DOI: 10.65322/j.srd.05192026.93

FAZOVIY STERJENNI TAKRORIY YUKLANISHDA ELASTIK-PLASTIK MASALALARINI YECHISH ALGORITMI

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Annotatsiya: *Mazkur maqolada chekli ayirmalar usulidan foydalanib, takroriy-o‘zgaruvchan yuklanish sharoitida fazoviy sterjenlarning elastik-plastik holatini tavsiflovchi masalalarni sonli yechish algoritmi ishlab chiqish masalasi yoritilgan. Qaralayotgan masalaning matematik modeli tabiiy chegaraviy shartlar bilan to‘ldirilgan, ikkinchi tartibli to‘qqizta nochiziqli differensial tenglamadan tashkil topgan sistema ko‘rinishida ifodalangan. Tadqiqotda A.A. Samarskiy va I.V. Fryazinov tomonidan taklif etilgan modifikatsiya asosida qurilgan ayirmali sxemaning hisoblash turg‘unligini asoslashga alohida e’tibor qaratilgan.*

Аннотация: *В статье рассматривается разработка алгоритма численного решения задач упругопластического деформирования пространственных стержней при повторно-переменном нагружении на основе метода конечных разностей. Математическая модель рассматриваемой задачи представлена системой из девяти нелинейных дифференциальных уравнений второго порядка с соответствующими естественными граничными условиями. Особое внимание уделено обоснованию, устойчивости вычислений, построенной на основе модификации А.А. Самарского - И.В. Фрязинова.*

Abstract: *This paper considers the development of an algorithm for the numerical solution of elastoplastic problems involving spatial rods subjected to repeated variable loading, based on the finite difference method. The mathematical model of the problem is represented by a system of nine second-order nonlinear differential equations subject to the corresponding natural boundary conditions. Particular attention is paid to justifying the computational stability of the finite difference scheme constructed using the A.A. Samarskii–I.V. Fryazinov modification.*

Kalit so'zlar: *Fazoviy sterjen, elastik-plastik masala, takroriy-o'zgaruvchan yuklanish, chekli ayirmalar usuli, Samarskiy - Fryazinov modifikatsiyasi, markaziy ayirmali sxema, uzilishli masala, sonli hisoblash algoritmi.*

Ключевые слова: *Пространственный стержень, упруго-пластическая задача, повторно-переменное нагружение, метод конечных разностей, модификация Самарского - Фрязинова, центральная разностная схема, разрывная задача, численный вычислительный алгоритм.*

Keywords: *spatial beam, elastic-plastic problem, repeated variable loading, finite difference method, Samarskii-Fryazinov modification, central difference scheme, discontinuous problem, numerical computational algorithm.*

Kirish. Kompyuter texnologiyalarining keng qo'llanilishi munosabati bilan differensial tenglama koeffitsiyentlari tegishli bo'lgan funksional fazoda chegaraviy masalalarni yechish uchun ayirmali sxemalarni ishlab chiqish maqsadga muvofiq ekanligi ayon bo'lmoqda. Bunday universal ayirmali sxemalar, tabiiyki, ko'rilayotgan masalalar sinfidagi istalgan boshlang'ich masala uchun va to'rlarning istalgan ketma-ketligida yaqinlashish va turg'unlik talablarini qanoatlantirishi kerak.

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Masalalar sinfini yechish uchun hisoblash algoritmining bir xilligi talabi bir jinsli ayirmali sxemalar tushunchasiga olib keladi. Bir jinsli ayirmali sxema deganda ko'rinishi na berilgan sinfdan aniq masalani tanlashga, na ayirmali to'rni tanlashga bog'liq bo'lmagan ayirmali sxema tushuniladi. Berilgan sinfdagi istalgan masala uchun to'rning barcha tugunlarida ayirmali tenglamalar bir xil ko'rinishga ega bo'ladi. Bir jinsli ayirmali sxemaning koeffitsiyentlari differensial tenglama koeffitsiyentlarining funksionallari sifatida aniqlanadi [1].

Algoritmik universallik – bu kirish ma'lumotlarining turli konfiguratsiyalarida yechimlarni ta'minlaydigan hisoblash modulining asosiy xarakterli xususiyatlaridan biridir.

V.K. Kabulovning aniqlashtirilgan nazariyasidan foydalanib, Mazing-Moskvitinning umumlashgan prinsiplari, Gusenkov-Shneyderovichning umumlashgan deformatsiyalanish diagrammasi va T. Buriyevning joriy koordinatalardagi siklik deformatsiyalanish diagrammasini hisobga olgan holda, tabiiy chegaraviy shartlarga ega ikkinchi tartibli to'qizta nochiziqli differensial tenglamalar sistemalari bilan tavsiflanadigan sterjenlarning nochiziqli masalalari matematik modellari Lagranj variatsion prinsipi asosida berilgan. [2, 3].

Masalaning qo'yilishi. Ma'lumki, agar takroriy o'zgaruvchan yuklanishlarda joriy tashqi yuk qiymati oshib ketsa, o'zgaruvchan yuklanish haqidagi teorema shartlari buziladi [4].

Chegaraviy masalalarni yechish uchun joriy kuchlanish komponentalarini joriy deformatsiya komponentalari orqali ifodalaymiz. Birinchi, ikkinchi va ixtiyoriy sondagi elastik-plastik yuklanishlar yoki yuksizlanishlar sohasida zarur amallarni bajarib, joriy koordinatalar sistemalarida plastiklik funksiyalari orqali kuchlanishlar va deformatsiyalar orasidagi munosabatlarni olamiz [5].

Ba'zi almashtirishlardan so'ng, tegishli chegaraviy shartlarga ega ikkinchi tartibli nochiziqli differensial tenglamalar sistemasini yechishga keltiriladi [6, 7, 8].

$$\frac{d}{d\bar{x}}\left[\left(A^{u}-A^{p(k)}\right)\frac{d\vec{V}^{(k)}}{d\bar{x}}+\left(B^{u}-B^{p(k)}\right)\vec{V}^{(k)}\right]+\left(C^{u}-C^{p(k)}\right)\frac{d\vec{V}^{(k)}}{d\bar{x}}+$$
$$+\left(D^{u}-D^{p(k)}\right)\vec{V}^{(k)}=\vec{F}^{(k)}+$$
$$+\frac{d}{d\bar{x}}\left[A^{p(k)}\frac{d\vec{V}^{0(k-1)}}{d\bar{x}}+B^{p(k)}\vec{V}^{0(k-1)}\right]+C^{p(k)}\frac{d\vec{V}^{0(k-1)}}{d\bar{x}}+D^{p(k)}\vec{V}^{0(k-1)}+$$
$$+\sum_{m=1}^{k-1}\left\{\frac{d}{d\bar{x}}\left[A^{po(k-m)}\frac{d}{d\bar{x}}\left(\vec{V}^{0(k-m)}-\vec{V}^{0(k-m-1)}\right)+B^{po(k-m)}\left(\vec{V}^{0(k-m)}-\vec{V}^{0(k-m-1)}\right)\right]+\right.$$
$$\left.+C^{po(k-m)}\frac{d}{d\bar{x}}\left(\vec{V}^{0(k-m)}-\vec{V}^{0(k-m-1)}\right)+D^{po(k-m)}\left(\vec{V}^{0(k-m)}-\vec{V}^{0(k-m-1)}\right)\right\} \quad (1)$$

va, mos ravishda, chegaraviy shartlar

$$\left\{\left(A^{u}-A^{p(k)}\right)\frac{d\vec{V}^{(k)}}{d\bar{x}}+\left(B^{u}-B^{p(k)}\right)\vec{V}^{(k)}-\vec{Q}^{(k)}-\right.$$
$$-A^{p(k)}\frac{d\vec{V}^{0(k-1)}}{d\bar{x}}-B^{p(k)}\vec{V}^{0(k-1)}-\sum_{m=1}^{k-1}\left[A^{po(k-m)}\frac{d}{d\bar{x}}\left(\vec{V}^{0(k-m)}-\vec{V}^{0(k-m-1)}\right)+\right.$$
$$\left.\left.+B^{po(k-m)}\left(\vec{V}^{0(k-m)}-\vec{V}^{0(k-m-1)}\right)\right\}\delta\vec{V}^{(k)}\right|_{\Gamma}=0 \quad . \quad (2)$$

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bu yerda $\vec{\vec{V}}^{(k)}$ – fiktiv koordinatalardagi to'qqizinchi tartibli izlanayotgan vektor funksiya [5].

$$\vec{\vec{V}}^{(k)} = \left|\overline{W}^{(k)}, \overline{\alpha}_1^{(k)}, \overline{\beta}_1^{(k)}, \overline{V}^{(k)}, \overline{\alpha}_2^{(k)}, \overline{\beta}_2^{(k)}, \overline{U}^{(k)}, \overline{\theta}^{(k)}, \overline{v}^{(k)}\right|^T.$$

Kiritilgan o'zgarmas koeffitsiyentli to'qqizinchi tartibli kvadrat matritsalar A^u, B^u, C^u, D^u va o'zgaruvchan koeffitsiyentli to'qqizinchi tartibli kvadrat matritsalar orasidagi farqlar $A^{p(k)}$, $B^{p(k)}$, $C^{p(k)}$, $D^{p(k)}$

Yechish usuli

(1) tenglamalarni quyidagi ko'rinishda yozamiz:

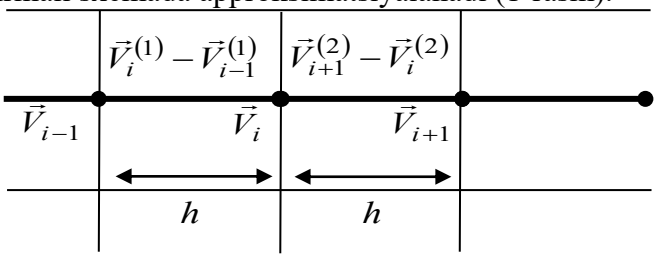
$$\frac{d}{d\bar{x}}\left[\left(A^u - A^{p(k)}\right)\frac{d\vec{V}^{(k)}}{d\bar{x}} + \left(B^u - B^{p(k)}\right)\vec{V}^{(k)}\right] + \left(C^u - C^{p(k)}\right)\frac{d\vec{V}^{(k)}}{d\bar{x}} + \left(D^u - D^{p(k)}\right)\vec{V}^{(k)} = \vec{F}^{(k)} + \vec{F}^{p(k)} + \vec{F}^{po(k-m)}, \tag{3}$$

$$\vec{F}^{p(k)} = \frac{d}{d\bar{x}}\left[A^{p(k)}\frac{d\vec{V}^{0(k-1)}}{d\bar{x}} + B^{p(k)}\vec{V}^{0(k-1)}\right] + C^{p(k)}\frac{d\vec{V}^{0(k-1)}}{d\bar{x}} + D^{p(k)}\vec{V}^{0(k-1)} \tag{4}$$

$$+ B^{po(k-m)}\left(\vec{V}^{0(k-m)} - \vec{V}^{0(k-m-1)}\right)\Big] + C^{po(k-m)}\frac{d}{d\bar{x}}\left(\vec{V}^{0(k-m)} - \vec{V}^{0(k-m-1)}\right) + \tag{5}$$

$$+ D^{po(k-m)}\left(\vec{V}^{0(k-m)} - \vec{V}^{0(k-m-1)}\right)\Big\}.$$

A.A. Samarskiy-I.V. Fryazinov modifikatsiyasida (3) vektor tenglama ikki guruhga ajratilgan ko'rinishdagi ayirmali sxemada approksimatsiyalanadi (1-rasm).



1-rasm. A.A. Samarskiy - I.V. Fryazinov modifikatsiyasi bo'yicha approksimatsiya sxemasi

$\omega_h = \{x_i = ih;\ \ i = 1,2,\ldots,n-1;\ x_0 = 0;\ x_n = 1\}$ tekis to'rni G sohada kiritib, (3) differensial tenglamani quyidagi aniqlik tartibiga ega ayirmali sxemalar bilan approksimatsiyalaymiz $O\left(h^2\right)$ [9, 10].

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$$\left.\begin{aligned}
&\frac{1}{h}\left(\frac{\left(A_{i+1}^{u}-A_{i+1}^{p(k)}\right)+\left(A_{i}^{u}-A_{i}^{p(k)}\right)}{2}\frac{\vec{V}_{i+1}^{(k)^{(1)}}-\vec{V}_{i}^{(k)^{(1)}}}{h}-\frac{\left(A_{i}^{u}-A_{i}^{p(k)}\right)+\left(A_{i-1}^{u}-A_{i-1}^{p(k)}\right)}{2}\frac{\vec{V}_{i}^{(k)^{(1)}}-\vec{V}_{i-1}^{(k)^{(1)}}}{h}\right)+\\
&+\frac{\left(B_{i+1}^{u}-B_{i+1}^{p(k)}\right)\vec{V}_{i+1}^{(k)^{(2)}}-\left(B_{i}^{u}-B_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(2)}}}{h}+\frac{\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i+1}^{(k)^{(2)}}-\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(2)}}}{h}+\\
&+\left(D_{i}^{u}-D_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(1)}}=\vec{F}_{i}^{(k)^{(1)}}+\vec{F}_{i}^{p(k)^{(1)}}+\vec{F}_{i}^{po(k-m)^{(1)}},\\
&\frac{1}{h}\left(\frac{\left(A_{i+1}^{u}-A_{i+1}^{p(k)}\right)+\left(A_{i}^{u}-A_{i}^{p(k)}\right)}{2}\frac{\vec{V}_{i+1}^{(k)^{(2)}}-\vec{V}_{i}^{(k)^{(2)}}}{h}-\frac{\left(A_{i}^{u}-A_{i}^{p(k)}\right)+\left(A_{i-1}^{u}-A_{i-1}^{p(k)}\right)}{2}\frac{\vec{V}_{i}^{(k)^{(2)}}-\vec{V}_{i-1}^{(k)^{(2)}}}{h}\right)+\\
&+\frac{\left(B_{i}^{u}-B_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(1)}}-\left(B_{i-1}^{u}-B_{i-1}^{p(k)}\right)\vec{V}_{i-1}^{(k)^{(1)}}}{h}+\frac{\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(1)}}-\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i-1}^{(k)^{(1)}}}{h}+\\
&+\left(D_{i}^{u}-D_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(2)}}=\vec{F}_{i}^{(k)^{(2)}}+\vec{F}_{i}^{p(k)^{(2)}}+\vec{F}_{i}^{po(k-m)^{(2)}}.
\end{aligned}\right\}\quad(6)$$

(6) tenglamalar sistemasini quyidagi ko'rinishda qayta yozish mumkin:

$$\left.\begin{aligned}
&\frac{1}{h}\left(\left(A_{i+1/2}^{u}-A_{i+1/2}^{p(k)}\right)\frac{\vec{V}_{i+1}^{(k)^{(1)}}-\vec{V}_{i}^{(k)^{(1)}}}{h}-\left(A_{i-1/2}^{u}-A_{i-1/2}^{p(k)}\right)\frac{\vec{V}_{i}^{(k)^{(1)}}-\vec{V}_{i-1}^{(k)^{(1)}}}{h}\right)+\\
&+\frac{\left(B_{i+1}^{u}-B_{i+1}^{p(k)}\right)\vec{V}_{i+1}^{(k)^{(2)}}-\left(B_{i}^{u}-B_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(2)}}}{h}+\\
&+\frac{\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i+1}^{(k)^{(2)}}-\left(C_{i}^{u}-C_{i+1}^{p(k)}\right)\vec{V}_{i}^{(k)^{(2)}}}{h}+\\
&+\left(D_{i}^{u}-D_{i}^{p(k)}\right)\vec{V}_{i+1}^{(k)^{(1)}}=\vec{F}_{i}^{(k)^{(1)}}+\vec{F}_{i}^{p(k)^{(1)}}+\vec{F}_{i}^{po(k-m)^{(1)}},\\
&\frac{1}{h}\left(\left(A_{i+1/2}^{u}-A_{i+1/2}^{p(k)}\right)\frac{\vec{V}_{i+1}^{(k)^{(2)}}-\vec{V}_{i}^{(k)^{(2)}}}{h}-\left(A_{i-1/2}^{u}-A_{i-1/2}^{p(k)}\right)\frac{\vec{V}_{i}^{(k)^{(2)}}-\vec{V}_{i-1}^{(k)^{(2)}}}{h}\right)+\\
&+\frac{\left(B_{i}^{u}-B_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(1)}}-\left(B_{i-1}^{u}-B_{i-1}^{p(k)}\right)\vec{V}_{i-1}^{(k)^{(1)}}}{h}+\\
&+\frac{\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(1)}}-\left(C_{i}^{u}-C_{i}^{p(k)}\right)\vec{V}_{i-1}^{(k)^{(1)}}}{h}+\\
&+\left(D_{i}^{u}-D_{i}^{p(k)}\right)\vec{V}_{i}^{(k)^{(2)}}=\vec{F}_{i}^{(k)^{(2)}}+\vec{F}_{i}^{p(k)^{(2)}}+\vec{F}_{i}^{po(k-m)^{(2)}}.
\end{aligned}\right\}\quad(7)$$

Bu yerda quyidagi belgilashlar kiritilgan:

DOI: 10.65322/j.srd.05192026.93

$$\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)=\frac{\left(A^u_{i+1}-A^{p(k)}_{i+1}\right)+\left(A^u_i-A^{p(k)}_i\right)}{2},$$

$$\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)=\frac{\left(A^u_i-A^{p(k)}_i\right)+\left(A^u_{i-1}-A^{p(k)}_{i-1}\right)}{2}.$$

Endi (7) tenglamalar sistemasidagi o'xshash hadlarni ixchamlaymiz va quyidagiga ega bo'lamiz:

$$\left.\begin{aligned}
&\frac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}\vec{V}^{(k)^{(1)}}_{i+1}-\left(\frac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}+\frac{\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)}{h}-h\left(D^u_i-D^{p(k)}_i\right)\right)\vec{V}^{(k)^{(1)}}_i+\\
&+\frac{\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)}{h}\vec{V}^{(k)^{(1)}}_{i-1}+\left(\left(B^u_{i+1}-B^{p(k)}_{i+1}\right)+\left(C^u_i-C^{p(k)}_i\right)\right)\vec{V}^{(k)^{(2)}}_{i+1}-\\
&-\left(\left(B^u_i-B^{p(k)}_i\right)+\left(C^u_i-C^{p(k)}_i\right)\right)\vec{V}^{(k)^{(2)}}_i=h\left(\vec{F}^{(k)^{(1)}}_i+\vec{F}^{p(k)^{(1)}}_i+\vec{F}^{po(k-m)^{(1)}}_i\right),\\
&\frac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}\vec{V}^{(k)^{(2)}}_{i+1}-\left(\frac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}+\frac{\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)}{h}-h\left(D^u_i-D^{p(k)}_i\right)\right)\vec{V}^{(k)^{(2)}}_i+\\
&+\frac{\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)}{h}\vec{V}^{(k)^{(2)}}_{i-1}+\left(-\left(B^u_i-B^{p(k)}_i\right)-\left(C^u_i-C^{p(k)}_i\right)\right)\vec{V}^{(k)^{(1)}}_i+\\
&+\left(-\left(B^u_{i-1}-B^{p(k)}_{i-1}\right)-\left(C^u_i-C^{p(k)}_i\right)\right)\vec{V}^{(k)^{(1)}}_{i-1}=h\left(\vec{F}^{(k)^{(2)}}_i+\vec{F}^{p(k)^{(2)}}_i+\vec{F}^{po(k-m)^{(2)}}_i\right).
\end{aligned}\right\} \quad (8)$$

$\vec{U}^{(k)}_i=\begin{bmatrix}\vec{V}^{(k)(1)}_i\\ \vec{V}^{(k)(2)}_i\end{bmatrix}$ vektorni kiritib, (8) tenglamalar sistemasini quyidagi ko'rinishda ifodalaymiz [1]:

$$\hat{A}^{(k)}_i\vec{U}^{(k)}_{i+1}-\hat{B}^{(k)}_i\vec{U}^{(k)}_i+\hat{C}^{(k)}_i\vec{U}^{(k)}_{i-1}=\hat{F}^{(k)}_i \quad \text{bunda} \quad i=1,2,...,n-1; \quad (9)$$

bu yerda $\vec{U}^{(k)}_i$ – izlanayotgan katakli vektor-funksiya; $\hat{A}^{(k)}_i$, $\hat{B}^{(k)}_i$, $\hat{C}^{(k)}_i$ – katakli matritsalar, $\hat{F}^{(k)}_i$ – esa katakli vektor bo'lib, ular quyidagi ko'rinishda ifodalanadi:

$$\hat{A}^{(k)}_i=\begin{Vmatrix}\dfrac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h} & \left(B^u_{i+1}-B^{p(k)}_{i+1}\right)+\left(C^u_i-C^{p(k)}_i\right)\\ \theta & \dfrac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}\end{Vmatrix},$$

$$\hat{B}^{(k)}_i=\begin{Vmatrix}\dfrac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}+\dfrac{\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)}{h}-h\left(D^u_i-D^{p(k)}_i\right) & \left(B^u_i-B^{p(k)}_i\right)+\left(C^u_i-C^{p(k)}_i\right)\\ -\left(B^u_i-B^{p(k)}_i\right)-\left(C^u_i-C^{p(k)}_i\right) & \dfrac{\left(A^u_{i+1/2}-A^{p(k)}_{i+1/2}\right)}{h}+\dfrac{\left(A^u_{i-1/2}-A^{p(k)}_{i-1/2}\right)}{h}-h\left(D^u_i-D^{p(k)}_i\right)\end{Vmatrix},$$

DOI: 10.65322/j.srd.05192026.93

$$\hat{C}_i^{(k)} = \begin{Vmatrix} \dfrac{\left(A_{i-1/2}^{u} - A_{i-1/2}^{p(k)}\right)}{h} & \theta \\ -\left(B_{i-1}^{u} - B_{i-1}^{p(k)}\right) + \left(C_i^{u} - C_i^{p(k)}\right) & \dfrac{\left(A_{i-1/2}^{u} - A_{i-1/2}^{p(k)}\right)}{h} \end{Vmatrix},$$

$$\hat{F}_i^{(k)} = \begin{Vmatrix} h\left(\vec{F}_i^{(k)(1)} + \vec{F}_i^{p(k)(1)} + \vec{F}_i^{po(k-m)(1)}\right) \\ h\left(\vec{F}_i^{(k)(2)} + \vec{F}_i^{p(k)(2)} + \vec{F}_i^{po(k-m)(2)}\right) \end{Vmatrix}. \qquad (10)$$

Endi (4) tenglamalardagi tashqi yukning $\vec{F}^{p(k)}$ qo'shiluvchilarini A.A. Samarskiy - I.V. Fryazinov modifikatsiyasida chekli ayirmalar usuli bo'yicha approksimatsiyalaymiz:

$$\frac{1}{h}\left[A_{i+1/2}^{p(k)}\frac{\vec{V}_{i+1}^{0(k-1)(1)} - \vec{V}_i^{0(k-1)(1)}}{h} - A_{i-1/2}^{p(k)}\frac{\vec{V}_i^{0(k-1)(1)} - \vec{V}_{i-1}^{0(k-1)(1)}}{h}\right] +$$
$$+\frac{B_{i+1}^{p(k)}\vec{V}_{i+1}^{0(k-1)(2)} - B_i^{p(k)}\vec{V}_i^{0(k-1)(2)}}{h} + C_i^{p(k)}\frac{\vec{V}_{i+1}^{0(k-1)(2)} - \vec{V}_i^{0(k-1)(2)}}{h} +$$
$$+ D_i^{p(k)}\vec{V}_i^{0(k-1)(1)} = \vec{F}_i^{p(k)(1)},$$

$$\frac{1}{h}\left[A_{i+1/2}^{p(k)}\frac{\vec{V}_{i+1}^{0(k-1)(2)} - \vec{V}_i^{0(k-1)(2)}}{h} - A_{i-1/2}^{p(k)}\frac{\vec{V}_i^{0(k-1)(2)} - \vec{V}_{i-1}^{0(k-1)(2)}}{h}\right] +$$
$$+\frac{B_i^{p(k)}\vec{V}_i^{0(k-1)(1)} - B_{i-1}^{p(k)}\vec{V}_{i-1}^{0(k-1)(1)}}{h} + C_i^{p(k)}\frac{\vec{V}_i^{0(k-1)(1)} - \vec{V}_{i-1}^{0(k-1)(1)}}{h} +$$
$$+ D_i^{p(k)}\vec{V}_i^{0(k-1)(2)} = \vec{F}_i^{p(k)(2)}. \qquad (11)$$

$\vec{U}_i^{0(k-1)} = \begin{bmatrix} \vec{V}_i^{0(k-1)(1)} \\ \vec{V}_i^{0(k-1)(2)} \end{bmatrix}$ vektorni kiritib, tashqi yuk tashkil etuvchilari sistemasini quyidagi ko'rinishda ifodalaymiz:

$$\hat{A}_i^{p(k)}\vec{U}_{i+1}^{0(k-1)} - \hat{B}_i^{p(k)}\vec{U}_i^{0(k-1)} + \hat{C}_i^{p(k)}\vec{U}_{i-1}^{0(k-1)} = \hat{F}_i^{p(k)} \text{ bunda } i = 1,2,...,n-1; \qquad (12)$$

bu yerda $\vec{U}_i^{0(k-1)}$ – ma'lum katakli vektor-funksiya; $\hat{A}_i^{p(k)}$, $\hat{B}_i^{p(k)}$ va $\hat{C}_i^{p(k)}$ – katakli matritsalar, $\hat{F}_i^{p(k)}$ – esa katakli vektor bo'lib, quyidagi ko'rinishda ifodalanadi:

DOI: 10.65322/j.srd.05192026.93

$$\hat{A}_i^{p(k)} = \begin{Vmatrix} \frac{A_{i+1/2}^{p(k)}}{h^2} & \frac{\left(B_{i+1}^{p(k)} + C_i^{p(k)}\right)}{h} \\ \theta & \frac{A_{i+1/2}^{p(k)}}{h^2} \end{Vmatrix}, \quad \hat{C}_i^{p(k)} = \begin{Vmatrix} \frac{A_{i-1/2}^{p(k)}}{h^2} & \theta \\ -\frac{B_{i-1}^{p(k)}}{h} - \frac{C_i^{p(k)}}{h} & \frac{A_{i-1/2}^{p(k)}}{h^2} \end{Vmatrix}, \quad (13)$$

$$\hat{B}_i^{p(k)} = \begin{Vmatrix} \frac{A_{i+1/2}^{p(k)}}{h^2} + \frac{A_{i-1/2}^{p(k)}}{h^2} - D_i^{p(k)} & \frac{\left(B_i^{p(k)} + C_i^{p(k)}\right)}{h} \\ -\frac{\left(B_i^{p(k)} + C_i^{p(k)}\right)}{h} & \frac{A_{i+1/2}^{p(k)}}{h^2} + \frac{A_{i-1/2}^{p(k)}}{h^2} - D_i^{p(k)} \end{Vmatrix}, \quad \hat{F}_i^{p(k)} = \begin{Vmatrix} \vec{F}_i^{p(k)^{(1)}} \\ \vec{F}_i^{p(k)^{(2)}} \end{Vmatrix}.$$

Shuningdek, (5) tenglamalardagi tashqi yukning $\vec{F}^{po(k-m)}$ qo'shiluvchilarini A.A. Samarskiy - I.V. Fryazinov modifikatsiyasi bo'yicha approksimatsiyalaymiz:

$$\sum_{m=1}^{k-1}\left\{\frac{1}{h}\left[A_{i+1/2}^{po(k-m)}\frac{\left(\vec{V}_{i+1}^{0(k-m)^{(1)}} - \vec{V}_{i+1}^{0(k-m-1)^{(1)}}\right) - \left(\vec{V}_i^{0(k-m)^{(1)}} - \vec{V}_i^{0(k-m-1)^{(1)}}\right)}{h} - \right.\right.$$

$$\left.\left. - A_{i-1/2}^{po(k-m)}\frac{\left(\vec{V}_i^{0(k-m)^{(1)}} - \vec{V}_i^{0(k-m-1)^{(1)}}\right) - \left(\vec{V}_{i-1}^{0(k-m)^{(1)}} - \vec{V}_{i-1}^{0(k-m-1)^{(1)}}\right)}{h}\right] + \right.$$

$$+ \frac{B_{i+1}^{po(k-m)}\left(\vec{V}_{i+1}^{0(k-m)^{(2)}} - \vec{V}_{i+1}^{0(k-m-1)^{(2)}}\right) - B_i^{po(k-m)}\left(\vec{V}_i^{0(k-m)^{(2)}} - \vec{V}_i^{0(k-m-1)^{(2)}}\right)}{h} +$$

$$+ C_i^{po(k-m)}\frac{\left(\vec{V}_{i+1}^{0(k-m)^{(2)}} - \vec{V}_{i+1}^{0(k-m-1)^{(2)}}\right) - \left(\vec{V}_i^{0(k-m)^{(2)}} - \vec{V}_i^{0(k-m-1)^{(2)}}\right)}{h} +$$

$$+ D_i^{po(k-m)}\left(\vec{V}_i^{0(k-m)^{(1)}} - \vec{V}_i^{0(k-m-1)^{(1)}}\right) = \vec{F}_i^{po(k-m)^{(1)}}$$

,

$$\sum_{m=1}^{k-1}\left\{\frac{1}{h}\left[A_{i+1/2}^{po(k-m)}\frac{\left(\vec{V}_{i+1}^{0(k-m)^{(2)}} - \vec{V}_{i+1}^{0(k-m-1)^{(2)}}\right) - \left(\vec{V}_i^{0(k-m)^{(2)}} - \vec{V}_i^{0(k-m-1)^{(2)}}\right)}{h} - \right.\right.$$

$$\left.\left. - A_{i-1/2}^{po(k-m)}\frac{\left(\vec{V}_i^{0(k-m)^{(2)}} - \vec{V}_i^{0(k-m-1)^{(2)}}\right) - \left(\vec{V}_{i-1}^{0(k-m)^{(2)}} - \vec{V}_{i-1}^{0(k-m-1)^{(2)}}\right)}{h}\right] + \right.$$

DOI: 10.65322/j.srd.05192026.93

$$+\frac{B_i^{po(k-m)}\left(\vec{V}_i^{0(k-m)^{(1)}}-\vec{V}_i^{0(k-m-1)^{(1)}}\right)-B_{i-1}^{po(k-m)}\left(\vec{V}_{i-1}^{0(k-m)^{(1)}}-\vec{V}_{i-1}^{0(k-m-1)^{(1)}}\right)}{h}+$$

$$+C_i^{po(k-m)}\frac{\left(\vec{V}_i^{0(k-m)^{(1)}}-\vec{V}_i^{0(k-m-1)^{(1)}}\right)-\left(\vec{V}_{i-1}^{0(k-m)^{(1)}}-\vec{V}_{i-1}^{0(k-m-1)^{(1)}}\right)}{h}+$$

$$+D_i^{po(k-m)}\left(\vec{V}_i^{0(k-m)^{(2)}}-\vec{V}_i^{0(k-m-1)^{(2)}}\right)=\vec{F}_i^{po(k-m)^{(2)}}.$$

(14)

$\vec{U}_i^{0(k-m)}-\vec{U}_i^{0(k-m-1)}=\begin{bmatrix}\left(\vec{V}_i^{0(k-m)(1)}-\vec{V}_i^{0(k-m-1)(1)}\right)\\ \left(\vec{V}_i^{0(k-m)(2)}-\vec{V}_i^{0(k-m-1)(2)}\right)\end{bmatrix}$ vektorni kiritib, tashqi yuk tashkil etuvchilari sistemasini (14) quyidagi ko'rinishda ifodalaymiz:

$$\hat{A}_i^{po(k-m)}\left(\vec{U}_{i+1}^{0(k-m)}-\vec{U}_{i+1}^{0(k-m-1)}\right)-\hat{B}_i^{po(k-m)}\left(\vec{U}_i^{0(k-m)}-\vec{U}_i^{0(k-m-1)}\right)+$$
$$+\hat{C}_i^{po(k-m)}\left(\vec{U}_{i-1}^{0(k-m)}-\vec{U}_{i-1}^{0(k-m-1)}\right)=\hat{F}_i^{po(k-m)} \quad (15)$$

bunda $i=1,2,...,n-1$.

Bu yerda $\left(\vec{U}_i^{0(k-m)}-\vec{U}_i^{0(k-m-1)}\right)$ – ma'lum katakli vektor-funksiya; $\hat{A}_i^{po(k-m)}$, $\hat{B}_i^{po(k-m)}$ va $\hat{C}_i^{po(k-m)}$ – katakli matritsalar, $\hat{F}_i^{po(k-m)}$ – esa katakli vektor bo'lib, quyidagi ko'rinishda ifodalanadi:

$$\hat{A}_i^{po(k-m)}=\begin{Vmatrix}\frac{A_{i+1/2}^{po(k-m)}}{h^2} & \frac{\left(B_{i+1}^{po(k-m)}+C_i^{po(k-m)}\right)}{h}\\ \theta & \frac{A_{i+1/2}^{po(k-m)}}{h^2}\end{Vmatrix},$$

$$\hat{B}_i^{po(k-m)}=\begin{Vmatrix}\frac{A_{i+1/2}^{po(k-m)}}{h^2}+\frac{A_{i-1/2}^{po(k-m)}}{h^2}-D_i^{po(k-m)} & \frac{\left(B_i^{po(k-m)}+C_i^{po(k-m)}\right)}{h}\\ -\frac{\left(B_i^{po(k-m)}+C_i^{po(k-m)}\right)}{h} & \frac{A_{i+1/2}^{po(k-m)}}{h^2}+\frac{A_{i-1/2}^{po(k-m)}}{h^2}-D_i^{po(k-m)}\end{Vmatrix},$$

$$\hat{C}_i^{po(k-m)}=\begin{Vmatrix}\frac{A_{i-1/2}^{po(k-m)}}{h^2} & \theta\\ -\frac{B_{i-1}^{po(k-m)}}{h}-\frac{C_i^{po(k-m)}}{h} & \frac{A_{i-1/2}^{po(k-m)}}{h^2}\end{Vmatrix},\quad \hat{F}_i^{po(k-m)}=\begin{Vmatrix}\vec{F}_i^{po(k-m)^{(1)}}\\ \vec{F}_i^{po(k-m)^{(2)}}\end{Vmatrix}. \quad (16)$$

(2) chegaraviy shartlarning A.A. Samarskiy - I.V. Fryazinov modifikatsiyasi bo'yicha approksimatsiyalari quyidagi ko'rinishga ega:

DOI: 10.65322/j.srd.05192026.93

$x=0$ va $x=N$:

$$\left.\begin{aligned}
&K_0\left(A_0^u-A_0^{p(k)}\right)\frac{-\vec{V}_2^{(k)^{(1)}}+4\vec{V}_1^{(k)^{(1)}}-3\vec{V}_0^{(k)^{(1)}}}{2h}+T_0\left(B_0^u-B_0^{p(k)}\right)\vec{V}_0^{(k)^{(1)}}=\\
&=\vec{Q}_0^{(k)^{(1)}}+\vec{Q}_0^{p(k)^{(1)}}+\vec{Q}_0^{po(k-m)^{(1)}},\\
&K_0\left(A_0^u-A_0^{p(k)}\right)\frac{-\vec{V}_2^{(k)^{(2)}}+4\vec{V}_1^{(k)^{(2)}}-3\vec{V}_0^{(k)^{(2)}}}{2h}+T_0\left(B_0^u-B_0^{p(k)}\right)\vec{V}_0^{(k)^{(2)}}=\\
&=\vec{Q}_0^{(k)^{(2)}}+\vec{Q}_0^{p(k)^{(2)}}+\vec{Q}_0^{po(k-m)^{(2)}},\\
&-K_N\left(A_N^u-A_N^{p(k)}\right)\frac{3\vec{V}_N^{(k)^{(1)}}-4\vec{V}_{N-1}^{(k)^{(1)}}+\vec{V}_{N-2}^{(k)^{(1)}}}{2h}+T_N\left(B_N^u-B_N^{p(k)}\right)\vec{V}_N^{(k)^{(1)}}=\\
&=\vec{Q}_N^{(k)^{(1)}}+\vec{Q}_N^{p(k)^{(1)}}+\vec{Q}_N^{po(k-m)^{(1)}},\\
&-K_N\left(A_N^u-A_N^{p(k)}\right)\frac{3\vec{V}_N^{(k)^{(2)}}-4\vec{V}_{N-1}^{(k)^{(2)}}+\vec{V}_{N-2}^{(k)^{(2)}}}{2h}+T_N\left(B_N^u-B_N^{p(k)}\right)\vec{V}_N^{(k)^{(2)}}=\\
&=\vec{Q}_N^{(k)^{(2)}}+\vec{Q}_N^{p(k)^{(2)}}+\vec{Q}_N^{po(k-m)^{(2)}}.
\end{aligned}\right\} \tag{17}$$

(17) dagi o'xshash hadlarni ixchamlaymiz va quyidagiga ega bo'lamiz:

$$\left.\begin{aligned}
&\left(2hT_0\left(B_0^u-B_0^{p(k)}\right)-3K_0\left(A_0^u-A_0^{p(k)}\right)\right)\vec{V}_0^{(k)^{(\alpha)}}+4K_0\left(A_0^u-A_0^{p(k)}\right)\vec{V}_1^{(k)^{(\alpha)}}-\\
&-K_0\left(A_0^{yn}-A_0^{n\pi(k)}\right)\vec{V}_2^{(k)^{(\alpha)}}=2h\left(\vec{Q}_0^{(k)^{(\alpha)}}+\vec{Q}_0^{p(k)^{(\alpha)}}+\vec{Q}_0^{po(k-m)^{(\alpha)}}\right),\\
&\left(2hT_N\left(B_N^u-B_N^{p(k)}\right)-3K_N\left(A_N^u-A_N^{p(k)}\right)\right)\vec{V}_N^{(k)^{(\alpha)}}+4K_N\left(A_N^u-A_N^{p(k)}\right)\vec{V}_{N-1}^{(k)^{(\alpha)}}-\\
&-K_N\left(A_N^{yn}-A_N^{n\pi(k)}\right)\vec{V}_{N-2}^{(k)^{(\alpha)}}=2h\left(\vec{Q}_N^{(k)^{(\alpha)}}+\vec{Q}_N^{p(k)^{(\alpha)}}+\vec{Q}_N^{po(k-m)^{(\alpha)}}\right),
\end{aligned}\right\} \tag{18}$$

bu yerda $\alpha=1,2$.

$\vec{U}_i^{(k)}=\begin{bmatrix}\vec{V}_i^{(k)(1)}\\ \vec{V}_i^{(k)(2)}\end{bmatrix}$ vektorni kiritib, (18) chegaraviy shartlar sistemasini quyidagi ko'rinishda ifodalaymiz:

$$i=0 \qquad \hat{L}_0^{(k)}\vec{U}_0^{(k)}+\hat{L}_1^{(k)}\vec{U}_1^{(k)}+\hat{L}_2^{(k)}\vec{U}_2^{(k)}=\hat{Q}_i^{(k)}, \tag{19}$$

$$i=N \qquad \hat{L}_3^{(k)}\vec{U}_N^{(k)}+\hat{L}_4^{(k)}\vec{U}_{N-1}^{(k)}+\hat{L}_5^{(k)}\vec{U}_{N-2}^{(k)}=\hat{Q}_i^{(k)}; \tag{20}$$

bu yerda $\hat{L}_\beta^{(k)}$ $\left(\beta=\overline{0,1,...,5}\right)$ – katakli matritsalar, $\hat{Q}_i^{(k)}$ – esa katakli vektor bo'lib, quyidagi ko'rinishda ifodalanadi:

DOI: 10.65322/j.srd.05192026.93

$$\hat{L}_0^{(k)} = \begin{Vmatrix} 2hT_0\left(B_0^u - B_0^{p(k)}\right) - 3K_0\left(A_0^u - A_0^{p(k)}\right) & \theta \\ \theta & 2hT_0\left(B_0^u - B_0^{p(k)}\right) - 3K_0\left(A_0^u - A_0^{p(k)}\right) \end{Vmatrix},$$

$$\hat{L}_1^{(k)} = \begin{Vmatrix} 4K_0\left(A_0^u - A_0^{p(k)}\right) & \theta \\ \theta & 4K_0\left(A_0^u - A_0^{p(k)}\right) \end{Vmatrix},$$

$$\hat{L}_2^{(k)} = \begin{Vmatrix} -K_0\left(A_0^u - A_0^{p(k)}\right) & \theta \\ \theta & -K_0\left(A_0^u - A_0^{p(k)}\right) \end{Vmatrix},$$

$$\hat{L}_3^{(k)} = \begin{Vmatrix} 2hT_N\left(B_N^u - B_N^{p(k)}\right) - 3K_N\left(A_N^u - A_N^{p(k)}\right) & \theta \\ \theta & 2hT_N\left(B_N^u - B_N^{p(k)}\right) - 3K_N\left(A_N^u - A_N^{p(k)}\right) \end{Vmatrix},$$

$$\hat{L}_4^{(k)} = \begin{Vmatrix} 4K_N\left(A_N^u - A_N^{p(k)}\right) & \theta \\ \theta & 4K_N\left(A_N^u - A_N^{p(k)}\right) \end{Vmatrix},$$

$$\hat{L}_5^{(k)} = \begin{Vmatrix} -K_N\left(A_N^u - A_N^{p(k)}\right) & \theta \\ \theta & -K_N\left(A_N^u - A_N^{p(k)}\right) \end{Vmatrix},$$

$$\hat{Q}_i^{(k)} = \begin{Vmatrix} 2h\left(\vec{Q}_i^{(k)^{(1)}} + \vec{Q}_i^{p(k)^{(1)}} + \vec{Q}_i^{po(k-m)^{(1)}}\right) \\ 2h\left(\vec{Q}_i^{(k)^{(2)}} + \vec{Q}_i^{p(k)^{(2)}} + \vec{Q}_i^{po(k-m)^{(2)}}\right) \end{Vmatrix}.$$

(2) chegaraviy shartlar tashkil etuvchilarining A.A. Samarskiy - I.V. Fryazinov modifikatsiyasi bo'yicha approksimatsiyalari quyidagi ko'rinishga ega:

$$\begin{cases} A_0^{p(k)} \dfrac{-\vec{V}_2^{0(k-1)^{(1)}} + 4\vec{V}_1^{0(k-1)^{(1)}} - 3\vec{V}_0^{0(k-1)^{(1)}}}{2h} + B_0^{p(k)}\vec{V}_0^{0(k-1)^{(1)}} = \vec{Q}_0^{p(k)^{(1)}}, \\ A_0^{p(k)} \dfrac{-\vec{V}_2^{0(k-1)^{(2)}} + 4\vec{V}_1^{0(k-1)^{(2)}} - 3\vec{V}_0^{0(k-1)^{(2)}}}{2h} + B_0^{p(k)}\vec{V}_0^{0(k-1)^{(2)}} = \vec{Q}_0^{p(k)^{(2)}}, \\ -A_N^{p(k)} \dfrac{3\vec{V}_N^{0(k-1)^{(1)}} - 4\vec{V}_{N-1}^{0(k-1)^{(1)}} + \vec{V}_{N-2}^{0(k-1)^{(1)}}}{2h} + B_N^{p(k)}\vec{V}_N^{0(k-1)^{(1)}} = \vec{Q}_N^{p(k)^{(1)}}, \\ -A_N^{p(k)} \dfrac{3\vec{V}_N^{0(k-1)^{(2)}} - 4\vec{V}_{N-1}^{0(k-1)^{(2)}} + \vec{V}_{N-2}^{0(k-1)^{(2)}}}{2h} + B_N^{p(k)}\vec{V}_N^{0(k-1)^{(2)}} = \vec{Q}_N^{p(k)^{(2)}}. \end{cases}$$

O'xshash hadlarni ixchamlaymiz va quyidagiga ega bo'lamiz:

DOI: 10.65322/j.srd.05192026.93

$$\left.\begin{aligned}\left(B_0^{p(k)}-\frac{3A_0^{p(k)}}{2h}\right)\vec{V}_0^{0(k-1)^{(\alpha)}}+\frac{4A_0^{p(k)}\vec{V}_1^{0(k-1)^{(\alpha)}}}{2h}-\frac{A_0^{p(k)}\vec{V}_2^{0(k-1)^{(\alpha)}}}{2h}=\vec{Q}_0^{p(k)^{(\alpha)}},\\ \left(B_N^{p(k)}-\frac{3A_N^{p(k)}}{2h}\right)\vec{V}_N^{0(k-1)^{(\alpha)}}+\frac{4A_N^{p(k)}\vec{V}_{N-1}^{0(k-1)^{(\alpha)}}}{2h}-\frac{A_N^{p(k)}\vec{V}_{N-2}^{0(k-1)^{(\alpha)}}}{2h}=\vec{Q}_N^{p(k)^{(\alpha)}}.\end{aligned}\right\} \tag{21}$$

$\vec{U}_i^{0(k-1)}=\begin{bmatrix}\vec{V}_i^{0(k-1)(1)}\\ \vec{V}_i^{0(k-1)(2)}\end{bmatrix}$ vektorni kiritib, (21) chegaraviy yuklar tashkil etuvchilari sistemasini quyidagi ko'rinishda ifodalaymiz:

$$i=0: \quad \hat{M}_0^{(k)}\vec{U}_0^{0(k-1)}+\hat{M}_1^{(k)}\vec{U}_1^{0(k-1)}+\hat{M}_2^{(k)}\vec{U}_2^{0(k-1)}=\hat{Q}_i^{p(k)}, \tag{22}$$

$$i=N: \quad \hat{M}_3^{(k)}\vec{U}_N^{0(k-1)}+\hat{M}_4^{(k)}\vec{U}_{N-1}^{0(k-1)}+\hat{M}_5^{(k)}\vec{U}_{N-2}^{0(k-1)}=\hat{Q}_i^{p(k)}; \tag{23}$$

bu yerda $\hat{M}_\beta^{(k)}\ \left(\beta=\overline{0,1,...,5}\right)$ – katakli matritsalar, $\hat{Q}_i^{p(k)}$ – esa katakli vektordir.

Shakllantirilgan (9), (19)-(20), (22)-(23) Koshi masalalarini yechish uchun matritsali haydash usulidan [1] foydalanamiz, unda to'g'ri yo'lda haydash koeffitsiyentlari hisoblanadi, teskari yo'lda esa (9) algebraik tenglamalar sistemasining yechimi topiladi.

Yechimni quyidagi ko'rinishda izlaymiz

$$\vec{U}_i^{(k)}=\hat{\alpha}_i^{(k)}\vec{U}_{i+1}^{(k)}+\vec{\beta}_i^{(k)} \quad \text{bunda} \quad i=N-1,....,1; \tag{24}$$

bu yerda $\hat{\alpha}_i^{(k)}$ va $\vec{\beta}_i^{(k)}$ – hozircha aniqlanmagan katakli matritsalar va vektorlar. Bu parametrlarni hisoblash uchun quyidagi rekurrent formulalarni olish mumkin [1]:

$$\hat{\alpha}_i^{(k)}=\left(\hat{B}_i^{(k)}-\hat{C}_i^{(k)}\hat{\alpha}_{i-1}^{(k)}\right)^{-1}\hat{A}_i^{(k)}, \quad \vec{\beta}_i^{(k)}=\left(\hat{B}_i^{(k)}-\hat{C}_i^{(k)}\hat{\alpha}_{i-1}^{(k)}\right)^{-1}\left(\hat{C}_i^{(k)}\vec{\beta}_{i-1}^{(k)}-\vec{F}_i^{(k)}\right); \quad i=1,2,3,...,N-1. \tag{25}$$

Har bir yuklanishda $\vec{U}_i^{(k)}$ ko'chishlar vektori Koshi masalasidan aniqlanadi. Hisoblash algoritmining oxirgi bosqichida ko'chishlar vektorining haqiqiy qiymatlari quyidagicha aniqlanadi:

$$\vec{V}_i^{(k,\gamma)}=\frac{\vec{V}_i^{(k)^{(1)}}+\vec{V}_i^{(k)^{(2)}}}{2}. \tag{26}$$

Bunda quyidagi shartlar ta'minlanishi kerak:

$$\max_i\left|\vec{V}_i^{(k,\bar{\gamma}+1)}-\vec{V}_i^{(k,\bar{\gamma})}\right|<\varepsilon_1\max_i\left|\vec{V}_i^{(k,\bar{\gamma}+1)}\right|, \tag{27}$$

bu yerda $\bar{\gamma}$ – iteratsiyalar soni; ε_1 – hisoblash aniqligi; k – takroriy-o'zgaruvchan yuklanishlar soni.

Xulosa. Joriy va fiktiv koordinatalar sistemalarida fazoviy o'zgaruvchan yuklanishda sterjenlarning kuchlanganlik holatini tadqiq qilish uchun tabiiy chegaraviy shartlarga ega ikkinchi tartibli nochiziqli differensial tenglamalar sistemalari bilan tavsiflanadigan ko'p parametrli

DOI: 10.65322/j.srd.05192026.93

matematik modellar ishlab chiqildi. Ushbu modellar turli yondashuvlar asosida siklik yuklanishda sterjenlarning kuchlanganlik holatini tadqiq qilish imkoniyatini ta'minlaydi

Takroriy-o'zgaruvchan elastik-plastik yuklanishlarda fazoviy sterjenlar masalalarini yechish uchun tabiiy chegaraviy shartlarga ega to'qqizta nochiziqli differensial tenglamalar sistemasining tezroq yaqinlashish imkoniyatini ta'minlaydi.

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