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IKKINCHI TARTIBLI YUKLANGAN ELLIPTIK-GIPERBOLIK TIPDAGI TENGLAMANI YECHISH USULLARI

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МЕТОДЫ РЕШЕНИЯ НАГРУЖЕННОГО ЭЛЛИПТИКО-ГИПЕРБОЛИЧЕСКОГО УРАВНЕНИЯ ВТОРОГО ПОРЯДКА

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METHODS OF SOLVING THE SECOND-ORDER LOADED ELLIPTIC-HYPERBOLIC EQUATION

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Annotatsiya
Keyingi yillarda chet el va mamlakatimiz olimlari ikkinchi tartibli aralash tipdagi tenglamalar uchun turli masalalarni yechishning samarali usullarini oʻrganish va izlashga alohida e’tibor qaratmoqda. Oʻrganilayotgan masalalar hayotda elektromagnit toʻlqinlarini tarqalishida, optimal boshqaruvda, tuproq namligi va namlik darajasini boshqarishda va uzoq muddatli baholashni tahlil qilishda qoʻlaniladi.

Kalit so’zlar: ikkinchi tartibli, tenglama, elliptic-giperbolik, elektromagnit to’lqinlari, chegaraviy masalalar

Аннотация
В последние годы зарубежные и отечественные ученые уделяют особое внимание изучению и поиску эффективных методов решения различных задач для уравнений смешанного типа второго порядка. Изученные вопросы находят применение в распространении электромагнитных волн, оптимальном управлении, управлении влажностью почвы и уровнем влажности, а также долгосрочном анализе оценок.

Ключевые слова: второй порядок, уравнение, эллиптико-гиперболическое, электромагнитные волны, краевые задачи.

Abstract
In recent years, foreign and domestic scientists have been paying special attention to studying and searching for effective methods of solving various problems for second-order mixed type equations. The issues studied have applications in electromagnetic wave propagation, optimal management, soil moisture and moisture level management, and long-term assessment analysis.

Key words: second order, equation, elliptic-hyperbolic, electromagnetic waves, boundary value problems

Ikkinchi tartibli aralash elliptik-giperbolik, parabolik-giperbolik va parabolik-elliptik tipdagi tenglamalar uchun qo‘yilgan chegaraviy masalalarni yechishga bo‘lgan qiziqish o‘tgan asirda ham kiyingi yillarda ham o‘rganilmoqda. Shu o‘rinda M.S. Salaxitdinov, T.J. Jo‘raev, V.N. Vragov, L.A. A.M. Naxushev, K.B.Sobitov, Zolina, X.G. Bjixatlov, A.Sopuev, M.Mamajonov, O.A. Repin, V.A. Eleev, D. Bazarov, A. O. Sopuev [38-39], B. Islomov, Z. Madraximovalarning ilmiy ishlarini ta’kidlashimiz mumkin.

1961 yildan boshlab A.V. Bitsadze va M.S.Salohiddinov tomonidan uchinchi tartibli aralash-qo‘shma eliptik-giperbolik tipdagi tenglamalar uchun korrekt chegaraviy masalalar o‘rganilgan. Ikkinchi va uchinchi tartibli parabolik-giperbolik tipdagi tenglamalar uchun ekstemum printsibi va integral tenglamalar usullaridan foydalanib local va nolocal masalalar M.S. Salaxitdinov, T.J. Jo‘raev, A. Sopuev, M. Mamajonov tomonidan o‘rganilgan.

1978 yilda M.M.Xachev tomonidan Lavrentev –Bitsadze tenglamasi uchun to‘rtburchakli sohada Dirixle masalasini bir qiymatli yechilishi isbotlangan. Bu yo‘nalish ushbu maqoladan so‘ng hech bir olim tomonidan rivojlantirilmadi. 2007 yildan boshlab esa K. B.Sabitov va uning o‘quvchilari, E. P. Melishevalarning ilmiy ishlarda to‘rtburchakli sohalarda spektal analiz usullaridan foydalanib turli xil chigaraviy masalalar (Dirixle, Neyman va nolokal) yechilgan.

Ikkinchi tartibli parabolik-giperbolik tipdagi tenglamalar uchun to‘rtburchak sohada qo‘yilgan teskari masalalar K. B.Sabitov va P. M. Сафин tomonidan o‘rganilgan. Tenglamaning parabolik qismida Caputa ma`nosidagi kasir tartibli operator qatnashgan parabolik-giperbolik tipdagi tenglamalar uchun qo‘yilgan chegaraviy masala spektal analiz usullaridan foydalanib B.I.Islomov va У. Ш. Убайдуллаев maqolasida o‘rganilgan.

Bizga m`lumki, to‘rtburchak sohada ikkinchi va uchinchi tartibli yuklangan elliptik-giperbolik tipidagi tenglama uchun qo‘yilgan masalani tahlil qilish hozirgacha yaxshi o‘rganilmagan. Shu sababli, maqola mavzusi dolzarbdir.

To‘g‘ri to‘rtburchak sohada yuklangan qismida izlanayotgan funksiyaning ikkinchi tartibli hosilasining izi qatnashgan ikkinchi tartibli elliptik-giperbolik tipdagi tenglama uchun chegaraviy masala.

$$Lu = u_{xx} + sign\, y u_{yy} - b^2 u(x,y) + \mu(y)\, u_{xx}(x,0) = 0 \qquad (1)$$

aralash tipdagi yuklangan tenglamani $D = \{(x,y):\ 0 < x < 1,\ -\alpha < y < \beta\}$ sohada qaraymiz(**1-chizma)**, bu yerda $b,\ \ \alpha > 0,\ \ \beta > 0$ – berilgan haqiqiy sonlar, agar $y > 0$ bo‘lsa $\mu(y) = -\mu_1$, agar $y < 0$ bo‘lsa $\mu(y) = \mu_2$, $\mu_i\ (i = 1,2) -$ o‘zgarmaslar.

1. Ikkinchi tartibli yuklangan elliptik-giperbolik tipdagi tenglama uchun chegaraviy masalani qo‘yish

Quyidagi belgilashlarni kiritamiz: $J = \{(x,y): 0 < x < 1,\ y = 0\}$,

$D_1 = D \cap \{(x,y):\ x > 0,\ y > 0\}$, $D_2 = D \cap \{(x,y):\ x > 0,\ y < 0\}$, $D = D_1 \cup D_2 \cup J$.

1- Masala. D sohada u shbu

$$u(x,y) \in C^1(\bar{D}) \cap C^2(D_1 \cup D_2),\quad u_{xx}(x,0) \in C(\Omega_1 \cup \Omega_2); \qquad (2)$$

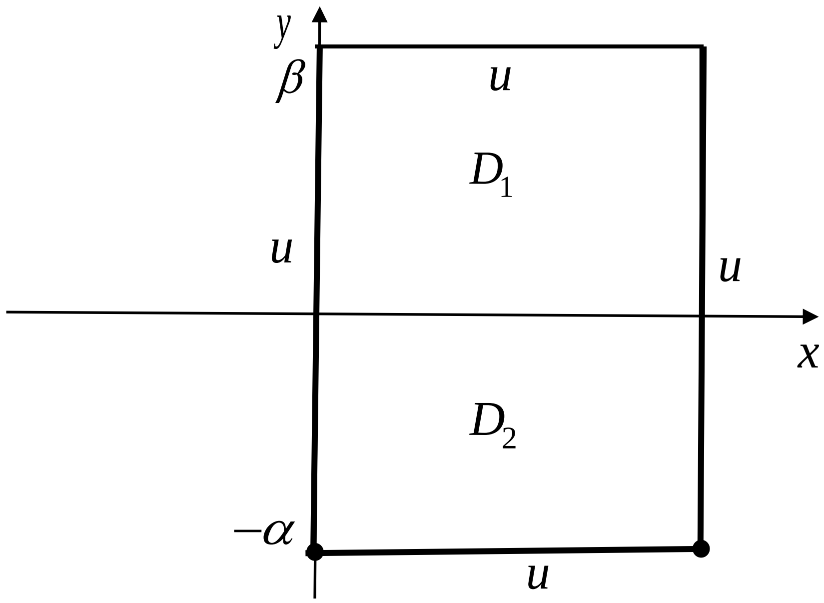
$$Lu(x,y) \equiv 0,\quad (x,y) \in D_1 \cup D_2; \qquad (3)$$

$$u(0,y) = u(1,y) = 0.\quad -\alpha \le y \le \beta; \qquad (4)$$

$$u(x,\beta) = \varphi(x),\quad u(x,-\alpha) = \psi(x),\quad 0 \le x \le 1; \qquad (5)$$

shartlarni qanoatlantiruvchi $u(x,y)$ funksiya topilsin, bu yerda $\psi(x)$, $\varphi(x)-$ berilgan etarlicha silliq funksiya,

$$\varphi(0)=\varphi(1)=\psi(0)=\psi(1)=0. \tag{6}$$



1-chizma.

2. Ikkinchi tartibli yuklangan elliptik-giperbolik tipdagi tenglama uchun chegaraviy masala yechimning yagonaligi

Teorema 1. Agar 1-masalani $u(x,y)$ yechimi mavjud bo'lsa, u holda bu yechim yagona bo'ladi faqat va faqatgina barcha $n\in N$ uchun

$$\tilde{\Delta}_{\alpha\beta}(n)=\frac{sin\rho_n\alpha}{\rho_n}\left[\mu_1\tilde{H}_{1n}(\beta)-\rho_n ch\rho_n\beta\right]+$$

$$+\frac{sh\rho_n\beta}{\rho_n}\left[\mu_2\tilde{H}_{2n}(-\alpha)-\rho_n cos\rho_n\alpha\right]\neq 0 \tag{7}$$

shart bajarilganda, bu yerda $\tilde{H}_{1n}(\beta)$ va $\tilde{H}_{2n}(-\alpha)$ funksiyalar kiyinchlik aniqlanadi.

1 - teoremaning isboti. 1-masalani ikkita $u_1(x,t)$ va $u_2(x,t)$ yechimi mavjud bo'lsin. U holda ularning $u(x,y)=u_1(x,y)-u_2(x,y)$ ayirmasi (1) tenglamani va bir jinsli shartlarni qanoatlantiradi:

$$u(x,-0)=u(x,+0),\quad (x,0)\in\overline{J}, \tag{8}$$

$$\lim_{y\to+0}u_y(x,y)=\lim_{y\to-0}u_y(x,y),\quad (x,0)\in J, \tag{9}$$

$$u(0,y)=0,\quad u(1,y)=0,\quad -\alpha\le y\le\beta, \tag{10}$$

$$u(x,-\alpha)=0,\quad u(x,\beta)=0,\quad 0\le x\le 1\ . \tag{11}$$

Ma'lumki, $L_2[0,1]$ da $\{X_n(x)\}\big|_{n=1}^{+\infty}=\{\sqrt{2}sin\pi nx\}\big|_{n=1}^{+\infty}$ funksiyalar to'liq ortonormal sistemani tashkil qiladi [23], [25]. [36] va [37] ishlarning g'oyasiga ko'ra quyidagi integral ifodani qaraymiz:

$$u_n(y)=\int_0^1 u(x,y)X_n(x)dx, \quad -\alpha\le y\le\beta. \tag{12}$$

(12) ga asoslanib, quyidagi funksiyani kiritamiz

$$u_{n,\varepsilon}(y)=\int_{\varepsilon}^{1-\varepsilon} u(x,y)X_n(x)dx, \tag{13}$$

bu yerda ε –yetarlicha kichik son.

(13) ni $y\in(-\alpha,0)\cup(0,\beta)$ da y bo'yincha ikki marta differensiallb, so'ngra (1) tenglamani hisobga olgan holda quyidagiga

$$u''_{n,\varepsilon}(y)=\int_{\varepsilon}^{1-\varepsilon} u_{yy}(x,y)X_n(x)dx=$$

$$=\int_{\varepsilon}^{1-\varepsilon}\left[b^2u(x,y)+\mu_1u_{xx}(x,0)-u_{xx}(x,y)\right]X_n(x)dx, \quad 0<y<\beta, \tag{14}$$

$$u''_{n,\varepsilon}(y)=\int_{\varepsilon}^{1-\varepsilon} u_{yy}(x,y)X_n(x)dx=$$

$$\int_{\varepsilon}^{1-\varepsilon}\left[u_{xx}(x,y)-b^2u(x,y)+\mu_2u_{xx}(x,0)\right]X_n(x)dx, \quad -\alpha<y<0 \tag{15}$$

ega bo'lamiz, bu yerda $X_n(x)=\sqrt{2}sin\lambda_nx, \quad \lambda_n=\pi n, \quad n\in N$.

Bundan, (14) va (15)ning o'ng tomonidagi integrallarni ikki marta bo'laklab integrallaymiz va $\varepsilon\to 0$ intiltiramiz, so'gra (10) ni hisobga olgan holda quyidagini

$$u''_n(y)-\rho_n^2u_n(y)=-\mu_1\lambda_n^2u_n(0), \quad 0<y<\beta, \tag{16}$$

$$u''_n(y)+\rho_n^2u_n(y)=-\mu_2\lambda_n^2u_n(0), \quad -\alpha<y<0 \tag{17}$$

hosil qilamiz.

(16) va (17) differensial tenglamalarning umumiy yechimi quyidagi

$$u_k(y)=\begin{cases} c_nch\rho_ny+d_n\,sh\rho_ny-\dfrac{\mu_1\lambda_n^2}{\rho_n}c_n\displaystyle\int_0^y sh\rho_n(y-t)dt, & 0\le y\le\beta, \\ \alpha_ncos\rho_ny+\beta_n\,sin\rho_ny-\dfrac{\mu_2\lambda_n^2}{\rho_n}\alpha_n\displaystyle\int_y^0 sin\rho_n(t-y)dt, & -\alpha\le y\le 0, \end{cases} \tag{18}$$

ko'rinishda bo'ladi, bu yerda $\alpha_n,\ \beta_n,\ c_n,\ d_n$ –ixtiyoriy o'zgarmaslar.

(2) va (12) ga ko'ra

$$u_n(0+0)=u_n(0-0), \quad u'_n(0+0)=u'_n(0-0)$$

ni e`tiborga olib, (3.18) dan

$$c_n=\alpha_n,\quad d_n=\beta_n. \tag{19}$$

(19) ni (18) ga qo‘yib, quyidagini

$$u_n(y)=\begin{cases} c_n ch\rho_n y+d_n\, sh\rho_n y-\dfrac{\mu_1}{\rho_n}\lambda_n^2 c_n\int\limits_0^y sh\rho_n(y-t)dt, & 0\le y\le\beta,\\ c_n cos\rho_n y+d_n\, sin\rho_n y-\dfrac{\mu_2}{\rho_n}\lambda_n^2 c_n\int\limits_y^0 sin\rho_n(t-y)dt, & -\alpha\le y\le 0\end{cases} \tag{20}$$

hosil qilamiz, bu yerda c_n, d_n lar ixtiyoriy o‘zgarmaslar.

Endi c_n va d_n o‘zgarmaslarni (5) shart va (12) formuladan foydalanib topib olaviz:

$$u_n(\beta)=\int\limits_0^1 u(x,\beta)X_n(x)dx=\int\limits_0^1\varphi(x)X_n(x)dx=\varphi_n, \tag{21}$$

$$u_n(-\alpha)=\int\limits_0^1 u(x,-\alpha)X_n(x)dx=\int\limits_0^1\psi(x)X_n(x)dx=\psi_n. \tag{22}$$

(21) va (22) ko‘ra (20) dan quyidagi sistemani

$$\begin{cases} c_n ch\rho_n\beta+d_n\, sh\rho_n\beta-\dfrac{\mu_1}{\rho_n}\lambda_n^2 c_n\int\limits_0^\beta sh\rho_n(\beta-t)dt=\varphi_n,\\ c_n cos\rho_n\alpha-d_n\, sin\rho_n\alpha-\dfrac{\mu_2}{\rho_n}\lambda_n^2 c_n\int\limits_{-\alpha}^0 sin\rho_n(t+\alpha)dt=\psi_n,\end{cases} \tag{23}$$

olamiz, bu yerda

$$\varphi_n=\sqrt{2}\int\limits_0^1\varphi(x)sin\pi nx,\qquad \psi_n=\sqrt{2}\int\limits_0^1\psi(x)sin\pi nx. \tag{24}$$

(23) sistemani yechish uchun uning diterminantini topamiz:

$$\tilde{\Delta}_{\alpha\beta}(n)=\begin{vmatrix} ch\rho_n\beta-\dfrac{\mu_1}{\rho_n}\lambda_n^2\mathrm{H}_{1n}(\beta) & sh\rho_n\beta\\ cos\rho_n\alpha-\dfrac{\mu_2}{\rho_n}\lambda_n^2\mathrm{H}_{2n}(-\alpha) & -sin\rho_n\alpha\end{vmatrix}=-ch\rho_n\beta sin\rho_n\alpha-sh\rho_n\beta cos\rho_n\alpha-$$

$$+\frac{\mu_1}{\rho_n}\lambda_n^2\mathrm{H}_{1n}(\beta)sin\rho_n\alpha+\frac{\mu_2}{\rho_n}\lambda_n^2\mathrm{H}_{2n}(-\alpha)sh\rho_n\beta,$$

bu yerda $\mathrm{H}_{1n}(\beta)=\int\limits_0^\beta sh\rho_n(\beta-t)dt,\qquad \mathrm{H}_{2n}(-\alpha)=\int\limits_{-\alpha}^0 sin\rho_n(t+\alpha)dt.$

Bundan, barcha $n\in N$ uchun

$$\tilde{\Delta}_{\alpha\beta}(n)=\frac{sin\rho_n\alpha}{\rho_n}\left[\mu_1\tilde{\mathrm{H}}_{1n}(\beta)-\rho_n ch\rho_n\beta\right]+$$

$$+\frac{sh\rho_n\beta}{\rho_n}\left[\mu_2\tilde{H}_{2n}(-\alpha)-\rho_n cos\rho_n\alpha\right]\neq 0 \qquad (7)$$

o‘rinli, bu yerda

$$\tilde{H}_{1n}(\beta)=\lambda_n^2\int_0^\beta sh\rho_n(\beta-t)dt, \qquad \tilde{H}_{2n}(-\alpha)=\lambda_n^2\int_{-\alpha}^0 sin\rho_n(t+\alpha)dt. \qquad (26)$$

(25) ga ko‘ra (23) sistemani yechimi ni topamiz:

$$c_n=\frac{1}{\tilde{\Delta}_{\alpha\beta}(n)}[\psi_n sh\rho_n\beta+\varphi_n sin\rho_n\alpha], \qquad (27)$$

$$d_n=\frac{1}{\tilde{\Delta}_{\alpha\beta}(n)\rho_n}\left[\varphi_n\left(\rho_n cos\rho_n\alpha+\mu_2\tilde{H}_{2n}(-\alpha)\right)-\psi_n\left(\rho_n ch\rho_n\beta+\mu_1\tilde{H}_{1n}(\beta)\right)\right]. \qquad (28)$$

(27) va (28) ni (20) ga qo‘yib, $u_n(y)$ ni ko‘rinishini topamiz:

$$u_n(y)=\begin{cases} c_n\left[ch\rho_n y-\frac{\mu_1}{\rho_n}\tilde{H}_{1n}(\beta)\right]+d_n\, sh\rho_n y, & 0\le y\le\beta,\\ c_n\left[cos\rho_n y-\frac{\mu_2}{\rho_n}\tilde{H}_{2n}(-\alpha)\right]+d_n\, sin\rho_n y, & -\alpha\le y\le 0\end{cases}$$

yoki

$$u_n(y)=\begin{cases} \frac{1}{\tilde{\Delta}_{\alpha\beta}(n)\rho_n}\Big\{[\psi_n sh\rho_n\beta+\varphi_n sin\rho_n\alpha]\left[\rho_n ch\rho_n y-\mu_1\tilde{H}_{1n}(\beta)\right]+\\ +\left[\varphi_n\left(\rho_n cos\rho_n\alpha+\mu_2\tilde{H}_{2n}(-\alpha)\right)-\psi_n\left(\rho_n ch\rho_n\beta+\mu_1\tilde{H}_{1n}(\beta)\right)\right]sh\rho_n y\Big\}, & 0\le y\le\beta,\\ \frac{1}{\tilde{\Delta}_{\alpha\beta}(n)\rho_n}\Big\{[\psi_n sh\rho_n\beta+\varphi_n sin\rho_n\alpha]\left[\rho_n cos\rho_n y-\mu_2\tilde{H}_{2n}(-\alpha)\right]+\\ +\left[\varphi_n\left(\rho_n cos\rho_n\alpha+\mu_2\tilde{H}_{2n}(-\alpha)\right)-\psi_n\left(\rho_n ch\rho_n\beta+\mu_1\tilde{H}_{1n}(\beta)\right)\right]sin\rho_n y\Big\}, & -\alpha\le y\le 0.\end{cases} \qquad (29)$$

Shunday qilib, $u_n(y)$ funksiyalar yagona aniqlangan, bu bizga 1 masala 1 teoremasini isbotlash imkonini beradi. Agar barcha $n\in N$ uchun (7) sart bajarilsa va $u(x,y)$ bir jinsli (8)-(11) masalaning yechimi bo‘lsa, u holda $\varphi_n=\psi_n\equiv 0$ va (27), (28) ni e`tiborga olib, (12) va (29) dan $u_n(y)=0$ ni olamiz. Bundan va (12) formuladan ixtiyoriy $y\in[-p,q]$ da quyidagiga ega bo‘lamiz:

$$\int_0^1 u(x,y)X_n(x)dx=0, \qquad -\alpha\le y\le\beta, \qquad n\in N=\{1,2,.....\}. \qquad (30)$$

(30) dan $\left\{\sqrt{2}\sin\pi nx\right\}_{n=1}^{\infty}$ sistemani $L_2[0,l]$ fazoda zichligidan**[56],** deyarli barcha $x\in[0,1]$ uchun va ixtiyoriy $y\in[-\alpha,\beta]$ da $u(x,y)=0$ bo‘lishi kelib chiqadi. (2) ga ko‘ra $u(x,t)$ funksiya $\overline{D}$ da uzluksiz bo‘lganligi uchun, $\overline{D}$ da $u(x,y)\equiv 0$ bo‘lishi kelib chiqadi.

Demak, 1 masalaning yechimi (7) shart bajarilganda yagonadir.

1 - teorema isbotlandi.

Qandaydir $\alpha,\ \beta$ va $n=k, k\in \mathrm{N}$ sonlar uchun (7) shart buzilsin, ya'ni

$$\tilde{\Delta}_{\alpha\beta}(k)=0. \qquad (31)$$

(7) dagi $\tilde{\Delta}_{\alpha\beta}(k)$ ни қуйидаги кўринишда ифодалаймиз[52, 61 bet],[35]:

$$\Delta_{\alpha\beta}(k)=-e^{\rho_k\beta}R_k(\beta)sin(\rho_k\alpha+\nu_k)+\frac{e^{\rho_k\beta}}{\rho_k}\omega_k(\alpha,\beta), \qquad (32)$$

bu yerda

$$R_k(\beta)=\sqrt{1+\frac{e^{-4\rho_k\beta}}{2}}=\frac{\sqrt{ch2\rho_k\beta}}{e^{\rho_k\beta}},\quad \nu_k=arcsin\frac{sh\rho_k\beta}{\sqrt{ch2\rho_k\beta}}. \qquad (33)$$

$$\omega_k(\alpha,\beta)=\frac{sin\rho_k\alpha}{e^{\rho_k\beta}}\tilde{\mathrm{H}}_{1k}(\beta)-\frac{\tilde{\mathrm{H}}_{2k}(-\alpha)sh\rho_k\beta}{e^{\rho_k\beta}}. \qquad (34)$$

Shuni takitlash lozimki, barcha $\beta>0,\quad k\geq 1$da (33) va (34) ifodalar chegaralangan[35]: agar $k\to\infty$ bo'lsa, $\nu_k=arcsin\dfrac{sh\rho_k\beta}{\sqrt{ch2\rho_k\beta}}\to\dfrac{\pi}{4}$ bo'ladi,

$$\frac{1}{\sqrt{2}}<R_k(\beta)<1, \qquad (35)$$

$$\left|\omega_k(\alpha,\beta)\right|\leq\frac{\mu_1+\alpha\mu_2}{2\pi}\leq\mu_3. \qquad (36)$$

Quyidagi natijalar o'rinli:

1-Natija. Qandaydir p,q va $n=k,\ k\in \mathrm{N}$ sonlar uchun (7) shart buzilsin, ya'ni $\tilde{\Delta}_{pq}(k)=0$ bo'lsin, u holda (8)-(11) bir jinsli masala notrivial yechimga ega bo'ladi:

$$u_k(x,y)=u_k(y)sin\pi kx, \qquad (37)$$

bu yerda

$$u_k(y)=\begin{cases}\dfrac{\theta_k}{\rho_k sh\rho_k\beta}\left[\rho_k sh\rho_k(\beta-y)-\mu_1\tilde{\mathrm{H}}_{1k}(\beta)sh\rho_k y\right]+\\ +\dfrac{\mu_1\theta_k}{\rho_k}\tilde{\mathrm{H}}_{1k}(y), & y>0,\\ \dfrac{\theta_k}{\rho_k sh\rho_k\beta}\left[-\rho_k sh\rho_k\beta cos\rho_k y-\left(\mu_1\tilde{\mathrm{H}}_{1k}(\beta)-\rho_k ch\rho_k\beta\right)sin\rho_k y\right]+\\ +\dfrac{\mu_2\theta_k}{\rho_k}\tilde{\mathrm{H}}_{2k}(y), & y<0,\end{cases} \qquad (38)$$

$\theta_k \neq 0 -$ ixtiyoriy o‘zgarmaslar.

(31) ga ko‘ra (38) dan quyidagini olamiz:

$$u_k(\beta) = 0, \quad u_k(-\alpha) = 0.$$

2-Natija. Cheksiz ko‘p $k \in \mathbb{N}^+$ uchun $\tilde{\Delta}_{\alpha\beta}(k) = 0$ tenglik o‘rinli bo‘lsa, u holda bunday k lar uchun 1-masala yechimi nokorrekt bo‘ladi.

Shuning uchun ushbu maqola mavzusida to‘rtburchak sohada ikkinchi tartibli yuklangan elliptik - giperbolik tipidagi tenglama uchun qo‘yilgan masalalarni yagonaligi, mavjudligi va turg‘nligi o‘rganilgan.

Maqola mavzusidan olingan natijalar nazariy ahamiyatga ega bo‘lib, keyinchalik ikkinchi va uchinchi tartibli yuklangan elliptik -giperbolik tipidagi tenglamalar nazariyasini rivojlantirishda, hamda bu tenglamaga keltiriladigan amaliy masalalarni yechishda qo‘llash mumkin.

Foydalanilgan adabiyotlar

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