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Nonlinear FEM models optimization on example of a stamping die

Optymalizacja nieliniowych modeli MES na przykładzie tłocznika

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Solving of optimization tasks using nonlinear FEM models creates problems because of large expenditure of calculation time. The response surface methodology RSM and hybrid search SHERPA algorithms in application of optimization of stamping die drawbeads are presented and compared in the paper.

KEYWORDS: optimization, nonlinear FEM models, stamping die, drawbeads

Modern software for computer-aided design, using the finite element method, more and more often contain modules for solving optimization tasks. The user may formulate and solve such problems as:

- parametric optimization (geometry optimization), where the decision variables are the dimensions or cross-sectional parameters of the FEM model, and the objective function may be stress, nodal displacement or natural frequency;
- topological optimization, where the shape of the designed part is sought, which ensures its best distribution in the space due to the criterion of maximum stiffness, minimal natural frequency, etc.;
- sensitivity analysis, in which the impact of changing selected parameters of the FEM model on the indicated size (criterion) is examined to determine the relevant parameters and eliminate the non-essential ones due to the improvement of a given criterion.

In the mentioned problems, the optimization task is solved:

$$Q(\bar{\boldsymbol{x}}) \rightarrow \min \tag{1}$$

with constraints:

$$\begin{gathered} g_j(\bar{\boldsymbol{x}}) \leq 0 \;\; j = 1, 2 \cdots n_g \\ h_k(\bar{\boldsymbol{x}}) \leq 0 \;\; j = 1, 2 \cdots n_h \\ x_i^d \leq x_i \leq x_i^g \;\; i = 1, 2 \cdots n \end{gathered}$$

where: $\bar{\boldsymbol{x}} = [x_1, x_2 \cdots x_n]^{\mathbf{T}}$ – vector of decision variables; $Q(\bar{\boldsymbol{x}})$ – objective function.

Improved solutions are most often searched according to the scheme:

$$\bar{\boldsymbol{x}}_{k+1} = \bar{\boldsymbol{x}}_k + \hat{\lambda}_k \bar{\boldsymbol{d}}_k \tag{2}$$

where: $\bar{\boldsymbol{d}}_k$ – the direction of the search; $\hat{\lambda}_k$ – step length, after which in the iteration *k* an improved solution is obtained [4].

The direction of the search is, for example, the direction opposite to the gradient of the objective function:

$$\bar{\boldsymbol{d}}_k = -\nabla^{\mathrm{T}} Q(\bar{\boldsymbol{x}}_k) \tag{3}$$

Because item $\bar{\boldsymbol{x}}_{k+1}$ is to remain in the feasible set (to meet the constraints), the direction of the search is corrected so that it is an acceptable direction of improvement [4], that is, to meet the conditions:

$$\begin{gathered} \bar{\boldsymbol{d}}_k \nabla^{\mathrm{T}} Q(\bar{\boldsymbol{x}}_k) < 0 \\ \bar{\boldsymbol{d}}_k \nabla^{\mathrm{T}} g_j(\bar{\boldsymbol{x}}_k) < 0 \;\;\; j = 1, 2, \cdots, n_g \end{gathered} \tag{4}$$

Due to the mentioned problems of the optimization of the FEM model in each iteration concerning the solution of the task of optimization, it is necessary to solve the subproblem of the structural or modal analysis of the FEM model. If the time of solving the subproblem is not too long with the available computer memory resources and the processor's processing power, the solution of the optimization task can be obtained in an acceptable time from the engineering point of view. The possible reduction of the calculation time can be achieved by improving the numerical efficiency of the FEM model (e.g. by reducing the number of degrees of freedom) or by defining the initial decision values of the optimization task in such a way that the starting point is closer to the optimal solution (this is the location of the point can be determined, for example, on the basis of a coarse search of a permissible set).

Optimization algorithms for non-linear FEM models

In the optimization of non-linear FEM models, it is worth paying attention to two problems that should be dealt with so that the computer available resources can be solved in an acceptable time:

- time of solving the task of non-linear FEM analysis is long enough that the implementation of the essential number of repetitions of a single iteration of the optimization algorithm results in too long total search time for the optimal solution – in this case there is insufficient numerical efficiency of the optimization algorithm;
- nature of the problem of FEM nonlinear analysis causes that the determined directions of search for improved solutions do not lead to an optimal solution after an acceptable number of repetitions of a single iteration of the

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optimization algorithm (the starting point has been incorrectly specified or the objective function's sensitivity to changes in the decision variables of the task is ambiguous) – including in the case of insufficient robustness of the optimization algorithm.

Optimization algorithms are still being searched for, which would be numerically efficient enough and robustness to non-linear model optimization problems. Further, two algorithms implemented include in the DynaForm program.

SHERPA algorithm [7]

SHERPA (*simultaneous hybrid exploration, that is, progressive and adaptive*) is an algorithm of simultaneous hybrid search, which is robust, progressive and adaptive. In essence, it is not a single algorithm, but a combination of two to ten different algorithms that work simultaneously, but the choice of algorithm and its parameters determining convergence and efficiency takes place automatically. As a result, SHERPA recognizes the nature of the optimized objective function and the feasible set, and then adapts to the optimization task to be solved, choosing the best algorithm with the best parameters at the moment. As with any other universal optimization algorithm, there is no guarantee that the algorithm will always find the optimal solution reliably and effectively. Numerical practice confirms, however, that statistically SHERPA is an algorithm that works well in many applications.

The most important optimization algorithms used by SHERPA are:

- local optimization algorithms, such as:

– Levenberg-Marquardt algorithm [2], which is quickly convergent (especially for not very complex models), and at the same time sensitive to the selection of the starting point;
– Nelder-Mead algorithm (crawling simplex) [3], which is resistant and moderately convergent (especially for complex models);

- global optimization algorithms, such as:

– differential evolution – moncar algorithm [6], which samples the large size feasible sets in the fastest way;
– grid search algorithm [4], which coarsely and quickly recognizes the nature of the objective function and the feasible set.

Response Surface Method (RSM) [1]

The RSM (response surface methodology) method approximates the response of the FEM model to changes in the decision variables of the optimization task. The surface of the answer, which becomes the surrogate (meta-model) of the original optimization task. If the response surface is approximated by a series of base functions:

$$y(\bar{\boldsymbol{x}}) \cong \sum_{i=1}^{L} a_i \phi_i(\bar{\boldsymbol{x}}) \quad (5)$$

This constant a_i is determined by minimizing the sum of squares of deviations of the response surface in P control points of the FEM model response:

$$\sum_{p=1}^{P} \left[y(\bar{\boldsymbol{x}}_p) - \sum_{i=1}^{L} a_i \phi_i(\bar{\boldsymbol{x}}) \right]^2 \to min \quad (6)$$

The solution of the task (6) is the constant vector:

$$\bar{\boldsymbol{a}} = ([\boldsymbol{X}]^T[\boldsymbol{X}])^{-1}[\boldsymbol{X}]^T\bar{\boldsymbol{y}} \quad (7)$$

where: $[\boldsymbol{X}] = [X_{pi}] = [\phi_i(X_{pi})]$.

By randomizing the location of control points, e.g. using the LHS (*latin hypercube sampling*) method, a metamodel of the original optimization task is obtained, which, by virtue of approximation according to formula (5), is much more effective numerically.

An example of the practical use of optimization algorithms for the non-linear FEM model for the improvement of the construction of the press-forming die for car body part is described below.

Optimization of the draw beads of die

In order to produce a drawpiece without defects, the stamped metal sheet (blanket) must be held in appropriate positions with the appropriate force between the punch and the die in order to induce the plastic deformation needed to obtain the designed shape of the drawpiece. This function is realized by the so-called draw beads i.e. grooves in the die or blank holders, cooperating with the thresholds in the punch, which, by putting resistance to the sheet being pulled during pressing, hold it with the appropriate force. The task of optimization of string draw beads was to determine such a their profile and location that eliminates the drawpiece defects in the form of cracks and wrinkles. An embossing with defects before the draw beads are optimized is shown in fig. 1.

Fig. 1. Drawpiece with defects in the form of cracks and wrinkles

For the purpose of the task, Dyna-Form models were built of FEM models and working surfaces of the die parts, i.e. die, punch and holders. Models of the working surface of the die were created from four node surface elements of the shell type, which were undeformable, and the form was carefully meshed using eight node surface elements of shell16 type (the so-called fully integrated shell). The blanket was attributed to the HSLA250 material, i.e. steel for cold stamping of the car body parts with a yield stress of 250 MPa and a ultimate stress of 345 MPa. The interactions of the die's working surfaces and the blanket were treated as one-sided constraints with friction and modeled with surface-to-surface contact elements. The coefficient of friction μ = 0.125 was assumed. In this way, a complete die and blanket FEM model was created, shown in fig. 2, which was used to simulate stamping and solve the task of optimizing draw beads.

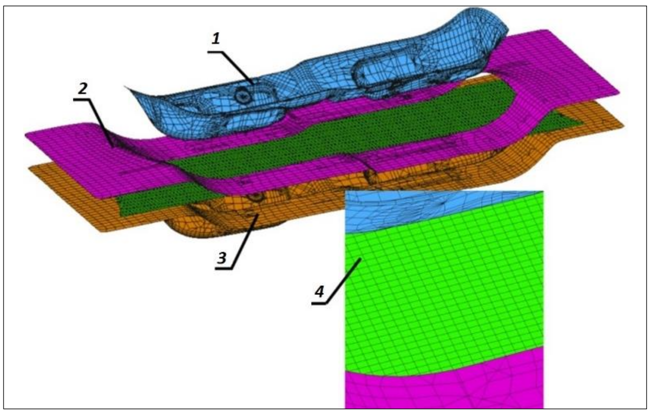

Fig. 2. Discrete model of the parts of the die and the blanket (*1* – stamp, *2* – holder, *3* – die, *4* – blanket)

In the optimization task, eight draw beads have been defined whose initial location, shown in fig. 3, results from the experience of the designers. The task is solved in the DynaForm program, in which the string draw beads is replaced by force in the plane of the blanket, distributed evenly along the defined line. The value of the force depends on the profile of the string draw beads as well as the thickness and type of the material of the blanket, and it is calculated according to the Stoughton algorithm [5]. The program uses the relative value of the force along the draw beads, which is the percentage of the maximum force that prevents the sheet from moving through the draw bead. The default initial value is 50% of this force. After solving the task, the determined relative values of forces along the drawbeads can be converted into appropriate profile drawbead cross section according to the aforementioned Stoughton algorithm.

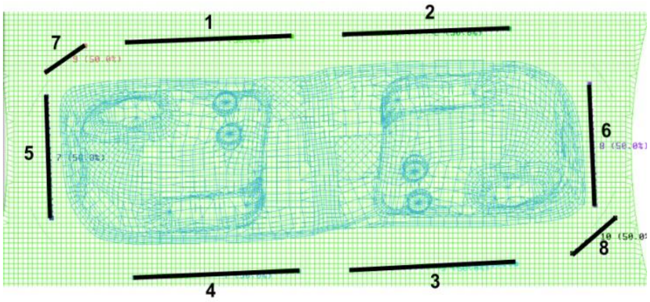

Fig. 3. Arrangement of string thresholds on the form

In order to carry out a forming simulation, a process kinematics was applied, according to which first the holder closes the blanket in the die, and then the advancing punch forming the blanket until the stamp and die are closed.

After the simulation, the quality of the drawpiece should be checked using the forming limit diagram FLD, where the risk of cracks and wrinkles in the drawpiece are given. Fig. 4 presents the simulation result for the drawpiece before optimizing the string draw beads, which confirms the risk of wrinkles and cracks in places where these defects did indeed occur (fig. 1). This indicates the correctness of the adopted FEM model. In order to obtain a non-defective drawpiece, forces along each of the draw bead should be selected so that cracks and wrinkles do not arise.

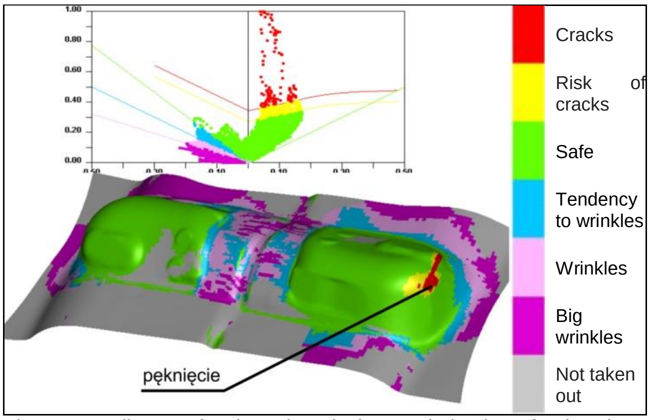

Fig. 4. FLD diagram for drawpiece before optimization of string draw beads

Solution of the optimization task

In the task of optimization of string draw beads, solved in the DynaForm program, the components of the decision variable vector $\bar{\boldsymbol{F}}$ were the values of forces along the draw beads, and the objective function $Q(\bar{\boldsymbol{F}})$ – the size of the drawpiece area in which there is a risk of cracking or wrinkling. The constraint was the percentage range of force along the draw beads: set $5\%F_i^{max} \le F_i \le 80\%F_i^{max}$. It was also assumed that the values of forces along thresholds 1 and 4 and 2 and 3 (fig. 3) are the same, which allowed to reduce the number of decision variables of the task to six.

To compare the quality of solutions and calculation time, the same optimization task was solved using the SHERPA and RSM algorithms. The table lists the optimal values of decision variables. As you can see, in the case of both algorithms, the solutions are similar, which confirms the correctness of the results. The indicative times of solving the optimization task on a computer with an Intel i7/3.2GHz/16GB RAM processor were different and amounted to: for the SHERPA algorithm – about 12 hours, for the RSM algorithm – about 192 hours.

Since the optimization goal was to improve the quality of the drawpiece, it is worth to perform the simulation of stamping and check the FLD diagram for optimal stringing draw beads. Fig. 5 presents such a diagram, from which it results that the optimization of the draw beads has brought the intended purpose (see fig. 4) and the drawpiece has no defects.

TABLE. Optimal forces along the thresholds $\hat{F}_i$ as a percentage of the force preventing the sheet from moving across the threshold

Threshold number		1, 4	2, 3	5	6	7	8
$\hat{F}_i$, %	by SHERPA	21	20	3	3	11	9
	by RSM	20	20	2	2	10	11

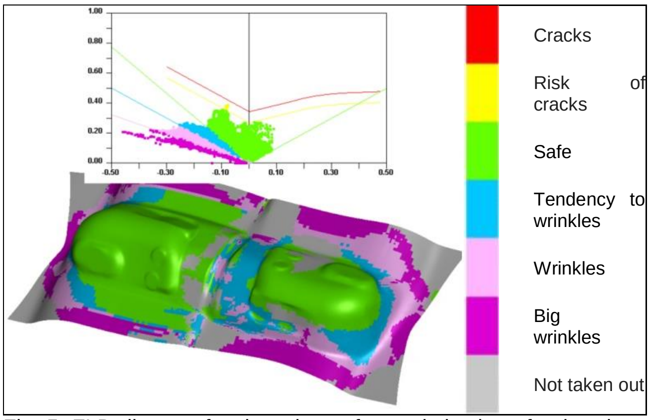

Fig. 5. FLD diagram for drawpiece after optimization of string draw beads

In practice, the optimum values of forces along the draw beads are automatically converted into the dimensions of their cross sections. Fig. 6 shows the DynaForm program dialog box, which gives the dimensions of an example draw bead No. 6 with semi-circular and rectangular profile.

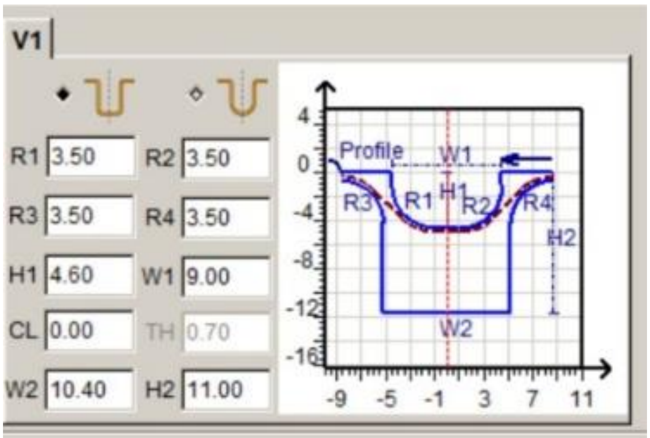

Fig. 6. Dimensions of a semicircular and rectangular draw bead no. 6 of optimal cross section

Conclusions

- Optimization problem solving algorithms available in the engineering software, in which the non-linear FEM response to changes in the decision variables of the task should be determined in a single iteration, are sufficiently effective in solving real project tasks.
- Quality of the solution obtained by the RMS and SHERPA algorithms is comparable, but the SHERPA algorithm is numerically much more effective – the computation time was about 16 times shorter.

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