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Section 3: Periodic Functions and Fourier Series

David R. Wilkins
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3 Periodic Functions and Fourier Series

Definition A function \( f: \mathbb{R} \rightarrow \mathbb{R} \) is said to be periodic if there exists some positive real number \( l \) such that \( f(x + l) = f(x) \) for all real numbers \( x \). The smallest real number \( l \) with this property is the period of the periodic function \( f \).

A periodic function \( f \) with period \( l \) satisfies \( f(x + ml) = f(x) \) for all real numbers \( x \) and integers \( m \).

The period \( l \) of a periodic function \( f \) is said to divide some positive real number \( K \) if \( K/l \) is an integer. If the period of the function \( f \) divides a positive real number \( K \) then \( f(x + mK) = f(x) \) for all real numbers \( x \) and integers \( m \).

Mathematicians have proved that if \( f: \mathbb{R} \rightarrow \mathbb{R} \) is any sufficiently well-behaved function from \( \mathbb{R} \) to \( \mathbb{R} \) with the property that \( f(x + 2\pi) = f(x) \) for all real numbers \( x \) then \( f \) may be represented as an infinite series of the form

\[
f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos nx + \sum_{n=1}^{\infty} b_n \sin nx.
\]  

In particular it follows from theorems proved by Dirichlet in 1829 that a function \( f: \mathbb{R} \rightarrow \mathbb{R} \) which satisfies \( f(x + 2\pi) = f(x) \) for all real numbers \( x \) can be represented as a trigonometrical series of this form if the function is bounded, with at most finitely many points of discontinuity, local maxima and local minima in the interval \([-\pi, \pi]\), and if

\[
f(x) = \frac{1}{2} \left( \lim_{h \to 0^+} f(x + h) + \lim_{h \to 0^+} f(x - h) \right)
\]

at each value \( x \) at which the function is discontinuous (where \( \lim_{h \to 0^+} f(x + h) \) and \( \lim_{h \to 0^+} f(x - h) \) denote the limits of \( f(x + h) \) and \( f(x - h) \) respectively as \( h \) tends to 0 from above).

Fourier in 1807 had observed that if a sufficiently well-behaved function could be expressed as the sum of a trigonometrical series of the above form, then

\[
a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \, dx,
\]

\[
a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx \, dx,
\]

\[
b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx \, dx
\]
for each positive integer \( n \). These expressions for the coefficients \( a_n \) and \( b_n \) may readily be verified on substituting the trigonometric series for the function \( f \) (equation (33)) into the integrals on the right hand side of the equation, provided that one is permitted to interchange the operations of integration and summation in the resulting expressions.

Now it is not generally true that the integral of an infinite sum of functions is necessarily equal to the sum of the integrals of those functions. However if the function \( f \) is sufficiently well-behaved then the trigonometric series for the function \( f \) will converge sufficiently rapidly for this interchange of integration and summation to be valid, so that

\[
\int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} a_m \cos mx \right) \, dx = \sum_{m=1}^{\infty} a_m \int_{-\pi}^{\pi} \cos mx \, dx \quad \text{etc.}
\]

If we interchange summations and integrations in this fashion and make use of the trigonometric integrals provided by Theorem 2.1, we find that

\[
\int_{-\pi}^{\pi} f(x) \, dx = a_0 \pi + \int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} a_m \cos mx \right) \, dx + \int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} b_m \sin mx \right) \, dx
\]

\[
= a_0 \pi + \sum_{m=1}^{\infty} a_m \int_{-\pi}^{\pi} \cos mx \, dx + \sum_{m=1}^{\infty} b_m \int_{-\pi}^{\pi} \sin mx \, dx
\]

\[
= a_0 \pi,
\]

Also

\[
\int_{-\pi}^{\pi} f(x) \cos nx \, dx
\]

\[
= \frac{1}{2} a_0 \int_{-\pi}^{\pi} \cos nx \, dx + \int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} a_m \cos mx \cos nx \right) \, dx
\]

\[
+ \int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} b_m \sin mx \cos nx \right) \, dx
\]

\[
= \sum_{m=1}^{\infty} a_m \int_{-\pi}^{\pi} \cos mx \cos nx \, dx + \sum_{m=1}^{\infty} b_m \int_{-\pi}^{\pi} \sin mx \cos nx \, dx
\]

\[
= a_n \pi,
\]

\[
\int_{-\pi}^{\pi} f(x) \sin nx \, dx
\]

\[
= \frac{1}{2} a_0 \int_{-\pi}^{\pi} \sin nx \, dx + \int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} a_m \cos mx \sin nx \right) \, dx
\]
\[
+ \int_{-\pi}^{\pi} \left( \sum_{m=1}^{\infty} b_m \sin mx \sin nx \right) dx
= \sum_{m=1}^{\infty} a_m \int_{-\pi}^{\pi} \cos mx \sin nx \, dx + \sum_{m=1}^{\infty} b_m \int_{-\pi}^{\pi} \sin mx \sin nx \, dx
= b_n \pi.
\]

A trigonometric series of the form (33) with coefficients \(a_n\) and \(b_n\) given by the integrals (34), (35) and (36) is referred to the Fourier series for the function \(f\). The coefficients defined by the integrals (34), (35) and (36) are referred to as the Fourier coefficients of the function \(f\).

**Example** Consider the function \(f: \mathbb{R} \to \mathbb{R}\) defined by

\[
f(x) = \begin{cases} 
\frac{1}{2} & \text{if } x = m\pi \text{ for some integer } m; \\
1 & \text{if } 2m\pi < x < (2m + 1)\pi \text{ for some integer } m; \\
0 & \text{if } (2m - 1)\pi < x < 2m\pi \text{ for some integer } m.
\end{cases}
\]

This function \(f\) has the property that \(f(x) = f(x + 2m\pi)\) for all real numbers \(x\) and integers \(m\), and can be represented by a Fourier series. The coefficients \(a_n\) and \(b_n\) of the Fourier series are given by the formulae

\[
a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \, dx,
\]

\[
a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx \, dx \quad (n > 0),
\]

\[
b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx \, dx \quad (n > 0),
\]

Now \(f(x) = 0\) if \(-\pi < x < 0\), and \(f(x) = 1\) if \(0 < x < \pi\). Therefore \(a_0 = 1\), and

\[
a_n = \frac{1}{\pi} \int_{0}^{\pi} \cos nx \, dx = \frac{1}{n\pi} \left[ \sin nx \right]_0^\pi
= 0 \quad (n > 0),
\]

\[
b_n = \frac{1}{\pi} \int_{0}^{\pi} \sin nx \, dx = \frac{1}{n\pi} \left[ -\cos nx \right]_0^\pi
= \frac{1}{n\pi} (1 - \cos n\pi) = \frac{1}{n\pi} (1 - (-1)^n)
= \begin{cases} 
\frac{2}{n\pi} & \text{if } n \text{ is odd and } n > 0, \\
0 & \text{if } n \text{ is even and } n > 0,
\end{cases}
\]

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We have here made use of the fact that \( \sin n\pi = 0 \) and \( \cos n\pi = (-1)^n \) for all integers \( n \).

Thus
\[
f(x) = \frac{1}{2} + \sum_{n \text{ odd}, n > 0} \frac{2}{n\pi} \sin nx
\]
\[
= \frac{1}{2} + \sum_{k=1}^{\infty} \frac{2}{(2k-1)\pi} \sin ((2k-1)x)
\]

3.1 Fourier Series of Even and Odd Functions

**Definition** A function \( f: \mathbb{R} \to \mathbb{R} \) is said to be even if \( f(x) = f(-x) \) for all real numbers \( x \). A function \( f: \mathbb{R} \to \mathbb{R} \) is said to be odd if \( f(x) = -f(-x) \) for all real numbers \( x \).

Let \( f: \mathbb{R} \to \mathbb{R} \) be an integrable function. Then

\[
\int_{-\pi}^{0} f(x) \, dx = \int_{0}^{\pi} f(-x) \, dx,
\]
\[
\int_{-\pi}^{0} f(x) \cos nx \, dx = \int_{0}^{\pi} f(-x) \cos nx \, dx,
\]
\[
\int_{-\pi}^{0} f(x) \sin nx \, dx = -\int_{0}^{\pi} f(-x) \sin nx \, dx
\]

(The first of these identities may be verified by making the substitution \( x \mapsto -x \) and then interchanging the two limits of integration. The second and the third follow from the first on replacing \( f(x) \) by \( f(x) \cos nx \) and \( f(x) \sin nx \) and noting that \( \cos(-nx) = \cos nx \) and \( \sin(-nx) = -\sin nx \).) It follows that the Fourier coefficients of \( f \) are given by the following formulae:

\[
a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \, dx = \frac{1}{\pi} \int_{0}^{\pi} (f(x) + f(-x)) \, dx,
\]
\[
a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx \, dx = \frac{1}{\pi} \int_{0}^{\pi} (f(x) + f(-x)) \cos nx \, dx,
\]
\[
b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx \, dx = \frac{1}{\pi} \int_{0}^{\pi} (f(x) - f(-x)) \sin nx \, dx
\]

for all positive integers \( n \).

Of course \( f(x) + f(-x) = 2f(x) \) and \( f(x) - f(-x) = 0 \) for all real numbers \( x \) if the function \( f: \mathbb{R} \to \mathbb{R} \) is even, and \( f(x) + f(-x) = 0 \) and \( f(x) - f(-x) = 2f(x) \) if the function \( f: \mathbb{R} \to \mathbb{R} \) is odd. The following results follow immediately,
**Theorem 3.1** Let $f: \mathbb{R} \to \mathbb{R}$ be an even periodic function whose period divides $2\pi$. Suppose that the function $f$ may be represented by a Fourier series. Then the Fourier series of $f$ is of the form

$$f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos nx,$$

where

$$a_0 = \frac{2}{\pi} \int_{0}^{\pi} f(x) \, dx$$

and

$$a_n = \frac{2}{\pi} \int_{0}^{\pi} f(x) \cos nx \, dx$$

for all positive integers $n$.

**Theorem 3.2** Let $f: \mathbb{R} \to \mathbb{R}$ be an odd periodic function whose period divides $2\pi$. Suppose that the function $f$ may be represented by a Fourier series. Then the Fourier series of $f$ is of the form

$$f(x) = \sum_{n=1}^{\infty} b_n \sin nx,$$

where

$$b_n = \frac{2}{\pi} \int_{0}^{\pi} f(x) \sin nx \, dx$$

for all positive integers $n$.

### 3.2 Fourier Series for General Periodic Functions

Let $f: \mathbb{R} \to \mathbb{R}$ be a periodic function whose period divides $l$, where $l$ is some positive real number. Then $f(x + l) = f(x)$ for all real numbers $x$. Let

$$g(x) = f \left( \frac{lx}{2\pi} \right)$$

so that $f(x) = g \left( \frac{2\pi x}{l} \right)$.

Then $g: \mathbb{R} \to \mathbb{R}$ is a periodic function, and $g(x + 2\pi) = g(x)$ for all real numbers $x$. If the function $f$ is sufficiently well-behaved (and, in particular, if the function $f$ is bounded, with only finitely many local maxima and minima and points of discontinuity in any finite interval, and if $f(x)$ at each point of discontinuity is the average of the limits of $f(x + h)$ and $f(x - h)$)
as \( h \) tends to zero from above) then the function \( g \) may be represented by a Fourier series of the form

\[
g(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos nx + \sum_{n=1}^{\infty} b_n \sin nx.
\]

The coefficients of this Fourier series are then given by the formulae

\[
a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} g(u) \, du,
\]
\[
a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} g(u) \cos nu \, du,
\]
\[
b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} g(u) \sin nu \, du
\]

for each positive integer \( n \). If we make the substitution \( u = \frac{2\pi x}{l} \) in these integrals, we find that

\[
f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos \left( \frac{2n\pi x}{l} \right) + \sum_{n=1}^{\infty} b_n \sin \left( \frac{2n\pi x}{l} \right), \quad (43)
\]

where

\[
a_0 = \frac{2}{l} \int_{-\frac{1}{2}l}^{\frac{1}{2}l} g \left( \frac{2\pi x}{l} \right) \, dx
\]
\[
= \frac{2}{l} \int_{-\frac{1}{2}l}^{\frac{1}{2}l} f(x) \, dx,
\]
\[
a_n = \frac{2}{l} \int_{-\frac{1}{2}l}^{\frac{1}{2}l} g \left( \frac{2\pi x}{l} \right) \cos \left( \frac{2n\pi x}{l} \right) \, dx
\]
\[
= \frac{2}{l} \int_{-\frac{1}{2}l}^{\frac{1}{2}l} f(x) \cos \left( \frac{2n\pi x}{l} \right) \, dx,
\]
\[
b_n = \frac{2}{l} \int_{-\frac{1}{2}l}^{\frac{1}{2}l} g \left( \frac{2\pi x}{l} \right) \sin \left( \frac{2n\pi x}{l} \right) \, dx
\]
\[
= \frac{2}{l} \int_{-\frac{1}{2}l}^{\frac{1}{2}l} f(x) \sin \left( \frac{2n\pi x}{l} \right) \, dx
\]

for all positive integers \( n \). Note that these integrals are taken over a single period of the function, from \(-\frac{1}{2}l\) to \(+\frac{1}{2}l\). It follows from the periodicity of
the integrand that these integrals may be replaced by integrals from $c$ to $c+l$ for any real number $c$, and thus

$$a_0 = \frac{2}{l} \int_c^{c+l} f(x) \, dx,$$

(44)

$$a_n = \frac{2}{l} \int_c^{c+l} f(x) \cos \left( \frac{2n\pi x}{l} \right) \, dx,$$

(45)

$$b_n = \frac{2}{l} \int_c^{c+l} f(x) \sin \left( \frac{2n\pi x}{l} \right) \, dx$$

(46)

for all positive integers $n$. (Indeed, if $h: \mathbb{R} \to \mathbb{R}$ is any integrable function with the property that $h(x+l) = h(x)$ for all real numbers $x$, and if $p$ and $q$ are real numbers with $p \leq q \leq p+l$ then

$$\int_p^{p+l} h(x) \, dx = \int_p^q h(x) \, dx + \int_q^{p+l} h(x) \, dx = \int_q^{q+l} h(x) \, dx.$$

Repeated applications of this identity show that

$$\int_p^{p+l} h(x) \, dx = \int_q^{q+l} h(x) \, dx$$

for all real numbers $p$ and $q$.)

**Example** Let $k$ be a positive real number. Consider the function $f: \mathbb{R} \to \mathbb{R}$ defined by

$$f(x) = \begin{cases} 
  e^{k(x-m)} & \text{if } m < x < m+1 \text{ for some integer } m; \\
  \frac{1}{2} (e^k + 1) & \text{if } x \text{ is an integer.}
\end{cases}$$

This function is periodic, with period 1, and may be expanded as a Fourier series

$$f(x) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} a_n \cos 2n\pi x + \sum_{n=1}^{\infty} b_n \sin 2n\pi x,$$

where

$$a_0 = 2 \int_0^1 f(x) \, dx,$$

$$a_n = 2 \int_0^1 f(x) \cos 2n\pi x \, dx \quad (n > 0),$$

$$b_n = 2 \int_0^1 f(x) \sin 2n\pi x \, dx \quad (n > 0).$$
Note that $f(x) = e^{kx}$ if $0 < x < 1$. We see therefore that

$$a_0 = 2 \int_0^1 e^{kx} \, dx = \frac{2}{k} \left[ e^{kx} \right]_0^1 = \frac{2}{k}(e^k - 1).$$

Now if $k$ and $\omega$ a positive real numbers then

$$\int e^{kx} \cos \omega x \, dx = \frac{k}{k^2 + \omega^2} e^{kx} \cos \omega x + \frac{\omega}{k^2 + \omega^2} e^{kx} \sin \omega x + C,$$

$$\int e^{kx} \sin \omega x \, dx = \frac{k}{k^2 + \omega^2} e^{kx} \sin \omega x - \frac{\omega}{k^2 + \omega^2} e^{kx} \cos \omega x + C,$$

where $C$ is a constant of integration. (These identities may be verified by differentiating the expressions on the right hand side.) We find therefore that

$$a_n = 2 \int_0^1 e^{kx} \cos 2n\pi x \, dx$$

$$= \left[ \frac{2k}{k^2 + 4n^2\pi^2} e^{kx} \cos 2n\pi x + \frac{4n\pi}{k^2 + 4n^2\pi^2} e^{kx} \sin 2n\pi x \right]_0^1$$

$$= \frac{2k}{k^2 + 4n^2\pi^2} (e^k - 1),$$

$$b_n = 2 \int_0^1 e^{kx} \sin 2n\pi x \, dx,$$

$$= \left[ \frac{2k}{k^2 + 4n^2\pi^2} e^{kx} \sin 2n\pi x - \frac{4n\pi}{k^2 + 4n^2\pi^2} e^{kx} \cos 2n\pi x \right]_0^1$$

$$= -\frac{4n\pi}{k^2 + 4n^2\pi^2} (e^k - 1),$$

for each positive integer $n$, since $\cos 2n\pi = 1$ and $\sin 2n\pi = 0$ when $n$ is an integer. Thus

$$e^{kx} = \frac{1}{k} (e^k - 1) + \sum_{n=1}^{\infty} \frac{2k}{k^2 + 4n^2\pi^2} (e^k - 1) \cos 2n\pi x$$

$$- \sum_{n=1}^{\infty} \frac{4n\pi}{k^2 + 4n^2\pi^2} (e^k - 1) \sin 2n\pi x$$

for all real numbers $x$ satisfying $0 < x < 1$.

### 3.3 Sine Series

Let $f: [0, l] \to \mathbb{R}$ be a function defined on the interval $[0, l]$, where $[0, l] = \{ x \in \mathbb{R} : 0 \leq x \leq l \}$. Suppose that $f(0) = f(l) = 0$. Let $f: \mathbb{R} \to \mathbb{R}$ be the
function defined such that
\[ \tilde{f}(x) = f(x - 2nl) \text{ if } 2nl \leq x \leq (2n + 1)l \text{ for some integer } n \]
and
\[ \tilde{f}(x) = -f((2n + 2)l - x) \text{ if } (2n + 1)l \leq x \leq (2n + 2)l \text{ for some integer } n. \]

The function \( \tilde{f}: \mathbb{R} \to \mathbb{R} \) is an odd function with the property that \( \tilde{f}(x + 2l) = \tilde{f}(x) \) for all real numbers \( x \). Indeed it is easily seen that \( \tilde{f}: \mathbb{R} \to \mathbb{R} \) is the unique odd function with this property which agrees with the function \( f \) on the interval \([0, l]\).

If the function \( f \) is sufficiently well-behaved (and, in particular, if the function \( f \) is bounded, with at most finitely many local maxima and minima and points of discontinuity, and has the property that \( f(x) \) at each point of discontinuity is the average of the limits of \( f(x + h) \) and \( f(x - h) \) as \( h \) tends to zero from above) then the function \( \tilde{f} \) may be represented as a Fourier series. This Fourier series is of the form

\[ \tilde{f}(x) = \sum_{n=1}^{\infty} b_n \sin \left( \frac{n\pi x}{l} \right), \]

where

\[
\begin{align*}
    b_n &= \frac{1}{l} \int_{-l}^{l} \tilde{f}(x) \sin \left( \frac{n\pi x}{l} \right) \, dx \\
    &= \frac{2}{l} \int_{0}^{l} \tilde{f}(x) \sin \left( \frac{n\pi x}{l} \right) \, dx
\end{align*}
\]

for all positive integers \( n \). (This follows from equations (43) and (46) on replacing \( l \) by \( 2l \), and then using the fact that \( \tilde{f}(-x) = -\tilde{f}(x) \) for all real numbers \( x \).)

Therefore every sufficiently well-behaved function \( f: [0, l] \to \mathbb{R} \) which satisfies \( f(0) = f(l) = 0 \) may be represented in the form

\[ f(x) = \sum_{n=1}^{\infty} b_n \sin \left( \frac{n\pi x}{l} \right), \quad (47) \]

where

\[
    b_n = \frac{2}{l} \int_{0}^{l} f(x) \sin \left( \frac{n\pi x}{l} \right) \, dx \quad (48)
\]

for each positive integer \( n \).
Example Let $l$ be a positive real numbers, and let $f: [0, l] \rightarrow \mathbb{R}$ be the function defined by $f(x) = x(l - x)$ (where $0 \leq x \leq l$). This function can be expanded in a sine series of the form

$$f(x) = \sum_{n=1}^{\infty} b_n \sin \left( \frac{n\pi x}{l} \right),$$

where

$$b_n = \frac{2}{l} \int_0^l f(x) \sin \frac{n\pi x}{l} \, dx.$$

Using the method of integration by parts, and the result that $\sin n\pi = 0$ and $\cos n\pi = (-1)^n$ for all integers $n$, we find then

$$b_n = \frac{2}{l} \int_0^l x(l - x) \sin \frac{n\pi x}{l} \, dx = -\frac{2}{n\pi} \int_0^l x(l - x) \frac{d}{dx} \left( \cos \frac{n\pi x}{l} \right) \, dx$$

$$= -\frac{2}{n\pi} \left[ x(l - x) \cos \frac{n\pi x}{l} \right]_0^l + \frac{2}{n\pi} \int_0^l (l - 2x) \cos \frac{n\pi x}{l} \, dx$$

$$= \frac{2}{n\pi} \int_0^l (l - 2x) \cos \frac{n\pi x}{l} \, dx$$

$$= \frac{2}{n^2\pi^2} \int_0^l (l - 2x) \frac{d}{dx} \left( \sin \frac{n\pi x}{l} \right) \, dx$$

$$= \frac{2}{n^2\pi^2} \left[ (l - 2x) \sin \frac{n\pi x}{l} \right]_0^l - \frac{2}{n^2\pi^2} \int_0^l \left( -2 \sin \frac{n\pi x}{l} \right) \, dx$$

$$= \frac{4l}{n^2\pi^2} \int_0^l \sin \frac{n\pi x}{l} \, dx = -\frac{4l^2}{n^3\pi^3} \left[ \cos \frac{n\pi x}{l} \right]_0^l$$

$$= \frac{4l^2}{n^3\pi^3} (1 - \cos n\pi)$$

$$= \begin{cases} \frac{8l^2}{n^3\pi^3} & \text{if } n \text{ is odd;} \\ 0 & \text{if } n \text{ is even.} \end{cases}$$

Thus

$$f(x) = \sum_{n \text{ odd}}^{\infty} \frac{8l^2}{n^3\pi^3} \sin \frac{n\pi x}{l}.$$

or (setting $n = 2k - 1$ for each positive integer $k$),

$$x(l - x) = \sum_{k=1}^{\infty} \frac{8l^2}{(2k - 1)^3\pi^3} \sin \frac{(2k-1)\pi x}{l} \quad (0 \leq x \leq l).$$

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3.4 Cosine Series

Let \( f: [0, l] \to \mathbb{R} \) be a function defined on the interval \([0, l]\), where \([0, l] = \{x \in \mathbb{R} : 0 \leq x \leq l\}\). Let \( \tilde{g}: \mathbb{R} \to \mathbb{R} \) be the function defined by

\[
\tilde{g}(x) = f(x - 2nl) \text{ if } 2nl \leq x \leq (2n + 1)l \text{ for some integer } n
\]

and

\[
\tilde{g}(x) = f((2n + 2)l - x) \text{ if } (2n + 1)l \leq x \leq (2n + 2)l \text{ for some integer } n.
\]

The function \( \tilde{g}: \mathbb{R} \to \mathbb{R} \) is an even function with the property that \( \tilde{g}(x + 2l) = \tilde{g}(x) \) for all real numbers \( x \). Indeed it is easily seen that \( \tilde{g}: \mathbb{R} \to \mathbb{R} \) is the unique even function with this property which agrees with the function \( f \) on the interval \([0, l]\).

If the function \( f \) is sufficiently well-behaved then the function \( \tilde{g} \) may be represented as a Fourier series. This Fourier series is of the form

\[
\tilde{g}(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos \left( \frac{n\pi x}{l} \right),
\]

where

\[
a_n = \frac{1}{l} \int_{-l}^{l} \tilde{g}(x) \cos \left( \frac{n\pi x}{l} \right) \, dx
\]

\[
= \frac{2}{l} \int_{0}^{l} \tilde{g}(x) \cos \left( \frac{n\pi x}{l} \right) \, dx
\]

for all non-negative integers \( n \). (This follows from equations (43), (44) and (45) on replacing \( l \) by \( 2l \), and then using the fact that \( \tilde{g}(-x) = \tilde{g}(x) \) for all real numbers \( x \).)

Therefore every sufficiently well-behaved function \( f: [0, l] \to \mathbb{R} \) may be represented in the form

\[
f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos \left( \frac{n\pi x}{l} \right)\]

(49)

where

\[
a_n = \frac{2}{l} \int_{0}^{l} f(x) \cos \left( \frac{n\pi x}{l} \right) \, dx
\]

(50)

for each positive integer \( n \).
Example Consider the function \( f: [0, 1] \rightarrow \mathbb{R} \) defined by
\[
f(x) = x \quad \text{if } 0 \leq x \leq 1.
\]
This function may be represented as a cosine series of the form
\[
f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos n\pi x
\]
where
\[
a_0 = 2 \int_0^1 f(x) \, dx = 2 \int_0^1 x \, dx = 1,
\]
and where
\[
a_n = 2 \int_0^1 f(x) \cos n\pi x \, dx
\]
for all positive integers \( n \). Using the method of integration by parts, and making use of the fact that \( \sin n\pi x = 0 \) and \( \cos n\pi x = (-1)^n \) for all integers \( n \), we find that
\[
a_n = 2 \int_0^1 x \cos n\pi x \, dx = \frac{2}{n\pi} \int_0^1 x \frac{d}{dx} (\sin n\pi x) \, dx
\]
\[
= \frac{2}{n\pi} [x \sin n\pi x]_0^1 - \frac{2}{n\pi} \int_0^1 \sin n\pi x \, dx = -\frac{2}{n\pi} \int_0^1 \sin n\pi x \, dx
\]
\[
= \frac{2}{n^2\pi^2} [\cos n\pi x]_0^1 = -\frac{2}{n^2\pi^2} (1 - (-1)^n)
\]
\[
= \begin{cases} 
-\frac{4}{n^2\pi^2} & \text{if } n \text{ is odd;} \\
0 & \text{if } n \text{ is even.}
\end{cases}
\]
Thus
\[
x = \frac{1}{2} - \sum_{n \text{ odd}}^{\infty} \frac{4}{n^2\pi^2} \cos n\pi x \quad \text{when } 0 \leq x \leq 1.
\]

Remark The function \( \tilde{g} \) defined by
\[
\tilde{g}(x) = \frac{1}{2} - \sum_{n \text{ odd}}^{\infty} \frac{4}{n^2\pi^2} \cos n\pi x
\]
for all real numbers \( x \) is an even periodic function, with period equal to 2, which coincides with the function \( f: [0, 1] \rightarrow \mathbb{R} \) on the interval \([0, 1]\), where \( f(x) = x \) for all real numbers \( x \) satisfying \( 0 \leq x \leq 1 \). It follows that
\[
\tilde{g}(x) = |x - 2m| \quad \text{whenever } m \text{ is an integer and } 2m - 1 \leq x \leq 2m + 1.
\]
Remark Setting $x = 1$ in the identity

$$x = \frac{1}{2} - \sum_{n \text{ odd}}^{\infty} \frac{4}{n^2 \pi^2} \cos n\pi x \quad \text{when } 0 \leq x \leq 1,$$

we find that

$$1 = \frac{1}{2} - \sum_{n \text{ odd}}^{\infty} \frac{4}{n^2 \pi^2} \cos n\pi = \frac{1}{2} + \sum_{n \text{ odd}}^{\infty} \frac{4}{n^2 \pi^2}$$

and thus

$$\sum_{n \text{ odd}}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{8}.$$

But

$$\sum_{n \text{ odd}}^{\infty} \frac{1}{n^2} = \sum_{n=1}^{\infty} \frac{1}{n^2} - \sum_{n=1}^{\infty} \frac{1}{(2n)^2} = \left(1 - \frac{1}{4}\right) \sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{3}{4} \sum_{n=1}^{\infty} \frac{1}{n^2}.$$ 

Therefore

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{6}.$$

Problems

1. Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be the periodic function with period $2\pi$ given for real numbers $x$ satisfying $-\pi \leq x \leq \pi$ by the formula

$$f(x) = \begin{cases} 
1 - \frac{2|x|}{\pi} & \text{if } -\frac{1}{2}\pi \leq x \leq \frac{1}{2}\pi; \\
0 & \text{if } -\pi \leq x \leq -\frac{1}{2}\pi \text{ or } \frac{1}{2}\pi \leq x \leq \pi.
\end{cases}$$

(Here $|x|$, the absolute value of $x$, is defined by $|x| = x$ if $x \geq 0$, and $|x| = -x$ if $x < 0$.) The function $f$ can be expanded as a Fourier series of the form

$$f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos nx.$$ 

(The terms involving $\sin nx$ are zero since the given function is even.) Find the coefficients $a_n$ of this series, and hence write down the Fourier series for the function $f$. 

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2. Calculate the Fourier series of the function \( f: \mathbb{R} \to \mathbb{R} \) which is periodic, with period \( 2\pi \), and which is defined on the interval \(-\pi \leq x \leq \pi\) by the following formulae:

\[
f(x) = \begin{cases} 
2 + \frac{2x}{\pi} & \text{if } -\pi \leq x \leq -\frac{1}{2}\pi; \\
1 & \text{if } -\frac{1}{2}\pi \leq x \leq \frac{1}{2}\pi; \\
2 - \frac{2x}{\pi} & \text{if } \frac{1}{2}\pi \leq x \leq \pi.
\end{cases}
\]

3. Let \( f: \mathbb{R} \to \mathbb{R} \) be defined such that

\[
f(x) = 4(x - m) \text{ if } m \leq x \leq m + \frac{1}{2} \text{ for some integer } m;
\]

\[
f(x) = 4(m + 1 - x) \text{ if } m + \frac{1}{2} \leq x \leq m + 1 \text{ for some integer } m.
\]

Express the function \( f \) as a Fourier series of the form

\[
f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos 2\pi nx.
\]