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A pseudo hermitian operator and non-trivial Riemann zeros

Yu Li

Abstract

Abstract: In this paper we construct a pseudo hermitian operator and reveal a connection between its eigenvalues and the non-trivial Riemann zeros.

Keywords. Riemann hypothesis, non-trivial Riemann zero, Pseudo hermitian operator, Berry-Keating operator

1 Introduction

One of the most attracting problems in Mathematics is Riemann hypothesis and it states that all the non-trivial zeros of Riemann zeta function

$$\zeta(s) = \sum_{n \geq 1} \frac{1}{n^s} = \frac{1}{\Gamma(s)} \int_0^{\infty} \frac{t^{s-1}}{e^t - 1} dt$$

have the real part $\frac{1}{2}$.

One proposed way of proving Riemann hypothesis, known as Hilbert-Pólya conjecture, is to find an unbounded self-adjoint operator such that the imaginary part of Riemann zeros corresponds to the eigenvalues of this operator. It has been suggested [4] that the possible approach to solve Hilbert-Pólya conjecture lies in a quantization of the classical Hamiltonian $H = XP$, where P is the canonical momentum operator associated with position operator X . Inspired of the previous works, an operator \tilde{H} similar to quantum analogy was proposed [3]. However, the momentum operator P in this case has no self-adjoint extension [2].

In this paper we define an operator \tilde{H} on the Hilbert space $\mathcal{H} = L^2[\frac{1}{2}, 1]$, then we show that momentum operator in this setting has the unique self-adjoint extension. Finally, we demonstrate that the operator is pseudo hermitian and prove a relationship between its eigenvalues and the non-trivial Riemann zeros.

2 Hurwitz zeta functions

The Hurwitz zeta function is originally defined for complex arguments s with $\Re(s) > 1$ and $x > 0$ by

$$\zeta(s, x) = \sum_{n \geq 0} \frac{1}{(n+x)^s}$$

Hurwitz zeta function has an analytic continuation on \mathbb{C} with the only singularity $s = 1$ and it can be represented [1, 7]

$$\zeta(s, x) = -\frac{\Gamma(1-s)}{2\pi i} \int_{\mathcal{C}} \frac{\xi^{s-x} e^{x\xi}}{e^\xi - 1} d\xi, \quad s \neq 1 \quad (1)$$

where \mathcal{C} is the contour around the negative real axis and it starts at $-\infty$, encircles the origin once in the positive direction without enclosing any of the points $\xi = \pm 2ni, \pm 4ni, \dots$ and returns to $-\infty$ [7]. The famous Riemann zeta function is the special case of Hurwitz zeta function with $x = 1$

$$\zeta(s, 1) = \zeta(s)$$

and also with $x = \frac{1}{2}$

$$\zeta(s, \frac{1}{2}) = (2^s - 1)\zeta(s) \quad (2)$$

The partial derivative of Hurwitz zeta function with respect to x

$$\frac{\partial \zeta(s, x)}{\partial x} = -s\zeta(s+1, x), \quad s \neq 0, 1; x > 0 \quad (3)$$

3 Non-trivial Riemann zeros

Let X be the position operator on $L^2[\frac{1}{2}, 1]$ and P_0 the momentum operator $P_0 = -i\frac{d}{dx}$ densely defined on $L^2[\frac{1}{2}, 1]$ with domain

$$D(P_0) = \left\{ f \in C^\infty[\frac{1}{2}, 1] : f(\frac{1}{2}) = f(1) \right\} \quad (4)$$

and obviously P_0 is essentially self-adjoint [5] and it has a unique self-adjoint extension $\overline{P_0} = P$. The functions $\varphi_n(x) = e^{2\pi i n(2x-1)}$ form an orthogonal basis for $L^2[\frac{1}{2}, 1]$ and the closure of $D(P_0)$ is all functions of $L^2[\frac{1}{2}, 1]$

$$D(P) = \overline{D(P_0)} = L^2[\frac{1}{2}, 1]$$

From the Stone's theorem on one-parameter unitary groups, $\{e^{itP}\}_t$ is a strongly continuous one-parameter group of unitary operators on $L^2[\frac{1}{2}, 1]$.

So both operators $e^{\pm iP} - I$ are bijective and bounded, and then the bounded inverses $(e^{\pm iP} - I)^{-1}$ exist, from the bounded inverse theorem in functional analysis.

We construct an operator \tilde{H} on $L^2[\frac{1}{2}, 1]$

$$\tilde{H} = (e^{iP} - I)^{-1} (XP + PX) (e^{iP} - I)$$

It holds obviously for $\frac{1}{2} \leq x \leq 1$ and $0 < \mathcal{R}(s) < 1$

$$(XP + PX)x^{-s} = i(2s - 1)x^{-s} \quad (5)$$

Here the operator $H_{\text{BK}} = XP + PX$ is called Berry-Keating operator [4].

The operator \tilde{H} is pseudo hermitian [6], i.e. there exists an invertible operator η such that the adjoint operator \tilde{H}^\dagger can be represented

$$\tilde{H}^\dagger = \eta \tilde{H} \eta^{-1}$$

Proposition 3.1. *\tilde{H} is pseudo hermitian and all eigenvalues are real.*

Proof. Let $\eta = (e^{iP} - I)^\dagger (e^{iP} - I)$, then

$$\tilde{H}^\dagger = \eta \tilde{H} \eta^{-1}$$

The operator η is positive definite, then all eigenvalues of \tilde{H} are real. \square

Let s denote a point in critical strip $0 < \mathcal{R}(s) < 1$ and we define a function ζ_s on interval $[\frac{1}{2}, 1]$ for Hurwitz zeta function

$$\zeta_s(x) := \zeta(s, x), \quad \frac{1}{2} \leq x \leq 1$$

If a complex number z is a non-trivial Riemann zero,

$$\zeta_z(1) = 0$$

then the function ζ_z vanishes at $x = \frac{1}{2}$ from (2)

$$\zeta_z\left(\frac{1}{2}\right) = 0$$

Proposition 3.2. *For each non-trivial Riemann zero z , ζ_z is an eigenfunction of \tilde{H} with eigenvalue $i(2z - 1)$.*

Proof. We consider for non-trivial Riemann zeros z the term

$$\frac{1}{iP} \left(\frac{iP}{e^{iP} - I} \right) x^{-z}, \quad \frac{1}{2} \leq x \leq 1$$

where $\frac{1}{iP}$ is defined as an integral operator on $L^2[\frac{1}{2}, 1]$ with boundary $x = \frac{1}{2}$

$$\frac{1}{iP}f(x) := \int_{\frac{1}{2}}^x f(\xi)d\xi, \quad f \in L^2[\frac{1}{2}, 1]$$

and $\frac{iP}{e^{iP}-I}f$ is defined as a Bernoulli generating function

$$\frac{iP}{e^{iP}-I}f(x) := \sum_{n \geq 0} \frac{B_n}{n!} (iP)^n f(x), \quad f \in L^2[\frac{1}{2}, 1]$$

Notice

$$(iP)^n x^{-z} = \frac{\Gamma(-z+1)}{\Gamma(-z+1-n)} x^{-z-n}$$

We use Hankel loop contour integral formula [7, 8]

$$\frac{1}{\Gamma(-z+1-n)} = \frac{1}{2\pi i} \int_{\mathcal{C}} \xi^{-(1-z-n)} e^{\xi} d\xi$$

where the integration is done along the Hankel-Bromwich contour and it begins at $-\infty$, circles the origin once in the positive direction, and returns to $-\infty$

$$\begin{aligned} (iP)^n x^{-z} &= \Gamma(1-z) \left(\frac{1}{2\pi i} \int_{\mathcal{C}} \xi^{-(1-z-n)} e^{\xi} d\xi \right) x^{-z-n} \\ &= \frac{\Gamma(1-z)}{2\pi i} \int_{\mathcal{C}} \left(\frac{\xi}{x} \right)^{z+n-1} e^{\xi} d\frac{\xi}{x} \end{aligned}$$

and then

$$\begin{aligned} \frac{iP}{e^{iP}-I} x^{-z} &= \sum_{n \geq 0} \frac{B_n}{n!} (iP)^n x^{-z} \\ &= \frac{\Gamma(1-z)}{2\pi i} \sum_{n \geq 0} \int_{\mathcal{C}} \frac{B_n}{n!} \left(\frac{\xi}{x} \right)^{z+n-1} e^{\xi} d\frac{\xi}{x} \end{aligned}$$

Let $u = \frac{\xi}{x}$ and $\mathcal{C}' = \frac{\mathcal{C}}{x}$ is still a loop around the negative real axis. Uniform convergence on closed interval justifies the interchange of integral and sum. Then Hurwitz zeta function can be reproduced (1)

$$\frac{iP}{e^{iP}-I} x^{-z} = \frac{\Gamma(1-z)}{2\pi i} \int_{\mathcal{C}'} \frac{u^z}{e^u-1} e^{ux} du = -z\zeta(z+1, x)$$

Then from (3)

$$\begin{aligned} \frac{1}{iP} \left(\frac{iP}{e^{iP}-I} \right) x^{-z} &= \int_{\frac{1}{2}}^x -z\zeta(z+1, \xi) d\xi \\ &= \zeta(z, x) - \zeta(z, \frac{1}{2}) = \zeta_z(x) \end{aligned}$$

The function ζ_z vanishes at $x = \frac{1}{2}$ for non-trivial Riemann zero z , then

$$\left(\frac{1}{e^{iP} - I}\right) x^{-z} = \frac{1}{iP} \left(\frac{iP}{e^{iP} - I}\right) x^{-z} = \zeta_z(x)$$

Combining (5), we reach

$$\tilde{H}\zeta_z = i(2z - 1)\zeta_z$$

□

Theorem 3.3. *The Riemann zeta function has its non-trivial zeros only at the complex numbers with real part $\frac{1}{2}$.*

Corollary. *The Hurwitz zeta function*

$$\zeta\left(s, \frac{1}{2}\right)$$

has its non-trivial zeros only at the complex numbers with real part $\frac{1}{2}$.

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