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A. Zh. Seytmuratov[1], D. M. Zharylgapova[1], N. K. Medeubaev[2], A. A. Ibraeva[1]

[1]Korkyt Ata Kyzylorda State University, Kyzylorda, Kazakhstan,
[2]E. A. Buketov Karaganda State University, Karaganda, Kazakhstan.
E-mail: angisin_@mail.ru, djm.06@mail.ru

APPLIED TASKS OF PLATES FLUCTUATION UNDER MORE DIFFICULT BOUNDARY CONDITIONS

Abstract. The results on the research of own and compelled fluctuations of flat elements taking into account lamination of material of plate, rheological viscous properties, anisotropies, etc. are given in this work.

At the research of harmonious waves in deformable bodies, the concept of phase speed as the speed of environment condition change is implemented; at the same time, the phase speed is expressed through the frequencies of own fluctuations and therefore the research of harmonious waves distribution has a direct bearing on the problems of definition of own forms and frequencies of the fluctuations limited in terms of plates.

More difficult fluctuation of rectangular flat element is the fluctuation when two of the opposite edges are hinge-supported, and two other edges have different types of fixing or they are free from tension.

This class of tasks leads to the transcendental equations for determination of frequencies of own fluctuations which can be solved both numerically and analytically.

The transcendental frequency equations can be reduced to algebraic ones and to investigate the influence of both boundary conditions at the edges of rectangular plate or rectangular flat element and parameters of geometrical and mechanical character on the frequencies of own fluctuations of rectangular flat elements.

Key words: plates, anisotropy, own fluctuations, compelled fluctuations, transcendental, equations, rheology.

We will consider flat element as isotropic uniform elastic plate of constant thickness [2].

We will be limited to the task solution based on approximate equation of quartic cross fluctuations

$$A_0\frac{\partial^4 W}{\partial t^4} - A_1\Delta\frac{\partial^2 W}{\partial t^2} + A_2\Delta^2 W + \frac{\partial^2 W}{\partial t^2} = \Phi(f_z, f_{jz})(j = x, y) \quad (1)$$

where coefficients A_j are equal to

$$A_0 = \frac{h^2(7-8\nu)}{12b^2(1-\nu)}; \quad A_1 = \frac{2h^2(2-\nu)}{3(1-\nu)}; \quad A_2 = \frac{2h^2b^2}{3(1-\nu)} \quad (2)$$

ν – Poisson ratio; b – speed of cross waves distribution in plate material.

As plate edges $(y = 0; l_2)$ are hinge-supported, the solution of the equation (1) we will find in

$$W(x,y,t) = \exp\left(i\frac{b}{h}\xi t\right)\sum_{k=1}^{\infty} W_k(x)\sin\left(\frac{k\pi y}{l_2}\right) \quad (3)$$

Substituting (3) in the equation (1), for W_k we get ordinary differential equation

$$\frac{d^4W_k}{dx^4} + B_0\frac{d^2W_k}{dx^2} + B_1W_k = 0 \quad (4)$$

where coefficients B_0, B_1 are equal to

$$B_0 = \left[\frac{A_1}{A_2} \xi^2 \left(\frac{b}{h} \right)^2 - 2\left(\frac{k\pi}{l_2} \right)^2 \right];$$

$$B_1 = \left[\left(\frac{k\pi}{l_2} \right)^4 + \frac{A_0}{A_2} \xi^4 \left(\frac{b}{h} \right)^4 - \frac{A_1}{A_2} \xi^2 \left(\frac{b}{h} \right)^2 \left(\frac{k\pi}{l_2} \right)^2 - \frac{1}{A_2} \left(\frac{b}{h} \right)^2 \xi^2 \right] \quad (5)$$

We will write down the common solution of the equation (4) as

$$W_k(x) = C_1 \left[\frac{\cos(a_0 x)}{a_0^n} + \frac{\cos(a_1 x)}{a_1^n} \right] + C_2 \left[\frac{\cos(a_0 x)}{a_0^n} + \frac{\cos(a_1 x)}{a_1^n} \right] + \\ + C_3 \left[\frac{\sin(a_0 x)}{a_0^m} + \frac{\sin(a_1 x)}{a_1^m} \right] + C_4 \left[\frac{\sin(a_0 x)}{a_0^m} + \frac{\sin(a_1 x)}{a_1^m} \right], \quad (6)$$

where C_j - integration constants; a_i, a_j - roots of the characteristic equation

$$a^4 + B_0 a^2 + B_1 = 0 \quad (7)$$

and are equal to

$$a_{0,1} = \sqrt{\frac{B_0}{2} \pm \sqrt{\left(\frac{B_0}{2} \right)^2 - B_1}} \quad (8)$$

Integers (n,m) are got out of solution simplification condition at the satisfaction of boundary condition at the left edge $x = 0$, and other boundary conditions at $x = l_1$ lead to the transcendental equation for the determination of frequencies of the plate own fluctuations.

We will analyze transcendental frequency equations of the first point.

In the beginning we will consider the simplest transcendental equation

$$\alpha_0 \cos(\alpha_0 l_1) \sin(\alpha_1 l_1) - \alpha_1 \sin(\alpha_0 l_1) \cos(\alpha_1 l_1) = 0. \quad (9)$$

We will implement designations

$$l = \frac{l_1}{h}; \quad \alpha_{0.1}^1 = \sqrt{\frac{B_0^1}{2} \pm \sqrt{\left(\frac{B_0^1}{2} \right)^2 - B_1^1}}; \quad (10)$$

$$B_0'' = [(2-\nu)\xi^2 - 2\gamma], \quad \gamma = \left(\frac{\pi k h}{l_2} \right)^2;$$

$$B_1^; = \left[\gamma^2 + \frac{7-8\nu}{8} \xi^4 - (2-\nu)\gamma\xi^2 - \frac{3}{2}(1-\nu)\xi^2 \right]$$

and further we will lower strokes for simplicity.

As sines and cosines from any argument are equal

$$\sin z = \sum_{i=0}^{\infty} (-1)^i \frac{z^{2i+1}}{(2i+1)!}; \quad \cos z = \sum_{j=0}^{\infty} (-1)^j \frac{z^{2j}}{(2j)!};$$

the equation (9) is equivalent to the following

$$\alpha_0 \alpha_1 \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} (-1)^{i+j} \frac{\alpha_1^{2i} \alpha_0^{2j} - \alpha_0^{2i} \alpha_1^{2j}}{(2i+1)!(2j)!} l^{2(i+j)} = 0 \quad (11)$$

If to accept that size is determined from the formula (8) with plus sign under the root, then it follows that this root does not turn zero at any values y, ν, ξ.

Therefore, in the beginning it is possible to put $a_1 = 0$ or for ξ we get the equation

$$\xi^4 - \frac{8\left[(2-\nu)\gamma + \frac{3}{2}(1-\nu)\right]}{(7-8\nu)}\xi^2 + \frac{8\gamma^2}{(7-8\nu)} = 0; \tag{12}$$

which roots are equal to

$$\xi_{1,2} = (7-8\nu)^{-\frac{2}{2}}\sqrt{4\left[(2-\nu)\gamma + \frac{3}{2}(1-\nu)\right] \pm \sqrt{8(1+\nu^2)\gamma^2 + 3\gamma(1-\nu)(2-\nu) + \frac{9}{4}(1-\nu)^2}} \tag{13}$$

as the ranks in the formulae of trigonometrical functions meeting ranks in the equation (11), equivalent to the equation (9) also meeting, at the research of private equation (11) it is possible to be limited to the final number of the first composed.

Having taken first three composed in the ranks (11), we will write down it as

$$\alpha_0\alpha_1(\alpha_1^2 - \alpha_0^2)\left\{\frac{1}{3}l^2 - \frac{1}{30}(\alpha_1^2 + \alpha_0^2)l^4 + \right\} \times \left[\frac{1}{840}(\alpha_1^4 + \alpha_0^2\alpha_1^2 + \alpha_0^4) + \frac{1}{360}\alpha_0^2\alpha_1^2\right]l^6 + \dots \} = 0 \tag{14}$$

Roots from the formula $\alpha_1 = 0$ are equal (13). The value $(a_1^2 - a_0^2)$ is other than zero at any y, v, ξ.

If in formula (14) to take only two first terms, then we get

$$(\alpha_1^2 + \alpha_0^2) - 10l^{-2} = 0$$

or

$$B_0 - 10l^{-2} = 0 \tag{15}$$

and frequency equation

$$\xi^2 = \frac{2\gamma + 10l^{-2}}{(2-\nu)}; \tag{16}$$

which positive root is equal to

$$\xi = \sqrt{\frac{2\gamma + 10l^{-2}}{(2-\nu)}} \tag{17}$$

If in formula to take all three first terms, then we will get

$$\left[(\alpha_1^4 + \alpha_0^4) + \frac{10}{3}\alpha_0^2\alpha_1^2\right] - 28(\alpha_1^2 + \alpha_0^2)l^{-2} + 280l^{-4} = 0 \tag{18}$$

or

$$\left[B_0^2 + \frac{4}{3}B_1\right] - 28B_0l^{-2} + 280l^{-4} = 0$$

and the frequency equation corresponding to them

$$\left[(2-\nu)^2 + \frac{7+8\nu}{6}\right]\xi^4 - \left[(2-\nu)\left(\frac{16}{3}\gamma + 28l^{-2}\right) + 2(1-\nu)\right]\xi^2 + \left[\frac{16}{3}\gamma^2 + 56\gamma l^{-2} + 280l^{-4}\right] = 0, \tag{19}$$

which has two positive roots.

It is similarly possible to take first four and more terms in the formula (11) and to get more exact frequency equation and corresponding frequencies ξ.

To find the frequency equation from ranks of the equation (11) it is necessary to find out condition of deduction legitimacy of finite number of terms in the ranks (11).

We will apply Dalamber's principle of ranks convergence to the ranks in the equation (11). We will get

$$\left|\frac{\alpha_0^2\alpha_1^2 l^2}{(2i+3)(2j+2)}\right| \le q^2 < 1 \tag{20}$$

where 0<q< 1.

It follows from the inequality (20) that

$$\left|a_0^2 a_1^2\right| \le q_{i,j}^2 = q_{i,j}^2 = q^2\frac{(2i+3)(2j+2)}{l^2} \tag{21}$$

The analysis of inequality (21) shows that it is correct when performing inequality

$$-\left(\frac{8}{7-8\nu}\right)q_{i,j}^2 \le \xi^4 - 2D\xi^2 + E \le \left(\frac{8}{7-8\nu}\right)q_{i,j}^2 = C_{i,j}^2$$

where coefficients D, E are equal to

$$D = \frac{4\left[(2-\nu)\gamma + \frac{3}{2}(1-\nu)\right]}{(7-8\nu)}; \quad E = \frac{8\gamma^2}{(7-8\nu)}$$

or inequalities

$$D^2 - E \le C_{i,j}^2 \tag{22}$$

At the set parameters of geometrical and mechanical character from the inequality (22) it is possible to define necessary number of the first terms in ranks (11) to find the frequency equation relative frequencies ξ.

We will consider transcendental equation frequency equation

$$2 - \frac{a_0^2 + a_1^2}{a_0 a_1}\sin(a_0 l_1)\sin(a_1 l_1) - 2\cos(a_0 l_1)\cos(a_1 l_1) = 0 \tag{23}$$

As well as transcendental equation (9), the equation (23) is equivalent to the following

$$a_0 a_1\left\{2\left[1 - \sum_{i=0}^{\infty}\sum_{j=0}^{\infty}(-1)^{i+j}\frac{a_0^{2i}a_1^{2j}}{(2i)!(2j)!}J^{2(i+j)}\right] - \right.$$
$$\left. -\left(a_0^2 + a_1^2\right)\sum_{i=0}^{\infty}\sum_{jj=0}^{\infty}(-1)^{i+j}\frac{a_0^{2i}a_1^{2j}}{(2i+1)!(2j+1)!}J^{2(i+j+1)}\right\} = 0 \tag{24}$$

It follows from the equation, that, first, $a_1 = 0$ also we got frequencies (13).

We will write down the equation (24), having written out the first terms

$$\left\{(a_0^2 + a_1^2)J^2 - \frac{1}{6}(5a_0^4 + 5a_1^4 + a_0^2 a_1^2)J^4 + \right\}\times$$
$$\times\frac{1}{90}\left[a_0^6 + a_1^6 + 7a_0^2 a_1^2(a_0^2 a_1^2)\right]J^6 + \dots \} = 0 \tag{25}$$

From (25) it also follows that it can be supposed $\left(a_0^2 + a_1^2\right) = 0$ and we will get

$$B_0 = 0 \quad \text{or} \quad \xi^2 - \frac{2\gamma}{(2-\nu)} = 0 \tag{26}$$

which root is equal to

$$\xi = \sqrt{\frac{2\gamma}{(2-\nu)}} \tag{27}$$

Similarly, we can put approximately

$$(a_0^2 + a_1^2) - \frac{J^2}{6}(5a_0^4 + 5a_1^4 + a_0^2 a_1^2) = 0 \tag{28}$$

and we will get frequency equation

$$(5B_0^2 - 9B_1) - \frac{6}{J^2} B_0 = 0 \tag{29}$$

having positive roots.

We will consider more difficult transcendental equation

$$\begin{aligned} &4\left[Q\left(Q - a_0^2 - a_1^2\right) + a_0^2 a_1^2\right]\left[1 - \cos(a_0 l_1) - \cos(a_1 l_1)\right] + \\ &+ 2\left[\frac{a_0^3}{a_1^3}\left(Q - a_1^2\right)^2 + \frac{a_1^3}{a_0^3}\left(Q - a_0^2\right)^2\right]\sin(a_0 l_1) - \sin(a_1 l_1) = 0, \end{aligned} \tag{30}$$

where

$$Q = \frac{3-2\nu}{7-4\nu}\left[\frac{\xi^2}{h^2} - 2\left(\frac{\pi k}{l_2}\right)^2\right]$$

which is equivalent to the following

$$\begin{aligned} &2\left[Q_0(Q_0 - a_0^2 - a_1^2) + a_0^2 a_1^2\right]\left[1 - \sum_{i=0}^{\infty}\sum_{j=0}^{\infty}(-1)^{i+j}\frac{a_0^{2i} a_1^{2j}}{(2i)!(2j)!}J^{2(i+j)}\right] + \\ &+ \left[a_0^4 (Q_0 - a_1^2)^2 + a_1^4 (Q_0 - a_0^2)^2\right]\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}(-1)^{i+j}\frac{a_0^{2i} a_1^{2j}}{(2i+1)!(2j+1)!}J^{2(i+j+1)} = 0 \end{aligned} \tag{31}$$

$$Q_0 = \left(\frac{3-2\nu}{7-4\nu}\right)(\xi^2 - 2\gamma).$$

We will write out the first terms in the equation (31)

$$\begin{aligned} &\left[\left(a_0^2 + a_1^2\right)L_1 + L_2\right]J^2 - \left[L_1\left(\frac{a_0^4 + a_1^4}{12} + \frac{a_0^2 a_1^2}{2}\right) + L_2\left(\frac{a_0^2 + a_1^2}{6}\right)\right]J^4 + \\ &+ \left\{\frac{1}{360} L_1\left[a_0^6 + a_1^6 + 15 a_0^2 a_1^2\left(a_0^2 + a_1^2\right)\right]\right\} + \\ &+ \frac{1}{20} L_2\left(a_0^4 + a_1^4 + \frac{10}{3} a_0^2 a_1^2\right)J^6 + \ldots = 0; \end{aligned} \tag{32}$$

$$L_1 = \left[Q_0\left(Q_0 - a_0^2 - a_1^2\right) + a_0^2 a_1^2\right],$$

$$L_2 = \left[a_0^4\left(Q_0 - a_1^2\right)^2 + a_1^4\left(Q_0 - a_0^2\right)^2\right].$$

Being limited by the first term in the formula (32), we will get

$$\left(a_0^2 + a_1^2\right)L_1 + L_2 = 0 \tag{33}$$

or

$$Q_0^2\left(B_0^2 - 2B_1\right) - 2Q_0 B_0 B_1 + 2B_1^2 + B_0\left[Q_0\left(Q_0 - B_0\right) + B_1\right] = 0 \tag{34}$$

The frequency equation (34) is the algebraic equation relatively to ξ and already depends on the parameter γ.

Equations of higher order relatively to ξ already depend on the parameter γ.

It is also possible to consider other boundary value problems.

Thus, transcendental frequency equations can be reduced to algebraic and to investigate influence of both boundary conditions at the edges of rectangular plate or rectangular flat element, and parameters of geometrical and mechanical character on frequencies of own fluctuations of rectangular flat elements.

We will generalize outcomes for rectangular plate or flat element which material satisfies viscoelastic model of Maxwell.

Let we have a rectangular uniform isotropic plate.

In this case, we will find the solution of approximate quartic equation

$$W = \exp\left(\frac{b}{h}\xi t\right)\sum_{k=1}^{\infty} W_k \sin\left(\frac{pky}{J_2}\right), \tag{35}$$

where ξ - complex frequency which valid part defines the law of attenuation of fluctuations and imaginary part determines frequencies of own fluctuations.

For W_k we get ordinary differential equation

$$\frac{d^4W_k}{dx^4} - \overline{B_0}\frac{d^2W_k}{dx^2} + \overline{B_1}W_k = 0 \tag{36}$$

where $\overline{B_0}, \overline{B_1}$ are equal to

$$\overline{B_0} = \left[2\gamma + \frac{A_1}{A_2}\frac{b}{h}\left(\frac{b}{h}\xi^2 + \frac{1}{\tau}\xi\right)\right]; \tag{37}$$

$$\overline{B_1} = \left[\frac{A_0}{A_2}\left(\frac{b}{h}\right)^4\xi^4 + 2\frac{A_0}{A_2\tau}\left(\frac{b}{h}\right)^3\xi^3 + \left(\frac{b}{h}\right)^2 \times \right.$$
$$\left.\left(\frac{1}{A_2} + \frac{1}{\tau^2}\frac{A_0}{A_2} + 2\gamma\frac{A_1}{A_2}\right)\xi^2 + \frac{1}{A_2\tau}\left(\frac{b}{h}\right)\times\left(1 + 2\gamma\frac{A_1}{A_2}\right)\xi + \gamma^2\right]$$

Coefficients A_j are provided in the previous paragraphs.

We will write down the common solution of the equation (36)

$$W_k = C_1\left[\frac{ch(a_0x)}{a_1^n} + \frac{ch(a_1x)}{a_1^n}\right] + C_2\left[\frac{ch(a_0x)}{a_0^n} + \frac{ch(a_1x)}{a_1^n}\right] +$$
$$+\left[\frac{sh(a_0x)}{a_0^m} + \frac{sh(a_1x)}{a_1^m}\right] + C_4\left[\frac{sh(a_0x)}{a_0^m} + \frac{sh(a_1x)}{a_1^m}\right], \tag{38}$$

i.e. instead of trigonometrical functions we have hyperbolic ones.

All considered regional tasks leading to the transcendental equations are solved similarly. Transcendental equations are got from previous where values a_j are necessary to replace with values ia_j, where i - imaginary unit.

For example, the transcendental equation (9) passes into the equation

$$a_0ch(a_0l_1)sh(a_1l_1) - a_1sh(a_0l_1)ch(a_1l_1) = 0 \tag{39}$$

which is equivalent to the following

$$a_0a_1\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\frac{a_1^{2i}a_1^{2j}a_0^{2i}}{(2i+1)!(2j)!}l^{2(i+j)} = 0;$$

$$a_{0,1} = \sqrt{\frac{\overline{B_0}}{2} \pm \sqrt{\frac{\overline{B_0^2}}{4} - B_1}} \quad (40)$$

One of the frequency equations of the formula (40) follows from the condition $a_j = 0$ and we get

$$\xi^4 + \frac{2}{\tau_0}\xi^3 + \frac{8}{(7-8\nu)}\left[(2-\nu)\gamma + \frac{(7-8\nu)}{8\tau_0^2} + \frac{3}{2}(1-\nu)\right]\xi^2 + \\ + \frac{12(1-\nu)}{(7-8\nu)\tau_0}\left[1 + 2(2-\nu)\gamma\right]\xi + \frac{8}{(7-8\nu)}\gamma^2 = 0, \quad (41)$$

Which coincides with the frequency equation of the approximate equation of quartic cross fluctuations (1) for rectangular hinge-supported plate on all four parties of plate, and it has two complex conjugate roots.

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А. Ж. Сейтмұратов[1], Д. М. Жарылғапова[1], Н. К. Медеубаев[2], А. А. Ибраева[1]

[1]Қорқыт Ата атындағы Қызылорда мемлекеттік университеті, Қазақстан,
[2]Бөкетов атындағы Қарағанды мемлекеттік университеті, Қазақстан

АСА КҮРДЕЛІ ШЕКАРАЛЫҚ ШАРТТАР КЕЗІНДЕГІ ПЛАСТИНАЛАР ТЕРБЕЛІСІНІҢ ҚОЛДАНБАЛЫ ЕСЕБІ

Аннотация. Берілген жұмыста пластинкадан құралған материалдың қатпарлылығын, реологиялық тұтқыр қасиеттерін, анизотропиясын және т.б. зерттеу нәтижелері есере отырып шешілген меншікті және еріксіз тербелістер есебіні қарастырылған.

Зерттеу натижесңінде гармоникалық толқындардың деформацияланатын денелер жағдайындағы фазалық жылдамдығын, орта күйінің өзгеру жылдамдығы деп қарастырады, бұл ретте фазалық жылдамдық жиілігі меншікті тербеліс арқылы өрнектеледі, сондықтан гармоникалық толқындардың таралу процессін зерттеу проблемаларын анықтау, меншікті нысандар мен берілген прластинкалардың жиілік шектелген тербелісіне тікелей қатысты болады.

Екі қарама-қарсы шеттері топсалап бекітілген, ал басқа екі жағы әр түрлі бекіту түрлерімен ұстатылған немесе кернеу әсер етпейтіндей болып орналасқан болса, онда бұл жағдай аса күрделі тікбұрышты жазық элемент тербелісі болып табылады.

Мұндай есептер классы сандық түрде де немесе аналитикалық түрде де шешілетін меншікті жиілік тербелісін анықтайтын трансценденттік теңдеулерге акеледі

Трансценденттік жиіліктік теңдеуін алгебралық түрге келтіре отырып, тік бұрышты пластинкалар шектік шарттарын, геометриялық және механикалық сипаттағы тік бұрышты жазық элементтің тербеліс теңдеуінің әсері негізінде зерттеуге болады.

Түйін сөздер: пластинка, анизотропия, меншікті тербелістер, еріксіз тербелістер, трансценденттік, теңдеу, реология.

А. Ж. Сейтмуратов[1], Д. М. Жарылгапова[1], Н. К. Медеубаев[2], А. А. Ибраева[1]

[1]Кызылординский государственный университет им. Коркыт Ата, Казахстан,
[2]Карагандинский государственный университет им. Е. Букетова, Казахстан

ПРИКЛАДНЫЕ ЗАДАЧИ КОЛЕБАНИЯ ПЛАСТИН ПРИ БОЛЕЕ СЛОЖНЫХ ГРАНИЧНЫХ УСЛОВИЯХ

Аннотация. В настоящей работе приводятся результаты по исследованию собственных и вынужденных колебаний плоских элементов с учётом слоистости материала пластинки, реологических вязких свойств, анизотропии и т.д.

При исследовании гармонических волн в деформируемых телах вводится понятие фазовой скорости как скорости изменения состояния среды, при этом фазовая скорость выражается через частоты собственных колебаний и поэтому исследование распространения гармонических волн имеет прямое отношение к проблемам определения собственных форм и частот колебаний ограниченных в плане пластин.

Более сложным колебанием прямоугольного плоского элемента является колебание, когда два из противоположных краёв шарнирно опёрты, а два других края – имеют различные виды закрепления или свободны от напряжений.

Данный класс задач приводит к трансцендентным уравнениям для определения частот собственных колебаний, которые можно решать как численно, так и аналитически.

Трансцендентные частотные уравнения можно сводить к алгебраическим и исследовать влияние, как граничных условий по краям прямоугольной пластинки или прямоугольного плоского элемента, так и параметров геометрического и механического характера на частоты собственных колебаний прямоугольных плоских элементов.

Ключевые слова: пластинки, анизотропия, собственные колебания, вынужденные колебания, трансцендентные, уравнения, реология.

Сведение об авторах:

Сейтмуратов Ангысын Жасаралович – д. ф.-м. н., профессор кафедры «Физика и математика» КГУ им. Коркыт Ата

Жарылгапова Дина Муратовна – к. п. н., старший преподаватель кафедры «Физика и математика» КГУ им. Коркыт Ата

Медеубаев Нурболат Куттымуратович – старший преподаватель кафедры «Алгебра, мат. логика и геометрия» КарГУ им. Букетова

Ибраева Анар Абдикаримовна – старший преподаватель кафедры «Физика и математика» КГУ им. Коркыт Ата