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The converse of a generalized Hölder inequality

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Abstract. Let (Ω, Σ, μ) be a measure space with two sets $A, B \in \Sigma$ such that $0 < \mu(A) < 1 < \mu(B) < \infty$, and k a fixed positive integer. Suppose that ϕ_1, \dots, ϕ_k , are arbitrary bijections of $(0, \infty)$. The main result says that if

$$\int_{\Omega} x_1 \cdot \dots \cdot x_k d\mu \leq \phi_1^{-1} \left(\int_{\Omega(x_1)} \phi_1 \circ x_1 d\mu \right) \cdot \dots \cdot \phi_k^{-1} \left(\int_{\Omega(x_k)} \phi_k \circ x_k d\mu \right)$$

for all μ -integrable nonnegative step functions x_1, \dots, x_k , then ϕ_1, \dots, ϕ_k must be conjugate power functions (here $\Omega(x) = \{\omega \in \Omega : x(\omega) \neq 0\}$).

Introduction

For a measure space (Ω, Σ, μ) denote by $S = S(\Omega, \Sigma, \mu)$ the linear space of all μ -integrable simple functions $x : \Omega \rightarrow \mathbb{R}$, and by $S_+ = S_+(\Omega, \Sigma, \mu)$ the set of all nonnegative $x \in S(\Omega, \Sigma, \mu)$. For an arbitrary bijection $\phi : (0, \infty) \rightarrow (0, \infty)$ the functional $p_\phi : S \rightarrow \mathbb{R}_+$ ($\mathbb{R}_+ := [0, \infty)$) given by

$$p_\phi(x) := \begin{cases} \phi^{-1} \left(\int_{\Omega(x)} \phi \circ |x| d\mu \right) & \text{if } \mu(\Omega(x)) > 0 \\ 0 & \text{if } \mu(\Omega(x)) = 0 \end{cases}, \quad x \in S(\Omega, \Sigma, \mu),$$

where $\Omega(x) := \{\omega \in \Omega : x(\omega) \neq 0\}$, is well defined (cf. [3]).

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Note that for $\phi(t) := \phi(1)t^p$, $t > 0$, where $p \in \mathbb{R} \setminus \{0\}$ is arbitrary fixed, we have

$$p_\phi(x) = \left(\int_{\Omega(x)} |x|^p d\mu \right)^{\frac{1}{p}}, \quad x \in S(\Omega, \Sigma, \mu), \quad \mu(\Omega(x)) > 0.$$

and for $p \geq 1$ the functional p_ϕ becomes the L^p -norm. Let k be a fixed positive integer, and ϕ_1, \dots, ϕ_k bijections of $(0, \infty)$. Suppose that the inequality

$$\int_{\Omega} x_1 \cdots x_k d\mu \leq p_{\phi_1}(x_1) \cdots p_{\phi_k}(x_k), \quad x_1, \dots, x_k \in S_+,$$

holds true. We prove that if ϕ_1, \dots, ϕ_k are *multiplicatively conjugate*, i.e. there is a constant $c > 0$ such that

$$\phi_1^{-1}(t)\phi_2^{-1}(t) \cdots \phi_k^{-1}(t) = ct, \quad t > 0,$$

and the measure space (Ω, Σ, μ) is not trivial, then ϕ_1, \dots, ϕ_k must be power functions. The main purpose of this paper is to prove that if there are two sets $A, B \in \Sigma$ such that

$$0 < \mu(A) < 1 < \mu(B) < \infty,$$

then ϕ_1, \dots, ϕ_k are multiplicatively conjugate power functions.

These results are the converses of a known generalized Hölder inequality (cf. Hardy–Littlewood–Pólya [1], p. 140, Theorem 188, also p. 21, Theorem 10). An analogous result for $k = 2$, under a little stronger assumptions, has been proved in [6].

The relevant results for the reversed Hölder inequality are also given.

1. Auxiliary results

A crucial role plays the following

Lemma 1 ([5]). *Let a and b be real numbers such that*

$$0 < \min\{a, b\} < 1 < a + b.$$

If a function $f : (0, \infty) \rightarrow \mathbb{R}_+$ satisfies the inequality

$$af(s) + bf(t) \leq f(as + bt), \quad s, t > 0,$$

then $f(t) = f(1)t$, ($t > 0$).

For the reversed inequality we have the following

Lemma 2 ([4]). Let a and b be real numbers such that

$$0 < \min\{a, b\} < 1 < a + b.$$

If a function $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ is bounded in a neighbourhood of 0, $f(0) = 0$ and

$$f(as + bt) \leq af(s) + bf(t), \quad s, t \geq 0,$$

then $f(t) = f(1)t$, ($t \geq 0$).

We need also the following result on a simultaneous system of two functional equations.

Lemma 3 ([2]). Let a, b, α, β be positive real numbers and suppose that $h : (0, \infty) \rightarrow (0, \infty)$ is continuous at least at one point and satisfies the system of functional equations

$$h(at) = \alpha h(t), \quad h(bt) = \beta h(t), \quad t > 0.$$

If $a \neq 1$ and $\frac{\log b}{\log a}$ is irrational then there exists a $q \in \mathbb{R}$ such that $h(t) = h(1)t^q$, for all $t > 0$.

2. The converse of generalized Hölder's inequality for multiplicatively conjugate functions

We start this section with the following

Theorem 1. Let (Ω, Σ, μ) be a measure space with two disjoint sets $A, B \in \Sigma$ of finite and positive measure, and k a fixed positive integer. If $\phi_1, \dots, \phi_k : (0, \infty) \rightarrow (0, \infty)$ are bijections such that for a positive c ,

$$(1) \quad \phi_1^{-1}(t) \cdot \dots \cdot \phi_k^{-1}(t) = ct, \quad t > 0,$$

and

$$(2) \quad \int_{\Omega} x_1 \cdot \dots \cdot x_k d\mu \leq p_{\phi_1}(x_1) \cdot \dots \cdot p_{\phi_k}(x_k), \quad x_1, \dots, x_k \text{ in } S_+,$$

then ϕ_1, \dots, ϕ_k are conjugate power functions, i.e. there are $q_1, \dots, q_k \in \mathbb{R}$, $q_1, \dots, q_k \geq 1$, such that

$$\phi_i(t) = \phi_i(1)t^{q_i}, \quad t > 0; \quad i = 1, \dots, k,$$

and

$$q_1^{-1} + \dots + q_k^{-1} = 1.$$

PROOF. For $k = 1$ we have $\phi_1^{-1}(t) = ct$, $t > 0$, and the theorem is obvious. A formal proof in the general case $k \geq 2$ requires quite complicated notation. Since the idea of the proof in the general case is exactly the same as in the case $k = 3$, we give the detailed argument for $k = 3$. For the simplicity of notations we put $\phi := \phi_1$, $\psi := \phi_2$, $\gamma := \phi_3$. By χ_A we denote the characteristic function of a set A . Put $a := \mu(A)$, $b := \mu(B)$. Setting in inequality (2) arbitrary $x, y, z \in S_+$ of the form:

$$\begin{aligned} x &:= x_1\chi_A + x_2\chi_B, & y &:= y_1\chi_A + y_2\chi_B, & z &:= z_1\chi_A + z_2\chi_B, \\ & & & & & x_i, y_i, z_i > 0, \end{aligned}$$

and making use of the definition of p_ϕ , we get the inequality

$$\begin{aligned} & ax_1y_1z_1 + bx_2y_2z_2 \\ & \leq \phi^{-1}(a\phi(x_1) + b\phi(x_2))\psi^{-1}(a\psi(y_1) + b\psi(y_2))\gamma^{-1}(a\gamma(y_1) + b\gamma(y_2)) \end{aligned}$$

for all $x_i, y_i, z_i > 0$. Replacing here x_i, y_i , and z_i , respectively by $\phi^{-1}(x_i)$, $\psi^{-1}(y_i)$, and $\gamma^{-1}(z_i)$, $i = 1, 2$, we obtain

$$\begin{aligned} (3) \quad & a\phi^{-1}(x_1)\psi^{-1}(y_1)\gamma^{-1}(z_1) + b\phi^{-1}(x_2)\psi^{-1}(y_2)\gamma^{-1}(z_2) \\ & \leq \phi^{-1}(ax_1 + bx_2)\psi^{-1}(ay_1 + by_2)\gamma^{-1}(az_1 + bz_2) \end{aligned}$$

for all $x_1, x_2, z_1, y_1, y_2, z_2 > 0$. Similarly, setting in (2)

$$x := x_1\chi_A, \quad y := y_1\chi_A, \quad z := z_1\chi_A, \quad x_1, y_1, z_1 > 0,$$

we obtain

$$\begin{aligned} a\phi^{-1}(x_1)\psi^{-1}(y_1)\gamma^{-1}(z_1) & \leq \phi^{-1}(ax_1)\psi^{-1}(ay_1)\gamma^{-1}(az_1), \\ & x_1, y_1, z_1 > 0. \end{aligned}$$

From (1) we have

$$(4) \quad \psi^{-1}(t)\gamma^{-1}(t) = \frac{ct}{\phi^{-1}(t)}, \quad t > 0.$$

Hence, taking $z_1 := y_1$, we get

$$\frac{\phi^{-1}(ay_1)}{\phi^{-1}(y_1)} \leq \frac{\phi^{-1}(ax_1)}{\phi^{-1}(x_1)}, \quad x_1, y_1 > 0.$$

This implies that the function $t \rightarrow \frac{\phi^{-1}(t)}{\phi^{-1}(a^{-1}t)}$ is constant in $(0, \infty)$ and, consequently, we have

$$(5) \quad \frac{\phi^{-1}(a^{-1}x_1)}{\phi^{-1}(a^{-1}y_1)} = \frac{\phi^{-1}(x_1)}{\phi^{-1}(y_1)}, \quad x_1, y_1 > 0.$$

In the same way we show that

$$(6) \quad \frac{\phi^{-1}(b^{-1}x_2)}{\phi^{-1}(b^{-1}y_2)} = \frac{\phi^{-1}(x_2)}{\phi^{-1}(y_2)}, \quad x_2, y_2 > 0.$$

From (3) and (4) we obtain

$$ay_1 \frac{\phi^{-1}(x_1)}{\phi^{-1}(y_1)} + by_2 \frac{\phi^{-1}(x_2)}{\phi^{-1}(y_2)} \leq (ay_1 + by_2) \frac{\phi^{-1}(ax_1 + bx_2)}{\phi^{-1}(ay_1 + by_2)}.$$

Replacing here x_1, x_2, y_1, y_2 resp. by $a^{-1}x_1, b^{-1}x_2, a^{-1}y_1, b^{-1}y_2$ we get

$$y_1 \frac{\phi^{-1}(a^{-1}x_1)}{\phi^{-1}(a^{-1}y_1)} + y_2 \frac{\phi^{-1}(b^{-1}x_2)}{\phi^{-1}(b^{-1}y_2)} \leq (y_1 + y_2) \frac{\phi^{-1}(x_1 + x_2)}{\phi^{-1}(y_1 + y_2)}.$$

Now from (5) and (6) we obtain the inequality

$$(7) \quad y_1 \frac{\phi^{-1}(x_1)}{\phi^{-1}(y_1)} + y_2 \frac{\phi^{-1}(x_2)}{\phi^{-1}(y_2)} \leq (y_1 + y_2) \frac{\phi^{-1}(x_1 + x_2)}{\phi^{-1}(y_1 + y_2)},$$

valid for all $x_1, x_2, y_1, y_2 > 0$. Setting

$$F(t) := \psi^{-1}(t)\gamma^{-1}(t), \quad t > 0,$$

and making again use of (4) we can write this inequality in the form

$$\phi^{-1}(x_1)F(y_1) + \phi^{-1}(x_2)F(y_2) \leq \phi^{-1}(x_1 + x_2)F(y_1 + y_2), \\ x_1, x_2, y_1, y_2 > 0.$$

Now we can prove that ϕ and F are homeomorphisms in $(0, \infty)$. In view of (1) it is sufficient to show that either ϕ^{-1} or F is increasing in $(0, \infty)$. Suppose for instance that F is not increasing in $(0, \infty)$. Thus $F(y_1) > F(y_1 + y_2)$ for some positive y_1, y_2 and the last inequality implies that $\phi^{-1}(x_1) < \phi^{-1}(x_1 + x_2)$ for all $x_1, x_2 > 0$, i.e. that ϕ^{-1} is increasing in $(0, \infty)$.

From (7), by induction, we obtain

$$y_1 \frac{\phi^{-1}(x_1)}{\phi^{-1}(y_1)} + \dots + y_n \frac{\phi^{-1}(x_n)}{\phi^{-1}(y_n)} \leq (y_1 + \dots + y_n) \frac{\phi^{-1}(x_1 + \dots + x_n)}{\phi^{-1}(y_1 + \dots + y_n)},$$

for all positive $x_1, \dots, x_n; y_1, \dots, y_n$ and $n \in \mathbb{N}$. Setting in this inequality $x_1 = \dots = x_n := s; y_1 = \dots = y_n := t$, we get

$$\frac{\phi^{-1}(nt)}{\phi^{-1}(t)} \leq \frac{\phi^{-1}(ns)}{\phi^{-1}(s)}, \quad s, t > 0; n \in \mathbb{N}.$$

It follows that for every $n \in \mathbb{N}$ the function $t \rightarrow \frac{\phi^{-1}(nt)}{\phi^{-1}(t)}$, $t > 0$, is constant. Hence for every $n \in \mathbb{N}$ there is $\alpha_n > 0$ such that

$$\phi^{-1}(nt) = \alpha_n \phi^{-1}(t), \quad t > 0.$$

Taking $n = 2$ and $n = 3$ we see that $h := \phi^{-1}$ satisfies the system of functional equations

$$h(2t) = \alpha h(t), \quad h(3t) = \beta h(t), \quad t > 0,$$

where $\alpha := \alpha_2$, $\beta := \alpha_3$. Since h is continuous and $\log 3 / \log 2$ is irrational, Lemma 3 implies that there is a $q_1 \in \mathbb{R}$ such that $h(t) = h(1)t^{1/q_1}$, $t > 0$, i.e.

$$\phi_1^{-1}(t) = \phi^{-1}(t) = \phi^{-1}(1)t^{1/q_1}, \quad t > 0.$$

By the monotonicity of ϕ^{-1} we have $q_1 > 0$.

In the same way one can show that $\phi_i^{-1}(t) = \phi_i^{-1}(1)t^{1/q_i}$ ($t > 0$) for some $q_i > 0$, and $i = 2, \dots, k$. By (1) we have

$$q_1^{-1} + \dots + q_k^{-1} = 1,$$

and consequently, $q_i > 1$, $i = 1, \dots, k$. This completes the proof. \square

Remark 1. Note that carrying out the argument for arbitrary $k \in \mathbb{N}$, $k \geq 3$, we can define the function F as follows

$$F(t) := \phi_2^{-1}(t) \cdot \dots \cdot \phi_k^{-1}(t), \quad t > 0.$$

Similarly, applying Lemma 2, we can prove

Theorem 2. Let (Ω, Σ, μ) be a measure space with two disjoint sets of finite and positive measure. If $\phi_1, \dots, \phi_k : (0, \infty) \rightarrow (0, \infty)$ are bijections such that for some positive c :

$$\phi_1^{-1}(t) \cdot \dots \cdot \phi_k^{-1}(t) = ct, \quad t > 0,$$

and

$$p_{\phi_1}(x_1) \cdot \dots \cdot p_{\phi_k}(x_k) \leq \int_{\Omega} x_1 \cdot \dots \cdot x_k d\mu, \quad x_1, \dots, x_k \in S_+,$$

then ϕ_1, \dots, ϕ_k are conjugate power functions i.e. there are $q_1, \dots, q_k \in \mathbb{R} \setminus \{0\}$ such that

$$\phi_i(t) = \phi_i(1)t^{q_i}, \quad t > 0; \quad i = 1, \dots, k,$$

and

$$q_1^{-1} + \dots + q_k^{-1} = 1.$$

3. The main theorem

The main goal of this paper is to prove the following

Theorem 3. Suppose that (Ω, Σ, μ) is a measure space with two sets $A, B \in \Sigma$ such that

$$0 < \mu(A) < 1 < \mu(B) < \infty.$$

If $\phi_1, \dots, \phi_k : (0, \infty) \rightarrow (0, \infty)$ are arbitrary bijections such that

$$\int_{\Omega} x_1 \cdots x_k d\mu \leq p_{\phi_1}(x_1) \cdots p_{\phi_k}(x_k), \quad x_1, \dots, x_k \in S_+,$$

then ϕ_1, \dots, ϕ_k are conjugate power functions i.e. there are $q_1, \dots, q_k \in \mathbb{R}$, $q_1, \dots, q_k \geq 1$, such that

$$\phi_i(t) = \phi_i(1)t^{q_i}, \quad t > 0; i = 1, \dots, k,$$

and

$$q_1^{-1} + \dots + q_k^{-1} = 1.$$

PROOF. Define $f : (0, \infty) \rightarrow (0, \infty)$ by

$$f(t) := \phi_1^{-1}(t)\phi_2^{-1}(t) \cdots \phi_k^{-1}(t), \quad t > 0,$$

and put $a := \mu(A)$ and $b := \mu(B \setminus A)$. Setting in the assumed inequality $x_i := s_i \chi_A + t_i \chi_{B \setminus A} \in S_+$ ($i = 1, \dots, k$), we obtain,

$$\begin{aligned} & a\phi_1^{-1}(s_1)\phi_2^{-1}(s_2) \cdots \phi_k^{-1}(s_k) + b\phi_1^{-1}(t_1)\phi_2^{-1}(t_2) \cdots \phi_k^{-1}(t_k) \\ & \leq \phi_1^{-1}(as_1 + bt_1)\phi_2^{-1}(as_2 + bt_2) \cdots \phi_k^{-1}(as_k + bt_k) \end{aligned}$$

for all positive $s_1, \dots, s_k; t_1, \dots, t_k$. Taking here $s_1 = s_2 = \dots = s_k := s$; $t_1 = t_2 = \dots = t_k := t$ gives

$$af(s) + bf(t) \leq f(as + bt), \quad s, t > 0.$$

Since $0 < a < 1 < a + b$ it follows by Lemma 1 that $f(t) = f(1)t$, ($t > 0$). Thus, by the definition of f , the functions ϕ_i , $i = 1, \dots, k$, are multiplicatively conjugate and our result is a consequence of Theorem 1. \square

Remark 2. In Theorem 3 (as well as in Theorem 1), if $k \geq 2$ then $q_i > 1$ for all $i = 1, \dots, k$. If $k = 1$ then $q_1 = 1$, and the basic Hölder inequality (2) becomes an equality.

Remark 3. Theorem 3 generalizes the main result of a paper [6] where the case $k = 2$ is considered, and the functions ϕ_1, ϕ_2 are assumed to be bijections of $\mathbb{R}_+ = [0, \infty)$.

Remark 4. If we assume that $\phi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, and

$$\phi(0) = 0,$$

then the definition of the functional $p_\phi : S_+ \rightarrow \mathbb{R}_+$ simplifies to the following formula

$$p_\phi(x) := \phi^{-1} \left(\int_{\Omega} \phi \circ x \, d\mu \right), \quad x \in S_+.$$

Using this remark, and applying Lemma 2 and Theorem 2, we can prove

Theorem 4. Suppose that (Ω, Σ, μ) is a measure space with two sets $A, B \in \Sigma$ such that $0 < \mu(A) < 1 < \mu(B) < \infty$. If $\phi_i : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ are bijections such that $\phi_i(0) = 0$, $i = 1, \dots, k$, the function $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ given by the formula

$$f(t) := \phi_1^{-1}(t) \cdot \dots \cdot \phi_k^{-1}(t), \quad t \geq 0,$$

is bounded in a neighbourhood of 0 and

$$p_{\phi_1}(x_1) \cdot \dots \cdot p_{\phi_k}(x_k) \leq \int_{\Omega} x_1 \cdot \dots \cdot x_k \, d\mu, \quad x_1, \dots, x_k \in S_+,$$

then ϕ_1, \dots, ϕ_k are conjugate power functions, i.e. there are $q_1, \dots, q_k \in \mathbb{R} \setminus \{0\}$, such that

$$\phi_i(t) = \phi_i(1)t^{q_i}, \quad t \geq 0; \quad i = 1, \dots, k,$$

and

$$q_1^{-1} + \dots + q_k^{-1} = 1.$$

Remark 5. In Theorem 4 (and Theorem 2), if $k \geq 2$ then at least one of the numbers q_i , $i = 1, \dots, k$, is negative, and the relevant power function ϕ_i is decreasing in $(0, \infty)$. If $k = 1$ then $q_1 = 1$, and the assumed reversed Hölder inequality becomes an equality.

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