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FORMATION OF COMPUTATIONAL SCHEMES OF ADDITIONAL TARGETED CONSTRAINTS THAT REGULATE THE FREQUENCY SPECTRUM OF NATURAL OSCILLATIONS OF ELASTIC SYSTEMS WITH A FINITE NUMBER OF DEGREES OF MASS FREEDOM, THE DIRECTIONS OF MOVEMENT OF WHICH ARE PARALLEL, BUT DO NOT LIE IN THE SAME PLANE PART 2: THE FIRST SAMPLE OF ANALYSIS

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Abstract: For some elastic systems with a finite number of degrees of freedom of masses, in which the directions of mass movement are parallel and lie in the same plane (for example, rods), special methods have been developed for creating additional constraints, the introduction of each of which purposefully increases the value of only one natural frequency and does not change any from the natural modes. The method of forming a matrix of additional stiffness coefficients that characterize such targeted constraint in this problem can also be applied when solving a similar problem for elastic systems with a finite number of degrees of mass freedom, in which the directions of mass movement are parallel, but do not lie in the same plane (for example, plates). At the same time, for such systems, only the requirements for the design schemes of additional targeted constraints are formulated, and not the methods for their creation. The distinctive paper is devoted to solution of corresponding sample of plate analysis with the use of approach that allows researcher to create computational schemes for additional targeted constraints for such systems.

Keywords: natural frequency, natural modes, generalized additional targeted constraint, sample of analysis

ФОРМИРОВАНИЕ РАСЧЕТНЫХ СХЕМ ДОПОЛНИТЕЛЬНЫХ СВЯЗЕЙ, ПРИЦЕЛЬНО РЕГУЛИРУЮЩИХ СПЕКТР ЧАСТОТ СОБСТВЕННЫХ КОЛЕБАНИЙ УПРУГИХ СИСТЕМ С КОНЕЧНЫМ ЧИСЛОМ СТЕПЕНЕЙ СВОБОДЫ МАСС, У КОТОРЫХ НАПРАВЛЕНИЯ ДВИЖЕНИЯ ПАРАЛЛЕЛЬНЫ, НО НЕ ЛЕЖАТ В ОДНОЙ ПЛОСКОСТИ ЧАСТЬ 2: ПЕРВЫЙ ТЕСТОВЫЙ ПРИМЕР

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Аннотация. Для некоторых упругих систем с конечным числом степеней свободы масс, у которых направления движения масс параллельны и лежат в одной плоскости, (например, стержни) разработаны методы создания дополнительных связей, введение каждой из которых прицельно увеличивает значение только одной собственной частоты и не изменяет ни одну из форм собственных колебаний. Метод формирования матрицы дополнительных коэффициентов жесткости, характеризующих в этой задаче такую прицельную связь, может быть применен и при решении аналогичной задачи для упругих систем с конечным числом степеней свободы масс, у которых направления движения масс параллельны, но не лежат в одной плоскости (например, пластины). Вместе с тем для таких систем сформулированы лишь требования к расчетным схемам дополнительных прицельных связей, а не методы их создания. В данной статье рассматривается пример применения для пластин разработанного подхода, позволяющего создавать расчётные схемы дополнительных прицельных связей и для таких систем.

Ключевые слова: частота собственных колебаний, форма собственных колебаний, обобщенная прицельная дополнительная связь, пример расчета

THE FIRST SAMPLE

Let us consider a hinged rectangular plate [4, 10-14, 19, 20] 6 *m* by 6 *m* in size, carrying concentrated masses (Fig. 1*a* [4])

$$m[1]=1000\,kg,\;\; m[2]=1100\,kg,$$
$$m[3]=1150\,kg,\;\; m[4]=1200\,kg\,.$$

The thickness of the plate is 0.12 *m*. The modulus of elasticity of the plate material

$$E=24\cdot 10^9\;N/m^2=24\cdot 10^9\;Pa\,.$$

Poisson's ratio $\nu_0=0.2$.

We choose the main system of the displacement method (Fig. 1b) [17], form the corresponding system of equations (1) from the paper [4] (matrices $A=\|r[i,k]\|$, $M=\|m[i]\|$). From equation (2) given in [4], we determine the eigenfrequencies and eigenmodes of the plate vibrations. The values of the eigenfrequencies of the plate and the coordinates of the eigenmodes corresponding to them are given in Table 1 (columns are the eigenfrequencies and coordinates of the eigenmodes).

Assume that it is required to increase the value of the first frequency of natural oscillations up to 100 s^{-1} (or up to 100 *Hz*, respectively). To do this, in accordance with formulas (7), (8), (9) given in [4], we form a matrix of additional stiffness coefficients (4) (see [4]). All the data necessary to use dependencies (7), (8), (9) from [4] are given in Table 1. After forming the matrix of additional stiffness factors, taking into account their influence, we determine from equation (10) given in [4], the modified spectrum eigenfrequencies and their corresponding vibration modes [1-6, 13]. The modified spectrum of natural frequencies and their corresponding forms are shown in Table 2.

It can be seen from the table that taking into account the additional stiffness factors did not change any of the modes of natural oscillations of the plate, but only increased the value of one of the frequencies from 61.6965 s^{-1} to the specified value of 100 s^{-1}.

The generalized targeted constraint must correspond to the matrix of additional stiffness coefficients.

One of the variants of the computational scheme of the targeted constraint is shown in Figure 1*a* and Figure 1*b*. The accepted version is once statically indeterminate and does not contain additional racks. Thus, its geometry is determined only by the lengths of the main vertical members, that is, by the values $l_{st}[i]$.

As noted above, now the problem is reduced to finding in the computation scheme of targeted constraint the lengths of the main vertical members $l_{st}[i]\;(i=1,2,..,4)$ from the conditions for the occurrence of forces $N_{st}[i],\;\; i=1,..,4$ in them, the ratios between which will be proportional to the ratios between the forces $R_0[i]=m[i]v[i,1],\;\; i=1,..,4$. The values $m[i]$ are shown in the initial data of the distinctive sample, and the values $v[i,1]$ are given in the first column of Table 1 and Table 2. The forces are shown in Table 3.

In order to use the algorithm for the formation of the computational scheme of targeted constraint, researcher must firstly select the base vertical member and set its length. For the base we will take the vertical member of the first node and set $l_{st}[1] = 2.45\,m$. We will take the initial values of other variable lengths $l_{st}[2] = 2.30\,m$, $l_{st}[3] = 2.00\,m$, $l_{st}[4] = 2.6\,m$.

Table 1. Values of eigenfrequencies (natural vibration frequencies) of the plate and coordinates of their corresponding eigenmodes (natural modes) (the first example).

ω	61.6965	141.4295	146.2905	205.4514
1	0.4908	0.0001	0.7080	-0.5893
2	0.4965	-0.7093	0.0895	0.5154
3	0.5058	-0.0676	-0.7003	-0.4432
4	0.5068	0.7016	0.0181	0.4367

Table 2. Modified frequency spectrum of natural vibrations of the plate and coordinates, corresponding to them natural forms (the first example).

ω	100.00	141.4295	146.2905	250.00
1	0.4908	0.0001	0.7080	-0.5893
2	0.4965	-0.7093	0.0895	0.5154
3	0.5058	-0.0676	-0.7003	-0.4432
4	0.5068	0.7016	0.0181	0.4367

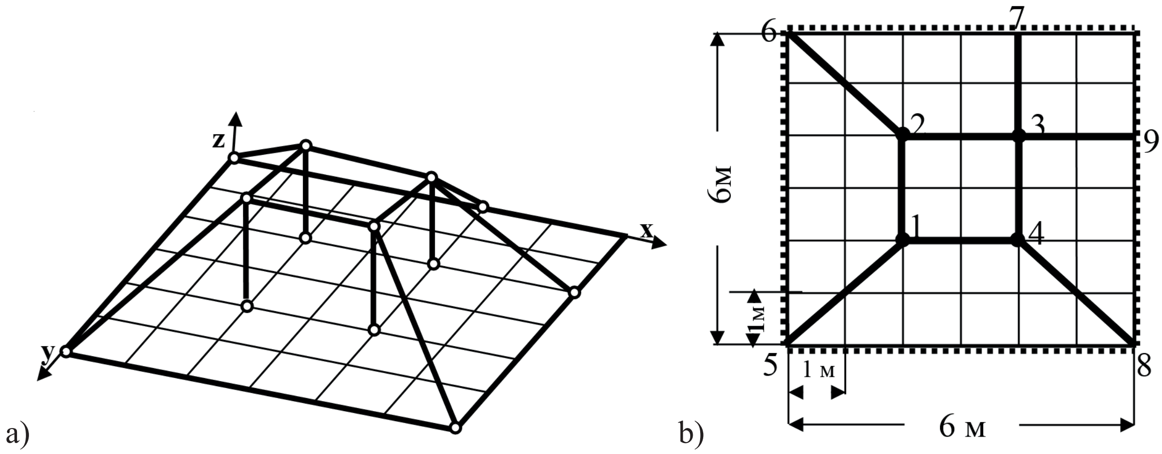

Figure 1. The first sample: variant of the computational targeted constraint: a) three-dimensional visualization; b) top view.

Table 3. To the analysis of the targeted constraint in the computational scheme (the first example).

i	1	2	3	4
$m[i]$	1000	1100	1150	1200
$v[i,1]$	0.4908	0.4965	0.5058	0.5068
$R_0[i]$	490.7597	546.1499	581.6800	608.1056

It is also necessary to set the force in one of the vertical members. Let's accept

$$N_{st}[1] = R_0[1] = 490.7597\,kg .$$

To find the minimum of the objective function (12), described in [4], the method of steepest descent in the space of varying lengths of vertical members $l_{st}[i]$, $i = 2, 3, 4$ was used. The formation of the computational scheme of the targeted constraint according to the above mentioned algorithm was carried out without restrictions on the length of the vertical members. Equilibrium equations were constructed for nodes located at the tops of the vertical members.

Table 4. The lengths of vertical members of targeted constraint and corresponding forces in them (the first sample).

$l_{st0}[1]=2.4500$	$N_{st}[1]=-490.7597$	$l_p[8,4]=3.7680$	$N_p[8,4]=747.1761$
$l_{st}[2]=2.3855$	$N_{st}[2]=-546.1499$	$l_p[9,3]=2.7948$	$N_p[9,3]=554.1850$
$l_{st}[3]=1.9521$	$N_{st}[3]=-581.6800$	$l_p[1,2]=2.0010$	$N_p[1,2]=396.7919$
$l_{st}[4]=2.4896$	$N_{st}[4]=-608.1056$	$l_p[2,3]=2.0464$	$N_p[2,3]=405.7875$
$l_p[5,1]=3.7420$	$N_p[5,1]=742.0097$	$l_p[3,4]=2.0710$	$N_p[3,4]=410.6569$
$l_p[6,2]=3.7001$	$N_p[6,2]=733.6948$	$l_p[1,4]=2.0004$	$N_p[1,4]=396.6633$
$l_p[7,3]=2.7948$	$N_p[7,3]=554.1850$		

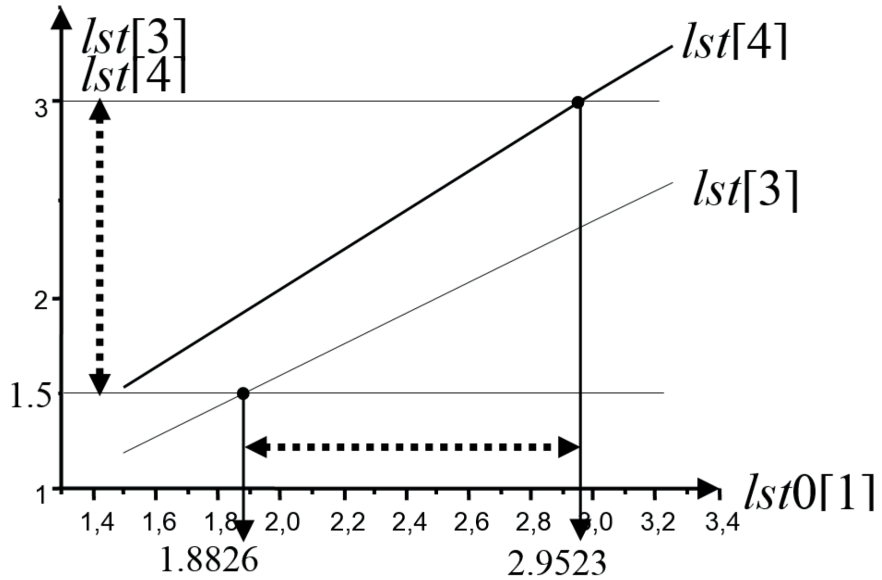

Figure 2. The first sample: parameters of targeted constraint.

The found lengths of the vertical members of targeted constraint and the forces in them are shown in Table 4.

From Table 4 it can be seen that the forces in the vertical member by absolute values coincide with the forces $R_0[i]$. This circumstance confirms the minimum of the objective function (12) [7-9, 15, 16, 18, 21-23] from [4] and the fulfillment of the requirement that the ratios between the forces $N_{st}[i]$ are proportional to the ratios between the values $R_0[i]$.

The cross-sectional areas of the vertical members of targeted constraint can be found from the condition that its stiffness coincides with the stiffness determined by the matrix of additional coefficients (4) from [4]. These conditions are realized by dependencies (9), (14), (15) from [4]. Since there are no additional vertical members in the computational scheme of the targeted constraint, then in (14) from [4] only the values

$$F_{st}[i]=F\alpha[i], \quad F_P[j]=F\beta[j]$$

remain, and in the brackets of expression (15) from [4] we have only the first two terms.
When minimizing the volume of the material of the targeted constraint from [4], researcher normally consider the case when, according to the design conditions

$$\alpha[i]=2\,,\quad \beta[i]=1\,.$$

All vertical members are solid round rods. The modulus of elasticity of the material of the vertical members in equal to $E=2.06\cdot10^{11}\,Pa$. Then, using (13), (14), (15) and (16) from [4], we obtain

$$F_{st}[i]=0.00057357\,m^2\,,\quad D_{st}=0.027024\,m\,,$$
$$F_p[i]=0.00028678\,m^2\,,\ D_p=0.0191088\,m\,,$$
$$V_{SV}=0.012467\,m^3\,,$$

where D_{st} and D_p are respectively, the diameters of the rods of the vertical members and belts of targeted constraint.
As noted above, when the length of the base vertical member changes, the ratios between the lengths of the base vertical members do not change, that is, the values χ_1 and χ_2 (see [4]) remain constant. Therefore, when changing the length of the base vertical member, the greatest length remains at the vertical member of the fourth node, and the smallest at the vertical member of the third node. Thus, when minimizing the function V_{SV} (see [4]), the values

$$\chi_1=l_{st}[1]/l_{st}[4]=0.9841\,;$$
$$\chi_2=l_{st}[1]/l_{st}[3]=1.551\,,$$

computed with the use of data from Table 4 do not change. Figure 2 shows the dependences of the lengths $l_{st}[3]$ and $l_{st}[4]$ on the change in the length of the base vertical member $l_{st0}[1]$.
On Figure 2 also shows in the direction of the y-axis the restrictions

$$3\,m\ge l_{st}[i]\ge 1.5\,m,\quad i=1,2,3,4$$

on the expression (17) from [4], and in the direction of the abscissa shows the range of permissible values of variable length $l_{st0}[1]$ according to the expression (18) from [4].
The targeted constraint was formed at an arbitrarily chosen value of the length of the base vertical member $l_{st}[1]=2.45\,м$. By varying the length of the base vertical member $l_{st0}[1]$, the researcher can use the one-dimensional search method to achieve the minimization of material consumption when creating targeted constraint. In this case, the values of variable length should be chosen in the range of admissible values (17), (18) from [4]. Table 5 lists seven options for choosing the length of the base vertical member. For each option, the values of the lengths of the remaining racks and the amount of sighting material are given V_{SV}.
Let's consider three options for forming restrictions on the lengths of the vertical members and, accordingly, the area of admissible values of the length of the base vertical member $l_{st0}[1]$. variable while minimizing the amount of sighting material:

1) $3\,м\ge lst[i]\ge 1.5\,m,\ \ i=1,2,3,4$ (17) from [1];
$2.9523\,m\ge l_{st0}[1]\ge 1.8826\,м$ (18) from [1];
2) $2.1848\,m\ge l_{st}[i]\ge 1.5\,м$ (17) from [1];
$2.15\,m\ge l_{st0}[1]\ge 1.8826\,м$ (18) from [1];
3) $3\,m\ge l_{st}[i]\ge 2.1\,m$ (17) from [1];
$2.9523\ m\ge l_{st0}[1]\ge 2.6356\,m$ (18) from [1].

In all variants, cases were considered when, according to the design conditions, we have

$$\alpha[i]=2\,,\quad \beta[i]=1\,.$$

On Figure 3 shows a graph of the change in the volume of material of targeted constraint depending on the length of the base vertical member $l_{st0}[1]$. Figure 3 also shows the ranges of acceptable values of the variable value of the three above options. In each area, the minimum volume values V_{SV} are marked.

The results of minimizing the volume for the first version of the restrictions are shown in the fourth row of Table 5. Here, the minimum value $V_{SV} = 0.01247\,m^3$ for $l_{st0}[1] = 2.45\,m$ is within the range of acceptable values $l_{st0}[1]$, that is, the global extremum is found. The areas and diameters of the sections of the vertical members of targeted constraint are equal to

Table 4. The parameters of targeted constraint (the first sample).

No.	$l_{st0}[1]$	$l_{st}[2]$	$l_{st}[3]$	$l_{st}[4]$	V_{SV}
1	1	0.9737	0.7968	1.0162	0.02495
2	1.5	1.4606	1.1952	1.5242	0.01567
3	2.15	2.0934	1.7131	2.1848	0.01268
4	2.45	2.3855	1.9521	2.4896	0.01247
5	2.6356	2.5662	2.1000	2.6782	0.01254
6	3.0	2.9211	2.3904	3.0485	0.01300
7	3.25	3.1645	2.5896	3.3025	0.01351

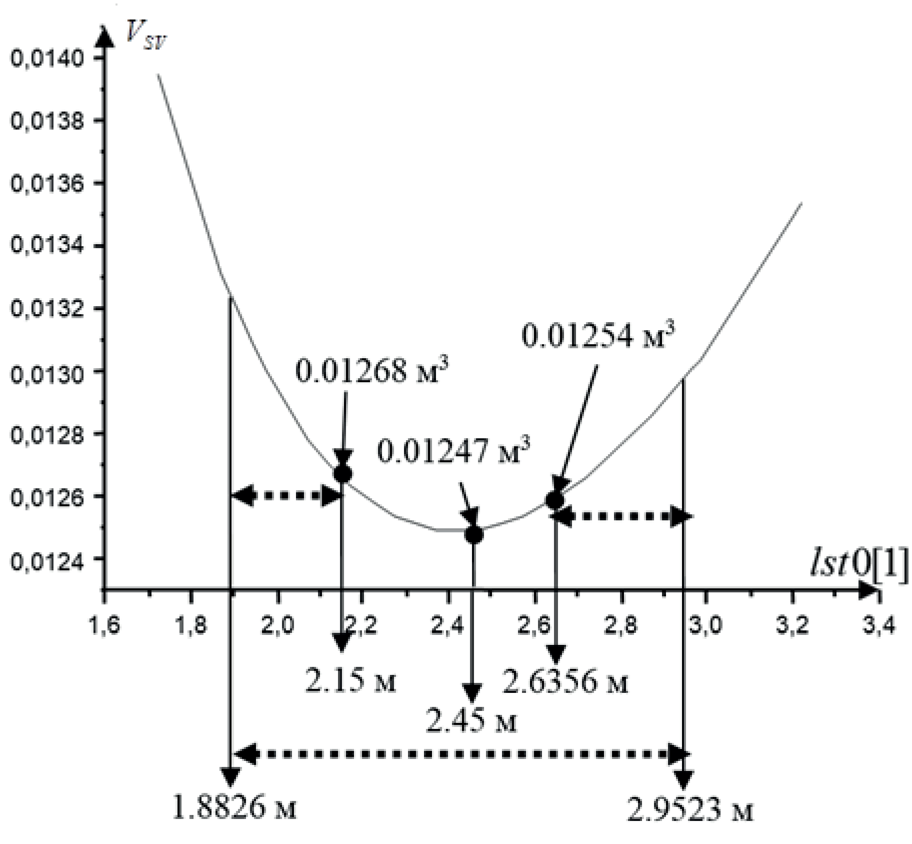

Figure 5. The graph of the change in the volume of material of the targeted constraint depending on the length of the base vertical member.

$F_{st} = 0.0005734\,m^2$, $D_{st} = 0.0270\,m$,

$F_p = 0.0002868\,m^2$, $D_p = 0.0191\,m$.

The results of the second variant are presented in the third row of Table 5. The minimum value $V_{SV} = 0.01268\,m^3$ is on the border of the range of acceptable values $l_{st0}[1]$, that is, the boundary optimum is found at $l_{st0}[1] = 2.15m$. The areas and diameters of the sections of the vertical members of targeted constraints are equal to

$$F_{st} = 0.0006295\,m^2,\ D_{st} = 0.02381\,m,$$
$$F_p = 0.0003148\,m^2,\ D_p = 0.02002\,m.$$

The results of the third variant are presented in the fifth row of Table 5. The minimum value $V_{SV} = 0.01254\,m^3$ is on the border of the range of acceptable values $l_{st0}[1]$, that is, the boundary optimum is found at $l_{st0}[1] = 2.635m$. The areas and diameters of the sections of the vertical members of targeted constraints are equal to

$$F_{st} = 0.0005513\,m^2,\ D_{st} = 0.02649\,m,$$
$$F_p = 0.0002756\,m^2,\ D_p = 0.01873\,m.$$

The results obtained were checked (verified) with the use of “LIRA-SAPR” software package. The eigenfrequencies and coordinates of the vibration modes of the plate with impact coupling, obtained using LIRA-SAPR [8], coincided with the data in Table 2.

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