Development of a method for multidisciplinary parametric optimization of vehicle hood reinforcement

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Abstract. The goal of this paper is to develop and test a multidisciplinary optimization technique for designing structures that are subjected to both static and dynamic loads, using the digital twin of a vehicle hood as an example. This method reduces the weight of the hood reinforcement and increases the probability of pedestrian survival when hitting the head. This is due to the implementation of technological and layout constraints, as well as the requirements for stiffness, frequency characteristics and hood denting.

1. Introduction
Currently, when structures are developed, the engineer is faced with the need to find a compromise between the technical requirements for the product, layout and technological limitations, requirements for the weight and cost of the final product.

Designing using Digital Twin technology and conducting Digital Certification avoids the long-term costly testing of prototypes and significantly reduces time-to-market, which gives a serious competitive advantage in global high-tech markets ([1], [2], [3], [4], [5], [6]).

A particular challenge is the design of structures that provide at the same time sufficient levels of stiffness under static loading and energy absorption during impacts both from the viewpoint of the opposite of these requirements and from the viewpoint of multidisciplinarity. For a hood, stiffness is calculated in a linear static formulation, denting - in a non-linear quasistatic one, and energy absorption - in a non-linear dynamic one.

In practice, to simulate the full range of structure operating conditions is often necessary to use several systems of finite element (FE) analysis, which means the Digital Twin contains several FE models for one structure for different types of calculations. This complicates the process of fine-tuning the design to the targets, because to account for the impact of structural changes in the design, one needs to repeat these changes in each of the models.

The principal novelty proposed in this work approach is the use at early finishing of the design to target of cross-platform parametric optimization methods, which allows combining design cases of different types and at the same time to consider the impact of design changes on all its features (unlike the existing method [7]) and to build into the model a number of technological limitations.

Implementation of the virtual tests described in the work was carried out on the basis of the platform CML-Bench™ (digital platform for the development of digital twins and an activity management system...
in the field of digital design, mathematical modeling and computer engineering, development of the engineering center CEC SPbPU) using computational resources of CNTI.

2. Pedestrian protection
According to NHTSA statistics ([8]), despite the total number of traffic fatalities decreases, more than 6,000 pedestrians die in accidents each year in the United States alone (Tab. 1).

| Year | Died, people |
|------|--------------|
|      | Total | Including pedestrians |
| 2017 | 37 473 | 6 075 |
| 2018 | 36 560 | 6 283 |

In Russia, the number of deaths per 1,000,000 population is 2.5 times higher than the average for European countries (Fig. 1). The high death rate is affected by both poor road conditions and using old cars with low quality pedestrian protection systems. However, certification rules regarding pedestrian protection are being tightened in Russia year by year, approaching European standards. Virtual tests of the hood for pedestrian protection are carried out on average at 150-180 points for each structure (Fig. 2).

When a car collides with a pedestrian, as a rule, the vehicle bumper first contacts lower leg and thigh, and then the head hits the hood area. Leg injuries are painful and can lead to long-term disability. However, head injuries are the most dangerous, which are often fatal ([11]). Therefore, it is so important to predict and prevent overloads that a person’s head experiences when hitting a car. The decisive factor determining the degree of head injury is the structure of the hood, since it should slow down the head, preventing critical overloads and excluding the possibility of contact of the head with massive elements of the underhood space ([12]).

The hood structure is tested for pedestrian protection according to the rules of the EuroNCAP rating test in this paper ([13], [14]).

The success of these tests is evaluated using HIC (Head Injury Criteria), which is based on the Wayne State Tolerance Curve ([15]) and displays the likely assessment of head injuries on impact.
Figure 2. Determination of the hood test points for pedestrian protection when hitting a head according to EuroNCAP rules ([4]).

\[ HIC_{15} = \max_{t_0} \left\{ \Delta t \left( \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} a(t) \, dt \right)^{2.5} \right\} \]  

Tab. II presents the rules for setting EuroNCAP rating points for the hood point where the test took place, depending on the value of the criteria.

| HIC_{15} | Rating Points |
|----------|---------------|
| < 650    | 1.00 Point    |
| 650 ≤ HIC_{15} < 1000 | 0.75 Points |
| 1000 ≤ HIC_{15} < 1350 | 0.50 Points |
| 1350 ≤ HIC_{15} < 1700 | 0.25 Points |
| 1700 ≤ HIC_{15} | 0.00 Points |

The percentage of the maximum number of points in the workspace was selected as the evaluation criteria, because in this task, virtual tests are not performed for all hood points.

\[ S = \frac{\sum_i \text{Points}_i}{\text{Number of grids}} \]  

Achieving the main goal - reducing the total criteria of HIC15 (increasing the S rating) when testing the hood for pedestrian protection - has to satisfy both the targetbook (requirements for stiffness, eigenfrequency and denting) and the requirement to reduce the weight of the structure while fulfilling technical limitations (technological and layout ones).

3. Smart digital twin of the vehicle hood

The developed highly adequate model (Digital Twin) of the vehicle hood contains:

a) Full-scale geometric (CAD) and finite element (CAE) models of the hood - Fig. 3a,

b) Information about all supports and joints (spot and arc welding, glue, bolts, hinges, rebound buffers, sealing) both between the hood parts and with adjacent assemblies (car body) and their necessary characteristics - Fig. 3b,

c) Complete data on the materials necessary for the assigned tasks: the elastic-plastic characteristics of steels, taking into account the dependence on the deformation rate for impacts and the fracture criteria, is an example for steel DX56D in Fig. 3c, as well as the assortment of material-thickness combinations available for the production of the hood by cold stamping (this information was provided by the customer and was later used to parameterize the model),

d) Information on operating conditions (Fig. 3d) and a matrix of targets for each type of load - Tab. III,
In this work, the operating modes of the hood are two tests for static stiffness (bending and torsion), two modal analyses (in the free and fixed state), a test for denting at four points, and a test for pedestrian protection at nine points. The last two tests were performed for the positions of the acting indenters/impactors located in the right (in the direction of the car) half of the hood, because the hood structure is symmetrical with respect to the central plane. Tests for pedestrian protection and denting at other points as part of the optimization are not carried out, because a change in the structure of the reinforcement in the central part slightly influences the test result in other parts of the design.

e) Information on layout and technological limitations.
The choice of materials and manufacturing technology, as a rule, is dictated by the desire to minimize the cost of the final product. In the case when the original design was made, the selection criteria may be to minimize investment in an existing process. In this work, the technological limitations on the hood are the inability to use lighter materials (aluminum alloys) and other manufacturing technologies, except for cold sheet stamping. Layout constraints prohibit changes to the exterior styling surface of the hood, as well as changes in the interface between the hood and the car body (i.e. in the areas of loops, rebound buffers, and sealing). Thus, the central part of the hood reinforcement is the working area for making changes to the structure that meets all the constraints (Fig. 4).
Table 3. Matrix of target indicators of the vehicle hood.

| Loadcase            | FE system | Controlled parameter          | Units   | Target |
|---------------------|-----------|-------------------------------|---------|--------|
| Static - Bending    | Optistruct| Bending stiffness             | kN/m    | ≥ 15   |
| Torsion             |           | Torsional stiffness           | kNm/rad | ≥ 30   |
| Modal - Free        | LS-Dyna   | First nonzero eigenfrequency  | Hz      | ≥ 35   |
|                     |           | First eigenfrequency          | Hz      | ≥ 26   |
| Denting             |           | Intrusion                     | mm      | ≤ 6    |
| Pedestrian Protection|          | HIC15                         | -       | < 650  |

Figure 4. The working capacity for optimization and the sketch design of the hood.

4. Sketch design and parametrization

The goal of parametric multidisciplinary hood optimization is to minimize the total pedestrian head injury criteria for all loadcases of the pedestrian protection test (maximize the S rating). In the adopted formulation, the target values from the targetbook were set as limitations on the responses from each loadcase.

The parametrization of the sketch FE model of the hood reinforcement is shown in Fig. 5. The thickness and material of the reinforcement can be changed within a discrete set of values corresponding to the available material-thickness combinations within the selected manufacturing technology. The shape parameters can vary in a continuous range of values determined by geometry feasibility (intersections inside the part and with other structural elements are unacceptable); reinforcement design changes are applied symmetrically (left and right).

Figure 5. Parametrization of the FE model of the hood for multidisciplinary optimization.
The ARSM (Adaptive Response Surface Method) algorithm was used for optimization, which works only with single-purpose tasks, but is the most effective for solving linear and nonlinear problems with a mixed type of variables (discrete and continuous) at the same time.

The optimization problem was formulated in the Altair HyperStudyTM, software system, which provides the user with a convenient environment for parameterizing models of various FE analysis systems (in this case, Optistruct and LS-DYNA). This program allows to achieve the identity of changes made to the design by pairing the parameters of different FE models within each other one Digital Twin, determining responses (controlled parameters) for each loadcase and setting goals on them, and also has a wide range of parametric optimization algorithms and tools for post-processing optimization results.

5. Result of the optimization
The parametric multidisciplinary optimization of the hood resulted in a set of model parameter values that ensured a minimum of the total criterion for a head injury during pedestrian protection tests. Fig. 6 shows a comparison of sketch and optimized structures of the hood reinforcement. The comparison of characteristics of these designs with the targets is presented in Tab. 4.

![Figure 6. Comparison of the geometry of the sketch and optimized hood reinforcement.](image_url)
### Table 4. Comparison of characteristics of initial and optimized hood structures with targets.

| Loadcase | Controlled parameter       | Units   | Hood structure | Target |
|----------|----------------------------|---------|----------------|--------|
|          |                            |         | Initial        | Optimized |
| Static   | Bending                    | kN/m    | 12.9           | 17     |
|          |                               |         | ≥ 15           |         |
|          | Torsoation                  | kNm/rad | 18             | 36.3   |
|          |                               |         | ≥ 30           |         |
| Modal    | First nonzero eigenfrequency | Hz      | 28.4           | 38.7   |
|          |                               |         | ≥ 35           |         |
|          | First eigenfrequency        | Hz      | 24.8           | 26.6   |
|          |                               |         | ≥ 26           |         |
| Denting  | Intrusion                  | mm      | 6.7            | 5.9    |
|          |                               |         | ≤ 6            |         |
|          |                            |         | 4.4            | 3.8    |
| Pedestrian Protection | HIC<sub>13</sub> | - | 1 112 | 618 |
|          |                            |         | 1 096 | 668 |
|          |                            |         | 993  | 959 |
|          |                            |         | 1 035 | 490 |
|          |                            |         | 969  | 873 |
|          |                            |         | 917  | 477 |
|          |                            |         | 857  | 583 |
|          |                            |         | 940  | 799 |
|          | Mass                       | kg      | 22.1           | 21.5   |
|          |                            |         | -              |         |

### 6. Conclusion

The resulting design of the central part of the hood using parametric multidisciplinary optimization satisfies the layout and technological limitations, meets the requirements for static stiffness, eigenfrequency, and denting. The weight of the optimized structure is 600 grams less than the original, while the rating of the optimized part of the hood according to the criteria of injury (S) increased from 68% to 87%. This increases the probability of a person’s survival when hitting his or her head against the central part of the hood.

When structures subject to dynamic influences are designed, this technique reduces the laboriousness of the design and obtains effective structures that go beyond the bounds of the intuition of the designer. Besides, this approach can be extended to other classes of problems.

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