) dy$  exists for all  $x$ ,
- there is a  $g \in L^1(\mathbf{R})$  such that  $|f(x, y)| \leq g(y)$  for all  $x, y \in \mathbf{R}$ ,

then  $\int_{-\infty}^{\infty} f(x, y) dy$  converges uniformly on  $\mathbf{R}$ .

- **Continuity:** If  $f : \mathbf{R}^2 \rightarrow \mathbf{C}$  is continuous on  $[c, d] \times [a, R]$ . Then

$$- F_R(x) = \int_a^R f(x, y) dy \text{ is continuous on } [c, d]$$

- and if in addition  $f$  is continuous on  $[c, d] \times [a, \infty[$  and  $F(x) = \int_a^{\infty} f(x, y) dy$  converges uniformly (on  $[c, d]$ ), then  $F$  is continuous.

- **Order of integration:** If  $f : \mathbf{R}^2 \rightarrow \mathbf{C}$  is continuous on  $[c, d] \times [a, \infty[$  and  $F(x)$  converges uniformly (on  $[c, d]$ ), then

$$\int_c^d \left( \int_a^{\infty} f(x, y) dy \right) dx = \int_a^{\infty} \left( \int_c^d f(x, y) dx \right) dy.$$

- Note that we can let  $a = -\infty$  in the previous theorems by exchanging  $[a, R]$  by  $[-R, R]$  and consider the principal values.

- **Leibniz's rule:** If

- $f : \mathbf{R}^2 \rightarrow \mathbf{C}$  and  $f'_x(x, y)$  exist and are continuous,
- $F(x) = \int_{-\infty}^{\infty} f(x, y) dy$  is convergent for every  $x$ ,
- and  $\int_{-\infty}^{\infty} f'_x(x, y) dy$  is uniformly convergent,

then

$$F'(x) = \frac{d}{dx} \int_{-\infty}^{\infty} f(x, y) dy = \int_{-\infty}^{\infty} f'_x(x, y) dy.$$

### 2 Fourier Series

For  $u \in L^1(-\pi, \pi)$ :

$$a_k = \frac{1}{\pi} \int_{-\pi}^{\pi} u(x) \cos kx dx \quad \text{and} \quad b_k = \frac{1}{\pi} \int_{-\pi}^{\pi} u(x) \sin kx dx \quad \text{or} \quad c_k = \frac{1}{2\pi} \int_{-\pi}^{\pi} u(x) e^{-ikx} dx$$

are the Fourier coefficients (real or complex) for  $u$ . The series

$$S(x) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos kx + b_k \sin kx) = \sum_{k=-\infty}^{\infty} c_k e^{ikx}$$

is called the **Fourier series** of the function  $u$  (real or complex). We write  $u(x) \sim S(x)$ . Note that:

- if  $u$  is even, then  $b_k = 0$  for  $k = 1, 2, 3, \dots$ ;
- if  $u$  is odd, then  $a_k = 0$  for  $k = 1, 2, 3, \dots$ .

If  $u$  is a  $T$ -periodic function, we define  $\Omega = \frac{2\pi}{T}$ . The real Fourier series of  $u$  is then given by

$$u(x) \sim \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos k\Omega x + b_k \sin k\Omega x),$$

where

$$a_k = \frac{2}{T} \int_{-T/2}^{T/2} u(x) \cos k\Omega x \, dx \quad \text{and} \quad b_k = \frac{2}{T} \int_{-T/2}^{T/2} u(x) \sin k\Omega x \, dx.$$

The complex Fourier series is given by

$$u(x) \sim \sum_{k=-\infty}^{\infty} c_k e^{ik\Omega x}, \quad \text{where } c_k = \frac{1}{T} \int_{-T/2}^{T/2} u(x) e^{-ik\Omega x} \, dx.$$

Sometimes we denote  $c_k = \widehat{u}[k]$ .

## 2.1 Parseval's identity

- **Parseval's identity:**

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} |u(x)|^2 \, dx = \sum_{k=-\infty}^{\infty} |c_k|^2 \quad \text{or} \quad \frac{1}{\pi} \int_{-\pi}^{\pi} |u(x)|^2 \, dx = \frac{|a_0|^2}{2} + \sum_{k=1}^{\infty} (|a_k|^2 + |b_k|^2),$$

where  $u(x) \sim \sum_{k=-\infty}^{\infty} c_k e^{ikx}$  (or the real counterpart).

- **Parseval's generalized identity:**

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} u(x) \overline{v(x)} \, dx = \sum_{k=-\infty}^{\infty} c_k \overline{d_k},$$

where  $u(x) \sim \sum_{k=-\infty}^{\infty} c_k e^{ikx}$  and  $v(x) \sim \sum_{k=-\infty}^{\infty} d_k e^{ikx}$ .

## 2.2 Convergence

**Kernels**

- The **Dirichlet kernel:**  $D_n(x) = \sum_{k=-n}^n e^{ikx}$ ,  $x \in \mathbf{R}$ ,  $n = 1, 2, 3, \dots$
- The **Fejér kernel:**  $F_n(x) = \frac{1}{n+1} \sum_{l=0}^n \sum_{k=-l}^l e^{ikx} = \sum_{k=-n}^n \left(1 - \frac{|k|}{n+1}\right) e^{ikx}$ ,  $n = 0, 1, 2, \dots$

## 2.3 Convergence Results

- If  $u \in L^1(-\pi, \pi)$ , then  $u$  has a Fourier series.
- Let  $u \in E'$ . Then

$$S_n(x) = \sum_{k=-n}^n c_k e^{ikx} \rightarrow \frac{u(x^+) + u(x^-)}{2}, \quad x \in [-\pi, \pi].$$

- If  $u \in E$  and  $D^\pm u(x)$  exists, then

$$\lim_{n \rightarrow \infty} S_n(x) = \frac{u(x^+) + u(x^-)}{2}.$$

- If  $\sum_{k=-\infty}^{\infty} |c_k| < \infty$ , then  $\sum_{k=-\infty}^{\infty} c_k e^{ikx}$  converges uniformly.
- If  $u \in E$ , then the Fejér means  $\overline{S}_n(x) \rightarrow \frac{u(x^+) + u(x^-)}{2}$ .
- If  $u, v \in E$  and  $\widehat{u}[k] = \widehat{v}[k]$ ,  $k \in \mathbf{Z}$ , then  $u(x) = v(x)$  whenever  $u$  and  $v$  are continuous at  $x$ .
- If  $u' \in E$ ,  $u$  is continuous and  $u(-\pi) = u(\pi)$ , then  $S_n(x)$  converges uniformly to  $u(x)$ .
- If  $u' \in E$  and  $u$  is continuous on  $[a, b] \subset ]-\pi, \pi[$ , then  $S_n(x)$  converges uniformly on  $[a, b]$ .
- If  $u \in E$  is continuous and  $u(-\pi) = u(\pi)$ , then  $\overline{S}_n(x)$  converges uniformly to  $u(x)$ .

The statement  $u' \in E$  does not mean that  $u'(x)$  exists everywhere, but that there exists a  $v \in E$  such that  $v(x) = u'(x)$  when  $u'(x)$  exists and that  $u'$  exists everywhere except at a finite number of points in  $[a, b]$ .

## 2.4 General Fourier Series

- For a given ON system, the complex numbers  $\langle v, e_k \rangle$ ,  $k = 1, 2, \dots$ , are called the **generalized Fourier coefficients** of  $v$ .
- If  $W = \{e_1, e_2, \dots\}$  is an ON system in  $V$ , then  $W$  is closed if and only if **Parseval's identity** holds:

$$\sum_{k=1}^{\infty} |\langle v, e_k \rangle|^2 = \|v\|^2, \quad v \in V;$$

or if  $a_k = \langle u, e_k \rangle$  and  $b_k = \langle v, e_k \rangle$ , then

$$\langle u, v \rangle = \sum_{k=1}^{\infty} a_k \overline{b_k}.$$

## 2.5 Rules for Fourier Coefficients

Let  $u, v \in E$  be periodic with period  $T > 0$  and define  $\Omega = 2\pi/T$ .

Table 1: Rules for Fourier Coefficients

Function	Fourier coefficient	Notes
$c_1 u(x) + c_2 v(x)$	$c_1 \widehat{u}[n] + c_2 \widehat{v}[n]$	
$(u * v)_T(x)$	$\widehat{u}[n] \widehat{v}[n]$	periodic convolution <sup>†</sup>
$u(x)v(x)$	$(\widehat{u} * \widehat{v})[n]$	
$e^{im\Omega x} u(x)$	$\widehat{u}[n - m]$	$m \in \mathbf{Z}$
$u(x - a)$	$e^{-in\Omega a} \widehat{u}[n]$	$a \in \mathbf{R}$
$u(ax)$	$\widehat{u}[n]$	period $T/a$ , $a > 0$
$u(-x)$	$\widehat{u}[-n]$	
$\overline{u(x)}$	$\widehat{u}[-n]$	
$u'(x)$	$in\Omega \widehat{u}[n]$	
$u^{(k)}(x)$	$(i\Omega n)^k \widehat{u}[n]$	$k = 1, 2, \dots$

<sup>†</sup>  $(u * v)_T(x) = \frac{1}{T} \int_0^T u(x-t)v(t) dt$ .

### 3 The Fourier Transform

The Fourier transform of a function  $u: \mathbf{R} \rightarrow \mathbf{C}$  given by

$$U(\omega) = \widehat{u}(\omega) = \mathcal{F}u(\omega) = \int_{-\infty}^{\infty} u(x)e^{-i\omega x} dx, \quad \omega \in \mathbf{R},$$

when this integral exists.

- If  $u \in L^1(\mathbf{R})$  then  $\mathcal{F}u(\omega)$  exists for all  $\omega \in \mathbf{R}$  and  $\|\mathcal{F}u\|_{\infty} \leq \|u\|_{L^1(\mathbf{R})}$ .
- For  $u \in G$ , the Fourier transform  $\mathcal{F}u$  is uniformly continuous on  $\mathbf{R}$ .
- The Riemann-Lebesgue lemma: For  $u \in G$  we have  $\mathcal{F}u(\omega) \rightarrow 0$  as  $|\omega| \rightarrow \infty$ .

#### 3.1 Convergence

Kernels

- The Dirichlet kernel (on  $\mathbf{R}$ ):

$$D_R(x) = \frac{\sin(Rx)}{\pi x}, \quad x \neq 0,$$

and  $D_R(0) = R/\pi$ .

- The Fejér kernel (on  $\mathbf{R}$ ):

$$F_M(t) = \frac{1}{2\pi} \int_{-M}^M \left(1 - \frac{|\omega|}{M}\right) e^{i\omega t} d\omega = \frac{1 - \cos Mt}{\pi M t^2} = \frac{M}{2\pi} \left(\frac{\sin(Mt/2)}{Mt/2}\right)^2,$$

where the last two equalities assumes that  $x \neq 0$ .

#### Inversion

- If  $u \in G(\mathbf{R})$  and  $D^{\pm}u(x)$  exists, then

$$\lim_{R \rightarrow \infty} \frac{1}{2\pi} \int_{-R}^R \mathcal{F}u(\omega) e^{i\omega x} d\omega = \frac{u(x^+) + u(x^-)}{2}.$$

- If  $u \in G(\mathbf{R})$ , then

$$\lim_{R \rightarrow \infty} \frac{1}{2\pi} \int_{-R}^R \mathcal{F}u(\omega) \left(1 - \frac{|\omega|}{R}\right) e^{i\omega x} d\omega = \frac{u(x^+) + u(x^-)}{2}.$$

- If  $u \in G(\mathbf{R})$ , then

$$\lim_{R \rightarrow \infty} \frac{1}{2\pi} \int_{-R}^R \mathcal{F}u(\omega) e^{i\omega x} d\omega = \frac{u(x^+) + u(x^-)}{2},$$

whenever the limit exists.

- **Uniqueness:** If  $u, v \in G(\mathbf{R})$  and  $\mathcal{F}u(\omega) = \mathcal{F}v(\omega)$  for every  $\omega \in \mathbf{R}$ , then  $u(x) = v(x)$  for every  $x \in \mathbf{R}$  where both  $u$  and  $v$  are continuous.

#### 3.2 Special Rules

- If  $u, U \in G(\mathbf{R})$  and  $U(\omega) = \mathcal{F}u(\omega)$ , then

$$\mathcal{F}^{-1}(U)(x) = \frac{1}{2\pi} \mathcal{F}((\mathcal{F}u)(-\omega))(x) \quad \text{and} \quad \mathcal{F}(\mathcal{F}u(\omega))(x) = 2\pi u(-x),$$

for every  $x$  where  $u$  is continuous and  $D^{\pm}u(x)$  exist.

- If  $u, v \in G(\mathbf{R})$  such that  $uv, \mathcal{F}u, \mathcal{F}v \in G(\mathbf{R})$ , then

$$\mathcal{F}(uv)(\omega) = \frac{1}{2\pi} (\mathcal{F}u * \mathcal{F}v)(\omega).$$

#### 3.3 Plancherel's Theorem

- If  $u \in G(\mathbf{R}) \cap L^2(\mathbf{R})$ , then  $\mathcal{F}u \in L^2(\mathbf{R})$ .
- Parseval's formula: If  $u, v \in G(\mathbf{R}) \cap L^2(\mathbf{R})$ , then

$$\int_{-\infty}^{\infty} u(x) \overline{v(x)} dx = \frac{1}{2\pi} \int_{-\infty}^{\infty} \mathcal{F}u(\omega) \overline{\mathcal{F}v(\omega)} d\omega.$$

#### 3.4 Rules for the Fourier Transform

Let  $u, v \in G(\mathbf{R})$  with  $U(\omega) = \mathcal{F}u(\omega)$  and  $V(\omega) = \mathcal{F}v(\omega)$ .

### 3.5 Fourier Transforms

Table 3: Fourier transforms

Function	Fourier transform	Notes
$e^{-ax^2}$	$\sqrt{\frac{\pi}{a}} e^{-\omega^2/4a}$	$a > 0$
$e^{-a x }$	$\frac{2a}{a^2 + \omega^2}$	$a > 0$
$\operatorname{sgn}(x)e^{-a x }$	$\frac{-2i\omega}{a^2 + \omega^2}$	$a > 0$
$H(x)e^{-ax}$	$\frac{1}{a + i\omega}$	$\operatorname{Re} a > 0$
$H(-x)e^{ax}$	$\frac{1}{a - i\omega}$	$\operatorname{Re} a > 0$
$\frac{1}{a^2 + x^2}$	$\frac{\pi e^{-a \omega }}{a}$	$a > 0$
$H(x+a) - H(x-a)$	$\frac{2 \sin a\omega}{\omega}$	$a > 0$
$\operatorname{sgn}(x)(H(x+a) - H(x-a))$	$\frac{2(1 - \cos a\omega)}{i\omega}$	$a > 0$
$(a -  x )(H(x+a) - H(x-a))$	$\frac{2(1 - \cos a\omega)}{\omega^2}$	$a > 0$
$\frac{1 - \cos at}{t^2}$	$\pi(a -  \omega )(H(\omega+a) - H(\omega-a))$	$a > 0$

Table 2: Rules for the Fourier transform

Function	Fourier transform	Notes
$c_1 u(x) + c_2 v(x)$	$c_1 U(\omega) + c_2 V(\omega)$	
$(u * v)(x)$	$U(\omega)V(\omega)$	
$e^{iax}u(x)$	$U(\omega - a)$	$a \in \mathbf{R}$
$u(x) \cos ax$	$\frac{U(\omega - a) + U(\omega + a)}{2}$	$a \in \mathbf{R}$
$u(x) \sin ax$	$\frac{U(\omega - a) - U(\omega + a)}{2i}$	$a \in \mathbf{R}$
$u(x - x_0)$	$e^{-ix_0\omega}U(\omega)$	$x_0 \in \mathbf{R}$
$u(ax)$	$\frac{1}{ a }U\left(\frac{\omega}{a}\right)$	$a \in \mathbf{R}, a \neq 0$
$\overline{u(x)}$	$\overline{U(-\omega)}$	
$u'(x)$	$i\omega U(\omega)$	$u \in C(\mathbf{R}), u' \in G$
$u^{(k)}(x)$	$(i\omega)^k U(\omega)$	$u^{(k)} \in G(\mathbf{R})$
$x^m u(x)$	$i^m U^{(m)}(\omega)$	$x^m u(x) \in G, m = 1, 2, 3, \dots$

### 4 The (unilateral) Laplace Transform

The Laplace transform of  $u: [0, \infty[ \rightarrow \mathbf{C}$  is given by

$$\mathcal{L}u(s) = \int_0^\infty u(t)e^{-st} dt,$$

for those  $s = \sigma + i\omega \in \mathbf{C}$ ,  $\sigma, \omega \in \mathbf{R}$ , where this integral is convergent.

- **Exponential growth:** A piecewise continuous  $u: [0, \infty[$  is of exponential growth (of order  $a$ ) if there exists constants  $a > 0$  and  $K > 0$  such that  $|u(t)| \leq Ke^{at}$  for  $t \geq 0$ . The set of all such functions will be denoted by  $X_a$ .
- **Existence of  $\mathcal{L}u(s)$ :** If  $u \in X_a$  for some  $a > 0$ , then the Laplace transform  $\mathcal{L}u(s)$  exists (at least) for  $\operatorname{Re} s > a$ .
- $\mathcal{L}u(s) \rightarrow 0$  as  $\mathbf{R} \ni s \rightarrow \infty$ .
- $\mathcal{L}u(s)$  converges uniformly for  $\operatorname{Re} s > a$ .
- $\mathcal{L}u(s)$  is analytic for  $\operatorname{Re} s > a$ .
- **Periodicity:** If there exists  $T > 0$  such that  $u(t+T) = u(t)$  for every  $t \geq 0$ , then

$$\mathcal{L}u(s) = \frac{1}{1 - e^{-sT}} \int_0^T u(\tau)e^{-s\tau} d\tau.$$

#### 4.1 Inversion

- If  $u \in X_a$  has right- and lefthand limits at a point  $t > 0$ , then

$$\lim_{L \rightarrow \infty} \frac{1}{2\pi} \int_{-L}^L \mathcal{L}u(\sigma + i\omega) e^{i\omega t} e^{i\omega t} d\omega = \frac{u(t^+) + u(t^-)}{2},$$

where the vertical line  $\text{Re } z = \sigma$  is contained in the region of convergence of  $\mathcal{L}u(s)$

- If  $u, v \in X_a$  and  $\mathcal{L}u(s) = \mathcal{L}v(s)$  on some vertical line  $\text{Re } s = \sigma$ , then  $u(t) = v(t)$  for all  $t$  where  $u$  and  $v$  are continuous.

#### 4.2 Limit Theorems

- **Final value theorem:**  
If  $u: [0, \infty[ \rightarrow \mathbf{C}$  is bounded and  $\lim_{t \rightarrow \infty} u(t) = A$ , then  $A = \lim_{s \rightarrow 0^+} s \mathcal{L}u(s)$ .
- **Initial value theorem:**  
If  $u: [0, \infty[ \rightarrow \mathbf{C}$  belongs to  $X_b$  and  $\lim_{t \rightarrow 0^+} u(t) = a$ , then  $a = \lim_{s \rightarrow \infty} s \mathcal{L}u(s)$ .

#### 4.3 Rules for the Laplace Transform

Let  $U(s) = \mathcal{L}u(t)$ ,  $\sigma > \sigma_u$  and  $V(s) = \mathcal{L}v(t)$ ,  $\sigma > \sigma_v$ .

Table 4: Rules for Laplace transforms

Function	Unilateral Laplace transform	Region of convergence
$c_1 u(t) + c_2 v(t)$	$c_1 U(s) + c_2 V(s)$	$\sigma > \max\{\sigma_u, \sigma_v\}$
$(u * v)(t)$	$U(s)V(s)$	unilateral conv. <sup>†</sup> ; $\sigma > \max\{\sigma_u, \sigma_v\}$
$e^{at}u(t)$	$U(s-a)$	$\sigma > \sigma_u + \text{Re } a$
$u(t-t_0)H(t-t_0)$	$e^{-ts}U(s)$	$\sigma > \sigma_u, t_0 > 0$
$u(at)$	$\frac{1}{a}U\left(\frac{s}{a}\right)$	$\sigma > a\sigma_u, a > 0$
$\overline{u(t)}$	$\overline{U(\overline{s})}$	$\sigma > \sigma_u$
$u'(t)$	$sU(s) - u(0)$	$\sigma > \sigma_u$
$u''(t)$	$s^2U(s) - su(0) - u'(0)$	$\sigma > \sigma_u$
$u^{(n)}(t)$	$s^n U(s) - s^{n-1}u(0) - \dots$ $\dots - su^{(n-2)}(0) - u^{(n-1)}(0)$	$\sigma > \max\{\sigma_u, \sigma_{u'}, \dots, \sigma_{u^{(n-1)}}\}$
$\int_0^t u(\tau) d\tau$	$\frac{U(s)}{s}$	$\sigma > \max\{\sigma_u, 0\}$
$t^m u(t)$	$(-1)^m U^{(m)}(s)$	$\sigma > \sigma_u$

<sup>†</sup>  $(u * v)(t) = \int_0^t u(\tau)v(t-\tau) d\tau$ .

#### 4.4 Laplace Transforms

Table 5: Laplace transforms

Function	Unilateral Laplace transform	Region of convergence
$H(t) = 1$	$\frac{1}{s}$	$\sigma > 0$
$t$	$\frac{1}{s^2}$	$\sigma > 0$
$t^m$	$\frac{m!}{s^{m+1}}$	$\sigma > 0$
$t^a$	$\frac{\Gamma(a+1)}{s^{a+1}}$	$m = 1, 2, 3, \dots$ $\sigma > 0$
$e^{at}$	$\frac{1}{s-a}$	$a > 0$ $\sigma > \text{Re } a$
$t^m e^{at}$	$\frac{m!}{(s-a)^{m+1}}$	$\sigma > \text{Re } a$ $m = 1, 2, 3, \dots$
$\cos at$	$\frac{s}{s^2 + a^2}$	$\sigma >  \text{Im } a $
$t \cos at$	$\frac{s^2 - a^2}{(s^2 + a^2)^2}$	$\sigma >  \text{Im } a $
$\sin at$	$\frac{a}{s^2 + a^2}$	$\sigma >  \text{Im } a $
$t \sin at$	$\frac{2as}{(s^2 + a^2)^2}$	$\sigma >  \text{Im } a $
$\frac{\sin at}{t}$	$\arctan\left(\frac{a}{s}\right)$	$\sigma >  \text{Im } a $
$\cosh at$	$\frac{s}{s^2 - a^2}$	$\sigma >  \text{Re } a $
$\sinh at$	$\frac{a}{s^2 - a^2}$	$\sigma >  \text{Re } a $
$J_0(at)$	$\frac{1}{\sqrt{a^2 + s^2}}$	$\sigma >  \text{Im } a $

#### 5 The (unilateral) Z Transform

The **Z transform** of a sequence  $u[k]$ ,  $k = 0, 1, 2, \dots$ , is defined by

$$\mathcal{Z}(u)(z) = \sum_{k=0}^{\infty} u[k] z^{-k},$$

for those  $z = x + iy \in \mathbf{C}$ ,  $x, y \in \mathbf{R}$ , where this series is absolutely convergent.

## 5.2 Z Transforms

- **Existence of  $\mathcal{Z}u(z)$ :** For a sequence  $u[k]$ ,  $k = 0, 1, 2, \dots$ , the Z transform  $\mathcal{Z}u(z)$  has a region of convergence  $R$  such that  $\mathcal{Z}u(z)$  is absolutely (uniformly) convergent for  $|z| > R$  and divergent for  $|z| < R$ . It is possible that  $R = 0$  or  $R = \infty$ .

- **Inversion.** If  $U(z) = \mathcal{Z}u(z)$ , then

$$u[k] = \frac{1}{2\pi i} \oint_{\gamma} z^{k-1} U(z) dz, \quad k = 0, 1, 2, \dots,$$

where  $\gamma$  is a closed curve (inside  $|z| > R_u$ ) counterclockwise around the origin.

- **Uniqueness:** If  $\mathcal{Z}u(z) = \mathcal{Z}v(z)$  for all  $|z| > R$  for some  $R > 0$ , then  $u[k] = v[k]$  for  $k = 0, 1, 2, \dots$
- **Initial value theorem:** If there's an  $R > 0$  such that  $\mathcal{Z}u(z)$  exists for  $|z| > R$ , then

$$\lim_{|z| \rightarrow \infty} \mathcal{Z}u(z) = u[0].$$

## 5.1 Rules for the Z Transform

Let  $U(z) = \mathcal{Z}(u[k])(z)$ ,  $|z| > R_u$  and  $V(z) = \mathcal{Z}(v[k])(z)$ ,  $|z| > R_v$ .

Table 6: Rules for Z transforms

Function	Unilateral Z transform	Region of convergence
$c_1 u[k] + c_2 v[k]$	$c_1 U(z) + c_2 V(z)$	$ z  > \max\{R_u, R_v\}$
$(u * v)[k]$	$U(z)V(z)$	unilateral conv. <sup>†</sup> ; $ z  > \max\{R_u, R_v\}$
$a^k u[k]$	$U\left(\frac{z}{a}\right)$	$ z  >  a R_u, a \in \mathbf{C} \setminus \{0\}$
$u[k-m]H[k-m]$	$z^{-m}U(z)$	$ z  > R_u, m = 1, 2, 3, \dots$
$u[k-m]$	$z^{-m}U(z) + z^{-m+1}u[-1] + \dots$ $\dots + z^{-1}u[-m+1] + u[-m]$	$ z  > R_u, m = 1, 2, 3, \dots$
$u[k+m]$	$z^m U(z) - z^m u[0] + \dots$ $\dots - z^2 u[m-2] - zu[m-1]$	$ z  > R_u, m = 1, 2, 3, \dots$
$\overline{u[k]}$	$\overline{U(\bar{z})}$	$ z  > R_u$
$\sum_{l=0}^k u[l]$	$\frac{z}{z-1} U(z)$	$ z  > \max\{R_u, 1\}$
$k^m u[k]$	$\left(-z \frac{d}{dz}\right)^m U(z)$	$ z  > R_u$

<sup>†</sup>  $(u * v)[k] = \sum_{l=0}^k u[l]v[k-l]$ .

Table 7: Z transforms

Function	Unilateral Z transform	Region of convergence
$\delta[k]$	1	$z \in \mathbf{C}$
$\delta[k-m]$	$z^{-m}$	$ z  > 0, m = 1, 2, \dots$
$H[k]$	$\frac{z}{z-1}$	$ z  > 1$
$k$	$\frac{z}{(z-1)^2}$	$ z  > 1$
$a^k$	$\frac{z}{z-a}$	$ z  >  a $
$ka^k$	$\frac{az}{(z-a)^2}$	$ z  >  a $
$k^2 a^k$	$\frac{az^2 + a^2 z}{(z-a)^3}$	$ z  >  a $
$k^3 a^k$	$\frac{az^3 + 4a^2 z^2 + a^3 z}{(z-a)^4}$	$ z  >  a $
$(k+1)a^k$	$\frac{z^2}{(z-a)^2}$	$ z  >  a $
$\binom{k+m}{m} a^k$	$\frac{z^{m+1}}{(z-a)^{m+1}}$	$ z  >  a , m = 2, 3, \dots$
$\binom{k}{m} a^k$	$\frac{a^m z}{(z-a)^{m+1}}$	$ z  >  a , m = 2, 3, \dots$
$\binom{k+n}{m} a^k$	$\frac{a^{m-n} z^{n+1}}{(z-a)^{m+1}}$	$ z  >  a , m = 2, 3, \dots$ $n = 1, \dots, m-1$
$\cos k\alpha$	$\frac{z^2 - z \cos \alpha}{z^2 - 2z \cos \alpha + 1}$	$ z  > 1$
$\sin k\alpha$	$\frac{z \sin \alpha}{z^2 - 2z \cos \alpha + 1}$	$ z  > 1$
$k \cos k\alpha$	$\frac{z^3 \cos \alpha - 2z^2 + z \cos \alpha}{(z^2 - 2z \cos \alpha + 1)^2}$	$ z  > 1$
$k \sin k\alpha$	$\frac{z^3 \sin \alpha - z \sin \alpha}{(z^2 - 2z \cos \alpha + 1)^2}$	$ z  > 1$
$\frac{a^k}{k!}$	$e^{a/z}$	$ z  > 0$
$\frac{1}{k} H[k-1]$	$\ln \frac{z}{z-1}$	$ z  > 1$
$\binom{n}{k} a^k b^{n-k}$	$\frac{(bz+a)^n}{z^n}$	$ z  > 0, n = 1, 2, 3, \dots$