

The background features a complex, layered design. At the top, there are faint, light blue gears and arrows pointing in various directions. A prominent feature is a large, semi-transparent gear that frames the central text. In the center, there is a vibrant orange and yellow circular graphic with a gear-like edge, surrounded by several concentric circles. Below this, a cluster of blue and dark blue rectangular blocks is arranged in a semi-circular pattern. The overall aesthetic is technical and scientific.

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Hardi tengsizligi va uning parametrining baholanishi

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Annotatsiya: Ushbu maqolada Hardi tengsizligi, Hardi tengsizligi haqida dastlabki tushunchalar, Hardi tengsizligi tadbig'iga oid dastlabki masalalar, bugunga qadar ilmiy-izlanishlar natijasi keltirilgan. Shu bilan bir qatorda Hardi tengsizligining parametri uchunmuhim baholashlar keltirib chiqarilgan.

Kalit so'zlar: Hardi tengsizligi, diskret Hardi operatori, Gurka masalasi, oddiy differensial tenglama, Hardi tengsizligi parametri

Hardy's inequality and estimation of its parameters

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Abstract: This article presents Hardy's inequality, initial concepts of Hardy's inequality, initial issues related to the application of Hardy's inequality, and the results of scientific research until today. In addition, important estimates for the parameter of Hardy's inequality are derived.

Keywords: Hardy inequality, discrete Hardy operator, Gurka problem, ordinary differential equation, Hardy inequality parameter

Ushbu maqolada Hardi tengsizligi, Diskret Hardi operatori, ularning qo'llanilish sohalari o'rganilgan. Diskret Hardi operatorini o'rganishimiz uchun avvalo uni funksional va garmonik tahlil qilishimiz kerak bo'ladi. Xususan so'nggi yillarda Hardi tengsizligini o'rganish bo'yicha ko'pgina yutuqlarga erishildi. Diskret Hardi operatori mavzusi shular jumlasidandir [1-12]. Ushbu borada bugungi kungacha o'rganilgan bir nechta masalalarni ko'rib chiqamiz va tahlil qilamiz. Hardi tengsizligidan foydalangan holda turli sohalari, xususan chiziqli integral tenglamalar, operatorlar nazariyasi, operatorlarni chiziqli va chegaralanganlikka tekshirishda [4-6] muhim natijalarga erishilgan. Dastlabki qo'yilgan masalalardan biri, bu bir o'lchovli Hardi tipidagi tengsizlikning haqiqiyliги va uning oddiy differensial tenglamaning yechilishi orasidagi bog'liqliqlikni ifodalovchi Gurka masalasi hisoblanadi. Gurkaning natijalari Bisak, Kafner va Tribel Mukenhaptlarning ko'pgina ishalariga asoslangan edi [13-18].

Gurka o‘zining ilmiy izlanishlari natijasida olgan natijasini ifodalash uchun zarur bo‘lgan tushunchalarni kiritamiz:

$v(x)$ funksiyani $\forall x \in (0, a)$ nuqtada birinchi tartibli hosilasi mavjud deb faraz qilib, $v(x)$ uchun ushbu munosabat o‘rinli bo‘lsin

$$\int_0^\varepsilon v^{1-p^*}(x) dx < +\infty \quad (2)$$

(1) munosabatda $\varepsilon \in (0, a)$ bo‘lib, bu yerda p^* , p ning konjugant soni hisoblanib, quyidagicha aniqlanadi:

$$\frac{1}{p} + \frac{1}{p^*} = 1$$

$\gamma > 0$ munosabatni qanoatlantiruvchi $y(x)$ yechimga ega ushbu tenglama berilgan bo‘lsin:

$$\gamma \frac{d}{dx} \left[v^{\frac{q}{p}}(x) (v'(x))^{\frac{q}{p^*}} \right] + u(x) y^{\frac{q}{p^*}}(x) = 0 \quad (3)$$

(3) tenglamada $u(x)$ lokal uzluksiz hamda birinchi tartibli hosilaga ega funksiya bo‘lib, (3) tenglama uchun quyidagi munosabatlar bajarilsin.

$$y(x) > 0, y'(x) > 0 \quad (0 < x < a).$$

Agar doimiy uzluksiz bo‘lgan $C_0 > 0$ soni va $(0, a)$ oraliqda mutlaqo uzluksiz bo‘lgan $f(0) = \lim_{t \rightarrow 0} f(t) = 0$ tenglik o‘rinli bo‘lladigan barcha $f(x)$ funksiyalar olinganda tengsizlikning ko‘rinishi quyidagicha bo‘ladi:

$$\left(\int_0^a |f(x)|^q u(x) dx \right)^{\frac{1}{p}} \leq C_0 \left(\int_0^a |f'(x)|^p v(x) dx \right)^{\frac{1}{p^*}} \quad (4)$$

Bu shart bir o‘lchovli uzluksiz Hardi tipidagi tengsizlikning haqiqiyliги uchun zaruriy va yetarlilik sharti hisoblanadi. Biroq, Gurka o‘z natijasi bo‘lmish (4) munosabatdagi C_0 ning optimal uzluksiz ekanligini isbotlay olmadi. Gurkaning g‘oyasi va (4) dan foydalanib, Gussoub va Moradifanlar n o‘lchovli tengsizlikning haqiqiyliги uchun shartlarni keltirib chiqardilar. Shuni ta’kidlab o‘tish kerakki bu shartlar faqat $p = q = 2$ bo‘lgandagina o‘rinli edi [19-23]. Bu shartlarning asosiy natijasi quyidagi teorema olib keladi. $B_R\{x\}$ belgilash orqali markazi $x \in R^n$ nuqtada bo‘lgan R radiusli $(0 < R \leq +\infty)$, R^n da $(n \geq 1)$ aniqlangan aylana chizig‘ini ifodalaymiz.

Teorema 1. Ixtiyoriy musbat radial V va W funksiyalar, C^1 fazoda $B_R\{0\}$ bo‘yicha aniqlangan bo‘lsin

Faraz qilaylik,

$$\int_0^a \frac{1}{r^{n-1}V(r)} dr = +\infty, \int_0^a \frac{1}{r^{n-1}V(r)} dr \leq \infty \Rightarrow 0 < a < R.$$

Munosabatlar bajarilib, ushbu oddiy differensial tenglama:

$$y''(r) + \left(\frac{n-1}{r} + \frac{V'(r)}{V(r)}\right)y'(r) + \frac{W(r)}{V(r)}y(r) = 0 \quad (5)$$

$[0, R]$ oraliqda musbat aniqlangan bo‘lsin (ba‘zan $y(R)=0$ bo‘lishi ham mumkin), u holda $y(x)$ funksiya uchun quyidagi tengsizlik o‘rinli bo‘ladi:

$$\int_{B_k} W(x)u^2(x)dx \leq \int_{B_k} V(x)|\nabla u(x)|^2 dx \quad (6)$$

Barcha $u \in C_0^\infty(B_R)$ ga tegishli bo‘lgan nuqtalarda o‘rinli.

Endi keyingi misolni ko‘raylik. Ikkinchi misol Hardi tipidagi tengsizlikda optimal o‘zgaraslarga erishgan har qanday funksiya xususiy bo‘lmagan qiymat tenglamasini qanoatlantirishini isbotlashdir. Buni ko‘rib chiqish uchun bir marta uni eng yuqori chegarasi:

$$\sup \left\{ \frac{\left(\int_0^1 |u(x)|^q dx\right)^{\frac{1}{q}}}{\left(\int_0^1 |u'(x)|^p dx\right)^{\frac{1}{p}}} : u \in L^2(0,1), u' \in L^2(0,1), u(0) = u(1) = 0 \right\} \quad (7)$$

Bunda $u(x)$ quyidagi yechimlarga ega bo‘ladi:

$$\begin{cases} (|u'|^{p-2}u')' + lu^{q-1} = 0 \\ u(0) = u(1) = 0, u \geq 0 \end{cases} \quad (8)$$

(8) tenglikda l Lagranj ko‘paytmasi bilan berilgan Lagranj soni bo‘lib, quyidagicha aniqlanadi:

$$l = \frac{\int_0^1 |u(x)|^p dx}{\int_0^1 |u(x)|^q dx}$$

Ko‘rinib turibdiki, $u(x) = 1$ va $v(x) = 1$ bo‘lganda $(0,1)$ bir o‘lchamli Hardi tipidagi tengsizlikning (4) optimal o‘zgaraslarga mos keladi. Buning asosiy g‘oyasi va olingan natija Johan Bernulliga tegishli bo‘lib hisoblanadi.

So‘nggi o‘n yillikda Hardi tipidagi tengsizliklarni qo‘llash yanada kengaydi. Ehtimollar nazariyasi ayniqsa stoxastik jarayonlarning turli barqarorlik tezligini o‘rganishda, masalan Chenning bir qator tadqiqotlarida bu o‘z aksini yaqqol topdi.

Uzluksiz holatdan farqli ravishda, bu maqolada Hardi tipidagi tengsizliklarning optimal parametri tahliliga qaratilgan.

Bizga berilgan ikki parametr p va q lar uchun $1 < p \leq q < \infty$ munosabat hamda musbat va diskret $[1, N] := \{1, 2, 3, \dots, N\}$ oraliqda aniqlangan (bu yerda

$N < +\infty$ deb olingan) u va v funksiyalar uchun yozilgan ushbu tengsizlik:

$$\left[\sum_{n=1}^N u_n \left(\sum_{i=1}^n x_i \right)^q \right]^{\frac{1}{q}} \leq A \left(\sum_{n=1}^N v_n x_n^p \right)^{\frac{1}{p}} \quad (9)$$

Yuqoridagi tengsizlikka Hardi tipidagi tengsizlik deyiladi. Bu yerda $x_n [1, N] := \{1, 2, 3, \dots, N\}$ oraliqda aniqlangan va manfiy bo'lmagan ketma-ketlikdir. Tengsizlik to'la o'rinli bo'lishi uchun A parametr optimal deb qabul qilinadi.

Ushbu maqolada biz optimal o'zgarmlarning bir necha variatsion formulalarini berib, variatsion formulalarning asosiy qo'llanilish sohalari, taqribiy protsedurasi va asosiy hisob-kitobalarini ko'rib chiqamiz.

Teorema 2. Hardi tipiga mansub (9) tengsizlikdagi A parametr uchun ushbu baholashlar o'rinlidir. Yuqoridan baholash:

$$A \leq \inf_{x \in A[1, N]} \left(\sup_{n \in [1, N]} II_n^*(x) \right)^{\frac{1}{p^*}} = \inf_{x \in A[1, N]} \left(\sup_{n \in [1, N]} I_n^*(x) \right)^{\frac{1}{p^*}} \quad (10)$$

Quyidan baholash:

$$A \geq \sup_{x \in A[1, N]} \|x\|_{l^p(v)}^{\frac{p-1}{q}} \left(\inf_{n \in [1, N]} II_n(x) \right)^{\frac{p-1}{q}} \geq \sup_{x \in A[1, N]} \|x\|_{l^p(v)}^{\frac{p-1}{q}} \left(\inf_{n \in [1, N]} I_n(x) \right)^{\frac{p-1}{q}}$$

Ushbu teoremani N ning chekli oraliqqa tegishli bo'lgan holatdagi isbotini Bennet o'z ilmiy-izlanishlarida asoslab bergan. Biz Hardi tengsizligi va oddiy differensial tenglamaning yechilish masalasi orasidagi bog'lanishni ushbu lemma orqali ifodalaymiz. Faraz qilaylik

$$\sum_{n=1}^N \hat{v}_n < \infty \quad (11)$$

munosabat o'rinli bo'lsin. $y_n \geq 0, n \in [1, N]$, Hardi tipidagi tengsizlik har bir manfiy bo'lmagan x ketma-ketlik uchun o'rinli bo'ladi. Bundan tashqari optimal parametr $A \leq \lambda^{\frac{1}{q}}$ tengsizlik ham o'rinlidir.

Lemma 1. Agar (11) qatorning yig'indisi chekli musbat son bo'lsa u holda (2) differensial tenglama quyidagi ko'rinishni oladi:

$$u_n (Hy(n))^{\frac{q}{p^*}} + \lambda \left(v_{n+1}^{\frac{q}{p}} y_{n+1}^{\frac{q}{p^*}} - v_n^{\frac{q}{p}} y_n^{\frac{q}{p^*}} \right) = 0 \quad (12)$$

Isbot. Qulaylik uchun, biz x ni

$$\sum_{n=1}^N v_n x_n^p < \infty$$

deb olamiz. Bizda y (12) tenglikni qanoatlantiruvchi $y_n \geq 0$ yechim bo'lsin, aniqlik kiritish uchun ushbu belgilashni qaraylik:

$$F_n = -\lambda \left(v_{n+1}^{\frac{q}{p}} y_{n+1}^{\frac{q}{p^*}} - v_n^{\frac{q}{p}} y_n^{\frac{q}{p^*}} \right),$$

$$G_n = x_p^n y_n^{-\frac{q}{p^*}}$$

(12) tenglikka binoan

$$F_n = u_n \left(\sum_{i=1}^n y_i \right)^{\frac{q}{p^*}} \quad (13)$$

Hyolder tengsizligini qo‘llah orqali biz quyidagi munosabatga ega bo‘lamiz:

$$u_n \left(\sum_{i=1}^n x_i \right)^q = u_n \left(\sum_{i=1}^n x_i y_i^{\frac{1}{p^*}} y_i^{-\frac{1}{p^*}} \right)^q \leq u_n \left(\sum_{i=1}^n x_i^p y_i^{-\frac{p}{p^*}} \right)^{\frac{p}{q}} \left(\sum_{i=1}^n y_i \right)^{\frac{q}{p^*}}$$

$$= F_n \left(\sum_{i=1}^n G_i \right)^{\frac{q}{p}} \quad (14)$$

Bu yerda $r = \frac{q}{p}$ deb belgilash kiritish orqali $\frac{1}{r}$ ga bog‘liq Hyolder- Minkovskiy tengsizligi hosil bo‘ladi.

$$\left(\sum_{n=1}^N u_n (Hx(n))^q \right)^{\frac{1}{r}} \leq \left(\sum_{n=1}^N F_n \left(\sum_{i=1}^n G_i \right)^r \right)^{\frac{1}{r}} \leq \sum_{n=1}^N G_n \left(\sum_{i=n}^N F_i \right)^{\frac{1}{r}}.$$

F_n ning ta‘rifiga ko‘ra biz quyidagini yoza olamiz:

$$\sum_{i=n}^N F_i = -\lambda \left(v_{N+1}^{\frac{q}{p}} y_{N+1}^{\frac{q}{p^*}} - v_n^{\frac{q}{p}} y_n^{\frac{q}{p^*}} \right) \leq \lambda v_n^{\frac{q}{p}} y_n^{\frac{q}{p^*}}.$$

Shunday qilib biz quyidagiga ega bo‘lamiz:

$$\left(\sum_{n=1}^N u_n (Hx(n))^q \right)^{\frac{1}{q}} \leq \lambda^{\frac{1}{q}} \left(\sum_{n=1}^N G_n v_n y_n^{\frac{p}{p^*}} \right)^{\frac{1}{q}} = \lambda^{\frac{1}{q}} \left(\sum_{n=1}^N v_n x_n^p \right)^{\frac{1}{p}}.$$

Bu (9) tengsizlikning $\lambda^{\frac{1}{q}}$ parametr orqali hosil qilingan shaklidir. ko‘rinib turibdiki, bu yerda $A \leq \lambda^{\frac{1}{q}}$. Lemma isbotlandi.

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