TOPOLOGY OPTIMIZATION OF A BICYCLE PART

PETR ZELENY, MILOS CADEK

Technical University of Liberec, Faculty of Mechanical Engineering, KSA, Liberec , Czech Republic

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e-mail: petr.zeleny@tul.cz

The paper contains suitable methodics to obtain optimal part design due to operational (static) load cases. The subject of optimization is an upper rocker of a special mountain bike frame. To obtain optimized part design a topology optimization method combined with a numerical shape optimization was used. Optimized part was manufactured by Selective Laser Melting technology. The paper begins with introduction of part's function and its operational load. Then used optimization tools are introduced and initial conditions sensitivity demonstration is performed. Manufactured part with optimized design is shown at the end of the paper.

KEYWORDS

topology optimization, 3D printing, SLM, FEA, MTB

1 INTRODUCTION

Optimized part is an upper rocker of a special mountain bike frame. Frame is designed for downhill and for a person with height disability. Suffering from achondroplasia his height is about 135 cm and weight about 45 kg. Upper rocker is a part of a rear suspension mechanism and it is mounted to the frame by using pins and ball bearings (Fig. 1). In the front end of the rocker, rear shock is mounted with an M6 screw. On the rear end ball bearings connect the rocker with the rest of a suspension mechanism via pin. Material of the rocker used for topology optimization calculations is either steel or aluminum alloy. Then the final part design is manufactured with Selective Laser Melting (SLM) technology on a 3D printer at KSA laboratory.

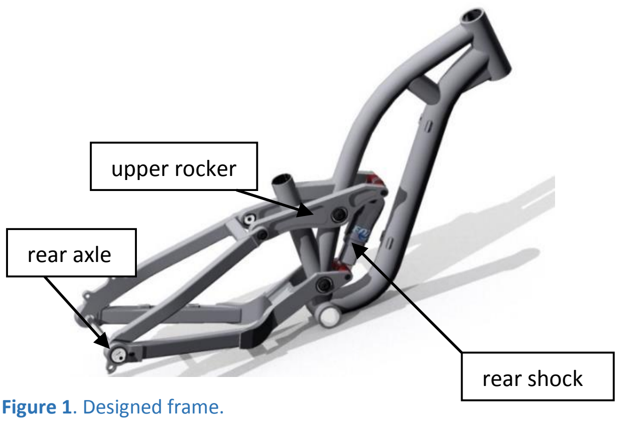

Figure 1. Designed frame.

2 ROCKER LOAD REACTIONS

Operational load for the rocker was determined by dynamic simulations, where several load cases were used. Used load cases are divided according to rider’s position on the bike "sit ride" and "stand ride". These load cases were evaluated as insufficient in terms of low reaction forces values. Therefore a dynamic coefficient was used and two more load cases were determined. These are called "rear wheel landing" and "two wheels landing". From these two load cases "rear wheel landing" has biggest reaction forces and therefore it was used as an optimization state.

2.1 *Rear wheel landing*

Reaction forces of the rocker were evaluated via dynamic simulation in PTC Creo Mechanism, where frame's position is fixed and the force is applied to the rear axle (Fig. 1). Vector of the force is oriented straight upwards and has a value of three times rider’s weight, where three is a value of dyn. coeff. and rider’s weight used for calculations is 50 kg, so that is F = 1500 N for "landing" force applied on the rear axle (Fig. 2). Value of dyn. coeff. was determined with help from bike industry engineers. Figure 2 shows used model and simulated reaction vectors in a compressed state. Figure 3 then shows simulated absolute values of those vectors.

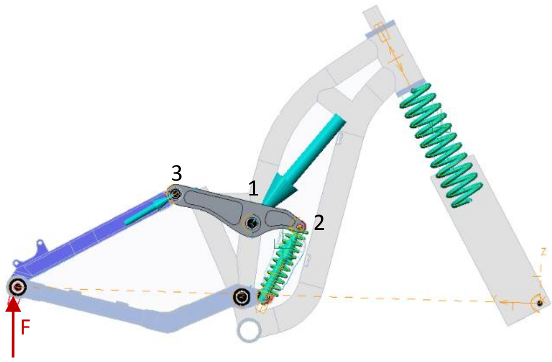

Figure 2. Reaction forces vectors and simulation model.

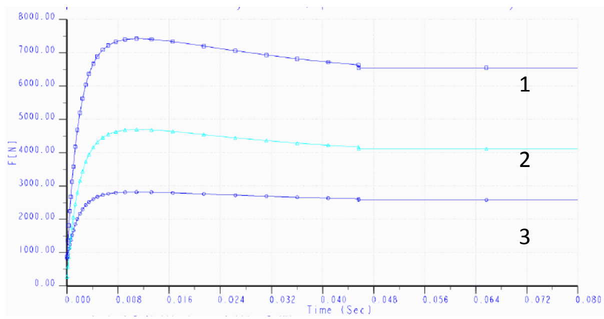

Figure 3. Measured reaction forces.

As figure 3 shows, there are three reactions that have to be divided into three load/constrain sets to perform optimization. Each set contains two pin constrains instead of reaction forces and only one reaction force. So the optimization task is not just one FEA, but three or more, for each iteration. This depends on the number of load cases for which the optimization is performed. For instance a random side force (100 N) on the rear end was added to the solution and so on. Other forces could be added to achieve higher stiffness in desired directions or to increase safety factor of the part in other load cases, like "two wheels landing" or "sit ride" where reaction force direction is slightly differently oriented, other load cases could be added. To keep reasonable computation time, we have optimized the part only for "rear wheel landing" and fictional side force on the rear end.

3 TOPOLOGY OPTIMIZATION

Topology optimization is a method that combines FEA results. In this method the goal is to find a solution with optimum material distribution in a certain volume. This volume is called design space. Design space is meshed with finite elements. Each iteration determines which elements will be empty and which will represent the material [Kubec 2010]. Optimization procedure is shown in fig 4.

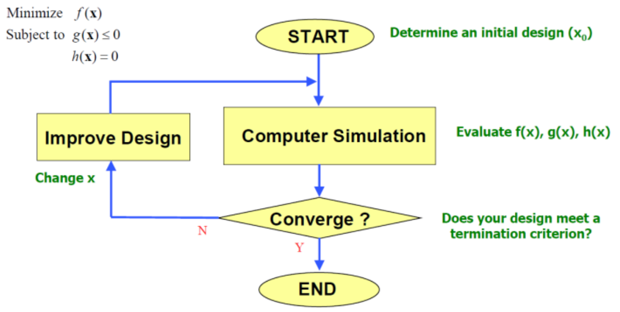

Figure 4. Basic optimization procedure. [Weck 2004]

In topology optimization, there are three types of parameters: Objective function, Design constrains and Design variables [Weck 2004]. Where for this case:

Objective function f(x): compliance
Design constrain g(x), h(x): mass, stress
Design variables (x): mesh density

In case of topology optimization the design variable is each element of design space mesh. Example below (Fig. 5) has 27 design variables. According to [Weck 2004], there are two types of design constrains: h(x) = 0 (equality constrains) and g(x) ≤ 0 (inequality constrains).

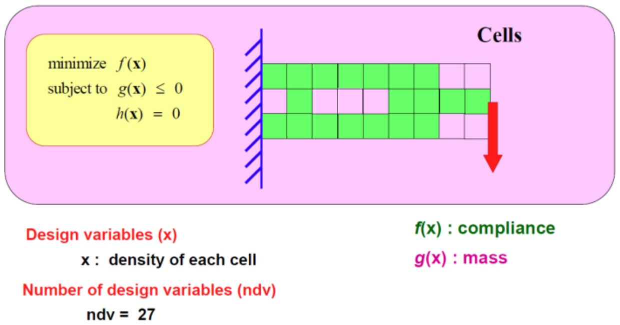

Figure 5. Topology optimization. [Weck 2004]

This paper contains topology optimization performed by two different software programs: CAESS ProTOpCI and ALTAIR solidThinking Inspire 2014.

There are also two different types of upper rocker. Type A (Fig. 1, 2) and type B (Fig. 6-12) which was replaced by type A later on, during bike frame design development, because there were slight changes in bicycle geometry that were needed to be done. Initial conditions sensitivity demonstration is performed on type B. Procedure for manufacturing computed topology is shown on a final design which is type A. [Cadek 2015]

To ensure time efficiency before proceeding to topology optimization process a 2D shape optimization of space design was performed.

3.1 Initial conditions and element size sensitivity

Demonstration of initial conditions and element size or mesh density sensitivity was performed with ALTAIR solidThinking Inspire software and CAESS proTOpCI. Where type B rocker was used, since the computations were made in early stages of a bike frame development.

For this part of the paper, several calculations were made. Each calculation has a different element size and a different targeted weight of the rocker after optimization. Material for these computations is steel. Figure 6 shows type B rocker after design space shape optimization was performed.

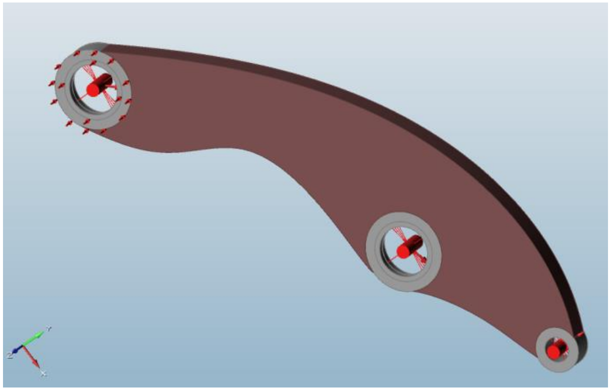

Figure 6. Type B rocker. Design space - brown. Non-design space - gray.

Figure 7 shows a calculation with 45 % max. weight (0.401 kg) and average element size is 2.05 mm. Figure 8 shows the same type of a calculation with different element size. In this case achieved weight was about 0.344 kg.

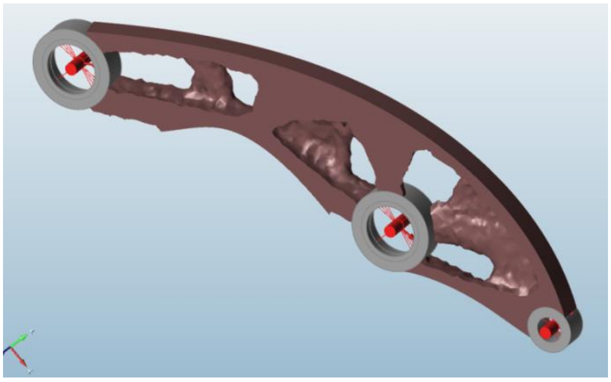

Figure 7. Type B rocker, m=0.401 kg, average element size 2.05 mm.

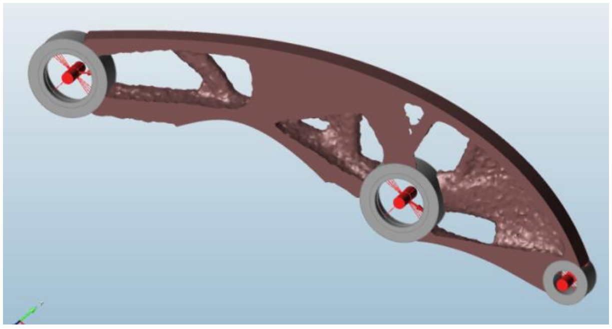

Figure 8. Type B rocker, m=0.344 kg, average element size 1.66 mm.

Figure 9 shows a computation of the same sort, but in different software. CAESS proTOpCI was used here to achieve the lowest possible weight. The design space has over 70 000 elements. The main difference between ALTAIR and CAESS software is in preprocessor. While ALTAIR has its own, CAESS uses PTC Creo Simulate module, which is much more advanced and therefore allows much more control over the calculated topology. ALTAIR software is suitable for fast analysis of an optimal material distribution over the design space and its sensitivity over initial conditions. Initial conditions sensitivity is demonstrated in figures 10 and 11, where fictional side force was applied to the rear end of the rocker. Average element size was changed again.

Figure 9. Type B rocker, m=0.104 kg, average element size 1.5 mm

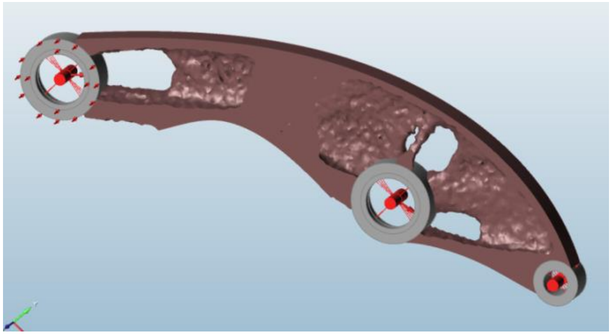

Figure 10. Type B rocker, m=0.366 kg, average element size 2.05 mm, rear side force F = 100 N.

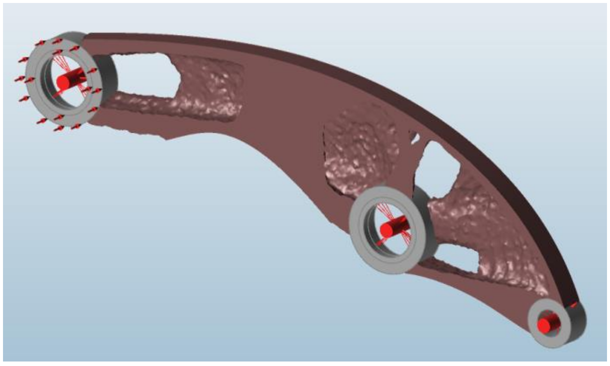

Figure 11. Type B rocker, m=0.359 kg, average element size 1.33 mm, rear side force F = 100 N.

CAESS proTOpCI also provides smoothing functions for computed surfaces, so it might be possible to 3D print the part right away from the software without CAD remodeling. Further modifications of the computed part could be also made by adding so called lattice functions or shell regions into the model (Fig. 12).

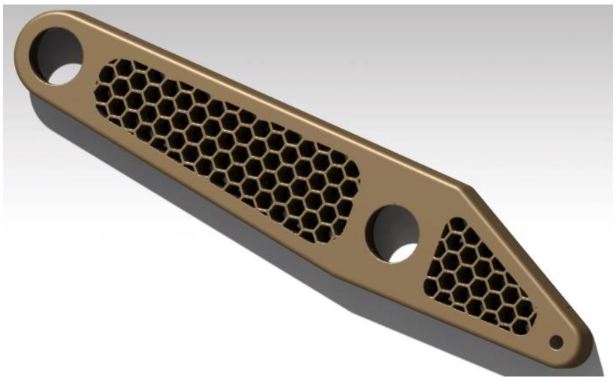

Figure 12. Type B rocker without 2D shape optimization, with hexagonal lattice regions.

3.2 *Final part design optimization*

Type A rocker material for computation was aluminum alloy EN AW 6061. Optimization was performed in both ALTAIR and CAESS software. At step 1. (Fig. 13), 2D shape optimization analysis in PTC Creo was performed. Then computed geometry was imported to ALTAIR software, where it was divided into design and non-design regions or space. Topology optimization was performed at step 2. Step 3 shows CAD model created in PTC Creo with a reference to step 2. Step 4 shows inserted lattice and shell regions, where on the outside shape of the model a hexagonal region was made and on the inside of the model several shell regions were inserted with a lattice cross - like shape reinforcement structure (Fig. 14, 15).

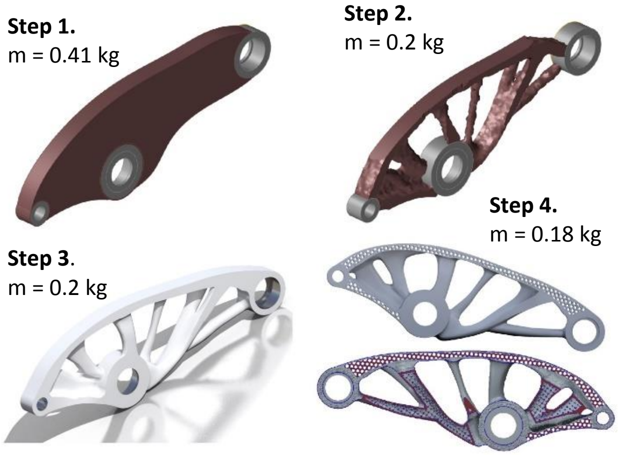

Figure 13. Type A rocker, design optimization process. [Cadek 2015]

Figure 14. Type A rocker, step 4, lattice structure with cross-section view. [Cadek 2015]

Lattice functions can be inserted only to predefined regions before importing a model from PTC Creo Simulate module. These regions has to be created in PTC Creo Simulate with volume region function. After that, model was imported to CAESS software, lattice structures (Fig. 15) were created via following script:

```
* Material regions information
*
* {Id=1; Name=soucast; Code=1}
* {Id=2; Name=hexagon; Code=1}
* {Id=3; Name=shell; Code=1}
*
* Default: Full solid structure (normal mode)
*
Set.Gen.RegionMatList = *
```

```
Set.Gen.IniTopParValue = 0.001
Cmd.CreateSolid
*
* Lattice region
*
Set.Gen.RegionMatList = 2
Set.Lat.TypeCode = 202
Set.Lat.Origin = 0,0,0
Set.Lat.CellSize = 2
Set.Lat.CellScale = 1,1,1
Set.Lat.Rotation = 0,0,0
Set.Lat.ThicknessMin = 1
Set.Lat.ThicknessMax = 1.5
Cmd.CreateLattice
*
* Lattice region
*
Set.Gen.RegionMatList = 1.
Set.Lat.TypeCode = 100
Set.Lat.Origin = 0,0,0
Set.Lat.CellSize = 3
Set.Lat.CellScale = 1,1,1
Set.Lat.Rotation = 0,0,0
Set.Lat.ThicknessMin = 0.9
Set.Lat.ThicknessMax = 1.5
Cmd.CreateLattice

* Shell region
*
Set.Gen.RegionMatList = 1
Set.Shell.ThicknessMin = 1.5
Set.Shell.ThicknessMax = 2
Cmd.CreateShell
*
```

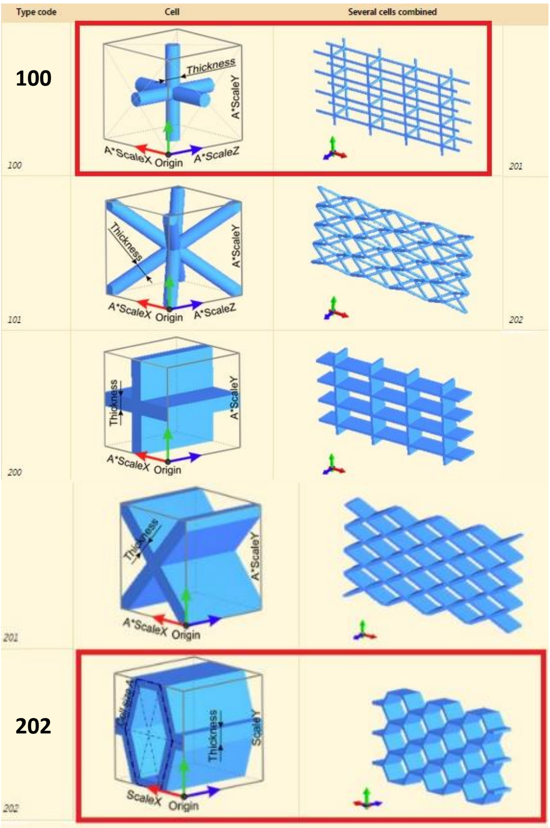

Figure 15. Available lattice structures. Used are marked red. [CAESS 2015]

ALTAIR software also contains FEA module, where it is possible to check the computed topology. Results are shown in figure 16. ALTAIR contains pretty handy postprocessor function that allows to hide a certain volume of the part according to selected interval of Von Mises stress, deformation, etc. Usage of this function is shown at the right side of figure 16, where the upper right corner is displaying volume with Von Mises stress values higher than 50 MPa. Highest Von Mises stress values are about 80 MPa, which is compared with yield strength of the material within allowable limits.

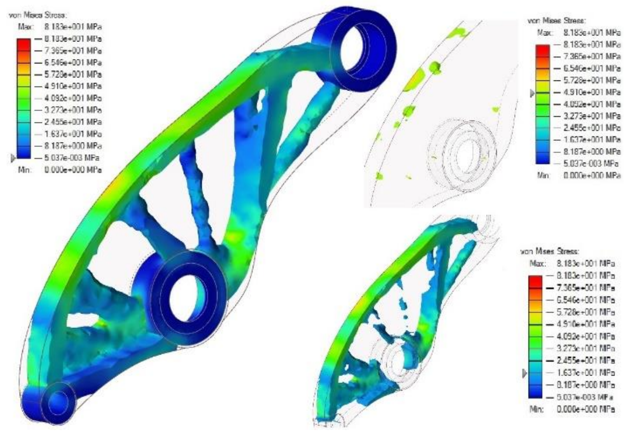

Figure 16. Finite element analysis of a type A rocker at step 2. [Cadek 2015]

4 MANUFACTURED PART

Upper rocker with optimized design was manufactured with Selective Laser Melting technology (Fig. 17, 18) at KSA laboratory. Material used for part manufacture was aluminum alloy AlSi12, with mechanical properties as follows:

R_m = 409 MPa, $R_{p0,2}$ = 211 MPa and after heat treatment process $R_{p0,2}$ = 280 MPa. [SLM 2014]

Figure 17. SLM 280 HL machine with a view to the workspace.

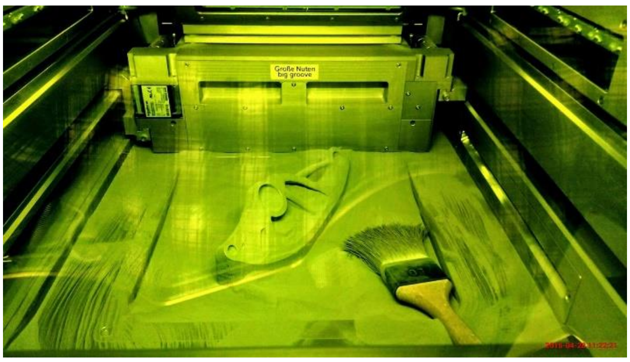

Figure 18. SLM 280 HL - workspace view, residual material cleaning to machine's filters for its reusage.

Material AlSi12 was used because it is relatively cheap, light and has suitable mechanical properties. To get even lighter design, we could use titanium powder. But it would be much more expensive and with no operational heat load, usage of Ti material is inadequate. Figures 19 and 20 show manufactured parts. In figure 19 is a manufactured part after heat treatment but still with supportive geometry. Heat treatment was performed in a laboratory furnace. The part was heated to 200°C for 7 hours. Due to heat treatment, the part is free of residual stress and has better mechanical properties. Manufactured part weight is about 160 g with residual powder still inside shell regions.

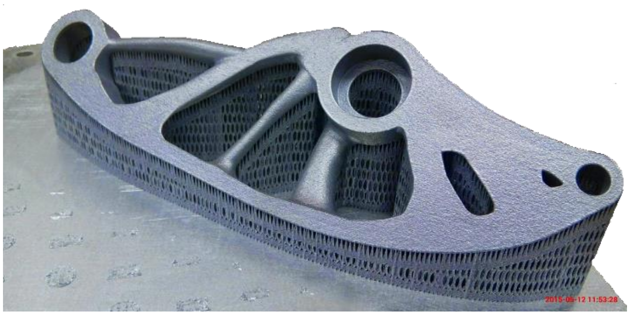

Figure 19. Manufactured part with supportive geometry.

Figure 20. Upper rockers with optimized design.

5 CONCLUSIONS

Applications on described research of mechanical parts with optimized design will grow. Manufacture of these optimized parts is with conventional methods very difficult or even impossible. To transform virtual parts with very complex shape to physical parts is possible or cost-effective only with 3D printing. A good example of this statement could be for instance 3D printing mechanical parts in aviation, where GE's Aviation division gets FAA (U.S. Federal Aviation Administration) certification for 3D printed fuel nozzles and other 3D printed part used in commercial jet engines from GE, which are used on the new Boeing 777 aircraft. With this being said, it is clear that 3D printed metal parts has the same quality as for instance those made by casting.

There are very little or none whatsoever design limitations with SLM. There is no porosity in a printed part, material has homogeneous structure and with effective material distribution it has potential to be very light without losing any of mechanical properties. [Ackermann 2014]

3D printing isn't suitable just for parts with optimized topology. For parts with complicated shape, which are made by using many technologies combined (casting, machining, welding, etc.), usage of 3D printing technology could be cheaper, effective and also environmental friendly (there is no material waste). Current use of this technology in aviation speaks for itself not just for time and economical advantages but even in reliability and safety. [GE 2015]

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CONTACTS

Ing. Milos Cadek
Technical University of Liberec
Faculty of Mechanical Engineering, KSA
Studentska 2, 461 17 Liberec 1, Czech rep.
+420 736 119 534, milos.cadek@gmail.com

Ing. Petr Zeleny, Ph.D.
Technical University of Liberec
Faculty of Mechanical Engineering, KSA
Studentska 2, 461 17 Liberec 1, Czech rep.
+ 420 485 353 354, petr.zeleny@tul.cz