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Published in:
Glasgow Mathematical Journal

DOI:
10.1017/S0017089517000398

Publication date:
2019

Document Version
Peer reviewed version

Citation for published version (APA):
Generalized Hardy-Cesàro operators between weighted spaces

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December 1, 2017

Abstract

We characterize those non-negative, measurable functions \( \psi \) on \([0, 1]\) and positive, continuous functions \( \omega_1 \) and \( \omega_2 \) on \( \mathbb{R}^+ \) for which the generalized Hardy-Cesàro operator

\[
(U_\psi f)(x) = \int_0^1 f(tx)\psi(t) \, dt
\]

defines a bounded operator \( U_\psi : L^1(\omega_1) \to L^1(\omega_2) \). This generalizes a result of Xiao ([7]) to weighted spaces. Furthermore, we extend \( U_\psi \) to a bounded operator on \( M(\omega_1) \) with range in \( L^1(\omega_2) \oplus C_0 \), where \( M(\omega_1) \) is the weighted space of locally finite, complex Borel measures on \( \mathbb{R}^+ \). Finally, we show that the zero operator is the only weakly compact generalized Hardy-Cesàro operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \).

1 Introduction

A classical result of Hardy ([5]) shows that the Hardy-Cesàro operator

\[
(U f)(x) = \frac{1}{x} \int_0^x f(s) \, ds
\]

defines a bounded linear operator on \( L^p(\mathbb{R}^+) \) with \( \|U\| = p/(p - 1) \) for \( p > 1 \). Clearly, \( U \) is not bounded on \( L^1(\mathbb{R}^+) \). Hardy’s result has been generalized in various ways, of which we will mention some, which have inspired this paper.

For \( 1 \leq p \leq q \leq \infty \) and non-negative measurable functions \( u \) and \( v \) on \( \mathbb{R}^+ \), Muckenhoupt ([6]) and Bradley ([3]) gave a necessary and sufficient condition for the existence of a constant \( C \) such that

\[
\left( \int_0^\infty \left( u(x) \int_0^x f(t) \, dt \right)^q \, dx \right)^{1/q} \leq C \left( \int_0^\infty (v(x)f(x))^p \, dx \right)^{1/p}
\]

for every positive, measurable function \( f \) on \( \mathbb{R}^+ \). This can be rephrased as a characterization of the weighted \( L^p \) and \( L^q \) spaces on \( \mathbb{R}^+ \) between which the Hardy-Cesàro operator \( U \) is bounded.

\(^0\)2010 Mathematics Subject Classification: 44A15, 47B34, 47B38, 47G10

\(^0\)Keywords: Generalized Hardy-Cesàro operators, weighted spaces, weak compactness.
In a different direction, for a non-negative measurable function \( \psi \) on \([0,1]\), Xiao ([7]) considered the generalized Hardy-Cesàro operators

\[
(U_\psi f)(x) = \int_0^1 f(tx)\psi(t) \, dt
\]

for measurable functions \( f \) on \( \mathbb{R}^n \). We remark that

\[
(U_\psi f)(x) = \frac{1}{x} \int_0^x f(s)\psi(s/x) \, ds
\]

for measurable functions \( f \) on \( \mathbb{R} \). Xiao proved that \( U_\psi \) defines a bounded operator on \( L^p(\mathbb{R}^n) \) (for \( p \geq 1 \)) if and only if

\[
\int_0^1 \frac{\psi(t)}{t^{n/p}} \, dt < \infty.
\]

Xiao’s result is the main motivation for this paper.

Finally, we mention that Albanese, Bonet and Ricker in a recent series of papers (see, for instance, [1] and [2]) have considered the spectrum, compactness and other properties of the Hardy-Cesàro operator on various spaces of continuous functions and discrete spaces.

In this paper we will study the generalized Hardy-Cesàro operators between weighted spaces of integrable functions, and we will obtain a generalization of Xiao’s result in this context. Let \( \omega \) be a positive, continuous function on \( \mathbb{R}^+ \) and let \( L^1(\omega) \) be the Banach space of (equivalence classes of) measurable functions \( f \) on \( \mathbb{R}^+ \) for which

\[
\|f\|_{L^1(\omega)} = \int_0^\infty |f(t)|\omega(t) \, dt < \infty.
\]

In the usual way we identify the dual space of \( L^1(\omega) \) with the space \( L^\infty(1/\omega) \) of measurable functions \( h \) on \( \mathbb{R}^+ \) for which

\[
\|h\|_{L^\infty(1/\omega)} = \text{ess sup}_{t \in \mathbb{R}^+} |h(t)|/\omega(t) < \infty.
\]

We denote by \( C_0(1/\omega) \) the closed subspace of \( L^\infty(1/\omega) \) consisting of the continuous functions \( g \) in \( L^\infty(1/\omega) \) for which \( g/\omega \) vanishes at infinity. Finally, we identify the dual space of \( C_0(1/\omega) \) with the space \( M(\omega) \) of locally finite, complex Borel measures \( \mu \) on \( \mathbb{R}^+ \) for which

\[
\|\mu\|_{M(\omega)} = \int_{\mathbb{R}^+} \omega(t) \, d|\mu|(t) < \infty.
\]

We consider the space \( L^1(\omega) \) as a closed subspace of \( M(\omega) \).

In Section [2] we characterize those functions \( \psi, \omega_1 \) and \( \omega_2 \) for which \( U_\psi \) defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \). These operators are extended to bounded operators on \( M(\omega_1) \) in Section [3] where we also obtain results about their ranges. Finally, in Section [4] we show that there are no non-zero weakly compact generalized Hardy-Cesàro operators from \( L^1(\omega_1) \) to \( L^1(\omega_2) \).
2 A characterization of the generalized Hardy-Cesàro operators

For a non-negative, measurable function \( \psi \) on \([0, 1] \) and positive, continuous functions \( \omega_1 \) and \( \omega_2 \) on \( \mathbb{R}^+ \), we say that condition (C) is satisfied if there exists a constant \( C \) such that

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt \leq C \omega_1(s)
\]

for every \( s \in \mathbb{R}^+ \).

**Theorem 2.1** Let \( \psi \) be a non-negative, measurable function on \([0, 1] \) and let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \). Then \( U_\psi \) defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \) if and only if condition (C) is satisfied.

**Proof** Assume that condition (C) is satisfied and let \( f \in L^1(\omega_1) \). Then

\[
\int_0^\infty \int_0^1 |f(s)| \frac{\psi(t)}{t} \omega_2(s/t) \, dt \, ds \leq C \int_0^\infty |f(s)| \omega_1(s) \, ds = C \|f\|_{L^1(\omega_1)} < \infty,
\]

so it follows from Fubini’s theorem that

\[
\int_0^1 \int_0^\infty |f(tx)| \psi(t) \omega_2(x) \, dx \, dt = \int_0^1 \int_0^\infty |f(s)| \frac{\psi(t)}{t} \omega_2(s/t) \, dt \, ds \leq C \|f\|_{L^1(\omega_1)} < \infty.
\]

Another application of Fubini’s theorem thus shows that \((U_\psi f)(x)\) is defined for almost all \( x \in \mathbb{R}^+ \) with

\[
\|U_\psi f\|_{L^1(\omega_2)} = \int_0^\infty |(U_\psi f)(x)| \omega_2(x) \, dx \leq \int_0^\infty \int_0^1 |f(tx)| \psi(t) \omega_2(x) \, dt \, dx
\]

\[
= \int_0^1 \int_0^\infty |f(tx)| \psi(t) \omega_2(x) \, dx \, dt \leq C \|f\|_{L^1(\omega_1)} < \infty.
\]

Hence \( U_\psi \) defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \).

Conversely, assume that \( U_\psi \) defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \). Since \( L^1(\omega_2) \) is a closed subspace of \( M(\omega_2) \) which we identify with the dual space of \( C_0(1/\omega_2) \), it follows from [4, Theorem VI.8.6] that there exists a map \( \rho \) from \( \mathbb{R}^+ \) to \( M(\omega_2) \) for which the map \( s \mapsto \langle g, \rho(s) \rangle = \int_{\mathbb{R}^+} g(x) \, d\rho(s)(x) \) is measurable and essentially bounded on \( \mathbb{R}^+ \) for every \( g \in C_0(1/\omega_2) \) with \( \|U_\psi\| = \text{ess sup}_{s \in \mathbb{R}^+} \|\rho(s)\|_{M(\omega_2)} \) and such that

\[
\langle g, U_\psi f \rangle = \int_0^\infty \langle g, \rho(s) \rangle f(s) \omega_1(s) \, ds = \int_0^\infty \int_{\mathbb{R}^+} g(x) \, d\rho(s)(x) \, f(s) \omega_1(s) \, ds
\]

for every \( g \in C_0(1/\omega_2) \) and \( f \in L^1(\omega_1) \). On the other hand

\[
\langle g, U_\psi f \rangle = \int_0^\infty g(x) (U_\psi f)(x) \, dx
\]

\[
= \int_0^\infty \int_0^x \frac{g(x)}{x} f(s) \psi(s/x) \, ds \, dx
\]

\[
= \int_0^\infty \frac{1}{\omega_1(s)} \int_s^\infty \frac{g(x)}{x} \psi(s/x) \, dx \, f(s) \omega_1(s) \, ds
\]
for every \( g \in C_0(1/\omega_2) \) and \( f \in L^1(\omega_1) \), so it follows that
\[
\int_{\mathbb{R}^+} g(x) \, d\rho(s)(x) = \frac{1}{\omega_1(s)} \int_s^\infty \frac{g(x)}{x} \psi(s/x) \, dx
\]
for almost all \( s \in \mathbb{R}^+ \) and every \( g \in C_0(1/\omega_2) \) (considering both sides as elements of \( L^\infty(\mathbb{R}^+) \)). Considered as elements of \( M(\omega_2) \) we thus have
\[
d\rho(s)(x) = \frac{1}{\omega_1(s)} \frac{1}{x} \psi(s/x) 1_{x \geq s} \, dx
\]
for almost all \( s, x \in \mathbb{R}^+ \). Hence \( \rho(s) \in L^1(\omega_2) \) with
\[
\|\rho(s)\|_{L^1(\omega_2)} = \int_0^\infty \omega_2(x) \, d\rho(s)(x)
\]
\[
= \frac{1}{\omega_1(s)} \int_0^\infty \frac{1}{x} \psi(s/x) 1_{x \geq s} \omega_2(x) \, dx
\]
\[
= \frac{1}{\omega_1(s)} \int_s^\infty \frac{1}{x} \psi(s/x) \omega_2(x) \, dx
\]
\[
= \frac{1}{\omega_1(s)} \int_0^1 \frac{\psi(t)}{t} \omega_2(s/t) \, dt
\]
for almost all \( s \in \mathbb{R}^+ \). Therefore
\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt = \|\rho(s)\|_{L^1(\omega_2)} \omega_1(s) \leq \|U_\psi\| \omega_1(s)
\]
for almost all \( s \in \mathbb{R}^+ \). Since both sides of the inequality are continuous functions of \( s \), the inequality holds for every \( s \in \mathbb{R}^+ \), so condition (C) holds. \( \square \)

Letting \( s = 0 \) in condition (C) we see that Xiao’s condition is necessary in our situation.

**Corollary 2.2** Let \( \psi \) be a non-negative, measurable function on \([0, 1]\) and let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \). If \( U_\psi \) defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \), then
\[
\int_0^1 \frac{\psi(t)}{t} \, dt < \infty.
\]

The following straightforward consequences can be deduced from Theorem 2.1.

**Corollary 2.3** Let \( \psi \) be a non-negative, measurable function on \([0, 1]\)

(a) Let \( \omega \) be a decreasing, positive, continuous function on \( \mathbb{R}^+ \), and assume that \( \int_0^1 \psi(t)/t \, dt < \infty \). Then \( U_\psi \) defines a bounded operator from \( L^1(\omega) \) to \( L^1(\omega) \).

(b) Let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \), and assume that \( \omega_2 \) is increasing. If \( U_\psi \) defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \), then there exists a constant \( C \) such that \( \omega_2(s) \leq C \omega_1(s) \) for every \( s \in \mathbb{R}^+ \).
(c) Let $\omega$ be an increasing, positive, continuous function on $\mathbb{R}^+$, and assume that there exists $a < 1$ and $K > 0$ such that $\psi(t) \geq K$ almost everywhere on $[a, 1]$. If $U_\psi$ defines a bounded operator from $L^1(\omega)$ to $L^1(\omega)$, then there exist positive constants $C_1$ and $C_2$ such that

$$C_1 \omega(s) \leq \int_0^1 \omega(s/t) \frac{\psi(t)}{t} \, dt \leq C_2 \omega(s)$$

for every $s \in \mathbb{R}^+$.

**Proof** (a): We have

$$\int_0^1 \omega(s/t) \frac{\psi(t)}{t} \, dt \leq \int_0^1 \frac{\psi(t)}{t} \, dt \omega(s)$$

for every $s \in \mathbb{R}^+$, so condition (C) is satisfied with $\omega_1 = \omega_2 = \omega$ and the result follows.

(b): We have

$$\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt \geq \int_0^1 \frac{\psi(t)}{t} \, dt \omega_2(s)$$

for every $s \in \mathbb{R}^+$. Since condition (C) is satisfied, the result follows.

(c): We have

$$\int_0^1 \omega(s/t) \frac{\psi(t)}{t} \, dt \geq K \int_a^1 \omega(s/t) \, dt \geq K(1-a)\omega(s)$$

for every $s \in \mathbb{R}^+$. The other inequality is just condition (C) with $\omega_1 = \omega_2 = \omega$. □

We finish the section with some examples of functions $\psi, \omega_1$ and $\omega_2$ for which $U_\psi$ defines a bounded operator from $L^1(\omega_1)$ to $L^1(\omega_2)$.

**Example 2.4**

(a) For $\alpha > 0$, let $\psi(t) = t^\alpha$ for $t \in [0, 1]$. Also, for $\beta_1, \beta_2 \in \mathbb{R}$, let $\omega_i(x) = (1 + x)^{\beta_i}$ for $x \in \mathbb{R}^+$ and $i = 1, 2$. Then $U_\psi$ defines a bounded operator from $L^1(\omega_1)$ to $L^1(\omega_2)$ if and only if $\beta_2 \leq \beta_1$ and $\beta_2 < \alpha$.

(b) For $\alpha > 0$, let $\psi(t) = t^\alpha$ for $t \in [0, 1]$. Also, let $\omega_1(x) = e^{-x}/(1 + x)$ and $\omega_2(x) = e^{-x}$ for $x \in \mathbb{R}^+$. Then $U_\psi$ defines a bounded operator from $L^1(\omega_1)$ to $L^1(\omega_2)$. Moreover, it is not possible to replace $\omega_1(x)$ by a function tending faster to zero at infinity.

(c) Let $\psi(t) = e^{-1/t^2}$ for $t \in [0, 1]$. Also, let $\omega_1(x) = e^{x^2/4}/x$ and $\omega_2(x) = e^x$ for $x \in \mathbb{R}^+$. Then $U_\psi$ defines a bounded operator from $L^1(\omega_1)$ to $L^1(\omega_2)$. Moreover, it is not possible to replace $\omega_1(x)$ by a function tending slower to infinity at infinity.

**Proof** (a): For $s \geq 1$ and $t \in [0, 1]$ we have $s/t < 1 + s/t \leq 2s/t$, so

$$\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt = \int_0^1 \left(1 + \frac{s}{t}\right)^{\beta_2} t^{\alpha-1} \, dt$$

$$\simeq s^{\beta_2} \int_0^1 t^{\alpha-\beta_2-1} \, dt$$

$$\simeq s^{\beta_2}$$
for \( s \geq 1 \) if \( \beta_2 < \alpha \) (where \( F(s) \approx G(s) \) for positive functions \( F \) and \( G \) on \([1, \infty)\) indicates the existence of positive constants \( C_1 \) and \( C_2 \) such that \( C_1 F(s) \leq G(s) \leq C_2 F(s) \) for all \( s \in [1, \infty) \)), whereas the integrals diverge if \( \beta_2 \geq \alpha \). Moreover, the expression

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt = \int_0^1 \left(1 + \frac{s}{t}\right)^{\beta_2} t^{\alpha-1} \, dt
\]

defines a positive, continuous function of \( s \) on \( \mathbb{R}^+ \), so it follows that condition (C) is satisfied if and only if \( \beta_2 \leq \beta_1 \) and \( \beta_2 < \alpha \).

(b): For \( s \geq 1 \) we have

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt = \int_s^\infty \frac{\omega_2(x)}{x} \psi(s/x) \, dx = \int_s^\infty \frac{e^{-x}}{x^\alpha} \, dx \leq \int_s^\infty \frac{e^{-x}}{x} \, dx \leq \frac{e^{-s}}{s}.
\]

Moreover,

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt \leq \int_0^1 \frac{\psi(t)}{t} \, dt < \infty
\]

for all \( s \in \mathbb{R}^+ \), so condition (C) is satisfied and \( U_{\psi} \) thus defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \). On the other hand, since

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt \geq \int_s^\infty \frac{e^{-x} s^\alpha}{x^\alpha} \, dx \geq \frac{1}{2^{\alpha+1}s} \int_s^\infty e^{-x} \, dx \geq \frac{1}{2^{\alpha+2}} \frac{e^{-s}}{s}
\]

for \( s \geq 1 \), it is not possible to replace \( \omega_1(x) \) by a function tending faster to zero at infinity.

(c): For \( s \in \mathbb{R}^+ \) we have

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt = \int_s^\infty \frac{\omega_2(x)}{x} \psi(s/x) \, dx = \int_s^\infty \frac{e^{-x^2/s^2}}{x} \, dx = \int_1^\infty \frac{e^{sy-y^2}}{y} \, dy.
\]

Moreover, for \( s \geq 4 \)

\[
\int_{s/4}^\infty \frac{e^{sy-y^2}}{y} \, dy \leq \frac{4}{s} \int_{s/4}^\infty e^{-(y-s/2)^2+s^2/4} \, dy = \frac{4}{s} \int_{-s/4}^s e^{-u^2} \, du \frac{e^{s^2/4}}{s}
\]

and

\[
\int_1^{s/4} \frac{e^{sy-y^2}}{y} \, dy \leq \int_1^{s/4} e^{sy} \, dy \leq \frac{e^{s^2/4}}{s},
\]

so condition (C) is satisfied and \( U_{\psi} \) thus defines a bounded operator from \( L^1(\omega_1) \) to \( L^1(\omega_2) \). On the other hand, the estimate

\[
\int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt = \int_1^\infty \frac{e^{sy-y^2}}{y} \, dy \geq \frac{1}{s} \int_{s/2}^{s/2+1} e^{-(y-s/2)^2+s^2/4} \, dy = \int_0^1 e^{-u^2} \, du \frac{e^{s^2/4}}{s}
\]

for \( s \geq 2 \) shows that it is not possible to replace \( \omega_1(x) \) by a function tending slower to infinity at infinity.

In Example 2.3(b) we have \( \omega_2(x)/\omega_1(x) \to \infty \) as \( x \to \infty \), which should be compared to the conclusion in Corollary 2.3(b). Conversely, Example 2.3(c) shows an example where we need \( \omega_2(x)/\omega_1(x) \to 0 \) rapidly as \( x \to \infty \) in order for \( U_{\psi} \) to be defined.
3 Extensions to weighted spaces of measures

Identifying the dual space of $L^1(\omega)$ with $L^\infty(1/\omega)$ as in the introduction, we have the following result about the adjoint of $U_\psi$.

**Proposition 3.1** Let $\psi$ be a non-negative, measurable function on $[0,1]$ and let $\omega_1$ and $\omega_2$ be positive, continuous functions on $\mathbb{R}^+$. Assume that condition (C) is satisfied so that $U_\psi : L^1(\omega_1) \to L^1(\omega_2)$ is a bounded operator, and consider the adjoint operator $U_\psi^* : L^\infty(1/\omega_2) \to L^\infty(1/\omega_1)$.

(a) For $h \in L^\infty(1/\omega_2)$ we have

$$
(U_\psi^* h)(x) = \int_0^1 h(x/t) \frac{\psi(t)}{t} dt
$$

for almost all $x \in \mathbb{R}^+$.

(b) $U_\psi^*$ maps $C_0(1/\omega_2)$ into $C_0(1/\omega_1)$.

**Proof** (a): Let $h \in L^\infty(1/\omega_2)$. Since $|h(x/t)| \leq \|h\|_{L^\infty(1/\omega_2)}\omega_2(x/t)$ for almost all $x,t \in \mathbb{R}^+$, it follows from condition (C) that $\int_0^1 h(x/t)\psi(t)/t \, dt$ is defined and satisfies

$$
\left| \int_0^1 h(x/t) \frac{\psi(t)}{t} dt \right| \leq \|h\|_{L^\infty(1/\omega_2)} \int_0^1 \omega_2(x/t) \frac{\psi(t)}{t} dt \leq C\|h\|_{L^\infty(1/\omega_2)} \omega_1(x)
$$

for almost all $x \in \mathbb{R}^+$. Hence the function $x \mapsto \int_0^1 h(x/t)\psi(t)/t \, dt$ belongs to $L^\infty(1/\omega_1)$. Also, for $f \in L^1(\omega_1)$ we have

$$
\langle f, U_\psi^* h \rangle = \langle U_\psi f, h \rangle = \int_0^\infty (U_\psi f)(s)h(s) \, ds
$$

$$
= \int_0^\infty \int_0^s \frac{1}{s} f(x)\psi(x/s)h(s) \, dx \, ds
$$

$$
= \int_0^\infty \int_x^\infty h(s) \frac{\psi(x/s)}{s} ds \, f(x) \, dx
$$

from which it follows that

$$
(U_\psi^* h)(x) = \int_x^\infty \frac{h(s)}{s} \psi(x/s) \, ds = \int_0^1 h(x/t) \frac{\psi(t)}{t} dt
$$

for almost all $x \in \mathbb{R}^+$.

(b): It suffices to show that $U_\psi^*$ maps $C_c(\mathbb{R}^+)$ (the continuous functions on $\mathbb{R}^+$ with compact support) into $C_0(1/\omega_1)$. Let $g \in C_c(\mathbb{R}^+)$, let $x_0 \in \mathbb{R}^+$ and let $(x_n)$ be a sequence in $\mathbb{R}^+$ with $x_n \to x_0$ as $n \to \infty$. Then

$$
(U_\psi^* g)(x_n) - (U_\psi^* g)(x_0) = \int_0^1 (g(x_n/t) - g(x_0/t)) \frac{\psi(t)}{t} dt
$$

for $n \in \mathbb{N}$. Since $g$ is bounded on $\mathbb{R}^+$ and since $\int_0^1 \psi(t)/t \, dt < \infty$ by Corollary 2.2, it follows from Lebesgue’s dominated convergence theorem that $(U_\psi^* g)(x_n) \to (U_\psi^* g)(x_0)$ as $n \to \infty$. Hence $U_\psi^* g$ is continuous on $\mathbb{R}^+$. Finally, from the expression

$$
(U_\psi^* g)(x) = \int_x^\infty \frac{g(s)}{s} \psi(x/s) \, ds
$$
it follows that \( \text{supp} U^*_\psi g \subseteq \text{supp} g \), so we conclude that \( U^*_\psi g \in C_c(\mathbb{R}^+) \subseteq C_0(1/\omega_1) \). \( \square \)

Let \( V_\psi \) be the restriction of \( U^*_\psi \) to \( C_0(1/\omega_2) \) considered as a map into \( C_0(1/\omega_1) \). We then immediately have the following result.

**Corollary 3.2** Let \( \psi \) be a non-negative, measurable function on \([0,1]\) and let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \). Assume that condition \( (C) \) is satisfied so that \( U^*_\psi : L^1(\omega_1) \to L^1(\omega_2) \) is a bounded operator. The bounded operator \( \overline{U}_\psi = V^*_\psi \) from \( M(\omega_1) \) to \( M(\omega_2) \) is an extension of \( U^*_\psi \).

Let \( \psi \) be a non-negative, continuous function on \([0,1]\) with \( \psi(0) = 0 \). For \( \mu \in M(\omega_1) \) and \( x > 0 \) let

\[
(W_\psi \mu)(x) = \frac{1}{x} \int_{(0,x)} \psi(s/x) \, d\mu(s).
\]

**Proposition 3.3** Let \( \psi \) be a non-negative, continuous function on \([0,1]\) and let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \). Assume that condition \( (C) \) is satisfied so that \( U^*_\psi : L^1(\omega_1) \to L^1(\omega_2) \) is a bounded operator. Then \( W_\psi \mu \in L^1(\omega_2) \) and

\[
\overline{U}_\psi \mu = W_\psi \mu + \int_0^1 \frac{\psi(t)}{t} \, dt \cdot \mu(\{0\}) \delta_0
\]

for \( \mu \in M(\omega_1) \). In particular \( \text{ran} \overline{U}_\psi \subseteq L^1(\omega_2) \oplus \mathbb{C} \delta_0 \) and \( \overline{U}_\psi \) maps \( M((0,\infty),\omega_1) \) into \( L^1(\omega_2) \).

**Proof** By Corollary 2.2 we have \( \int_0^1 \psi(t)/t \, dt < \infty \), so it follows that \( \psi(0) = 0 \). Let \( \mu \in M(\omega_1) \) with \( \mu(\{0\}) = 0 \). By condition \( (C) \) we have

\[
\int_{(0,\infty)} \int_s^\infty \frac{1}{x} \psi(s/x) \omega_2(x) \, dx \, d|\mu|(s) = \int_{(0,\infty)} \int_0^1 \omega_2(s/t) \frac{\psi(t)}{t} \, dt \, d|\mu|(s)
\]

\[
\leq C \int_{(0,\infty)} \omega_1(s) \, d|\mu|(s) = C \|\mu\|_{M(\omega_1)} < \infty,
\]

so it follows from Fubini’s theorem that

\[
\int_0^\infty \frac{1}{x} \int_{(0,x)} \psi(s/x) \, d|\mu|(s) \omega_2(x) \, dx < \infty.
\]

Hence \( W_\psi \mu \in L^1(\omega_2) \). Moreover, for \( g \in C_0(1/\omega_2) \) we have

\[
\langle g, \overline{U}_\psi \mu \rangle = \langle V_\psi g, \mu \rangle = \int_{(0,\infty)} \int_0^1 g(s/t) \frac{\psi(t)}{t} \, dt \, d\mu(s)
\]

\[
= \int_{(0,\infty)} \int_s^\infty g(x) \psi(s/x) \, dx \, d\mu(s)
\]

\[
= \int_0^\infty \frac{1}{x} \int_{(0,x)} \psi(s/x) \, d\mu(s) \, g(x) \, dx
\]

\[
= \int_0^\infty (W_\psi \mu)(x) g(x) \, dx = \langle g, W_\psi \mu \rangle,
\]
so we conclude that \( U_\psi \mu = W_\psi \mu \). Finally, for \( g \in C_0(1/\omega_2) \) we have

\[
\langle g, U_\psi \delta_0 \rangle = \langle V_\psi g, \delta_0 \rangle = (V_\psi g)(0) = g(0) \int_0^1 \frac{\psi(t)}{t} \, dt = \langle g, \int_0^1 \frac{\psi(t)}{t} \, dt \cdot \delta_0 \rangle.
\]

Since \( W_\psi \delta_0 = 0 \) this finishes the proof. \( \square \)

The conclusion about the range of \( U_\psi \) can be generalized to the case, where \( \psi \) is not assumed to be continuous.

**Proposition 3.4** Let \( \psi \) be a non-negative, measurable function on \([0, 1]\) and let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \). Assume that condition (C) is satisfied so that \( U_\psi : L^1(\omega_1) \rightarrow L^1(\omega_2) \) is a bounded operator. Then \( \text{ran} \, U_\psi \subseteq L^1(\omega_2) \oplus \mathbb{C} \delta_0 \).

**Proof** Choose a sequence of non-negative, continuous functions \((\psi_n)\) on \([0, 1]\) with \( \psi_n \leq \psi \) and

\[
\int_0^1 \frac{\psi(t) - \psi_n(t)}{t} \, dt \rightarrow 0 \quad \text{as} \ n \rightarrow \infty.
\]

For \( \mu \in M(\omega_1) \) and \( g \in C_0(1/\omega_2) \) we have

\[
|\langle g, (U_\psi - U_{\psi_n}) \mu \rangle| = |\langle (V_\psi - V_{\psi_n}) g, \mu \rangle| \\
= \left| \int_{\mathbb{R}^+} \int_0^1 g(x/t) \frac{\psi(t) - \psi_n(t)}{t} \, dt \, d\mu(x) \right| \\
\leq \|g\|_{C_0(1/\omega_2)} \int_{\mathbb{R}^+} \int_0^1 \omega_2(x/t) \frac{\psi(t) - \psi_n(t)}{t} \, dt \, d|\mu|(x).
\]

Let

\[
p_n(x) = \int_0^1 \omega_2(x/t) \frac{\psi(t) - \psi_n(t)}{t} \, dt
\]

for \( x \in \mathbb{R}^+ \) and \( n \in \mathbb{N} \). By condition (C) there exists a constant \( C \) such that \( p_n(x) \leq C \omega_1(x) \) for every \( x \in \mathbb{R}^+ \) and \( n \in \mathbb{N} \). Moreover, for every \( x \in \mathbb{R}^+ \) we have \( p_n(x) \rightarrow 0 \) as \( n \rightarrow \infty \) by Lebesgue’s dominated convergence theorem. Hence

\[
\|U_\psi - U_{\psi_n}\|_{M(\omega_2)} = \sup_{\|g\|_{C_0(1/\omega_2)} \leq 1} |\langle g, (U_\psi - U_{\psi_n}) \mu \rangle| \leq \int_{\mathbb{R}^+} p_n(x) \, d|\mu|(x) \rightarrow 0
\]

as \( n \rightarrow \infty \) again by Lebesgue’s dominated convergence theorem. Consequently, \( U_{\psi_n} \rightarrow U_\psi \) strongly as \( n \rightarrow \infty \). Since \( \text{ran} \, U_{\psi_n} \subseteq L^1(\omega_2) \oplus \mathbb{C} \delta_0 \) for \( n \in \mathbb{N} \) by Proposition 3.3 the same thus holds for \( \text{ran} \, U_\psi \). \( \square \)

**Corollary 3.5** Let \( \psi \) be a non-negative, measurable function on \([0, 1]\) and let \( \omega_1 \) and \( \omega_2 \) be positive, continuous functions on \( \mathbb{R}^+ \). Assume that condition (C) is satisfied so that \( U_\psi : L^1(\omega_1) \rightarrow L^1(\omega_2) \) is a bounded operator. For \( s > 0 \) we then have \((U_\psi \delta_s)(x) = \psi(s/x)/x\) for almost all \( x \geq s \) and \((U_\psi \delta_s)(x) = 0\) for almost all \( x < s \).
Proof For $\psi$ continuous, this follows from Proposition 3.3. For general $\psi$ it follows from the approach in the proof of Proposition 3.4 using $U_{\psi_n} \to U_{\psi}$ strongly as $n \to \infty$. 

It follows from Corollary 3.5 that

$$\|U_{\psi_\delta}\|_{M(\omega_2)} = \int_0^\infty \frac{\omega_2(x)}{x} \psi(s/x) \, dx = \int_0^1 \frac{\omega_2(s/t)}{t} \psi(t) \, dt,$$

whereas $\|\delta\|_{M(\omega_1)} = \omega_1(s)$. Since $U_{\psi}$ is bounded we thus recover condition (C). If we without using Theorem 2.1 could show that if $U_{\psi} : L^1(\omega_1) \to L^1(\omega_2)$ is a bounded operator, then is has a bounded extension $U_{\psi} : M(\omega_1) \to M(\omega_2)$ for which Corollary 3.5 holds, then we would in this way obtain an alternative proof of condition (C).

4 Weakly compact operators

We finish the paper by showing that there are no non-zero, weakly compact generalized Hardy-Cesàro operators between $L^1(\omega_1)$ and $L^1(\omega_2)$.

Proposition 4.1 Let $\psi$ be a non-negative, measurable function on $[0,1]$ and let $\omega_1$ and $\omega_2$ be positive, continuous functions on $\mathbb{R}^+$. Assume that condition (C) is satisfied so that $U_{\psi} : L^1(\omega_1) \to L^1(\omega_2)$ is a bounded operator. If $\psi \neq 0$, then $U_{\psi}$ is not weakly compact.

Proof For $f \in L^1(\omega_1)$ and $x \in \mathbb{R}^+$ we have

$$(U_{\psi} f)(x) = \frac{1}{x} \int_0^x f(s) \psi(s/x) \, ds = \int_0^\infty f(s) \rho(s)(x) \omega_1(s) \, ds,$$

where (with a slight change of notation compared to the proof of Theorem 2.1)

$$\rho(s)(x) = \frac{1}{\omega_1(s)} \frac{1}{x} \psi(s/x) 1_{x \geq s}$$

for $x, s \in \mathbb{R}^+$. In the proof of Theorem 2.1 we saw that $\rho(s) \in L^1(\omega_2)$ with $\|\rho(s)\|_{L^1(\omega_2)} \leq C$ for a constant $C$ for almost all $s \in \mathbb{R}^+$. It thus follows from [1, Theorem VI.8.10] that $U_{\psi}$ is weakly compact if and only if $\{\rho(s) : s \in \mathbb{R}^+\}$ is contained in a weakly compact set of $L^1(\omega_2)$ (except possibly for $s$ belonging to a null-set). Consider $\rho(s)$ as an element of $C_0(1/\omega_2)^*$ for $s \in \mathbb{R}^+$ and let $g \in C_0(1/\omega_2)$. Then

$$\langle g, \rho(s) \rangle = \int_0^\infty g(x) \rho(s)(x) \, dx$$

$$= \frac{1}{\omega_1(s)} \int_0^\infty \frac{g(x)}{x} \psi(s/x) \, dx$$

$$= \frac{1}{\omega_1(s)} \int_0^1 \frac{g(s/t)}{t} \psi(t) \, dt.$$

Since $g(s/t) \to g(0)$ as $s \to 0_+$ for all $t > 0$, it follows from Lebesgue’s dominated convergence theorem that

$$\langle g, \rho(s) \rangle \to \frac{1}{\omega_1(0)} g(0) \int_0^1 \frac{\psi(t)}{t} \, dt$$
as $s \to 0_+$. We therefore conclude that

$$\rho(s) \to \frac{1}{\omega_1(0)} \int_0^1 \frac{\psi(t)}{t} dt \cdot \delta_0$$

weak-star in $M(\omega_2)$ as $s \to 0_+$. Since $\delta_0 \notin L^1(\omega_2)$, it follows that $\{\rho(s) : s \in \mathbb{R}^+\}$ is not contained in a weakly compact set of $L^1(\omega_2)$ (even excepting null sets), and the result follows.

\[\square\]

References


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