DOI:10.22337/2587-9618-2022-18-4-71-81

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 3: THE SECOND SAMPLE OF ANALYSIS AND CONCLUSION

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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 3: ВТОРОЙ ТЕСТОВЫЙ ПРИМЕР И ЗАКЛЮЧЕНИЕ

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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 SECOND SAMPLE OF ANALYSIS

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 $\nu_0 = 0.2$.

Assume that it is required to increase the value of the fourth frequency of natural oscillations up to 250 s^{-1} (or up to 250 *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 2 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 205.4514 s^{-1} to the specified value of 250 s^{-1}.

The initial variant of the computational scheme of the targeted constraint is shown in Figure 1*a* and Figure 1*b*.

For the base we will take the vertical member of the first node. Let's compute the forces

$$R_0[i] = m[i]v[i,4],\;\; i = 1,..,4$$

were $m[i]$ are given values; $v[i,4]$ are presented at the fourth columns of Table 1 and Table 2.

The forces are shown in Table 3.

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

$$N_{st}[1] = R_0[1] = 589.2890kg$$

Let's perform the formation of design schemes of sighting for different values of the lengths of the base vertical member $l_{st0}[1]$. Table 4 contains fifteen variants of lengths of the base vertical member $l_{st0}[1]$.

The development (formation) of computational schemes of targeted constraint was done without taking into account restrictions on the length of the vertical members. Consideration of restrictions will be considered as well.

In each variant, after the development of the computational scheme, the areas of transverse sections of the rods of the targeted constraint were computed. As in the first sample […], when minimizing the volume of the targeted constraint material (formula (16)_from […]), the case is considered when, according to the design conditions, we have $\alpha[i] = 2$ and $\beta[i] = 1$. Let's consider all the rods of a solid circular section. The modulus of elasticity of the material of the rods is equal to $E = 2.06 \cdot 10^5 MPa$. The cross-sectional areas of the rods and the volume of the bonding material were determined by dependences (13)-(16) from [4].

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

ω	61.6965	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

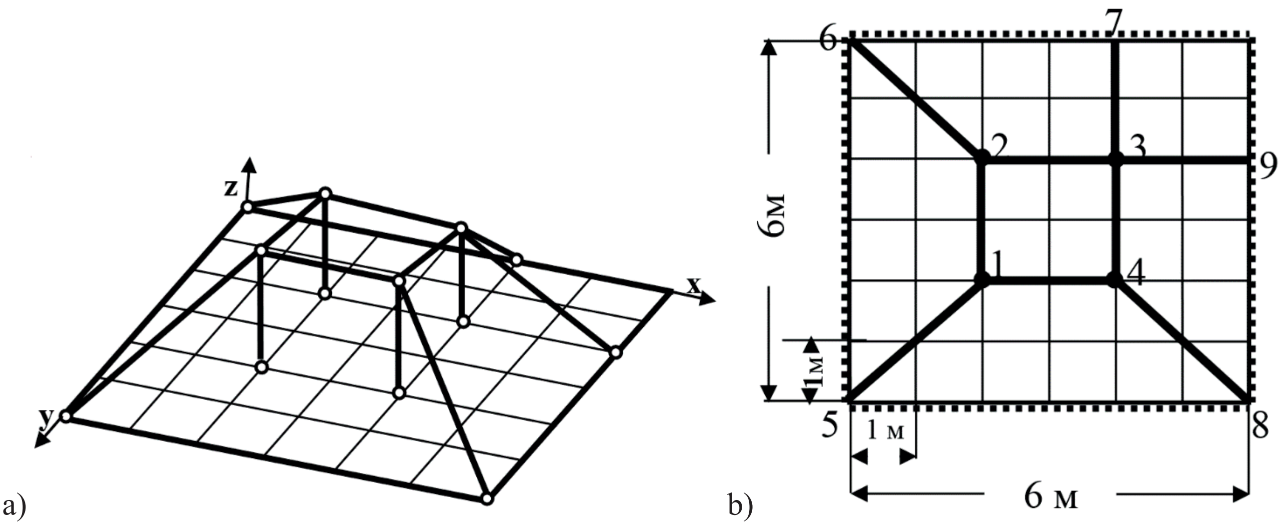

Figure 1. The second sample: variant of the computational targeted constraint: a) three-dimensional visualization; b) top view.

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
$v[i,1]$	-0.5893	0.5154	-0.4432	0.4367
$R_0[i]$	-589.2890	566.8873	-509.7103	524.0320

For each version of the length of the base vertical member, Table 8 shows the lengths of the remaining vertical members and the amount of targeted constraint material V_{VS}.

In all considered variants, the lengths of the first and third vertical members are positive, and the lengths of second and fourth vertical members are negative.

Table 8 shows that the minimum amount of constraints material is achieved at $l_{st0}[1] = 1.17m$ (highlighted line number 11 from Table 4). The areas and diameters of the cross-sections of the targeted constraint vertical members are equal the following:

$$F_{st} = 0.0004865\,м^2,\ D_{st} = 0.02489\,м,$$

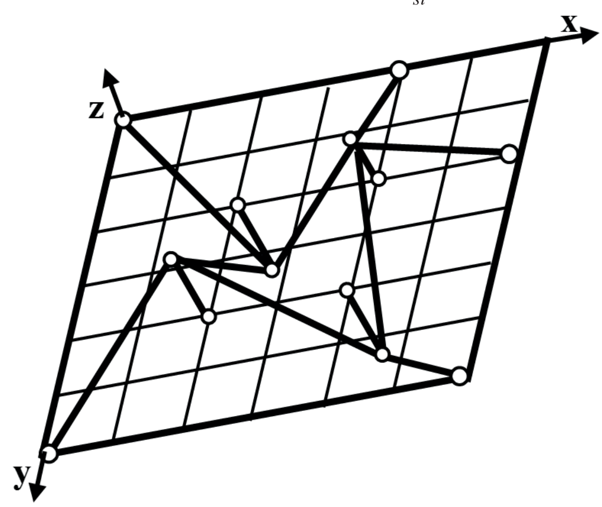

Figure 2. The second sample: general view of this targeted constraint.

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

$$F_p = 0.0002432\,м^2,\ D_p = 0.01760\,м.$$

The general view of this targeted constraint is shown in Figure 2.

As we have already noted, structurally, such a computational scheme is almost unrealizable. In these cases, the targeted constraint should be shifted in the direction of movement of the masses in the positive or negative direction of the axis Z by the value at which the values of all lengths of the main vertical members will be of the same sign. When performing a shift, the relationship between the forces in the rods is preserved.

When the constraint is shifted in the positive direction of axis Z by the value of $Z_V = (l_{st}[k])_{\min} + l_{\min}$ the length of all vertical members will become "positive". In this case, the length of the largest vertical member will be $(l_{st}[i])_{\max} + (l_{st}[k])_{\min} + l_{\min}$, and the length of the smallest vertical member will be $l_{\min}$.

When the constraint is shifted in the negative direction of axis Z by the value of $Z_N = (l_{st}[i])_{\max} + l_{\min}$ the length of all vertical members will become "negative". In this case, the largest absolute value of length of all vertical member will be $(l_{st}[i])_{\max} + (l_{st}[k])_{\min} + l_{\min}$, and the smallest absolute value of length of all vertical member will be $l_{\min}$.

When forming restrictions on the lengths of the vertical members and, accordingly, the area of admissible values of the length of the vertical member $l_{st0}[1]$, which is variable when minimizing the volume of the material of the targeted constraint, it is necessary to determine the value

$$\chi_3 = \frac{l_{st0}[[g]}{(l_{st}[i])_{\max} + (l_{st}[k])_{\min}}.$$

Table 5. Results representing the computational schemes of targeted constraints taking into account shifts in a one-dimensional search for the minimum volume of targeted constraints material (the second sample)

$l_{st0}[1]$	Z_V					
	$l_{st}[1]$	$l_{st}[2]$	$l_{st}[3]$	$l_{st}[4]$	V_{SV}	Z_V
1.07	2.352	0.100	1.901	0.232	0.008941	1.282
1.08	2.373	0.100	1.918	0.233	0.008938	1.293
1.09	2.395	0.100	1.935	0.235	0.008920	1.305
1.10	2.416	0.100	1.952	0.236	0.008910	1.316
1.11	2.437	0.100	1.969	0.237	0.008902	1.327
1.12	2.458	0.100	1.9857	0.239	0.0088961	1.338
1.13	2.479	0.100	2.002	0.240	0.008891	1.349
1.14	2.500	0.100	2.019	0.241	0.008888	1.360
1.15	2.521	0.100	2.036	0.242	0.008887	1.371
1.16	2.542	0.100	2.053	0.243	0.008887	1.382
1.17	2.563	0.100	2.070	0.244	0.008888	1.393
1.18	2.584	0.100	2.086	0.246	0.008890	1.404
1.19	2.605	0.100	2.103	0.2467	0.008895	1.415
1.2	2.626	0.100	2.120	0.248	0.008900	1.426
1.25	2.731	0.100	2.204	0.254	0.008946	1.481

$l_{st0}[1]$	Z_N					
	$l_{st}[1]$	$l_{st}[2]$	$l_{st}[3]$	$l_{st}[4]$	V_{SV}	Z_N
1.07	-0.100	-2.352	-0.551	-2.221	0.009497	-1.17
1.08	-0.100	-2.373	-0.555	-2.240	0.009488	-1.18
1.09	-0.100	-2.395	-0.560	-2.260	0.009481	-1.19
1.10	-0.100	-2.416	-0.564	-2.280	0.009476	-1.2
1.11	-0.100	-2.437	-0.568	-2.300	0.009473	-1.21
1.12	-0.100	-2.458	-0.572	-2.320	0.009471	-1.22
1.13	-0.100	-2.479	-0.576	-2.339	0.009471	-1.23
1.14	-0.100	-2.500	-0.581	-2.359	0.009473	-1.24
1.15	-0.100	-2.521	-0.585	-2.379	0.009476	-1.25
1.16	-0.100	-2.542	-0.589	-2.399	0.009481	-1.26
1.17	-0.100	-2.563	-0.593	-2.419	0.009487	-1.27
1.18	-0.100	-2.584	-0.598	-2.439	0.009495	-1.28
1.19	-0.100	-2605	-0.602	-2.458	0.009504	-1.29
1.2	-0.100	-2.626	-0.606	-2.478	0.009514	-1.3
1.25	-0.100	-2.731	-0.627	-2.577	0.009587	-1.35

It will be the same for all variants, presented in Table 4. If we determine χ_3 from the data of row number 11 of Table 4, then we get

$$\chi_3 = 1.7/(1.17 + 1.2929) = 0.475 .$$

Let's consider two options for forming restrictions on the lengths of the vertical members and, accordingly, the range of acceptable values for the length of the base vertical member $l_{st0}[1]$, which is variable while minimizing the volume of targeted constraint material:

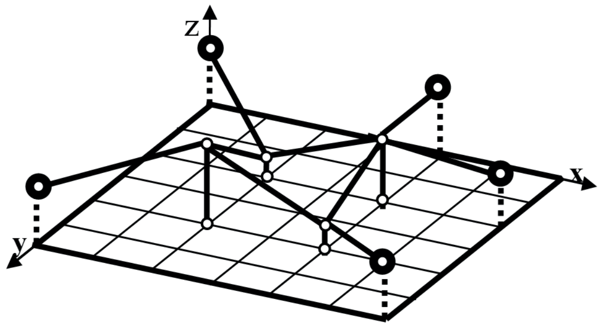

Figure 3. The second sample: general view of this targeted constraint.

1) $l_{\max} = 2.6\,м$, $l_{\min} = 0.1\,м$;

$(l_{\max} - l_{\min}) \cdot \chi_3 \geq l_{st0}[g]$; $1.1875 \geq l_{st0}[1]$;

2) $l_{\max} = 2.4\,м$, $l_{\min} = 0.1\,м$: $1.0925 \geq l_{st0}[1]$.

Let's shift each variant of the computational scheme of targeted constraint from Table 4 both in the positive and in the negative direction of the axis Z. The results representing the computational schemes of targeted constraints, taking into account shifts in a one-dimensional search for the minimum volume of targeted constraint material, are shown in Table 5.

The values of the shift values of the computational schemes Z_V and Z_N were determined according to the data in Table 4 and taking into account the selected option of restrictions.

In the first variant of the restrictions on the length of base vertical member, when $l_{st0}[1] \leq 1.1875\,м$, and the targeted constraint is shifted in the positive direction of the axis Z, the minimum volume of targeted constraint material $V_{SV} = 0.008887\,м^3$ is reached at $l_{st}[g] = 1.16\,м$. The areas and cross-sectional diameters of the rods of targeted constraint are equal to

$$F_{st} = 0.0005078\,м^2,\ D_{st} = 0.02543\,м,$$
$$F_p = 0.0002539\,м^2,\ D_p = 0.01798\,м.$$

The lengths of the vertical members are given in table 9 at $l_{st}[g] = 1.16\,м$. They are all positive. The optimum is achieved when the restrictions on the length of the base vertical member in the form of inequality ($l_{st0}[1] = 1.16\,м < 1.1875\,м$) are met. Thus, this extremum is global. A general view of this targeted constraint is shown in Figure 3.

Also, in the first version of the restrictions on the length of base vertical member, constraint is shifted in the negative direction of the axis Z. In this case, the minimum volume of material $V_{SV} = 0.009471\,м^3$ is achieved at $l_{st}[g] = 1.12\,м$, and the areas and diameters of the cross-sections of the rods of targeted constraint are equal to

$$F_{st} = 0.0005298\,м^2,\ D_{st} = 0.02597\,м,$$
$$F_p = 0.0002649\,м^2,\ D_p = 0.01837\,м.$$

The lengths of the vertical members are given in Table 5 at $l_{st}[g] = 1.12\,м$. The lengths of all vertical members are negative in this case. Since the optimum is reached when the restrictions on the length of the base vertical member in the form of inequality $l_{st0}[1] = 1.12\,м < 1.1875\,м$ are met, this extremum is also global. The general view of this targeted constraint is shown in Figure 4. This version of the computational scheme can also be implemented when the direction of the axis Z is reversed. It is obvious that this action does not change the targeted properties of the constraint. A general view of the targeted constraint for such a case is shown in Figure 5.

In the second variant of the restrictions on the length of base vertical member with $l_{st0}[1] \le 1.0925\,м$ and shift of the targeted constraint in the positive direction of the axis Z or in the negative, the minimum volume of targeted constraint material is reached at the border of the area of admissible values of the length of the base vertical member at $l_{st0}[1] = 1.0925\,м$ (Table 5).

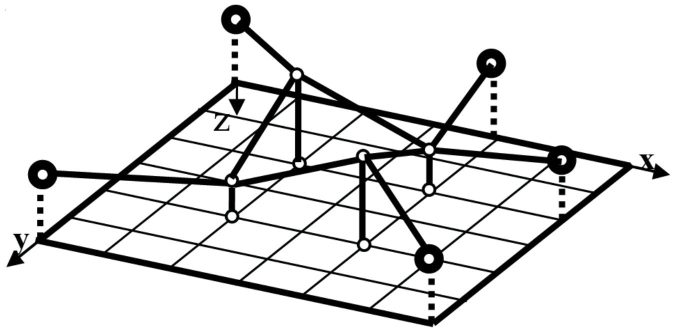

Figure 4. The second sample: general view of this targeted constraint.

When the targeted constraint is shifted in the positive direction of the axis Z, the minimum is $V_{SV} = 0.008920\,м^3$, and the areas and diameters of the sections of the rods of targeted constraint are equal to

$$F_{st} = 0.0005250\,м^2,\ D_{st} = 0.02585\,м,$$
$$F_p = 0.0002625\,м^2,\ D_p = 0.01828\,м.$$

When the targeted constraint is shifted in the negative direction of the axis Z, the minimum is $V_{SV} = 0.009481\,м^3$, and the areas and diameters of the sections of the rods of targeted constraint are equal to

$$F_{st} = 0.0005375\,м^2,\ D_{st} = 0.02616\,м,$$
$$F_p = 0.0002688\,м^2,\ D_p = 0.01850\,м.$$

So, in the second variant of restrictions on the lengths of the vertical members, the minimums of the volume of the targeted constraint material turned out to be boundary. Therefore, their values are somewhat higher than the corresponding values for the first variant of restrictions, in which the minima V_{SV} were implemented as global ones.

CONCLUSION

The first sample, considered in […] confirms the possibility of development of computational scheme of targeted constraint for systems with a finite number of degrees of freedom of masses, in which the directions of mass movement are parallel, but do not lie in the same plane. It also illustrates the possibility of minimizing the volume of material when creating targeted constraint. At the same time, the limitations of the lengths of the main vertical members, which determine the geometry of the targeted constraint, were taken into account. In the first sample the special case is considered – all the lengths of the main vertical members turned out to be positive within development of computational scheme of the targeted constraint.

The second sample illustrates an approach that makes it possible to develop targeted constraints taking into account the restrictions on the lengths of the vertical members and modify the computational schemes for cases where the values of the lengths of some main vertical members turn out to be positive, while others are negative.

So, the distinctive series of papers proposes an approach that allows researcher to create (develop) computational schemes of targeted constraints for elastic systems with a finite number of degrees of freedom of masses, in which the directions of mass movement are parallel, but do not lie in the same plane. Some special properties of such targeted constraints are revealed. Within development of computational scheme of the targeted constraint, the material consumption for its creation is minimized, and some design limitations are taken into account. Particular attention is paid to the modification of targeted constraints, when, during their development, it becomes necessary to shift the computational scheme.

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