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Evaluation of the operational reliability of metro car bogie frames based on finite element method and optimization models

A.M. Yusufov[1][a], Sh.Kh. Abdurasulov[1][b], A.P. Vohidov[1], J. Ulugov[1], A. Mahmudjanov[1]
[1]Tashkent state transport university, Tashkent, Uzbekistan

Abstract: This article analyzes the technical condition and reliability of metro car bogie frames during long-term operation. Within the scope of the study, typical failures occurring in bogie frames are systematized, and their causes and consequences are identified. The stress-strain state and the factor of safety of the structure are analyzed using the Finite Element Method (FEM). Furthermore, a mathematical model based on Palmgren-Miner's fatigue theory is proposed to estimate the residual service life of the frames and optimize the maintenance process. Solving the model using the simplex method allows for transitioning from a "maintenance based on service life" strategy to a "maintenance based on technical condition" strategy, thereby reducing costs associated with unscheduled repairs.
Keywords: bogie frame, finite element method (FEM), metal fatigue, maintenance, optimization, mathematical model, simplex method, reliability, residual life, non-destructive testing

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Metropoliten vagonlari aravacha ramalarining ekspluatatsion ishonchliligini chekli elementlar usuli va optimallashtirish modellari asosida baholash

Yusufov A.M.[1][a], Abdurasulov Sh.X.[1][b], Vohidov A.P.[1], Ulugov J.[1], Mahmudjanov A.[1]
[1]Toshkent davlat transport universiteti, Toshkent, Uzbekistan

Annotatsiya: Mazkur maqolada metropoliten vagonlari aravacha ramalarining uzoq muddatli ekspluatatsiya jarayonidagi texnik holati va ishonchliligi tahlil qilingan. Tadqiqot doirasida aravacha ramalarida yuzaga keladigan tipik nosozliklar tizimlashtirilib, ularning kelib chiqish sabablari va oqibatlari aniqlangan. Chekli elementlar usuli (ChEU) yordamida konstruksiyaning kuchlanganlik-deformatsiya holati (KDH) va mustahkamlik zaxirasi koeffitsienti tahlil qilingan. Shuningdek, ramalarning qoldiq resursini baholash va texnik xizmat ko'rsatish jarayonini optimallashtirish maqsadida Palmgren-Maynerning charchoqlik nazariyasiga asoslangan matematik model taklif etilgan. Modelning simpleks-usul yordamida yechilishi "foydalanilgan resurs bo'yicha xizmat ko'rsatish"dan "texnik holati bo'yicha xizmat ko'rsatish" strategiyasiga o'tish hamda rejadan tashqari ta'mirlash xarajatlarini kamaytirish imkonini beradi.
Kalit so'zlar: aravacha ramasi, chekli elementlar usuli (ChEU), metall toliqishi, texnik xizmat ko'rsatish, optimallashtirish, matematik model, simpleks-usul, ishonchlilik, qoldiq resurs, putur yetkazmasdan tekshirish

1. Kirish

MDH mamlakatlari metropolitenlarida o'nlab yillar davomida metropoliten harakatlanuvchi tarkiblari asosiy harakat tarkibi bo'lib kelmoqda. Vagon telejkasi lokomotiv va vagonlarning eng muhim, yuqori yuklanish ostida ishlaydigan konstruktiv qismlaridan biri hisoblanadi. Uning texnik holati nafaqat vagonning yurish sifatiga, balki temir yo'l harakati xavfsizligini ta'minlashning hal qiluvchi omili hisoblanadi [1-3].

Jadal foydalanish sharoitida, ayniqsa belgilangan xizmat muddatini o'tab bo'lgan vagonlarda, telejka ramasi elementlarida metallning charchoqlik hodisalari natijasida mikro-yoriqlar va boshqa turdagi shikastlanishlar to'planib boradi [4-8]. Metall konstruksiyadagi bunday nuqsonlarning o'z vaqtida tashxis qilinmasligi hamda shikastlangan qismlarning o'z vaqtida almashtirilmasligi, yakuniy natijada vagonning kutilmagan nosozliklariga, ekspluatatsiya xarajatlarining oshishiga va butun harakat tarkibining ishonchliligi pasayishiga olib keladi.

Mazkur maqolaning maqsadi metropoliten aravacha ramasi konstruksiyasining kuchlanish holatini tahlil qilish, unda uchraydigan tipik nosozliklarni tizimlashtirish hamda ramalarning qoldiq resursini baholash va ularning xizmat muddatini uzaytirish bo'yicha samarali texnik tavsiyalarni ishlab chiqishdan iborat [9-14].

2. Tadqiqot metodologiyasi

Aravacha ramasining tuzilishi

Metropiten harakat tarkibidagi 81-714 va 81-717 rusumli vagonlar telejkalari tortuvchi elektr dvigatellarni ramaga tayanchli osma sxemasi asosida loyihalashtirilgan murakkab payvandlangan konstruksiya hisoblanadi. Yurish qismining konstruktiv parametrlari quyidagi ma'lumotlar bilan tavsiflanadi: telejka bazasi 2100 mm, jihozlari bilan

[a] https://orcid.org/ 0000-0002-1651-5493
[b] https://orcid.org/0000-0001-5581-507X

birga yuklangan holdagi massasi 7,55 tonnani tashkil etadi, g‘ildirakning aylana bo‘ylab diametri esa 780 mm ga teng.

Telejka ramasi statik va dinamik yuklamalarni qabul qiluvchi asosiy ko‘taruvchi element hisoblanadi. U ikkita quti ko‘rinishidagi kesimga ega bo‘lgan bo‘ylama va ikkita ko‘ndalang balkadan tashkil topgan qattiq fazoviy payvandlangan konstruksiyadir. Kesimning bunday geometriyasi egilish va burilishga nisbatan yuqori qarshilik momentini ta’minlaydi, bu metropoliten sharoitida foydalanishda o‘ta muhim ahamiyatga ega.

Konstruksiyada tortuvchi dvigatellarni osib qo‘yish tugunlariga alohida e’tibor qaratilgan. Ko‘ndalang balkalarning birida dvigatelni osish tizimi ko‘zda tutilgan bo‘lib, bunda reaktiv tortqi yuklamalarni qayta taqsimlashda kalit rolini o‘ynaydi va tortuvchi uzatma ishlaganda yuzaga keladigan buruvchi momentlar hamda og‘irlik yuklamalaridan ramani tushiradi (yukini yengillashtiradi). Payvandlangan birikmalardan foydalanish ishlab chiqarish bosqichlarida sifatni qat’iy nazorat qilishni, ekspluatatsiya jarayonida esa kuchlanish to‘plangan zonalarda charchoqlik yoriqlari rivojlanishining oldini olish uchun vaqti-vaqti bilan ultratovush yoki magnit kukunli nazorat o‘tkazishni talab qiladi [15-18].

Aravacha ramalaridagi nosozliklar tahlili

“Toshkent metropoliteni” AJ harakat tarkibi vagonlari ekspluatatsiya ma’lumotlarining tahlili shuni ko‘rsatadiki, telejka ramalaridagi barcha nosozliklarning 49,1–64,7 foizi yetaklovchi kronshteynlar va markaziy osma tizimining qoplamalari hissasiga to‘g‘ri keladi.

“Toshkent metropoliteni” AJ parkidagi vagonlarning ramali telejkalarida kuzatiladigan nosozliklar ushbu rasmda keltirilgan. Nosozlikkacha bo‘lgan o‘rtacha ishlash muddati (resurs) $1102{,}5 \times 10^3$ km ni tashkil etadi, belgilangan me’yoriy resurs esa 2500×10^3 km ga teng. Bu shuni anglatadiki, konstruksiyaning amaldagi resursi me’yoriy ko‘rsatkichning yarmidan ham kamroqdir.

Tekshiruvlar natijasida quyidagi turdagi shikastlanishlar aniqlandi:

- Bo‘ylama balkalardagi yoriqlar — siklik yuklamalar ta’sirida kuchlanishlarning charchoqlik natijasida to‘planishi oqibatida o‘rta shpinton vtulka zonasida hosil bo‘ladi.
- Yetaklovchi kronshteynlarning buzilishi — reaktiv tortqini mahkamlash tugunining yetarlicha qattiq emasligi tufayli yuzaga keladigan eng tez-tez uchraydigan nosozlik turi.
- Markaziy osma tizimi qoplamalarining yeyilishi — bu tirqishlarning kattalashishiga va dinamik tavsiflarning yomonlashishiga olib keladi.
- Reduktor kronshteynlari deformatsiyasi — yo‘lning zarbiy yuklamalari uzoq vaqt ta’sir etishi natijasida yuzaga keladi.
- Payvand choklarining shikastlanishi — kuchlanish to‘plangan zonalarda (balkalar tutashgan joylarda) qatlamlarga ajralish va yoriqlar.
- Korroziyaviy shikastlanishlar — tunnel sharoitida ekspluatatsiya qilinadigan, himoya qoplamasi bo‘lmagan yuzalar uchun xosdir.

Nosozliklarning turlar bo‘yicha taqsimoti 2-jadvalda keltirilgan.

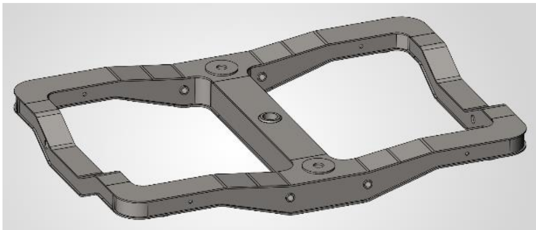
2-jadval

Metropiten aravacha ramasining nosozliklari

Nosozlik turi	**%**	**Sababi**	**Oqibati**
Yetaklovchi kronshteynlarning shikastlanishi	35,2	Metall charchoqligi, zarbiy yuklamalar	Tortish kinematikasi-ning buzilishi
Osma tizimi qoplamalarining yeyilishi	29,5	Ishqalanish, moylashning yetarli emasligi	Dinamikaning yomon-lashishi
Bo‘ylama balkalardagi yoriqlar	18,7	Kuchlanish konsentrat-siyasi	Ko‘taruv-chanlik qobiliyatini yo‘qotish xavfi
Payvand choklarining shikastlanishi	11,3	Charchoqlik, tebranish yuklamalari	Rama tugunlarining qatlamlarga ajralishi
Boshqa nuqsonlar	5,3	Turli omillar	Ishonchlilik-ning pasayishi

Aravacha ramasining chekli elementlar usuli asosida mustahkamlik tahlili

Metropoliten vagonlari telejka ramasining konstruktiv yaxlitligini baholash maqsadida zamonaviy muhandislik dasturiy ta’minoti yordamida chekli elementlar usuli (ChEU) tatbiq etildi. Tahlil jarayoni geometrik modellashtirish, diskretizatsiya va statik kuchlanishlar holatini o‘rganish bosqichlarini qamrab oldi. Quyidagi 1-rasmda aravacha ramasining 3D modeli keltirib o‘tilgan.



1-rasm. Aravacha ramasining 3D modeli

Tadqiqotning dastlabki bosqichida aravacha ramasining yuqori aniqlikdagi chekli elementlar to‘ri 2-rasmda keltirib o‘tilgan [19]. Model hisob-kitobni aniqligini ta’minlash maqsadida “aralash egri chiziqli” usulda diskretizatsiya qilindi.

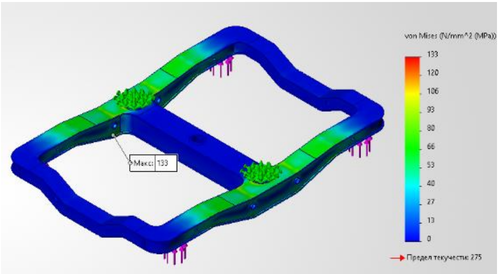
2-rasm. Telejka ramasi konstruksiyasining chekli elementlar to‘ri

Tahlil jarayoning texnik parametrlariga ko‘ra, 202 409 tugun va 97 223 elementdan iborat ushbu modelda elementlarning 92,7 foizi sifat ko‘rsatkichi bo‘yicha 3 dan kichik bo‘lgan tomonlar nisbatiga ega ekanligi aniqlandi. Mustahkamlik hisobi tahlili uchun asosiy texnik parametrlar 3-rasmda keltirib o‘tilgan.

Имя исследования	Metro_Aravachasi* (-По умолчанию-)
ДетализацияТип сетки	Сетка на твердом теле
Используемое разбиение	Сетка на основе смешанной кривизны
Точки Якобиана для сетки высокого качества	16 точек
Макс. размер элемента	30 mm
Мин размер элемента	1,5 mm
Качество сетки	Высокая
Всего узлов	202409
Всего элементов	97223
Максимальное соотношение сторон	10,748
Процент элементов с соотношением сторон < 3	92,7
Процент элементов с соотношением сторон > 10	0,00206
Процент искаженных элементов	0
Число искаженных элементов	0
Заново создать независимую сетку из неудавшихся деталей	Выкл
Повторно использовать сетку для одинаковых тел	Выкл
Количество тел, для которых была повторно использована сетка	0
Время для завершения сетки (hh:mm:ss)	00:00:27

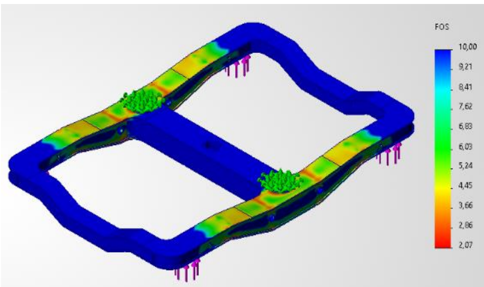
3-rasm. Sonli tahlil uchun kiritilgan asosiy texnik parametrlar

Ekspluatatsion yuklamalar ta'sirida Von Mises kuchlanishlarining taqsimlanishi tahlili 4-rasmda keltirib o'tilgan. Natijalar maksimal kuchlanish qiymati 133 MPa ekanligini ko'rsatdi, bu qiymatlar asosan kronshteynlar va payvand choklariga to'g'ri keladi.



4-rasm. Ekspluatatsion yuklamalar ostidagi kuchlanganlik-deformatsiya holati epyurasi

Xavfsizlik koeffitsienti tahlili natijalari konstruksiyaning eng yuqori kuchlanish zonalari, xususan, kronshteynlar va payvand choklarida ham mustahkamlik zahirasi 2,07 ekanligi aniqlani [20]. Ushbu ko'rsatkich materialning oquvchanlik chegarasi va amaldagi kuchlanishlar o'rtasidagi farq statik yuklanishlar uchun yetarli mustahkamlik zaxirasini ta'minlashini ko'rsatadi. 5-rasmda keltirilgan diskretizatsiya parametrlarining yuqori sifat darajasi (92,7% elementlar 3 dan kichik tomonlar nisbatiga egaligi) olingan natijalarning ishonchliligini kafolatlaydi. Shunday bo'lsa-da, ekspluatatsiya jarayonidagi siklik dinamik tebranishlar va tunnel sharoitidagi korroziya omillari ushbu zaxirani vaqt o'tishi bilan kamaytirishi mumkin. Binobarin, mazkur zaxira koeffitsienti statik xavfsizlikni ta'minlasa-da, charchoqlik nazariyasi asosida dinamik ishonchlilikni muntazam nazorat qilish zarur.



5-rasm. Aravacha ramasining mustahkamlik zahira koeffitsienti epyurasi

Ushbu ChEU tahlili shuni isbotlaydiki, rejadan tashqari ta'mirlash xarajatlarini kamaytirish uchun mustahkamlik zahira koeffisienti qiymati pastroq bo'lgan qizil va sariq rangli hududlar (kronshteynlar va payvand choklari) muntazam ravishda putur yetkazmasdan tekshiruv obyekti bo'lishi shart. Ushbu vizual va raqamli natijalar keyingi bo'limda taklif etilayotgan matematik optimallashtirish modeli uchun asosiy ilmiy asos bo'lib xizmat qiladi[21].

3. Natija va muhokamalar

Resursni baholash va optimallashtirishning matematik modeli

Telejka ramasining qoldiq resursini miqdoriy baholash uchun Palmgren-Maynerning charchoqlik shikastlanishlarini jamlashning chiziqli qonuniga asoslangan modeldan foydalanish taklif etiladi. Texnik xizmat ko'rsatish (TXK) uchun resurslarni taqsimlashni optimallashtirish masalasi ekspluatatsiya xarajatlarini minimallashtirish va ishonchlilik hamda harakat xavfsizligi cheklovlariga rioya qilish vazifasi sifatida shakllantiriladi.

Ekspluatatsiya xarajatlarini minimallashtirishning maqsadli funksiyasi quyidagi ko'rinishga ega:

$$Z = \sum_{i=1}^{n} c_i \cdot x_i \to \min$$

Cheklovlar tizimiga rioya qilgan holda:

$$\sum_{i=1}^{n} a_{ij} \cdot x_i \geq R_j, \quad j = 1,2,\dots,m$$

Bu yerda:

- Z — ramaning soz holatini saqlash uchun ketadigan umumiy ekspluatatsiya xarajatlari;
- c_i — i-elementga (kronshteynlar, qoplamalar, payvand choklari) xizmat ko'rsatishning solishtirma qiymati;
- x_i — i-elementga ajratiladigan resurs hajmi (moliyaviy yoki vaqt ko'rinishida);
- a_{ij} — i-elementning ishonchlilik bo'yicha j-cheklovga ta'sir koeffitsienti;
- R_j — ishonchlilik (xavfsizlik) bo'yicha j-mezonning minimal ruxsat etilgan qiymati.

Modelning amaliy tatbiqida uchta kritik tugunni ko'rib chiqamiz: x_1 — yetaklovchi (povodkovaya) kronshteynlar, x_2 — markaziy osma tizimining qoplamalari, x_3 — bo'ylama balkalarning payvand choklari. c_1, c_2, c_3 solishtirma xarajatlarning vazn koeffitsientlari berilganda, cheklovlar tizimi quyidagi ko'rinishni oladi:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 \geq R_{min\_yuk} \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 \geq R_{xizmat\_davri} \end{cases}$$

Bu yerda:

- R_{min_yuk} — konstruksiyaning statik va dinamik yuklamalarni qabul qilish bo'yicha minimal talab qilinadigan chidamlilik chegarasi;
- $R_{xizmat\ davri}$ — ramaning belgilangan xizmat muddati davomida ishlash qobiliyatini ta'minlovchi resurs ko'rsatkichi.

Ushbu masalani simpleks-usul yordamida yechish telejkaning har bir tuguniga xizmat koʻrsatish uchun xarajatlarni taqsimlashning optimal strategiyasini aniqlash imkonini beradi. Ushbu matematik modelni qoʻllash “foydalanilgan resurs boʻyicha xizmat koʻrsatish strategiyasidan” “texnik holati boʻyicha xizmat koʻrsatish” strategiyasiga oʻtishni ta’minlaydi, bu esa rejadan tashqari ta’mirlash hajmini kamaytirish va ta’mirlash deposi moddiy resurslarini oqilona ishlatishga imkon beradi.

4. Xulosa

Olib borilgan tadqiqotlar va metropoliten harakatlanuvchi tarkiblar aravacha ramalarining ekspluatatsiya jarayonini tahlil qilish shuni koʻrsatadiki, amaldagi texnik xizmat koʻrsatish tizimi zamonaviy talablarga toʻliq javob bermaydi. Konstruksiyalarning faktik resursi belgilangan me’yoriy koʻrsatkichning yarmidan ham kamroqni tashkil etishi tizimli yondashuvni tubdan qayta koʻrib chiqish zaruratini belgilaydi.

Tadqiqot natijalari shuni tasdiqlaydiki, aravacha ramalaridagi nosozliklarning asosiy qismi, xususan, yetaklovchi kronshteynlar va markaziy osma tizimi qoplamalarining shikastlanishi, konstruksiyaning yuqori dinamik va tebranish yuklamalari ostida ishlashi bilan bevosita bogʻliq. Chekli elementlar usuli (ChEU) yordamida oʻtkazilgan sonli tahlillar maksimal kuchlanish konsentratsiyalari aynan kronshteynlar va payvand choklari tutashgan kritik zonalarga toʻgʻri kelishini ilmiy jihatdan asosladi.

Taklif etilgan optimallashtirish modeli asosida “foydalanilgan resurs boʻyicha xizmat koʻrsatish” dan “texnik holati boʻyicha xizmat koʻrsatish” strategiyasiga oʻtish rejadan tashqari ta’mirlash xarajatlarini sezilarli darajada qisqartirishning yagona samarali yoʻlidir. Bunda simpleks-usul yordamida moddiy resurslarni eng zaif va muhim tugunlarga yoʻnaltirish ramalarning konstruktiv ishonchliligini oshiradi. Shuningdek, metall konstruksiyalarda charchoqlik yoriqlarini barvaqt aniqlash uchun muntazam ravishda putur yetkazmasdan tekshirish usullarini joriy etish hamda tunnel sharoitidagi korroziyaga qarshi kurashish choralarini kuchaytirish harakat xavfsizligini ta’minlashning asosiy kafolatidir.

Umuman olganda, ishlab chiqilgan matematik model va sonli tahlil natijalari “Toshkent metropoliteni” AJ harakat tarkibining texnik ishonchliligini oshirish, ekspluatatsiya xarajatlarini optimallashtirish va vagonlar aravacha ramalarining xizmat muddatini samarali uzaytirish uchun muhim ilmiy-texnik baza boʻlib xizmat qiladi.

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Mualliflar to‘g‘risida ma’lumot/ Information about the authors

Yusufov Abdulaziz / Abdulaziz Yusufov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrasi dotsenti, t.f.f.d., (PhD), E-mail: abdulazizyusufovv@bk.ru Tel.: +99894 308 88 08 https://orcid.org/ 0000-0002-1651-5493

Abdurasulov Sherzamin / Sherzamin Abdurasulov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrasi katta o‘qituvchisi, t.f.f.d., (PhD), E-mail: sherzamin.tstu@gmail.com Tel.: + 99890 021 04 93 https://orcid.org/0000-0001-5581-507X
Vohidov Azizbek / Azizbek Vohidov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrasi tayanch doktoranti Tel.: +99891 233 00 55
Ulugov Javoxir / Javokhir Ulugov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrasi magistranti Tel.: +99890 947 18 08
Makhmudjanov Abbos / Abbos Makhmudjanov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrasi magistrianti Tel.: +99890 628 11 31

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