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**“GLOBAL RAQAMLI INTEGRATSIYALASHUV:
2030-YILGACHA YASHIL IQTISODIYOTGA O'TISHDA
TEXNOLOGIK VA INDUSTRIAL SANOATNI RIVOJLANTIRISH
ORQALI MIKRO VA MAKROIQTISODIY BARQAROR
O'SISHNI TA'MINLASH DOLZARBLIGI”**

**“GLOBAL DIGITAL INTEGRATION: THE RELEVANCE OF
ENSURING MICRO AND MACROECONOMIC SUSTAINABLE
GROWTH THROUGH TECHNOLOGICAL AND INDUSTRIAL
DEVELOPMENT IN THE TRANSITION TO A GREEN
ECONOMY BY 2030”**

**«ГЛОБАЛЬНАЯ ЦИФРОВАЯ ИНТЕГРАЦИЯ:
АКТУАЛЬНОСТЬ ОБЕСПЕЧЕНИЯ УСТОЙЧИВОГО
МИКРО- И МАКРОЭКОНОМИЧЕСКОГО РОСТА ЧЕРЕЗ
РАЗВИТИЕ ТЕХНОЛОГИЧЕСКОЙ И ИНДУСТРИАЛЬНОЙ
ПРОМЫШЛЕННОСТИ В ПЕРЕХОДЕ К ЗЕЛЁНОЙ
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- 05.01.00 – Axborot texnologiyalari, boshqaruv va kompyuter grafikasi
- 05.01.01 – Muhandislik geometriyasi va kompyuter grafikasi. Audio va video texnologiyalari
- 05.01.02 – Tizimli tahlil, boshqaruv va axborotni qayta ishlash
- 05.01.03 – Informatikaning nazariy asoslari
- 05.01.04 – Hisoblash mashinalari, majmualari va kompyuter tarmoqlarining matematik va dasturiy ta'minoti
- 05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
- 05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
- 05.01.07 – Matematik modellash
- 05.01.11 – Raqamli texnologiyalar va sun'iy intellekt
- 05.02.00 – Mashinasozlik va mashinashunoslik
- 05.02.08 – Yer usti majmualari va uchish apparatlari
- 05.03.02 – Metrologiya va metrologiya ta'minoti
- 05.04.01 – Telekommunikatsiya va kompyuter tizimlari, telekommunikatsiya tarmoqlari va qurilmalari. Axborotlarni taqsimlash
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- 05.05.05 – Issiqlik texnikasining nazariy asoslari
- 05.05.06 – Qayta tiklanadigan energiya turlari asosidagi energiya qurilmalari
- 05.06.01 – To'qimachilik va yengil sanoat ishlab chiqarishlari materialshunosligi
- 05.08.03 – Temir yo'l transportini ishlatish
- 05.09.01 – Qurilish konstruksiyalari, bino va inshootlar
- 05.09.04 – Suv ta'minoti. Kanalizatsiya. Suv havzalarini muhofazalovchi qurilish tizimlari
- 10.00.06 – Qiyosiy adabiyotshunoslik, chog'ishtirma tilshunoslik va tarjimashunoslik
- 10.00.04 – Yevropa, Amerika va Avstraliya xalqlari tili va adabiyoti
- 08.00.01 – Iqtisodiyot nazariyasi
- 08.00.02 – Makroiqtisodiyot
- 08.00.03 – Sanoat iqtisodiyoti
- 08.00.04 – Qishloq xo'jaligi iqtisodiyoti
- 08.00.05 – Xizmat ko'rsatish tarmoqlari iqtisodiyoti
- 08.00.06 – Ekonometrika va statistika
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- 08.00.08 – Buxgalteriya hisobi, iqtisodiy tahlil va audit
- 08.00.09 – Jahon iqtisodiyoti
- 08.00.10 – Demografiya. Mehnat iqtisodiyoti
- 08.00.11 – Marketing
- 08.00.12 – Mintaqaviy iqtisodiyot
- 08.00.13 – Menejment
- 08.00.14 – Iqtisodiyotda axborot tizimlari va texnologiyalari
- 08.00.15 – Tadbirkorlik va kichik biznes iqtisodiyoti
- 08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
- 08.00.17 – Turizm va mehmonxona faoliyati

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MUNDARIJA

ICT week Uzbekistan 2025: Milliy texnologiyalar haftaligining yakunlari va ularning O'zbekiston IT-ekotizimiga ta'siri.....	16
Jumaboyev Akmaljon Sheraliyevich	
THE ROLE OF STATE FINANCIAL CONTROL IN THE EFFICIENT USE OF BUDGET FUNDS	20
Gulyor Akhmatovna Kasimova, Biybinaz Makhmut qizi Esenbaeva	
РОЛЬ ЦИФРОВЫХ ПЛАТЁЖНЫХ СИСТЕМ В ФОРМИРОВАНИИ ФИНТЕХ-ЭКОСИСТЕМЫ РЕСПУБЛИКИ УЗБЕКИСТАН	22
Шамахмудова Шоира Олег кизи	
UZBEKISTAN'S STRATEGY FOR TRANSITION TO A GREEN ECONOMY: LABOR MARKET TRANSFORMATION, CHALLENGES AND PROSPECTIVE OPPORTUNITIES.....	27
Akbarova Barno Shukhratovna, Chintemirova Diyora Shukhratovna	
MODELS FOR MANAGING EDUCATIONAL REFORMS IN THE CONTEXT OF CULTURAL DIFFERENCES.....	32
Abdulmajeed Nabeel Azouz	
4-SANOAT INQILOBINING RAQAMLI TURIZMGA TA'SIRINI BAHOLASH	38
Sevinchova Nilufar Ne'mat qizi	
КОНЦЕПТУАЛЬНАЯ МОДЕЛЬ ИНТЕГРИРОВАННОЙ СИСТЕМЫ ESG-ТРАНСФОРМАЦИИ ПРОМЫШЛЕННОГО ПРЕДПРИЯТИЯ КАК ДРАЙВЕР ИНВЕСТИЦИОННОЙ ПРИВЛЕКАТЕЛЬНОСТИ.....	41
Ташпулатов Дильмурад Рустамович	
RAQAMLI IQTISODIYOTDA FOIZSIZ MOLIYA MEKANIZMLARINING RIVOJLANISH ISTIQBOLLARI.....	44
Adilov Zuxriddin Marip o'g'li	
XIZMAT KO'RSATISH TARMOG'INI RIVOJLANTIRISH VA BOSHQARISHNI TAKOMILLASHTIRISH	47
Tadjimirzayev Anvar Abduvaxidovich	
RAQAMLI IQTISODIY DINAMIKANI KOMPLEKS FUNKSIYALAR YORDAMIDA MODELLASHTIRISH.....	52
Ibrohimova Nilufar Qahramon qizi	
SANOAT SEKTORIDA BARQAROR RIVOJLANISHNI TA'MINLASHDA "YASHIL" INVESTITSİYALARINING IQTISODIY AHAMIYATI.....	55
Ibragimov Zaxid Taxirovich	
LOGISTIKA PROVAYDERLARI XIZMATLARIDAN FOYDALANISH ASOSIDA TEMIR YO'L TRANSPORTI RAQOBATBARDOSHLIGINI OSHIRISH.....	59
Raximov Xasan Shukurjonovich	
СОВРЕМЕННЫЕ ПОДХОДЫ К ИСПОЛЬЗОВАНИЮ ИНСТРУМЕНТОВ УПРАВЛЕНИЯ ПРОЕКТАМИ В РАЗЛИЧНЫХ ОТРАСЛЯХ ЭКОНОМИКИ	64
Сидиков Зиёдулло Равшанович, Холиярова Шохиста Кахрамоновна	
SUG'URTA TASHKILOTLARINING BOZOR IQTISODIYOTIDAGI AHAMIYATI	68
Azamatova G.I.	
DON MAHSULOTLARINI YETISHTIRISH VA QAYTA ISHLASHDA INVESTITSİYALAR SAMARADORLIGINI OSHIRISH YO'LLARI.....	71
Po'latova Sug'diyona, S.Y.Xamidova	
MAHALLIY BUDJETLARNING DAROMAD BAZASINI KENGAYTIRISH ASOSIDA XARAJATLAR BARQARORLIGINI TA'MINLASH (SURXONDARYO VILOYATI MISOLIDA).....	74
Safarmurodova Marjona To'raqulovna	
O'ZBEKISTONDA INVESTITSIYA FAOLIYATINI RIVOJLANTIRISHDA SOLIQ IMTIYOZLARI VA PREFERENSIYALARINING IQTISODIY AHAMIYATI.....	77
Allaberganova Kumush Javlonbek qizi, Beknazarova N.T.	



РАЗВИТИЕ OPEN BANKING КАК ДРАЙВЕР ФОРМИРОВАНИЯ КОНКУРЕНТНОЙ ФИНТЕХ-ЭКОСИСТЕМЫ В УЗБЕКИСТАНЕ	80
Эшмуротов Дониёр Ихтиёр ўғли	
NAVIGATING TAX RISKS ARISING IN THE MANAGEMENT OF ENTERPRISES.....	83
Maxmudov Rahimjon Hamid o'g'li	
DVIGATELNING TASHQI TEZLIK TAVSIFNOMASIGA DVIGATEL QUVVATI, TIRSAKLI VALINING MAKSIMAL AYLANISHLAR SONI, SOATLI YONILG'I SARFI VA SOLISHTIRMA YONILG'I SARFLARIGA TA'SIRI.....	86
Abdug'aniyev Shohruh Oxunjon o'g'li, Abdusattorov Nodirjon Abduljalil o'g'li	
FROM TRADITIONAL BANKING TO FINTECH ECOSYSTEMS: PERFORMANCE IMPLICATIONS	90
Rano Parpieva	
ZAMONAVIY SHAROITDA MEHNAT MOTIVATSIYASI NAZARIYASINI RIVOJLANTIRISHDA INSONIY MUNOSABATLAR MAKTABINING AHAMIYATI	92
Aslanov Aziz Mexmonovich	
ВОДНО-ЭКОНОМИЧЕСКИЙ КОМПРОМИСС В СИСТЕМЕ ЦУР УЗБЕКИСТАНА: ЭМПИРИЧЕСКИЙ АНАЛИЗ МЕЖЦЕЛЕВЫХ КОНФЛИКТОВ	96
Салахутдинова Юлдуз Голибовна	
THE ECONOMIC IMPORTANCE OF INTERNATIONAL TRADE AND ITS ROLE IN GLOBAL GROWTH	99
Nurova Farog'at Salohiddin qizi	
AHOLINING MOLIYAVIY FIRIBGARLIKKA ALDANISH EHTIMOLINI KAMAYTIRISHDA MOLIYAVIY TA'LIMNING O'RNI.....	102
Irgashev Anvar Farxodovich	
SUN'IY INTELLEKT ASOSIDA TASHQI SAVDONI OPTIMALLASHTIRISH VA ENERGETIKA XAVFSIZLIGINI BOSHQARISH MEKANIZMLARI.....	105
Nosirbekov Sanjarbek Toxirbekovich	
SANOATDA IQTISODIY MOLIYAVIY HISSOBOTLAR XALQARO STANDARTLARINI RAQOBATBARDOSH KORPORATIV STRATEGIYALARNI SHAKLLANTIRISHDA QO'LLASH	107
Turaboyev Ibroxim Ismoil o'g'li	
KICHIK BIZNESDA INVESTITSIYA SAMARADORLIGINI BAHOLASH MEKANIZMLARINI TAKOMILLASHTIRISH YO'LLARI.....	111
Xakimov Akbar Anvarovich	
AXBOROT-KOMMUNIKATSIYA TEXNOLOGIYALARI SOHASIDA NOMODDIY AKTIVLARNING IQTISODIY MAZMUN-MOHİYATI	114
Ishanqulov Izzatilla Nurillayevich	
MEHNAT HAQIDAN OLINADIGAN SOLIQLAR VA MAJBURIY TO'LOVLAR HISOBINI O'ZBEKISTON RESPUBLIKASI SOLIQ KODEKSI ASOSIDA TAKOMILLASHTIRISH	117
Nomozov Ilhomjon Ziyodullo o'g'li	
FINTECH TEXNOLOGIYALARI ASOSIDA TIJORAT BANKLARI RAQAMLI INFRATUZILMASINI MODERNIZATSIYA QILISH	119
Hazratkulov Faxriyor Abdumuxammad o'g'li	
ОЦЕНКА ЛИДЕРСКОЙ ЗРЕЛОСТИ ОРГАНИЗАЦИЙ СФЕРЫ КУЛЬТУРЫ В УСЛОВИЯХ ТРАНСФОРМАЦИИ КРЕАТИВНОЙ ЭКОНОМИКИ УЗБЕКИСТАНА	122
Абдусаламова Фароғат Сунатиллаевна	
STATE OF DEVELOPMENT AND DYNAMICS OF THE FRUIT PROCESSING INDUSTRY.....	125
Yusufova Laylo Gayrat kizi	
STARTAP LOYIHALARINING MILLIY IQTISODIYOTNING INNOVATSION RIVOJLANISHIDAGI ROLI.....	132
Ko'chimova Madinabonu Qaxramon qizi, Sheraliyev Nurbek Jumanazar o'g'li	
AKSIYADORLIK JAMIYATLARI SAMARADORLIGI VA BOZOR QIYMATINI SHAKLLANTIRISHNING KO'P FAKTORLI MODELLARI	135
Jumatova Gulzar Maxmud qizi	



INNOVATSION RIVOJLANISHDA MEHNAT RESURSLARINING SAMARADORLIGINI HISOBLASH USULLARI.....	139
Artiqova O'g'iljon Zafar qizi	
INSTITUTIONAL FEATURES OF STATE REGULATION OF PRODUCT QUALITY MANAGEMENT	143
Atakulov Askad Raimkulovich	
TA'LIM MARKAZINING OBRO'SI VA RAQOBATBARDOSHLIGIGA MALAKALI XODIMLARNING TA'SIRINI BAHOLASH.....	146
Razzoqova Zebo Xusniddinova	
THE IMPACT OF RAPID TAX DISPUTE RESOLUTION SYSTEMS ON THE BUSINESS ENVIRONMENT AND PROSPECTS FOR THEIR DEVELOPMENT.....	149
Solihova Xumora Xasan kizi	
МОДЕЛИРОВАНИЕ МАКРОЭКОНОМИЧЕСКОГО ВЛИЯНИЯ ОБЩЕСТВА 5.0 НА УСТОЙЧИВОЕ СОЦИАЛЬНО-ЭКОНОМИЧЕСКОЕ РАЗВИТИЕ СТРАН БРИКС-Т.....	153
Калдибаев Нурлан Алимжанович	
AKSIYADORLIK JAMIYATLARIDA MOLIVAVIY SHAFFOFLIKNING INVESTITSION JOZIBADORLIKKA TA'SIRI.....	156
Kurashev Sobir Saidmurod o'g'li	
O'ZBEKISTONDA REKREATSION TURIZMNI RIVOJLANTIRISHNING ILMIY-AMALIY O'ZIGA XOS JIHATLARI	159
Po'latova Mavluda Sanjar qizi	
ПРИЗНАКИ ПРОБЛЕМНЫХ КРЕДИТОВ И УПРАВЛЕНИЕ ИХ КАЧЕСТВОМ.....	162
Улмасой Ахмедова Хусан кизи	
THE ECONOMIC ESSENCE OF LABOR AND ITS INTERPRETATION IN THE CONTEXT OF INTERNATIONAL FINANCIAL REPORTING STANDARDS.....	165
Nomozov Ilhomjon Ziyadullah ugli	
MADANIYLASHTIRILGAN GO'SHTNING QAYTA ISHLANGAN GO'SHT MAHSULOTLARI XOM ASHYOSIDA ISHTIROKI.....	168
Xaydarova Sitara Suranbay qizi	
NOMODDIY AKTIVLAR AUDITIDA RISKLARNI BAHOLASH VA AUDITORLIK DALILLARINI TO'PLASH USLUBIYOTINI TAKOMILLASHTIRISH.....	170
Ishanqulov Izzatilla Nurillayevich	
MEHNAT HAQI AUDITINING NAZARIY-USLUBIY ASOSLARI VA XALQARO AUDIT STANDARTLARI (ISA) KONTEKSTIDAGI TALQINI.....	173
Nomozov Ilhomjon Ziyodullo o'g'li	
BANK RISKLARINING BANK FAOLIYATIDAGI AHAMIYATI, TURLARI VA XUSUSIYATLARI.....	175
Hakimova Nargiza Abduraimovna	
RAQAMLI TRANSFORMATSIYA TADBIQ QILISH YO'NALISHLARI VA INSTRUMENTLARI TAHLILI	180
Abdurahmonov Abdumalik Abdurashidovich	
MODERN TRENDS IN THE DEVELOPMENT OF SUBJECTS ENGAGED IN MEAT PROCESSING IN THE CONTEXT OF INNOVATIVE DIRECTION.....	184
Sitara Khaydarova	
"XAVFSIZ SHAHAR" TIZIMLARIDA RAQAMLI TEXNOLOGIYALAR VA SUN'IY INTELLEKTDAN FOYDALANISH ISTIQBOLLARI.....	188
Iminov Akbarjon Odiljon o'g'li	
O'ZBEKISTONDA NATIJAGA YO'NALTIRILGAN BYUDJETLASHTIRISHNI JORIY ETISHDA DAVLAT MOLIVASI STATISTIKASI: JORIY HOLAT VA ISTIQBOLLI REJALARI.....	190
Artikov Baxtiyor Maxkamovich	
DAVLAT QARZINI SAMARALI BOSHQARISH VA BARQAROR IQTISODIY RIVOJLANISHNI TA'MINLASH MEXANIZMLARI	193
Sattoriy Fayzulloh Abdijabbor o'g'li	



O'Z KAPITALI HISOBINI YURITISHDA XALQARO MOLIYAVIY HISOBOT STANDARTLARINI QO'LLASHNING NAZARIY VA AMALIY ASOSLARI	196
Axmedov Latayibxon Mamitxonovich	
BIZNES JARAYONLARINI MODELLASHTIRISH ORQALI KORXONA SAMARADORLIGINI OSHIRISH YO'LLARI	200
Qarshiyeva Moxinur Olim qizi	
THE IMPACT OF MANAGING THE INTERREGIONAL MOBILIZATION OF QUALIFIED TEACHERS ON THE QUALITY OF EDUCATION.....	202
Karimov Dostonjon Karimovich	
O'ZBEKISTON KIMYO SANOATI KORXONALARINING IQTISODIY SAMARADORLIGI HOLATI.....	204
Suyarov Shaxzod Salim o'g'li	
ФАКТОРЫ И ПРОБЛЕМЫ ОСУЩЕСТВЛЕНИЯ УСТОЙЧИВОГО РАЗВИТИЯ МЕЖДУНАРОДНЫХ ДЕНЕЖНЫХ ПЕРЕВОДОВ В УЗБЕКИСТАНЕ.	206
Гимранова О. Б.	
ASSESSING DIGITAL MATURITY IN HIGHER EDUCATION INSTITUTIONS: AN INTEGRATED FRAMEWORK APPROACH.....	209
Berdiyev Temurbek	
ТЕОРЕТИКО-НАУЧНЫЕ ОСНОВЫ ПОВЫШЕНИЯ ЭКОНОМИЧЕСКОГО ПОТЕНЦИАЛА ПРЕДПРИЯТИЙ НЕФТЕГАЗОВОЙ ПРОМЫШЛЕННОСТИ	213
Бекмухамедова Малика Искандарбековна	
ЭКОНОМИЧЕСКАЯ СУЩНОСТЬ И ОСОБЕННОСТИ ЦИФРОВИЗАЦИИ ФОНДОВОГО РЫНКА В УЗБЕКИСТАНЕ	218
Шомуродов Равшан Турсункулович, Юсупова Нигора Собитжон кизи	
IQTISODIYOTDA OZIQ-OVQAT XAVFSIZLIGINI TA'MINLASHNING INSTITUTIONAL MECHANISMS.....	223
Amirov Otabek Xudoyberdi o'g'li	
TRANSPORT TIZIMI IQTISODIY SAMARADORLIGINI OSHIRISHNING NAZARIY ASOSLARI	226
Mannonov Shoxruhmirza Abdurashid o'g'li	
AXBOROT-KOMMUNIKATSIYA TEXNOLOGIYALARI SOHASIDA MOLIYAVIY NATIJALAR AUDITI METODOLOGIYASINI TAKOMILLASHTIRISHNING YAXLIT TIZIMI	231
Bekchanov Faxriddin Atabekovich	
FINANCING SYSTEM OF EXPORT ACTIVITIES OF SMALL BUSINESS ENTITIES IN THE IMPROVING....	234
Karamatdinova Aysawle Paraxatovna	
GENERATIV SUN'IY INTELLEKT INFRATUZILMASINING MINTAQAVIY IQTISODIYOTNI TRANSFORMATSIYA QILISHDAGI O'RNI	236
Saidov Jaloladdin Allaberganovich	
STRATEGIC INTEGRATION OF DIGITAL MARKETING TECHNOLOGIES IN SMALL AND MEDIUM-SIZED ENTERPRISES: DRIVERS, BARRIERS, AND ECONOMIC PERFORMANCE.....	239
Pirmatov Oybek Shovkat ugli	
QORAQALPOG'ISTON RESPUBLIKASIDA KICHIK VA O'RTA BIZNESNING HUDUDIY RIVOJLANISH XUSUSIYATLARI.....	243
Reimbergenov Xurrambek Xushnudovich	
FEATURES AND PRINCIPLES OF ECONOMETRIC MODELING OF INDUSTRIAL DEVELOPMENT.....	246
Choriev Tolib Azamovich	
FEATURES OF INVESTMENT BEHAVIOUR IN THE CONTEXT OF FINTECH TECHNOLOGY DEVELOPMENT	251
Karimova Nurjakhon Olim kizi	
DAVLAT-XUSUSIY SHERIKLIK ASOSIDA HUDUDIY INFRATUZILMAGA INVESTITSİYALARNI JALB ETISH MECHANISMS TAKOMILLASHTIRISH	255
Ismoilov Azizbek Rustamjon o'g'li	



RAQAMLI IQTISODIYOT SHAROITIDA ELEKTRON BOZORLAR ORQALI XALQARO SAVDONI RIVOJLANTIRISH ISTIQBOLLARI.....	259
Hamroyeva Umida	
TO'QIMACHILIK KORXONALARIDA TEXNOLOGIK MODERNIZATSIYANING IQTISODIY MAZMUNI VA NAZARIY ASOSLARI.....	262
Sarimsaqov Sherzod Xamidovich	
INCREASING THE COMPETITIVENESS OF ENTERPRISES IN THE CONSTRUCTION MATERIALS INDUSTRY	268
Toshpulatov Asronbek Mutalibovich	
O'ZBEKISTON TIJORAT BANKLARINING KAPITAL BOZORI ORQALI RESURS BAZASINI KENGAYTIRISH AMALIYOTI VA ISTIQBOLLARI.....	272
Otabek Oltiboyev	
TASHQI SAVDO OPERATSIYALARIDA VALYUTA NAZORATINI TAKOMILLASHTIRISH ORQALI EKSPORTNI RAG'BATLANTIRISH	275
Israilov Avazbek Rustam o'g'li	
XALQARO UNIVERSITET BOSHQARUVIDA STAKEHOLDER YONDASHUVI: ZAMONAVIY MODELLAR VA RIVOJLANISH TENDENSIYALARI.....	277
Tursunmuratov Sherzod Turdimuratovich	
ВОПРОСЫ ИСПОЛЬЗОВАНИЯ МЕХАНИЗМОВ ГОСУДАРСТВЕННОЙ ПОДДЕРЖКИ В УПРАВЛЕНИИ ДЕЯТЕЛЬНОСТЬЮ СЕМЕЙНЫХ ПРЕДПРИЯТИЙ.....	279
Султанов Бобирмирзо Мавлонжон угли	
TRANSPORT SOHASIDA AYOLLAR BANDLIGINI TA'MINLASH MUAMMOLARINI INTEGRATSIYALASHGAN BOSHQARUVNI TAKOMILLASHTIRISH ASOSIDA HAL ETISH	283
Abdukarimova Dilnozaxon Mamurjon qizi	
RAQAMLI IQTISODIYOT SHAROITIDA TO'QIMACHILIK SANOATINI RIVOJLANTIRISHNING USTUVOR YO'NALISHLARI	287
Nurullayeva Mexribon Muratovna	
OPTIMIZATION OF THE FOOD SUPPLY AND DELIVERY SYSTEM IN TASHKENT REGION	290
Mavlanov Sobirjon Pardabayevich	
THEORETICAL FOUNDATIONS OF SOCIAL PROTECTION AND ITS INTERRELATIONSHIP WITH SUSTAINABLE ECONOMIC DEVELOPMENT.....	293
Abduzoirov Mukhiddin, Abdulloev Amrullo, Inomjon Qudratov	
SUG'URTA XIZMATLARI BOZORINI BOSHQARISHGA OID ILMIY YONDASHUVLARNING EVOLYUTSIYASI..	299
Kurbonov S.A.	
INSTITUTIONAL FACTORS IN THE DEVELOPMENT OF WOMEN'S ENTREPRENEURSHIP IN RURAL UZBEKISTAN: AN ECONOMIC AND STATISTICAL ANALYSIS	304
Saidakbarova Ziyoda Doniyor qizi	
ФАКТОРИНГ КАК ИНСТРУМЕНТ УПРАВЛЕНИЯ ДЕБИТОРСКОЙ ЗАДОЛЖЕННОСТЬЮ ТЕКСТИЛЬНЫХ ПРЕДПРИЯТИЙ	310
Дадабоева Муштари Хамидиллаевна	
QISHLOQ XO'JALIGINI RIVOJLANTIRISHDA AGROKLASTERLARNING O'RNI VA ISTIQBOLLARI	314
Berdiyev Abdumalik Hakimovich	
RAQAMLI ASALARICHILIK TEXNOLOGIYALARI SAMARADORLIGINI OSHIRISH TAMOYILLARI	318
Farmanov Jonibek Ziyadullaevich	
СУЩНОСТЬ И ОСОБЕННОСТИ УВЕЛИЧЕНИЯ КАПИТАЛИЗАЦИИ КОММЕРЧЕСКИХ БАНКОВ.....	322
Шомуродов Равшан, Жуманазаров Шахобиддин	
INVESTITSION FAOLLIKNI OSHIRISHNING MOLIYA-KREDIT MEKANIZMI: XORIJIY DAVLATLAR AMALIY TAJRIBASI	326
I. Madaminov	



TRANSPORT SOHASIDA AYOLLAR BANDLIGINI OSHIRISHNING AYOLLAR FAROVONLIGI VA IQTISODIY RIVOJLANISHGA TA'SIRI	329
Raxmatov Ziyodullo, Abdukarimova Dilnozaxon	
НАПРАВЛЕНИЯ СОВЕРШЕНСТВОВАНИЯ УПРАВЛЕНИЯ МИГРАЦИОННЫМИ ПРОЦЕССАМИ В РЕСПУБЛИКЕ УЗБЕКИСТАН НА ОСНОВЕ ЦИФРОВЫХ ТЕХНОЛОГИЙ	332
Ёкубжон Тоҳиров	
ВЗАИМОСВЯЗЬ ВЫБРОСОВ CO ₂ , ЭКОНОМИЧЕСКОГО РАЗВИТИЯ И ДОСТУПА К ЧИСТОМУ ТОПЛИВУ И ТЕХНОЛОГИЯМ С РАСХОДАМИ НА ЗДРАВООХРАНЕНИЕ В УЗБЕКИСТАНЕ: ЭКОНОМЕТРИЧЕСКИЙ АНАЛИЗ	336
Эркинбаева Камила Жавланбековна	
ВЛИЯНИЕ НЕФТЯНОЙ ЗАВИСИМОСТИ И УРОВНЯ ЭКОНОМИЧЕСКОГО РАЗВИТИЯ НА ЭНЕРГЕТИЧЕСКИЙ РИСК УЗБЕКИСТАНА: ЭКОНОМЕТРИЧЕСКИЙ АНАЛИЗ.....	341
Эркинбаева Камила, Бекзод Кузибаев	
МЕХАНИЗМ РЕАЛИЗАЦИИ ТУРИСТСКИХ ПРОДУКТОВ НА ОСНОВЕ МЕСТНЫХ СООБЩЕСТВ	347
Абзалова Нозимахон Нодирбек кизи	
THE ROLE OF DIGITAL PLATFORMS IN CONDUCTING ELECTRONIC SALES OF ENTERPRISE PRODUCTS	350
Tuychiyev Shavkatjon Shokirali o'g'li	
LATENT DEMAND AND THE CAPACITY ILLUSION IN RAIL TRANSPORT	354
Kurambayev Alisher Saburbayevich	
TIJORAT BANKLARINING INVESTITSIYA PORTFELINI "YASHILLASHTIRISH" VA EKOLOGIK LOYIHALARNI MOLİYALASHTIRISHNI RIVOJLANTIRISH ISTIQBOLLARI	357
Soliyev Muhammad Umar Baxromjon o'g'li	
SCENARIO FORECASTING OF TEXTILE SECTOR DEVELOPMENT	361
Nurullayeva Mexribon Muratovna	
AHOLI DAROMADLARINI SHAKLLANTIRISH VA ULARNING TURMUSH DARAJASIGA TA'SIRINI TAKOMILLASHTIRISH.....	365
Abidova Shahnoza Abduvaliyevna	
INFRATUZILMA LOYIHALARINI MOLİYALASHTIRISHDA TASHABBUSLI BUDJET MEXANIZMINING O'RNİ	367
Yarbazarov Shavkat Butayevich	
YASHIL IQTISODIYOT SHAROITIDA BARQAROR IQTISODIY RIVOJLANISH MEXANIZMLARI	370
Usanova Feruza, Muratov Shukrullo	
THE IMPACT OF CUSTOMER TRUST ON PURCHASE DECISIONS IN E-COMMERCE.....	372
Maxmudova Munisaxon Abbas qizi	
ACTIVITY-BASED COSTING IN RAILWAY PASSENGER TRANSPORT	376
Eshboyev Ulugbek Farxodovich	
MOLIYAVIY INVESTITSIYALARNING TIJORAT BANKLARI INVESTITSIYA FAOLIYATIDAGI IQTISODIY AHAMIYATI	380
Primova Dilafruz To'liqinovna	
INSTITUTIONAL DETERMINANTS OF THE SHADOW ECONOMY AND THEIR IMPACT ON HOUSEHOLD WELFARE	382
Afenov Nursultan Nugmatillaevich	
DEVELOPING A DIGITAL PLATFORM MODEL FOR THE DEVELOPMENT OF THE SERVICE SECTOR IN TASHKENT CITY	386
Abikayumov Bekzod Turdiniyozovich	
TIJORAT BANKLARI CHAKANA XIZMATLARINI RIVOJLANTIRISHNING NAZARIY ASOSLARI.....	390
Axmedov Sardorbek Abdukarim o'g'li	



ASSESSING UNIVERSITY DIGITAL MATURITY AS A DRIVER OF INTERNATIONAL COMPETITIVENESS: IMPROVING THE EVALUATION MECHANISM	395
Kungratov Ilmurod Kuzibay ugli	
ENHANCING THE EFFICIENCY OF MARKETING PROJECT MANAGEMENT THROUGH ARTIFICIAL INTELLIGENCE IN THE DIGITAL ECONOMY	398
Xushnoza Abdulazizova Abduhayot qizi	
INVESTITION FAOLLIK MEXANIZMINI TAKOMILLASHTIRISH YO'NALISHLARI	401
Asatova Shahzodaxon Zabixillo qizi	
THE ECONOMIC ESSENCE AND MODERN REQUIREMENTS OF THE FOOD SUPPLY CHAIN.....	404
Mavlanov Sobirjon Pardabayevich	
SANOAT KORXONALARIDA JAMOANI BOSHQARISH JARAYONINI TAKOMILLASHTIRISH.....	409
Xusanova Malohat Mingnorovna	
FINITE ELEMENT INVESTIGATION OF THE DYNAMIC DEFORMATION OF SINGLE-LAYER ISOTROPIC PLATES INTERACTING WITH A VISCOELASTIC MEDIUM	411
Butayev R.B., Mirzoyeva G.T., Nabiyeu B.E., Karimova S.T.	



FINITE ELEMENT INVESTIGATION OF THE DYNAMIC DEFORMATION OF SINGLE-LAYER ISOTROPIC PLATES INTERACTING WITH A VISCOELASTIC MEDIUM

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Abstract. This thesis investigates the dynamic stress–strain state of single-layer isotropic plates interacting with a viscoelastic medium using the finite element method (FEM). The plate is modeled within the classical Kirchhoff–Love theory, while the foundation is represented by a Kelvin–Voigt-type viscoelastic (Winkler–Pasternak) model. A finite-element discrete model is constructed, the mass, stiffness, and dissipative matrices are derived, and a time-integration algorithm based on the Newmark method is developed. Numerical results for free and forced vibrations are presented in tables and diagrams for various dissipation and foundation-stiffness parameters, and regularities in the dynamic amplification factor and amplitude decay are established.

Keywords: isotropic plate, viscoelastic medium, finite element method, forced vibrations, dynamic stress–strain state, Newmark method, dissipative matrix.

Annotatsiya. Ushbu tezisda qovushqoq-elastik muhit bilan o'zaro ta'sirlashuvchi bir qatlamli izotrop plastinalarning dinamik kuchlanish-deformatsiya holati chekli elementlar usuli (ChEU) yordamida tadqiq etilgan. Plastina klassik Kirchhoff–Love nazariyasi doirasida modellashdirilgan, asos esa Kelvin–Voigt tipidagi qovushqoq-elastik (Winkler–Pasternak) model orqali ifodalangan. Chekli elementli diskret model tuzilgan, massa, bikrlilik va dissipativ matritsalar keltirib chiqarilgan hamda Newmark usuliga asoslangan vaqt bo'yicha integrallash algoritmi ishlab chiqilgan. Erkin va majburiy tebranishlarning turli dissipatsiya hamda asos bikrligi parametrlaridagi sonli natijalari jadval va diagrammalarda keltirilgan, shuningdek, dinamik kuchayish koeffitsiyenti va amplitudaning so'nish qonuniyatlari aniqlangan.

Kalit so'zlar: izotrop plastina, qovushqoq-elastik muhit, chekli elementlar usuli, majburiy tebranishlar, dinamik kuchlanish-deformatsiya holati, Newmark usuli, dissipativ matritsa.

Аннотация. В данном тезисе исследовано динамическое напряжённо-деформированное состояние однослойных изотропных пластин, взаимодействующих с вязкоупругой средой, с использованием метода конечных элементов (МКЭ). Пластина моделируется в рамках классической теории Кирхгофа–Лява, а основание представлено вязкоупругой моделью типа Кельвина–Фойгта (Винклера–Пастернака). Построена конечно-элементная дискретная модель, получены матрицы масс, жёсткости и диссипации, а также разработан алгоритм интегрирования по времени на основе метода Ньюмарка. Численные результаты для свободных и вынужденных колебаний при различных параметрах диссипации и жёсткости основания представлены в таблицах и диаграммах, а также установлены закономерности изменения коэффициента динамического усиления и затухания амплитуды.

Ключевые слова: изотропная пластина, вязкоупругая среда, метод конечных элементов, вынужденные колебания, динамическое напряжённо-деформированное состояние, метод Ньюмарка, диссипативная матрица.

INTRODUCTION

In modern construction and mechanical-engineering practice, thin plates are a principal structural element of numerous structures and frequently operate in direct contact with a foundation possessing viscoelastic properties (soil, a polymer layer, a damping material, etc.). Under external dynamic loading (vibrations transmitted from machinery, seismic action, blast waves), an accurate prediction of the real behavior of such a system is of considerable importance for ensuring the strength and safety of structures.

An analytical solution of plate–foundation interaction problems exists only for a limited number of geometric shapes and boundary conditions; for this reason, numerical methods—in particular the finite element method (FEM)—are widely used in practice. The advantage of FEM lies in its ability to account for arbitrary geometry, inhomogeneous material properties, and complex boundary conditions.

The aim of this study is a comprehensive investigation, within a unified finite-element mathematical model, of the following problems for single-layer isotropic plates in contact with a viscoelastic medium: (1) free vibrations (natural frequencies and mode shapes), (2) forced vibrations, and (3) the dynamic stress–strain state.

Mathematical formulation of the problem

A rectangular isotropic plate is considered within the framework of the Kirchhoff–Love hypothesis: the mid-surface of the plate lies in the plane $z = 0$, its thickness is h , and its surface is $a \times b$. The reaction of the viscoelastic foundation located beneath the plate is assumed, according to the Kelvin–Voigt model, to be proportional to the deflection and to its rate of change:

$$q_{as}(x,y,t) = k w(x,y,t) + c \partial w(x,y,t) / \partial t - G_p \nabla^2 w(x,y,t) \quad (1)$$

where k is the Winkler-type stiffness coefficient of the foundation, c is the viscous (dissipative) coefficient of the foundation, G_p is the Pasternak-type shear-layer parameter, and $\nabla^2 = \partial^2 / \partial x^2 + \partial^2 / \partial y^2$ is the Laplace operator.

The flexural equation of motion of the plate (the dynamic equilibrium equation) has the following form:

$$D \nabla^4 w + \rho h \partial^2 w / \partial t^2 + \eta D \nabla^4 (\partial w / \partial t) + q_{as}(x,y,t) = q(x,y,t) \quad (2)$$

where $D = Eh^3 / [12(1 - \nu^2)]$ is the cylindrical (flexural) stiffness of the plate, E is the modulus of elasticity, ν is Poisson's ratio, ρ is the material density, η is the internal-friction (viscosity) parameter of the plate material, and $q(x,y,t)$ is the external distributed dynamic load.

Equation (2) is a generalization of the classical biharmonic equation of the Kirchhoff–Love theory that additionally accounts for the viscoelastic foundation and the internal dissipation of the material. Either hinged (Navier-type) support or clamped conditions along all four edges of the plate are considered as boundary conditions.

Finite element discretization

To solve the problem by FEM, the plate is subdivided into rectangular Kirchhoff-type plate elements (with 3 degrees of freedom per node: w , θ_x , θ_y). The deflection field of the element is interpolated by means of shape functions:

$$w^{(e)}(x,y,t) = \sum_i N_i(x,y) q_i^{(e)}(t) = N(x,y) q^{(e)}(t) \quad (3)$$

On the basis of Hamilton's principle (or the principle of virtual work), the stiffness, mass, and dissipative (damping) matrices for each element are determined as follows:

$$K^{(e)} = \int B^T D_b B \, d\Omega + \int k N^T N \, d\Omega + \int G_p \nabla N^T \nabla N \, d\Omega \quad (4)$$

$$M^{(e)} = \int \rho h N^T N \, d\Omega, \quad C^{(e)} = \eta K_b^{(e)} + \int c N^T N \, d\Omega \quad (5)$$

where B is the bending-strain matrix, D_b is the bending elasticity matrix, and $K_b^{(e)}$ is the part corresponding only to the intrinsic bending stiffness of the plate. By assembling all element matrices in the global coordinate system, the overall equation of motion of the system is obtained:

$$M \ddot{q} + C \dot{q} + K q = Q(t) \quad (6)$$

where $q(t)$ is the vector of generalized nodal displacements, and $Q(t)$ is the vector of external loads reduced to the nodes.

Free vibrations: the eigenvalue problem

In the absence of dissipative forces ($C = 0$) and external load ($Q = 0$), equation (6) reduces to the standard generalized eigenvalue problem for determining the natural frequencies and mode shapes:

$$(K - \omega_i^2 M) \varphi_i = 0, \quad i = 1, 2, \dots, n \quad (7)$$

where ω_i is the natural frequency of the i -th mode, and φ_i is the corresponding mode shape (vibration form). The problem was solved by the subspace iteration method or the Lanczos algorithm.

Forced vibrations: the Newmark method

To integrate equation (6) with respect to time, the unconditionally stable Newmark- β method was used ($\beta = 0.25$, $\gamma = 0.5$ — the average-acceleration method):

$$q_{n+1} = q_n + \Delta t \dot{q}_n + \Delta t^2 [(1/2 - \beta) \ddot{q}_n + \beta \ddot{q}_{n+1}] \quad (8)$$

$$\dot{q}_{n+1} = \dot{q}_n + \Delta t [(1 - \gamma) \ddot{q}_n + \gamma \ddot{q}_{n+1}] \quad (9)$$

At each time step the effective stiffness matrix $\hat{K} = K + \gamma / (\beta \Delta t) C + 1 / (\beta \Delta t^2) M$ is formed, the system of linear



algebraic equations is solved, and once q_{n+1} is found, the acceleration and velocity are updated by formulas (8)–(9).

For the numerical study, a square plate hinged along all four edges was considered, with sides $a = b = 1.0$ m and thickness $h = 0.01$ m. Material parameters: $E = 2.1 \times 10^{11}$ Pa, $\nu = 0.3$, $\rho = 7850$ kg/m³. Foundation parameters: $k = 5 \times 10^7$ N/m³, $G_p = 2 \times 10^5$ N/m. A harmonic concentrated force $F(t) = F_0 \cdot \sin(\Omega t)$, $F_0 = 10^4$ N, $\Omega = 14$ rad/s was applied at the center of the plate.

Grids of various densities were considered to evaluate the convergence of the FEM solution with respect to discretization density. The results are given in Table 1.

Table 1

Convergence of the natural frequency and maximum deflection with respect to the finite-element grid density¹

Grid (n×n)	Number of elements	ω_1 , rad/s	ω_2 , rad/s	wmax, mm	Computation time, s
8×8	64	19.42	48.77	8.71	1.2
16×16	256	18.77	47.05	9.24	3.8
24×24	576	18.58	46.58	9.36	9.4
32×32	1024	18.51	46.41	9.39	18.7
40×40 (exact solution)	1600	18.49	46.34	9.41	31.5

Table 1 shows that for grids of 24×24 and finer, the results converge to the accurate (analytically approximated) solution to within less than 0.5%; a 24×24 grid was therefore adopted for all subsequent calculations, providing an acceptable balance between computational accuracy and computation time.

The variation of the deflection at the center of the plate with time for various dissipative (viscosity) parameters η is shown in Fig. 1.

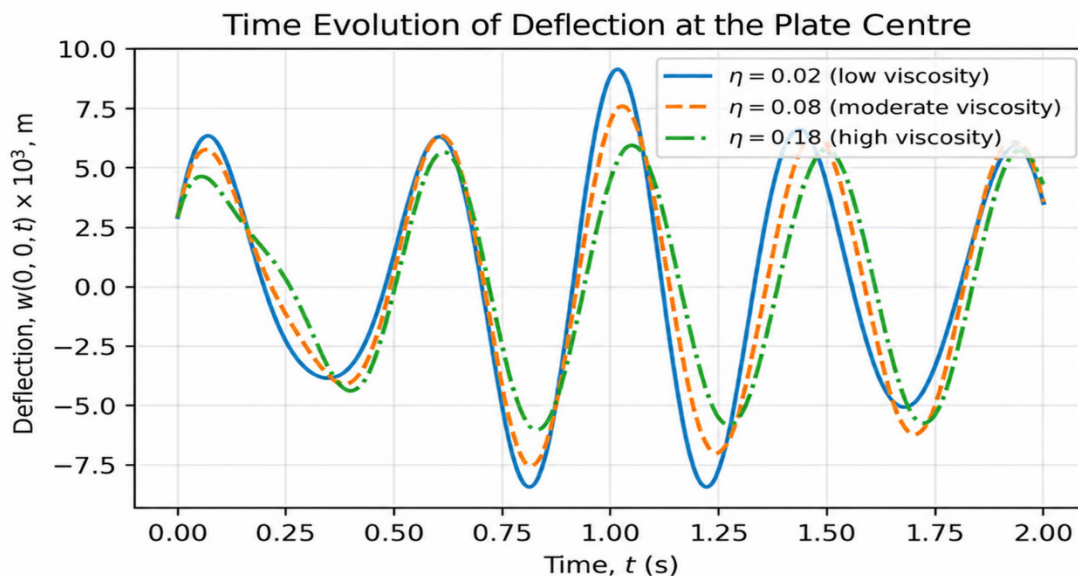
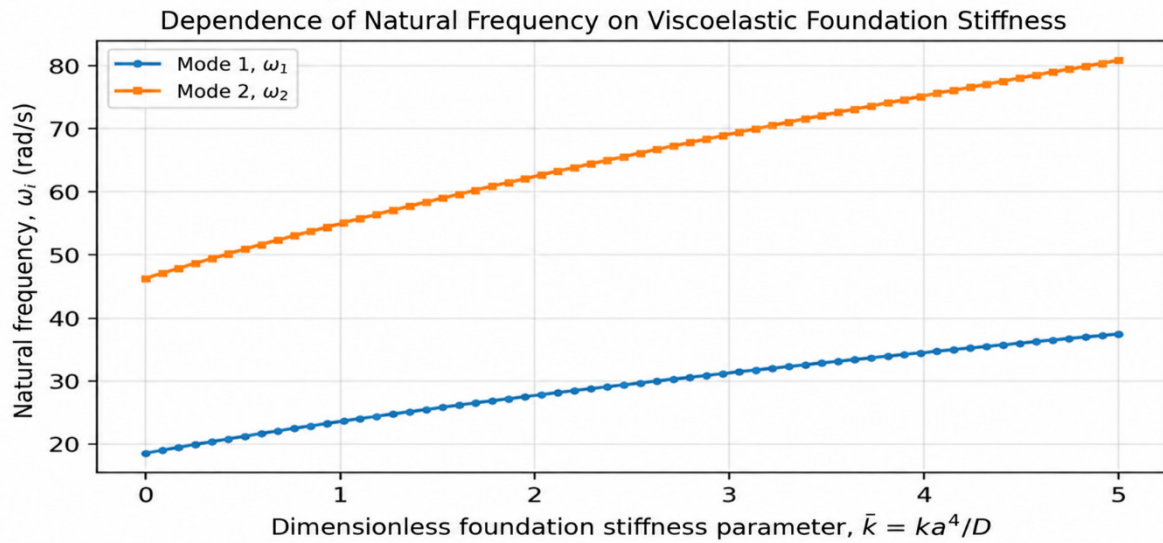


Fig. 1. Variation of the deflection at the center of the plate with time (for various η)²

Fig. 1 shows that as the dissipative parameter η increases, the vibration amplitude in the steady (stationary) state decreases, and the decay rate of the transient process increases—a physically expected result confirming the energy-absorption property of the viscoelastic foundation.

¹ Source: Authors' calculations.

² Source: Authors' calculations.



2.

Fig. 2. Dependence of the first and second natural frequencies on the foundation stiffness³

As expected, both natural frequencies increase monotonically with an increase in the foundation stiffness ($\bar{k}$), since a stiffer foundation increases the overall stiffness of the system.

To analyze the dynamic stress-strain state, the maximum equivalent stress in the plate ($\sigma_{\max}$, von Mises) was computed for the static and dynamic loading cases, and the dynamic amplification factor $K_d = \sigma_{\max, \text{dyn}} / \sigma_{\max, \text{stat}}$ was determined for various values of η (Table 2).

Table 2

Static and dynamic stresses and the dynamic amplification factor for various dissipation parameters⁴

η (dissipation parameter)	$\sigma_{\max}$, static, MPa	$\sigma_{\max}$, dynamic, MPa	Dynamic factor K_d	Amplitude decay, %
0.02	42.6	78.3	1.84	6.1
0.05	42.6	71.5	1.68	14.8
0.08	42.6	65.2	1.53	22.4
0.12	42.6	58.9	1.38	31.7
0.18	42.6	51.4	1.21	42.9

The results in Table 2 show that an increase in the dissipative parameter η from 0.02 to 0.18 leads to a decrease in the dynamic amplification factor K_d from 1.84 to 1.21, i.e., by approximately 34%. This indicates that accounting for the dissipative properties of the viscoelastic medium can contribute to a more accurate assessment of the dynamic loading level of the structure and may support more efficient material utilization while maintaining the required safety criteria.

CONCLUSION AND SUGGESTIONS

In this study, the processes of dynamic deformation of single-layer isotropic plates interacting with a viscoelastic medium were comprehensively investigated on the basis of the finite element method. The main results are as follows:

- A finite-element mathematical model of the plate–foundation system was developed on the basis of the Kirchhoff–Love theory and a Kelvin–Voigt-type viscoelastic foundation model, and the mass, stiffness, and dissipative matrices were derived in explicit form;
- A time-integration algorithm based on the Newmark method was constructed and shown to give stable and accurate results for various levels of dissipation;
- A 24×24 finite-element grid was found to provide sufficient accuracy (error below 0.5%) for practical calculations;

³ Source: Authors' calculations.

⁴ Source: Authors' calculations.



— It was numerically demonstrated that an increase in the dissipative parameter of the foundation leads to a substantial decay of the vibration amplitude (up to 43%) and to a decrease of approximately 34% in the dynamic amplification factor.

The results obtained can contribute to a more accurate assessment of the dynamic loading level of plate-type structures resting on a viscoelastic foundation and may support more efficient material utilization in their design.

Further research may extend this approach to multilayer and composite plates, as well as to inhomogeneous (functionally graded) foundation models.

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