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MAST BEHAVIOUR ANALYSIS AND PECULIARITIES OF NUMERICAL MODELLING

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Abstract. Paper is assigned to numerical analysis peculiarities of masts applying specialised computer-aided design packages. Mast's deformable behaviour is described as non-linear one. The test problem of mast is solved by two widely applied in Lithuania computational packages STAADpro and Robot Millennium and the specialised programme for mast design SUDM. A corrected analytical method for mast guy analysis, taking into account a force component, acting along the guy supports. A performed numerical experiment is aimed to clarify the possibilities of the above-mentioned numerical analysis instruments for geometrical non-linear modelling of structure. The accuracy errors when determining the mast stress and strain fields by numerical analysis packages comparing with the ones obtained by a corrected analytical method are indicated. Possibilities of employing the considered computer-aided design programming packages for practical design of masts are discussed.

Keywords: guyed mast, cable, non-linear analysis, modelling peculiarities.

1. Introduction

An active spread of telecommunication services in Lithuania during last decade stimulated the design of tall telecommunication buildings. It directed the researches to concentrate on methods, evaluating correct deformable behaviour of masts and towers. A special attention was focused on the mast, a technically and economically efficient structure among tall buildings. Last time few interesting investigations, assigned to actual problems of mast analysis and design (Juozaitis *et al.* 2001; 2002; Juozaitis, Šapalas 1998) were presented.

The mast, not a very complicated structure to equip, belongs to the class of prestressed structures of geometrically non-linear behaviour (Sokolov 1961; Wahba *et al.* 1998; Voevodin 1989; Gantes *et al.* 1993). Analysis of such structures, taking into account not only static but also dynamic action of wind, is complicated (Juozaitis *et al.* 2002; Gantes *et al.* 1993; Ben Kahla 2000; Ghodrati Amini 2002; Guevera, McClure 1993; Melbourne 1997; Peil *et al.* 1996; Yan-Li 2003). A non-linear mast deforming is conditioned in principle by guys, ie pre-stressed suspension cables. Their response to loading is described by strongly geometrically non-linear behaviour (Juozaitis *et al.* 2002; Wahba *et al.* 1998; Voevodin 1989; Irvine 1992; Petersen 1993; Steel structures… 2002; Palkowski 1990; Halasz, Petersen 1970). The previously employed analytical methods, employed for mast analysis (Voevodin 1989; Steel structures…2002; Halasz, Petersen 1970), do not satisfy the modern design requirements and extent of such structures. Currently in Lithuania the computer-aided design packages (STAADpro, Robot Millennium) are successfully applied for such type of structures. But one must accept the fact that not all of them are capable to model non-linear mast behaviour with a sufficient accuracy. When performing mast static calculations, the errors are committed. The latter can condition the essential influence not only on the mast technical-economical efficiency, but the most important, – on the reliability of structure.

One must note, that the behaviour of prestressed suspension cable, serving as mast guy, has an essential influence on stress and strain state of the mast. Different design methods are employed for calculation of guys (Juozaitis, Šapalas 1998; Wahba *et al.* 1998; Voevodin 1989; Irvine 1992; Petersen 1993; Steel structures… 2002; Palkowski 1990). A temperature gradient, as possible external action, is evaluated in these methods. The guys sometimes are modelled as bars-strings aiming to simplify the calculations (Irvine 1992; Petersen 1993; Steel structures…2002; Sander 1987). But such an approximation of cable-guy deformable response, partially evaluating actual cable kinematic displacements, should be named as an approximate and close to linear modelling one. The corrected methods presented in investigations (Falke, J., Falke, J. 1980; Juozapaitis, Daniūnas 2005) evaluate the load component, acting along the axis of connecting supports. Here it is assumed that suspension cable-guy deforms nut according to the quadratic parabola curve and the magnitudes of support reactions depend on the above-mentioned component of loading. One must mark that exact determining the cable-guy support reactions has a significant influence when estimating stress and strain of the mast.

The problem of mast behaviour is realised via two widely in Lithuania applied computer-aided design packages STAADpro and Robot Millennium and a special mast calculation program SUDM. The testing mast solution is also realised when applying the corrected analytical method for mast guys, taking into account loading components acting along their supports. The geometrical non-linear structure modelling possibilities of above numerical analysis instruments are considered when analysing the numerical solutions. The accuracy errors when determining the mast internal forces and displacements by numerical analysis packages comparing with ones obtained by the corrected analytical method are indicated. Possibilities of employing the considered computer-aided design programming packages for a practical design of masts are discussed.

2. Modelling mast behaviour by computer-aided design packages

Currently in Lithuania the software packages STAADpro, Robot Millennium etc are widely employed in designing building structures. These packages are also employed for analysis and design of steel masts. Designers can also apply a special package SUDM for mast numerical analysis, created by taking part of researchers from Vilnius Gediminas Technical University (VGTU).

STAADpro is one of the most widely known and employed in Lithuania and Europe computer-aided design programs. The command Member Cable is assigned for cable analysis. The cable is modelled as a tensile member, taking into account the axial stresses of such a member and its sag. The cable (non-straight and pre-stressed) stiffness is determined via stiffness parameter:

$$K_{comb} = \frac{EA}{L}\left[1 + \frac{w^2 L^2 EA \cos^2 \alpha}{12T^3}\right],$$

where: EA – axial member stiffness; L – member length; w – member dead load intensity; T – internal force of pre-stressing; α – angle between member axis and horizontal axis.

One must note that such modelling practically excludes the lateral loading. The behaviour of such a member corresponds to a certain stiffness spring behaviour. It evaluates two effects, namely, elastic elongation and geometry (sag) change.

Robot Millennium is also well-known in Lithuania and W. Europe for designing building structures. The guy is modelled by a cable with a small primary sag, subjected by distributed or concentrated loads, acting in the plane of sag. Cable calculation evaluates primary mounting pre-stressing, support flexibility and temperature gradient. A geometrically non-linear behaviour of guy is evaluated by employing the following expression for calculating the flexible space cable:

$$L_1 - L_2 = \Delta = \frac{Hl}{EA} - \frac{H_0 l}{EA} + \alpha \Delta T l + \delta -$$
$$\int \frac{[Q_y(x)]^2 + [Q_z(x)]^2}{[H + N(x)]^2} dx + \int \frac{[Q_y{}^0(x)]^2 + [Q_z{}^0(x)]^2}{[H_0 + N_0(x)]^2} dx,$$

where:

L_1, L_2 – cable span before and after deformation; Δ – cable span change; H_0, H – cable thrusting (tensile) force before and after deformation; l –cable primary length; ΔT – temperature change; δ – cable primary extension/shortening; $Q(x)$ – shearing force function, analogous to a simple beam; $N(x)$ – axial force function.

One must note that in the program the loading component, acting along the line connecting supports, is evaluated when modelling the guy. This influences obtaining more exact mast analysis results.

The program **SUDM** is assigned for stability and dynamic response evaluation of masts. It has been created in Ukrainian research and design institute "Ukrniiprojekstolkonstrukcija". The part assigned for graphic representation of results was created in laboratory of numerical modelling and analysis of VGTU. The program is one among few specialised mast analysis programs, applied in Lithuania. It allows to evaluate static and dynamic wind loadings, temperature gradient, pre-stressing of guys (mounting state), ice covering.

A special subroutine is assigned for dynamic analysis. The linearised equations of motion, ie usual dynamic of linear structural response are employed. The static and dynamic calculations are performed by FEM. Geometrical non-linearity is evaluated via self-correcting iterative method, ie displacement increments are identified per iterative solution process of linear equations. Cable is modelled by one finite element, represented via elastic flexible suspension strand.

The program **SUDM** enables to perform the general stability analysis of mast, represented as space structural system. Two methods evaluating stability reserve coefficient are employed, namely: in respect of mast compressive force and in respect of increment of loading intensity.

3. Mast analysis by corrected analytical method

Evaluation accuracy of mast stress and strain state depends on design model of the guy. As it was mentioned before, the investigations (Falke, J., Falke, J. 1980; Juozapaitis, Daniūnas 2005) introduce methods evaluating the loading component acting along the axis of supports when calculating suspension cables. The investigation (Halasz, Petersen 1970) presents relations to determine suspension cable internal forces and displacements, taking into account flexibility of supports. The support reactions F_{za} and F_{zb} of inclined suspension cable are determined by (Juozapaitis, Daniūnas 2005):

$$F_{za} \cong \frac{q_z l}{2} + \frac{2}{3} q_x f, \quad (1)$$

$$F_{zb} \cong \frac{q_z l}{2} - \frac{2}{3} q_x f, \quad (2)$$

where q_z and q_x are the vertical and horizontal components of loading; f is cable sag.

The cable thrusting force at any point is expressed by:

$$H(x) \cong H_m + \frac{q_x l}{2}\left(1 - \frac{2x}{l}\right), \quad (3)$$

where $H_m = \frac{q_z l^2}{8f}$ is cable thrusting force at cable middle span l.

The axial curve of deformed inclined cable is defined by the relation:

$$z(x) = \frac{M_z(x) + M_x(x)}{S(x)}, \quad (4)$$

here
$$M_z(x) = \frac{q_z l^2}{8}\left(\frac{4x}{l} - \frac{4x^2}{l^2}\right), \quad (5)$$

$$M_x(x) = \frac{2}{3} q_x l f\left(\frac{2x^3}{l^3} - \frac{3x^2}{l^2} + \frac{x}{l}\right). \quad (6)$$

The primary (mounting) stress and strain state of cable is expressed via two its parameters, namely: the prestressing primary internal force H_{m0} and by the primary sag f_0. The compatibility and that of equilibrium equations of characteristic mast nodes equations are involved when calculating masts. The first equations is assigned for cable, taking into account the mast stem (pole) Δh. In local coordinates it reads:

$$\Delta h = \frac{(H_m - H_{m0}) s_0}{EA} - \frac{8}{3}\left[\frac{f^2}{(l + \Delta h)} - \frac{f_0{}^2}{l}\right]. \quad (7)$$

The first item of the formula (7) define the cable elastic deformation, the second one – evaluate displacement (sag) of kinematic nature.

The cable sag is split into elastic and kinematic components aiming to reduce the amount of iterative calculations. The latter are defined for fixed mast stem (pole). Its expression:

$$f_k = f_0 \sqrt{\frac{(l + \Delta h)}{l}\left[1 \pm \frac{3}{8}\frac{\Delta h l}{f_0^2}\right]}. \quad (8)$$

When the kinematic nature sag f_k is known, one can easily identify an increment of elastic cable-guy sag:

$$\Delta f_{el} = \sqrt{f_k^2 + \frac{3}{8}\frac{(H_m - H_{m0}) l^2}{EA}} - f_k. \quad (9)$$

Having rearranged formula (9), one can obtain an approximate relation for evaluating the Δf_{el}. It reads:

$$\Delta f_{el} \cong \frac{3}{128}\frac{l^4}{EAf_k}\left[\frac{q_z}{f_k + \Delta f_{el}} - \frac{q_{z0}}{f_0}\right], \quad (10)$$

where q_{z0} is cable mounting loading; q_z – cable exploitation loading.

The calculation process of mast can be split into two levels of iterations. The strain state of guys-cables in case of fixed displacements of mast stem (pole) is defined during the first one. The second one is assigned for determining the displacements and internal forces of mast stem(pole). As it was mentioned above, the latter employ the equilibrium equations (containing the support reactions of inclined cables) of mast stem (pole), created in global coordinates.

4. Mast design model for numerical experiment

The numerical experiment was performed aiming to identify possibilities of computer-aided design packages STAADpro, Robot Millennium and the program SUDM when modelling the geometrically non-linear system. A design model of plane mast (Fig. 1) was chosen to obtain the evident and reliable results. The model contains only two identical guys, fixed on top of the mast.

Height of mast is 35.35 m. The span of guys is 50.0 m. Cross-sectional area of mast stem (pole) is $A = 115$ cm^2, its moment of inertia $J = 78\,720$ cm^4. Cross-sectional area of guys is $A = 1.165$ cm^2. The uniformly distributed wind load, acting on mast stem (pole) is described by intensity $w_1 = 0.4$ kN/m, and that of on guys by $w_2 = 0.0056$ kN/m. A concentrated force $W = 2.0$ kN is applied to the mast top.

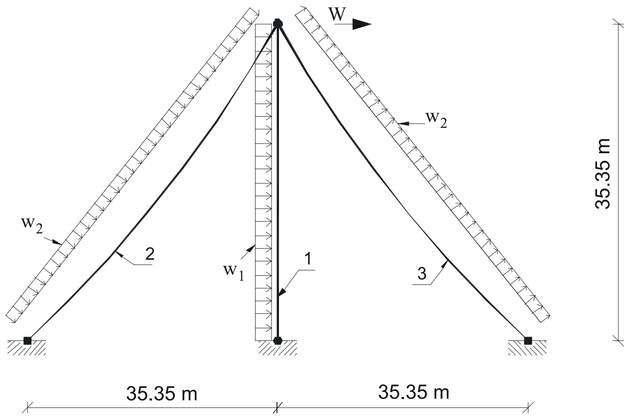

Fig. 1. Design model for mast numerical experiment

A sufficiently large range of pre-stressing force $H_{m0} = 2.0 \div 11.0$ kN was chosen for numerical simulations. During experiment the mounting and exploitative mast states were considered. The internal forces of mast structural elements and mast stem (pole) displacements were determined.

5. Results of numerical experiment

Internal forces and displacements of mast design model were calculated applying the above-mentioned programming packages STAADpro, Robot Millennium, SUDM and the presented in the paper analytical method, evaluating mast geometrical non-linear behaviour. In addition, a linear mast analysis was performed.

During analysis of obtained results a special attention was concentrated on an influence of pre-stressing tensile force to mast displacements and internal forces of it's elements.

Figs 2 and 3 present the relations of mast top displacement vs pre-stressing tensile forces. Relations represent results obtained via all above-mentioned methods. The graphs illustrate the non-linear relationship of mast displacement vs prestressing force. Increasing the cable H_{m0} from 1.0 kN till 5.0 kN the mast displacement reduces up to 9 times. The graph also shows that results obtained via non-linear analytical method and Robot Millennium package practically coincide. The largest difference between results is only 0.75 % in case of $H_{m0} = 2.0$ kN. When increasing the pre-stressing force up to 11.0 kN, the displacement magnitudes coincide completely.

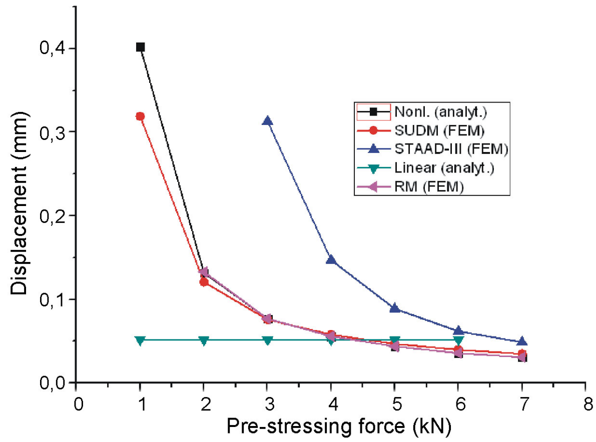

Fig. 2. Graph of mast stem (pole) upper displacement vs pre-stressing force in case of $H_{m0} = 1{,}0 \div 7{,}0$ kN

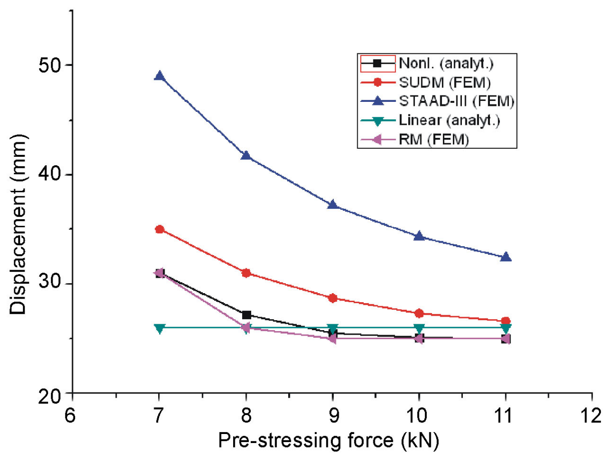

Fig. 3. Graph of mast stem (pole) upper displacement vs pre-stressing force in case of $H_{m0} = 7{,}0 \div 11{,}0$ kN

One must note that displacements obtained by the specialised program SUDM correlate sufficiently well with results obtained via non-linear analytical method. When prestressing internal force is small, the displacements obtained by SUDM are less than the ones obtained via analytical methods (the error reaches approx 10 %). And when $H_{m0} \geq 4.0$ kN, the obtained displacement magnitudes are greater the one, obtained by the analytical method (error is approx 4–8 %).

The graphs of Figs 2 and 3 illustrate evidently an essential difference between results obtained via STAADpro vs Robot Millenium and SUDM computational programs. When $H_{m0} = 2.0$ kN, the mast displacement according STAADpro is 7.5 times greater the one obtained by Robot Millennium and non-linear analytical methods. When increasing the pre-stressing force magnitude, the results obtained via STAADpro gradually approach to the ones, obtained theoretically. However, we must note that in all range of H_{m0} variation STAADpro yields the grater displacement magnitudes. The significantly larger mast displacements are conditioned by the reason that for small H_{m0} magnitudes only the one tensile cable (direct to wind face) is activated in STAADpro program calculations.

One must pay an attention to results of linear analytical calculations, where guys are modelled via simple bar elements. The obtained displacements are insensitive to pre-stressing internal force and are significantly less in case of $H_{m0} \leq 4.0$ kN (Figs 2 and 3). Only for $H_{m0} = 6.0$ kN one can notice the jump, resulting in the reduction of displacements by 2 times. It is resulted by an additional activation of the second (right mast part-outside wind face).

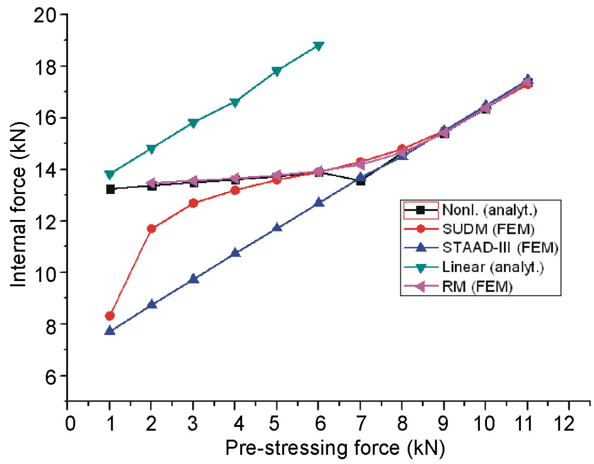

Fig. 4. Graph of general internal force vs H_{m0} of mast cable left (direct to wind) part

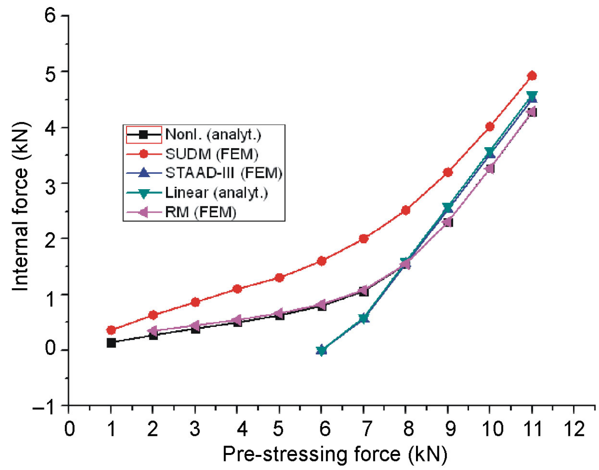

Fig. 5. Graph of general internal force vs H_{m0} of mast cable right (outside wind) part

The internal forces in pre-stressed cables-guys depend on the primary pre-stressing and accumulated self pre-stressing. The left (direct to wind face) general internal force increases and that of the right (outside wind face) cable – decreases (Figs 4 and 5). The obtained graphs illustrate the best matching of results obtained by non-linear analytical method and Robot Millennium program. The relative difference among results obtained by the above results is only approx 1 %. The results obtained via the program SUDM fit sufficiently well with the ones of Robot Millennium package and non-linear analytical method. The maximal difference in respect of left guy internal force, determined by above methods is in case of small magnitudes ($H_{m0} = 1.0 \div 3.0$ kN) of pre-stressing force. It varies 10–15 %. An increment of H_{m0} reduces the error gradually up to 1 %.

The program STAADpro results the greater error when estimating the internal forces of left cable-guy. In case of small pre-stressing force ($H_{m0} = 1.0 \div 3.0$ kN) the error reaches approx 25–35 %. The internal forces obtained via STAADpro are less the ones, obtained via analytical method.

One can notice the break (jump) in the graph internal force of cable-guy, analysed via analytical linear approach in case of $H_{m0} = 6.0$ kN. It means an activation of outside wind face cable for this magnitude of H_{m0}.

The Fig. 5 shows that internal forces of right (outside wind face) cable-guy tends to increase. But one must know that their magnitudes are significantly less the ones of left cable. When internal forces of pre-stressing are small ($H_{m0} = 1.0 \div 4.0$ kN), the ones of right (outside wind face) cable-guy do not increase 1.0 kN. Having compared the results obtained by employed programming packages and via non-linear analytical method, one can find the smallest difference obtained via Robot Millennium and non-linear analytical methods. The difference does not exceed approx 5–6 %. More significant errors are obtained when employing the programming package SUDM. In case of small primary pre-stressing ($H_{m0} = 1.0 \div 3.0$ kN), the error in respect of the above-mentioned cable-guy reaches approx 120–150 %. For larger magnitudes of H_{m0} the error reduce up to 20–25 %.

The errors obtained by employing the STAADpro are greater. Firstly, when primary pre-stressing force vary in the bounds $H_{m0} = 1.0 \div 6.0$ kN, the internal force of this cable are equal to zero, ie this cable is not activated. When increasing the magnitudes of pre-stressing force the error produced by STAADpro program reduce and for $H_{m0} = 9.0 \div 11.0$ kN they are approx 6–7 %. One must note that results obtained via linear analytical method are very close to the ones, obtained via STAADpro (Fig. 5).

6. Conclusions

An analysis of plane model of mast via computational packages STAADpro and Robot Millenium and that of specialised program for mast design SUDM proved that not all of these computational analysis instruments are sufficient for accurate enough modelling of geometrically non-linear behaviour of mast. It was found that an employment of Robot Millenium software yields results practically compatible with the ones obtained by the corrected analytical method within the whole axial force variation intervals of must guys. Note that displacements of guy determined by software STAADpro significantly differs (even up to 7,5 times) from those obtained via Robot Millenium and analytical analysis instruments. The errors, being obtained by the using the STAADpro computational package, are prescribed by the reason that only tensile direct wind face guy is employed in whole structural behaviour in case of relatively small prestressing of guys. The analysis of internal forces of guys also yields that the maximal errors (approx 58 %) again are obtained when using the STAADpro software, when the employment of the SUDM package yields the minimal errors (about 7–12 %). The usage of Robot Millenium computational package gives the above values practically compatible with those obtained analytically.

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STIEBŲ ELGSENOS ANALIZĖ IR SKAITINIO MODELIAVIMO YPATUMAI

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S a n t r a u k a

Straipsnyje aptariami stiebų kaip netiesiškai deformuojamų konstrukcinių sistemų skaičiavimo ypatumai naudojant kompiuterinio projektavimo specializuotus programinius paketus. Sprendžiamas stiebo elgsenos analizės ir skaičiavimo uždavinys pasitelkiant dvi plačiai Lietuvoje taikomas statybinių konstrukcijų kompiuterinio projektavimo programas STAAD-pro ir Robot Millennium bei specializuotą stiebų skaičiavimo programą SUDM. Straipsnyje pateikiama ir patikslinta analizinė stiebo atotampos skaičiavimo metodika, rodanti apkrovos komponentę, veikiančią išilgai atotampos atramų. Remiantis atliktu skaitiniu eksperimentu, yra sprendžiama apie minėtųjų kompiuterinio projektavimo programinių paketų galimybes modeliuoti geometriškai netiesinės sistemos elgseną. Nurodomos šių programinių paketų stiebų elementų įrąžų bei poslinkių apskaičiavimo lyginant su patikslinta analizine skaičiavimo metodika paklaidos, aptariamos minėtųjų kompiuterinio projektavimo programų praktinio taikymo stiebams skaičiuoti galimybės.

Reikšminiai žodžiai: stiebai, kabamasis lynas, netiesinė analizė, skaitinis modeliavimas.

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