

Norm estimates of discrete Schrödinger operators

Ryszard Szwarc*

Abstract

Harper's operator is defined on $\ell^2(\mathbb{Z})$ by

$$H_\theta \xi(n) = \xi(n+1) + \xi(n-1) + 2 \cos n\theta \xi(n),$$

where $\theta \in [0, \pi]$. We show that the norm of $\|H_\theta\|$ is less than or equal to $2\sqrt{2}$ for $\pi/2 \leq \theta \leq \pi$. This solves a conjecture stated in [1]. The general formula for estimating the norm of self adjoint tridiagonal infinite matrices is also derived.

1 Introduction

This paper is an appendix to [1]. The authors considered there a random walk on the discrete Heisenberg group. They reduced the problem of determining the spectrum of the corresponding transition operator to estimating the norm of the Harper operator, well known in mathematical physics (see the references in [1]). This is a discrete Schrödinger operator which acts on square summable doubly infinite sequences $\{\xi(n)\}_{-\infty}^{+\infty}$, according to the rule

$$H_\theta \xi(n) = \xi(n+1) + \xi(n-1) + 2 \cos n\theta \xi(n), \quad (1)$$

*This work has been partially supported by KBN (Poland) under grant 2 P03A 030 09.

⁰1991 *Mathematics Subject Classification.* Primary 47B39

⁰*Key words and phrases:* difference operator, Harper's operator, norm estimate

where θ is a fixed angle from the interval $[0, \pi]$. The authors of [1] were satisfied with the estimate

$$\|H_\theta\| \leq 2(1 + \sqrt{2} + \cos \theta). \quad (2)$$

This estimate is interesting only in the interval $[\pi/2, \pi]$ because elsewhere the obvious estimate by 4 is sharper than the one in (2). The authors conjectured, supported by numerical evidence, that in the interval $[\pi/2, \pi]$ the estimate $2\sqrt{2}$ holds. In this note we prove this conjecture, by introducing a method of estimating the norms of tridiagonal operators, which originates in the theory of orthogonal polynomials.

2 Norm estimates

We start with a general method of estimating the norms of self adjoint tridiagonal operators. The method goes back to the theory of orthogonal polynomials, where it is used to localize the supports of orthogonality measures (see [2, Theorem I.9.2]).

Let J be a linear operator defined on $\ell^2(\mathbb{Z})$ by

$$J\xi(n) = \lambda_{n+1}\xi(n+1) + \beta_n\xi(n) + \lambda_n\xi(n-1), \quad (3)$$

where $\beta_n \in \mathbb{R}$ and $\lambda_n > 0$ are fixed bounded sequences.

Proposition 1 *Let m and M be such that $M > \max \beta_n$, and $m < \min \beta_n$. Assume also that there exist sequences $0 < g_n < 1$ and $0 < h_n < 1$ such that*

$$\frac{\lambda_n^2}{(M - \beta_{n-1})(M - \beta_n)} \leq g_n(1 - g_{n-1}), \quad (4)$$

$$\frac{\lambda_n^2}{(m - \beta_{n-1})(m - \beta_n)} \leq h_n(1 - h_{n-1}). \quad (5)$$

Then $mI \leq J \leq MI$, i.e. the spectrum of J is contained in the interval $[m, M]$.

Proof. Let $\xi(0) = 1$ and define $\xi(n)$ recursively for $n \neq 0$ by

$$\frac{\lambda_n\xi(n-1)}{(M - \beta_n)\xi(n)} = g_n.$$

Then $\xi(n) > 0$. By (3) and (4) we get

$$J\xi(n) \leq M\xi(n).$$

Let $\beta = -\min \beta_n$. Then $\beta + \beta_n \geq 0$, for each n . We have

$$(J + \beta I)\xi(n) \leq (M + \beta)\xi(n).$$

The matrix $J + \beta I$ has nonnegative entries and the sequence $\xi(n)$ is positive. Thus by Schur's test (see [3, Theorem 5.2]) we obtain

$$\|J + \beta I\| \leq M + \beta.$$

In particular

$$J + \beta I \leq (M + \beta)I.$$

This shows the upper estimate of the spectrum of J .

The lower estimate can be obtained from the upper estimate of the matrix $-J$. But this matrix has negative entries on the upper and lower diagonals. So instead of $-J$ we consider the unitarily equivalent matrix $J' = -UJU^{-1}$, where

$$U\xi(n) = (-1)^n \xi(n).$$

The operator J' acts as follows

$$J'\xi(n) = \lambda_{n+1}\xi(n+1) - \beta_n\xi(n) + \lambda_n\xi(n-1).$$

Observe that assumption (4) of Proposition 1 is satisfied for J' with $M = -m$. Hence by the first part of the proof we get $J' \leq -mI$. Since J is similar to $-J'$ we get $J \geq mI$. \square

The converse of Proposition 1 also holds. In fact, we have the following.

Proposition 2 *Assume that the operator J in (3) satisfies $mI \leq J \leq MI$. Then $M > \max \beta_n$ and $m < \min \beta_n$ and there exist sequences $0 < g_n < 1$ and $0 < h_n < 1$ such that (4) and (5) hold.*

Proof. We focus on showing (4), since (5) can be proved analogously by considering the operator J' introduced in the proof of Proposition 1. Let e_n denote the sequence whose terms are all zero except for the n th term which is equal to 1. By $J \leq MI$ we get

$$\beta_n = (Je_n, e_n) \leq M(e_n, e_n) = M. \quad (6)$$

We claim that the inequality in (6) is strict for each n . Otherwise we would have $Je_n = Me_n$. This is impossible, because $Je_n(n+1) = \lambda_{n+1} \neq 0$. Thus we proved the first part of Proposition 2.

In the remaining part we will make use of the following lemma, whose origins lie in the Frobenius–Perron method in the theory of finite stochastic matrices (see [4, Lemma 9.2.2]).

Lemma 1 *Let $A = \{a(i, j)\}$ be $N \times N$ symmetric matrix with nonnegative entries, such that $a(i, i+1) > 0$ and $a(i+1, i) > 0$ for $i = 1, 2, \dots, N-1$. Let $M \geq \|A\|$, where $\|A\|$ denotes the operator norm with respect to ℓ^2 -norm on \mathbb{R}^N . There exists a nonzero vector $\xi \in \mathbb{R}^N$ with positive coordinates, such that*

$$A\xi(n) \leq M\xi(n), \quad 1 \leq n \leq N.$$

Proof. Assume $M = \|A\|$. Then M or $-M$ is the eigenvalue of A . Thus there is $\xi \neq 0$ such that

$$A\xi = \pm M\xi.$$

Taking absolute values of both sides gives

$$A|\xi| \geq M|\xi|. \quad (7)$$

We claim that there holds the equality in (7). If not, we would have

$$M(|\xi|, |\xi|) \geq ((A|\xi|, |\xi|) > M(|\xi|, |\xi|),$$

a contradiction. Thus

$$A|\xi| = M|\xi|.$$

We will show that the coordinates $\xi(n)$ are all nonzero. Assume that $\xi(n) = 0$. Then

$$a(n-1, n)|\xi(n-1)| + a(n+1, n)|\xi(n+1)| \leq M|\xi(n)| = 0.$$

Hence $\xi(n \pm 1) = 0$. Repeating this reasoning we finally get that $\xi(m) = 0$ for all $m = 1, 2, \dots, N$, which contradicts $\xi \neq 0$. This completes the proof of Lemma 1. \square

Let us return to the proof of Proposition 2. Let $\beta = -\min \beta_n$. Then the matrix $A = J + \beta I$ has nonnegative entries and $A \leq (M + \beta)I$. Let P_N denotes the projection onto $2N + 1$ dimensional subspace of $\ell^2(\mathbb{Z})$ acting by

$$P_N\xi = \sum_{-N}^N \xi(n)e_n.$$

Let A_N denote the truncated matrix $P_N A P_N$. It is clear that

$$A_N \leq A \leq (M + \beta)I.$$

By Lemma 1 there exist sequences $\xi_N \in \mathbb{R}^{2N+1}$ with positive entries such that

$$A_N \xi_N(n) \leq (M + \beta) \xi_N(n) \quad -N \leq n \leq N. \quad (8)$$

Since the entries of ξ_N are positive we may assume, by multiplying by a positive constant if necessary, that $\xi_N(0) = 1$. We may also assume that (8) holds for all $n \in \mathbb{Z}$ extending ξ_N by 0 for $|n| > N$. We will show by induction that for any fixed $n \in \mathbb{Z}$ the sequence of values $N \mapsto \xi_N(n)$ is bounded. For $n = 0$ it is constantly 1. Let $n = \pm 1$. Then by (8) we have

$$A_N \xi_N(0) = \lambda_1 \xi_N(1) + (\beta_0 + \beta) \xi_N(0) + \lambda_0 \xi_N(-1) \leq M \xi_N(0).$$

Since $\beta_1 + \beta \geq 0$ we get

$$\lambda_1 \xi_N(1) + \lambda_0 \xi_N(-1) \leq M.$$

Since $\lambda_{\pm 1} \neq 0$, we conclude that $\xi_N(\pm 1)$ are bounded. Similarly the induction step follows from the inequalities

$$\begin{aligned} \lambda_{n+1} \xi_N(n+1) &\leq M \xi_N(n), \\ \lambda_n \xi_N(n-1) &\leq M \xi_N(n). \end{aligned}$$

Now, using Helly's selection principle we can choose a subsequence N_k of N s for which all sequences $N_k \mapsto \xi_{N_k}(n)$ are convergent. Let

$$\xi(n) = \lim_k \xi_{N_k}(n).$$

By (8) we get

$$A \xi(n) = (J + \beta I) \xi(n) \leq (M + \beta) \xi(n).$$

We have $\xi(n) \geq 0$ and $\xi(0) = 1$. Similarly as in the proof of Lemma 1 we can derive that $\xi(n) > 0$ because the matrix $J + \beta I$ has nonnegative entries. Hence we constructed a positive sequence $\xi(n)$ such that

$$J \xi(n) \leq M \xi(n), \quad n \in \mathbb{Z}.$$

Now by taking

$$g_n = \frac{\lambda_n \xi(n-1)}{(M - \beta_n) \xi(n)}$$

we get (4). \square

Let us turn to the Harper operator H_θ , i.e. $\lambda_n \equiv 1$ and $\beta_n = 2 \cos n\theta$. We will focus on the upper estimate M . It will follow from the proof that the lower estimate is equal $-M$ in this case. It follows also from the fact that the spectrum of H_θ is symmetric about the origin (see [1, comments before (2)]).

Let $M > 2$ be the smallest number such that

$$\frac{1}{(M - 2 \cos(n-1)\theta)(M - 2 \cos n\theta)} \leq \frac{1}{4} = \frac{1}{2}(1 - \frac{1}{2}). \quad (9)$$

By Proposition 1 we get $H_\theta \leq MI$. The condition (9) gives the same estimate as in Proposition 4 from [1]. To get sharper estimate $2\sqrt{2}$ we need a better choice of g_n .

Theorem 1 *Let $\frac{\pi}{2} \leq \theta \leq \pi$. Then $\|H_\theta\| \leq 2\sqrt{2}$.*

Proof. We will have to find an appropriate g_n in order to satisfy (9) with $M = 2\sqrt{2}$. First we will look for g_n in the form

$$g_n = \frac{1}{2} - \frac{\alpha_n}{2\sqrt{2} - 2 \cos n\theta}. \quad (10)$$

Now assumption (9) can be transformed into

$$(\sqrt{2} - \cos n\theta - \alpha_n)(\sqrt{2} - \cos(n-1)\theta + \alpha_{n-1}) \geq 1. \quad (11)$$

So the problem reduces to finding α_n such that (11) is satisfied and both the factors are positive. We will first look for α_n in the form

$$\alpha_n = \gamma_n - \sin n\theta \cot \frac{\theta}{2}. \quad (12)$$

Then

$$\begin{aligned} \alpha_n + \cos n\theta &= \gamma_n - \frac{\sin(2n-1)\frac{\theta}{2}}{\sin \frac{\theta}{2}}, \\ \alpha_{n-1} - \cos(n-1)\theta &= \gamma_{n-1} + \frac{\sin(2n-1)\frac{\theta}{2}}{\sin \frac{\theta}{2}}. \end{aligned}$$

Let $\theta = \pi - 2\varphi$. Then $0 \leq \varphi \leq \frac{\pi}{4}$. Moreover

$$\begin{aligned}\alpha_n + \cos n\theta &= \gamma_n + s_n, \\ \alpha_n - \cos(n-1)\theta &= \gamma_{n-1} - s_n,\end{aligned}$$

where

$$s_n = (-1)^{n+1} \frac{\cos(2n-1)\varphi}{\cos \varphi}. \quad (13)$$

Now (11) takes the form

$$(\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) \geq 1. \quad (14)$$

We will use essentially the following fact, which follows obviously from (13).

Fact 1. *If $|s_n| > 1$ then $|s_{n\pm 1}| < 1$ for $0 \leq \varphi \leq \pi/4$.*

Now we are going to define the sequence γ_n . First we will take care of those n for which $|s_n| > 1$ or $|s_{n+1}| > 1$. If $s_n > 1$ we put

$$\gamma_n = \frac{1 - s_n^2}{\sqrt{2} + s_n}.$$

If $s_{n+1} < -1$ we put

$$\gamma_n = \frac{1 - s_{n+1}^2}{\sqrt{2} - s_{n+1}}.$$

By Fact 1 we do not run into contradiction, because the indices with the property $|s_n| > 1$ must be at least at the distance 2 from each other, if $0 \leq \varphi \leq \pi/4$. Next we put $\gamma_n = 0$ for all n for which γ_n has not been defined yet. Now we have to check if (14) is satisfied. In doing this we will use the another obvious fact.

Fact 2. Let $|x| < 1 < y$ and $x^2 + y^2 \leq 2$. Then

$$\frac{y^2 - 1}{\sqrt{2} + y} \leq \frac{1 - x^2}{\sqrt{2} + x}.$$

Lemma 2 $s_n^2 + s_{n+1}^2 \leq 2$.

Proof. We have

$$\begin{aligned}
s_n^2 + s_{n+1}^2 &= \frac{\cos^2(2n-1)\varphi}{\cos^2 \varphi} + \frac{\cos^2(2n+1)\varphi}{\cos^2 \varphi} \\
&= \frac{2 + \cos(2n-1)2\varphi + \cos(2n+1)2\varphi}{2 \cos^2 \varphi} = \frac{1 + \cos 2\varphi \cos 4n\varphi}{\cos^2 \varphi} \\
&\leq \frac{1 + \cos 2\varphi}{\cos^2 \varphi} = 2
\end{aligned}$$

□

We return to the proof of (14). We will consider the four cases.

(i) $\gamma_{n-1} = \gamma_n = 0$.

Then $|s_n| \leq 1$. Therefore

$$(\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) = 2 - s_n^2 \geq 1.$$

(ii) $\gamma_{n-1} = 0, \gamma_n \neq 0$.

This has two subcases.

(a) $s_n > 1$.

Then

$$\begin{aligned}
&(\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) \\
&= \left(\sqrt{2} - s_n - \frac{1 - s_n^2}{\sqrt{2} + s_n} \right) (\sqrt{2} + s_n) = 1.
\end{aligned}$$

(b) $s_{n+1} < -1$.

By Fact 1 we have $|s_n| < 1$. Therefore

$$\begin{aligned}
&(\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) \\
&= \left(\sqrt{2} - s_n - \frac{1 - s_{n+1}^2}{\sqrt{2} - s_{n+1}} \right) (\sqrt{2} + s_n) \\
&\geq (\sqrt{2} - s_n)(\sqrt{2} + s_n) = 2 - s_n^2 \geq 1.
\end{aligned}$$

(iii) $\gamma_{n-1} \neq 0, \gamma_n = 0$.

This also splits in two subcases.

(a) $s_{n-1} > 1$.

Then $|s_n| < 1$ and

$$\begin{aligned} & (\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) \\ &= (\sqrt{2} - s_n) \left(\sqrt{2} + s_n + \frac{1 - s_{n-1}^2}{\sqrt{2} + s_{n-1}} \right). \end{aligned}$$

This expression takes the value greater than 1 if

$$\frac{s_{n-1}^2 - 1}{\sqrt{2} + s_{n-1}} \leq \frac{1 - s_n^2}{\sqrt{2} - s_n}.$$

The last inequality follows from Fact 2 and Lemma 1.

(b) $s_n < -1$.

Then

$$\begin{aligned} & (\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) \\ &= (\sqrt{2} - s_n) \left(\sqrt{2} + s_n + \frac{1 - s_n^2}{\sqrt{2} - s_n} \right) = 1. \end{aligned}$$

(iv) $\gamma_{n-1} \neq 0, \gamma_n \neq 0$.

By Fact 1 this is possible only when $s_{n-1} > 1, |s_n| < 1$ and $s_{n+1} < -1$.

By Fact 2 and Lemma 1 we have

$$\frac{s_{n-1}^2 - 1}{\sqrt{2} + s_{n-1}} \leq \frac{1 - s_n^2}{\sqrt{2} - s_n}.$$

Hence

$$\begin{aligned} & (\sqrt{2} - s_n - \gamma_n)(\sqrt{2} + s_n + \gamma_{n-1}) \\ &= \left(\sqrt{2} - s_n + \frac{s_{n+1}^2 - 1}{\sqrt{2} - s_{n+1}} \right) \left(\sqrt{2} + s_n + \frac{1 - s_{n-1}^2}{\sqrt{2} + s_{n-1}} \right) \\ &\geq \left(\sqrt{2} - s_n + \frac{s_{n+1}^2 - 1}{\sqrt{2} - s_{n+1}} \right) \left(\sqrt{2} + s_n - \frac{1 - s_n^2}{\sqrt{2} - s_n} \right) \\ &= 1 + \frac{s_{n+1}^2 - 1}{(\sqrt{2} - s_n)(\sqrt{2} - s_{n+1})} \geq 1. \end{aligned} \quad \square$$

Remark 1. Taking $\gamma_n \equiv 0$ in (14) gives

$$\|H_\theta\| \leq 2\sqrt{1 + \sin^{-2}\frac{\theta}{2}}.$$

Let us try to determine the smallest positive M such that (9) holds. By solving the quadratic inequality generated by (9) we get that M satisfies

$$M \geq 2\cos\frac{\theta}{2}\cos(2n+1)\frac{\theta}{2} + 2\sqrt{1 + \sin^2\frac{\theta}{2}\sin^2(2n+1)\frac{\theta}{2}}. \quad (15)$$

Let $a = \sin^2\frac{\theta}{2}$ and $x = \sin^2(2n+1)\frac{\theta}{2}$. Then it suffices that M satisfies

$$M = 2 \max\{\sqrt{1-a}\sqrt{1-x} + \sqrt{1+ax} \mid 0 \leq x \leq 1\}.$$

By an easy calculus the maximum is attained at $x = 0$ or at $x = a - a^{-1} + 1$ according to whether $a \leq \frac{\sqrt{5}-1}{2}$ or $a > \frac{\sqrt{5}-1}{2}$. Summarizing we get

$$\|H_\theta\| \leq M = \begin{cases} 2 + 2\cos\frac{\theta}{2} & \text{if } \sin^2\frac{\theta}{2} \leq \frac{\sqrt{5}-1}{2}, \\ 2\sqrt{1 + \sin^{-2}\frac{\theta}{2}} & \text{if } \sin^2\frac{\theta}{2} \geq \frac{\sqrt{5}-1}{2}. \end{cases} \quad (16)$$

Now, combining this with Theorem 1 and the fact that $\theta = \pi/2$ falls into the first case of formula (16), gives

$$\|H_\theta\| \leq \begin{cases} 2 + 2\cos\frac{\theta}{2} & \text{if } 0 \leq \theta \leq \frac{\pi}{2} \\ 2\sqrt{2} & \text{if } \frac{\pi}{2} \leq \theta \leq \pi. \end{cases}$$

Remark 2. Proposition 2 can be used to show that the estimate $2\sqrt{2}$ is sharp for the endpoint π , which has been also proved in [1] by different methods. Indeed, assume that $\|H_\pi\| \leq M$. Then there exists $0 < g_n < 1$ such that

$$\frac{1}{(M-2)(M+2)} \leq g_n(1-g_{n-1}).$$

Assume for a contradiction that $M^2 < 8$. Then

$$\frac{1}{4} < \frac{1}{(M-2)(M+2)} \leq g_n(1-g_{n-1}).$$

One can easily check that the sequence g_n is increasing. Let g denotes its limit. Then

$$\frac{1}{4} < \frac{1}{(M-2)(M+2)} \leq g(1-g) \leq \frac{1}{4}.$$

This is a contradiction. Hence $M \geq 2\sqrt{2}$.

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Institute of Mathematics
Wrocław University
pl. Grunwaldzki 2/4
50–384 Wrocław, Poland
e-mail: szwarc@math.uni.wroc.pl