

Optimization of turbine blade fir-tree root geometry utilizing LS-Prepost in pre- and post-processing

Jiří Jankovec¹

¹Research and Testing Institute Plzen, Czech Republic

Abstract

The turbine blade fir-tree root is a type of blade to disc connection, usually used for low pressure steam turbine blades. This part of turbine is exposed to extreme loading conditions caused by centrifugal loading during turbine operation and therefore there is a need to find a design that exhibits lower stresses, which determine low-cyclic fatigue life of the fir-tree root. This paper describes utilization of LS-Prepost [1] in optimization loop for design of new turbine blade fir-tree root geometry. The LS-Prepost pre- and post- processor offers a wide range of functionalities for geometry and mesh generation and is well suited for collaboration with the solver of LS-DYNA [2] commercial FE-code and with LS-OPT [3] optimization program. The other inconsiderable advantage of LS-Prepost is that it is delivered free with LS-DYNA and therefore it is not necessary to utilize any commercial Pre- and post-processor to parametrically control geometry of the analyzed problem.

1 Introduction

Relatively long blades are usually used for last stages of steam turbines; they are extremely loaded during their operation. According to more demanding requirements for turbine operations (e.g. higher number of start ups during normal service in peaking power plants) the ways to reduce maximal peak stresses occurred in the fir-tree root structure of those blades are sought. This will prolong the fatigue life of these turbine components. Therefore request for finding a new (optimized) shape of blade fir-tree root appeared. Although some authors [4], [5] have already solved similar problem, own approach was applied for blade fir-tree root shape parameterization and optimization utilizing the LSTC software tools. The implicit solver of LS-DYNA together with pre- and post-processor LS-Prepost was used to analyze and evaluate the mechanical loading of turbine blade fir-tree root. The LS-OPT program was used to automatically control the optimization process.

2 Shape of the fir-tree root

The original shape of blade fir-tree root (2D shape, which is drawn in 3rd dimension along a line or along a circular arc) is composed of circular arcs and lines, which are tangentially continuous and which form three teeth. Due to the geometrical symmetry and the symmetrical character of the centrifugal loading only left half of the fir-tree root basic shape is modeled (See Fig.1).

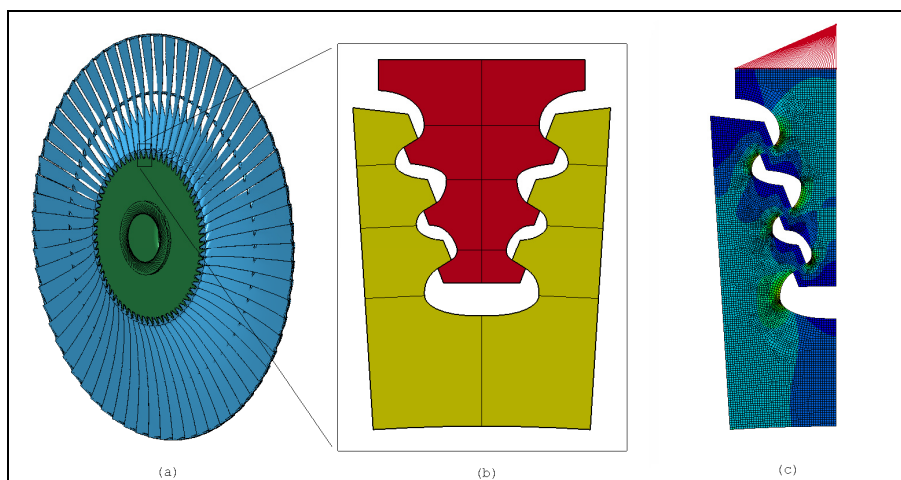


Fig. 1: (a) Whole turbine bladed wheel, (b) detail of blade fir-tree root, (c) analyzed part of the blade fir-tree root structure.

3 Structural requirements for blade fir-tree root

The low-cyclic fatigue life of blade fir-tree root is determined by stresses induced by centrifugal loading [6]; therefore peak stresses in the structure should be as low as possible.

There are also limitations, which the structure has to fulfill. These limitations are defined for

- average normal stress in each neck of the blade and disc (Fig.2 (a)):

$$\begin{aligned} \sigma_{B_1} &\leq \sigma_{B_allow} & \sigma_{D_1} &\leq \sigma_{D_allow} \\ \sigma_{B_2} &\leq \sigma_{B_allow} & \text{and} & & \sigma_{D_2} &\leq \sigma_{D_allow} \\ \sigma_{B_3} &\leq \sigma_{B_allow} & & & \sigma_{D_3} &\leq \sigma_{D_allow} \end{aligned} \quad (1)$$

Here σ_{B_allow} is allowable stress for average normal stress in blade neck.

Here σ_{D_allow} is allowable stress for average normal stress in disc neck.

- average shear stress in each tooth of the blade and disc (Fig.2 (b)):

$$\begin{aligned} \tau_{B_1} &\leq \tau_{B_allow} & \tau_{D_1} &\leq \tau_{D_allow} \\ \tau_{B_2} &\leq \tau_{B_allow} & \text{and} & & \tau_{D_2} &\leq \tau_{D_allow} \\ \tau_{B_3} &\leq \tau_{B_allow} & & & \tau_{D_3} &\leq \tau_{D_allow} \end{aligned} \quad (2)$$

Here τ_{B_allow} is allowable stress for average shear stress in blade tooth.

Here τ_{D_allow} is allowable stress for average shear stress in disc tooth.

- average contact pressure in each teeth contact zone (Fig.2 (c)):

$$\begin{aligned} p_{cont_1} &\leq p_{allow} \\ p_{cont_2} &\leq p_{allow} & \text{where } p_{allow} &= \min(p_{B_allow}, p_{D_allow}) \\ p_{cont_3} &\leq p_{allow} \end{aligned} \quad (3)$$

Here p_{B_allow} is allowable contact pressure for average contact pressure on blade cont. zone.

Here p_{D_allow} is allowable contact pressure for average contact pressure on disc cont. zone.

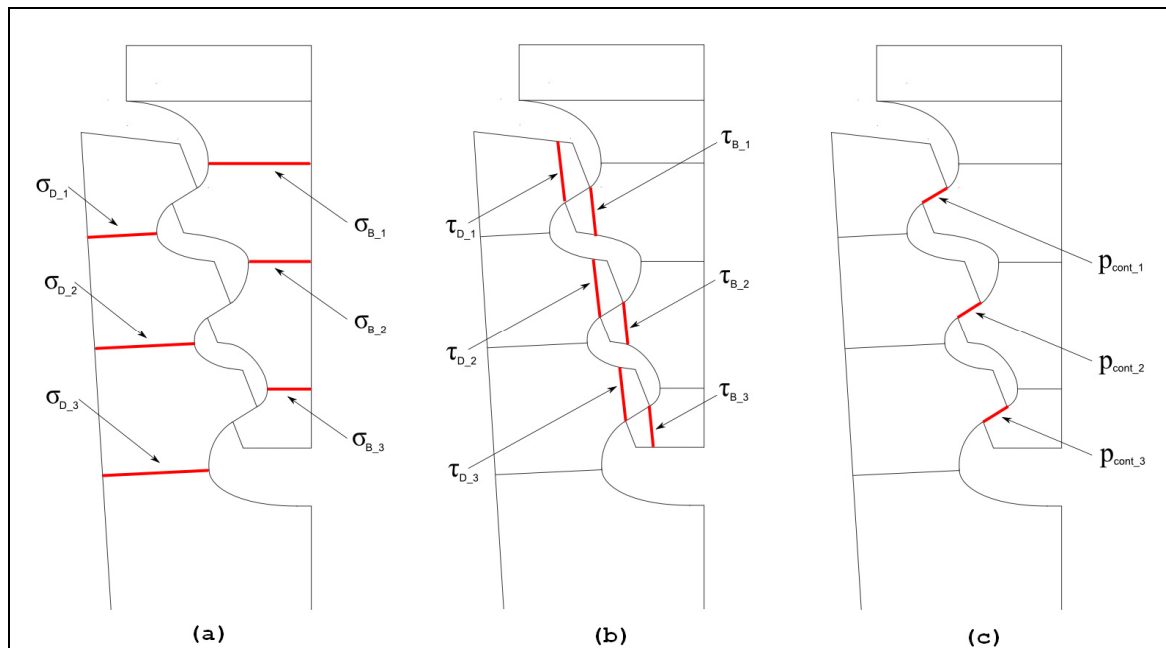


Fig.2: (a) Evaluation zones for normal stress (a), shear stress (b) and contact pressure (c).

4 Generation of the FE-model

4.1 Parameterization of the shape

The parameterization of the blade fir-tree root shape originated from the idea that firstly the starting points of teeth contact zones and secondly the neck locations of each tooth are placed. Then the placement of curves connecting these basic locations was performed.

The knowledge of neck location is important to place there the coordinate systems and cutting planes for the evaluation of average normal stresses. Starting and ending points of teeth contact zones are important for the average teeth shear stress evaluation and for the average contact pressure evaluation.

Transition from teeth contact zones to neck locations both on blade and disc was conducted using Bezier curves (see Fig.3), which are capable to smoothly connect the existing basic curves and the weight of defining vectors can be controlled in LS-Prepost (GUI command: Geometry -> Curve -> Bridge Edge). Parameters used for the whole fir-tree root shape generation are shown in Fig.4.

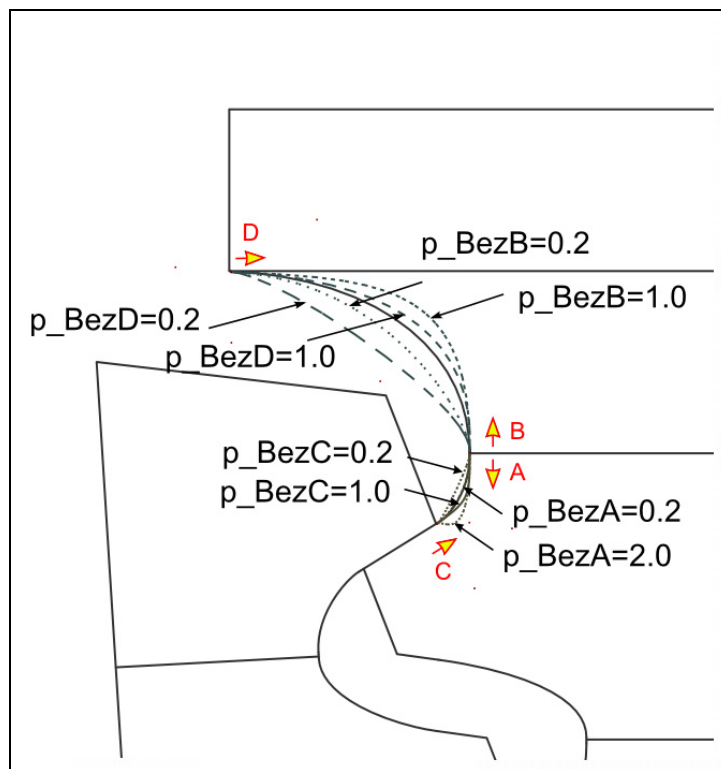


Fig.3: Bezier curves above and below the 1st blade neck and their weighting parameterization.

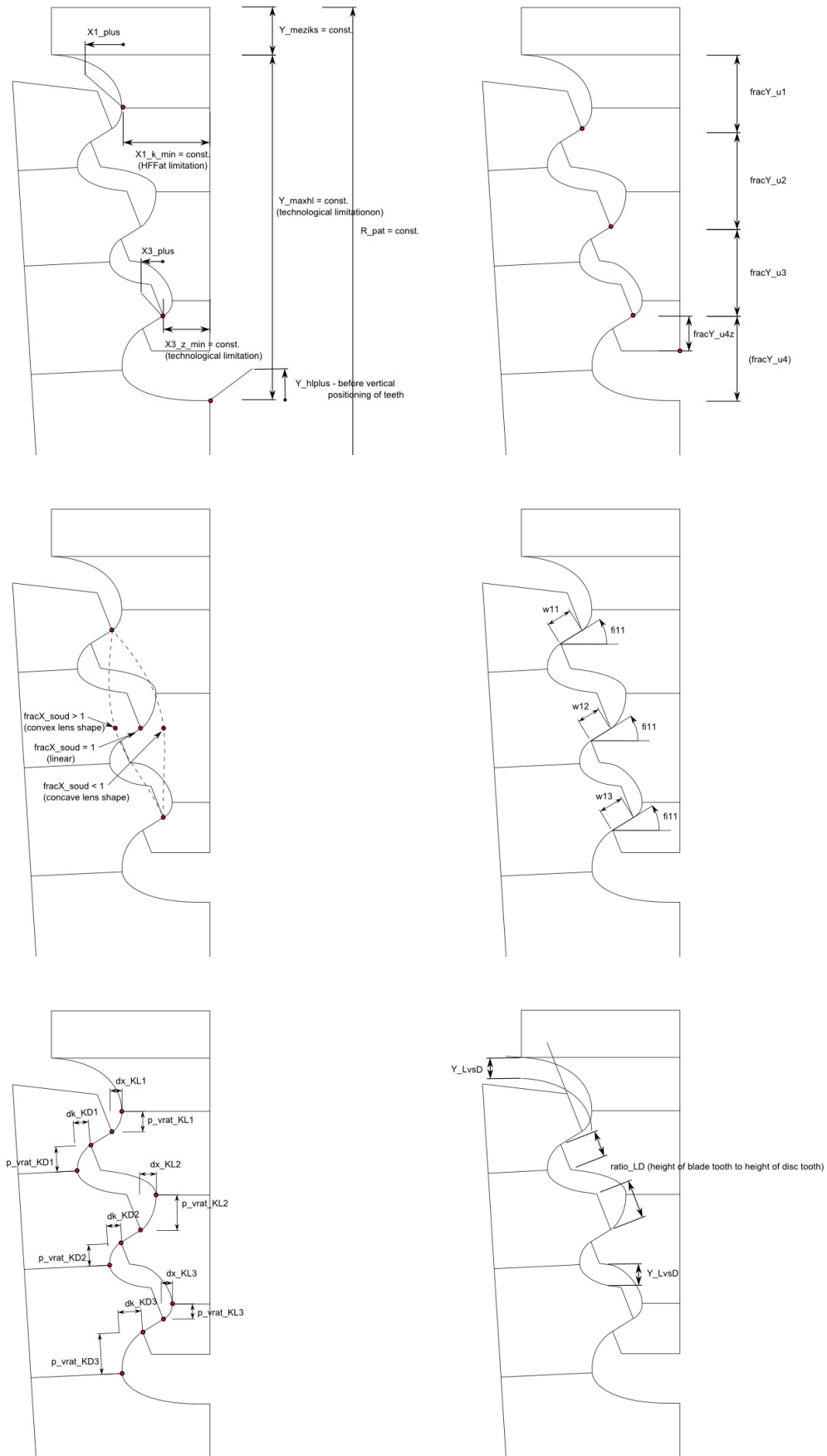


Fig.4: Parameters and dimension for building the basic shape.

4.2 Model generation in LS-Prepost

Above described blade fir-tree root shape parameterization was used to generate points, curves and surfaces in LS-Prepost. The surfaces were then meshed with the VSM (Variable Size Meshing) procedure, which is able to locally refine mesh in places of high geometry curvatures and thus later obtain correct peak stresses from the simulation.

The VSM generated 2D mesh was extruded in 3rd direction (1 element of length 1 mm in z-direction). Thus the hexahedral mesh of the problem was created. The elements were separated into different part numbers to facilitate later the results evaluation and optionally to enable optimization of particular sub-domain of blade fir-tree root structure. Different parts differentiated by colors are shown in Fig.5.

The node sets for boundary conditions (BC); coordinate systems for BC definitions and for cross-sections were defined in the next phase of the model preparation.

The keywords defining control parameters for the implicit LS-DYNA solver together with boundary constraints (symmetrical boundary conditions) and load definitions (angular velocity and force representing rotating mass of blade) were incorporated into the model importing an external key-file into LS-Prepost. The whole LS-DYNA model was then saved from LS-Prepost into a DYN-file.

All above described operations were performed using parameterized LS-Prepost cfile (command file).

In this cfile expressions are used to define geometry constraints and dependencies.

The scripting command language (SCL) enables calling external SCL-scripts (sco-files), which are suitable for more advanced programming techniques (e.g. for programming loops, conditions, etc.). SCL-scripts were utilized for correct meshing checks (e.g. see Fig.6) in this task or for determination of last created entity numbers to enable a repeated usage of command sequences.

The LS-Prepost parameters were used for LS-DYNA keyword definition in this process. In Fig.7 a part of cfile code for keyword definition is shown.

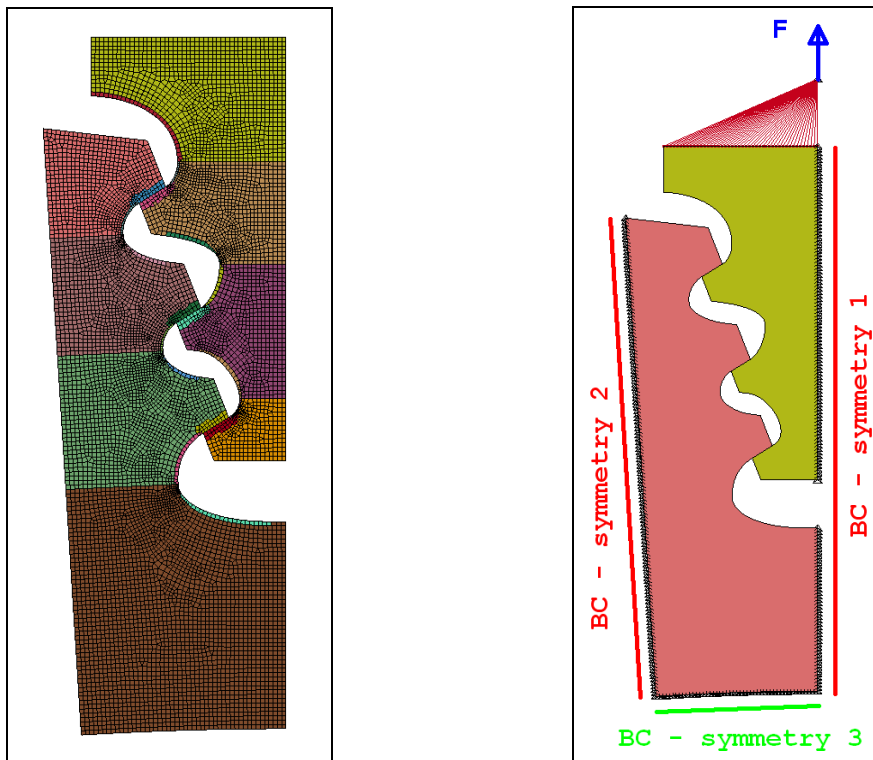


Fig.5: Parts differentiated by colors and boundary conditions definition.

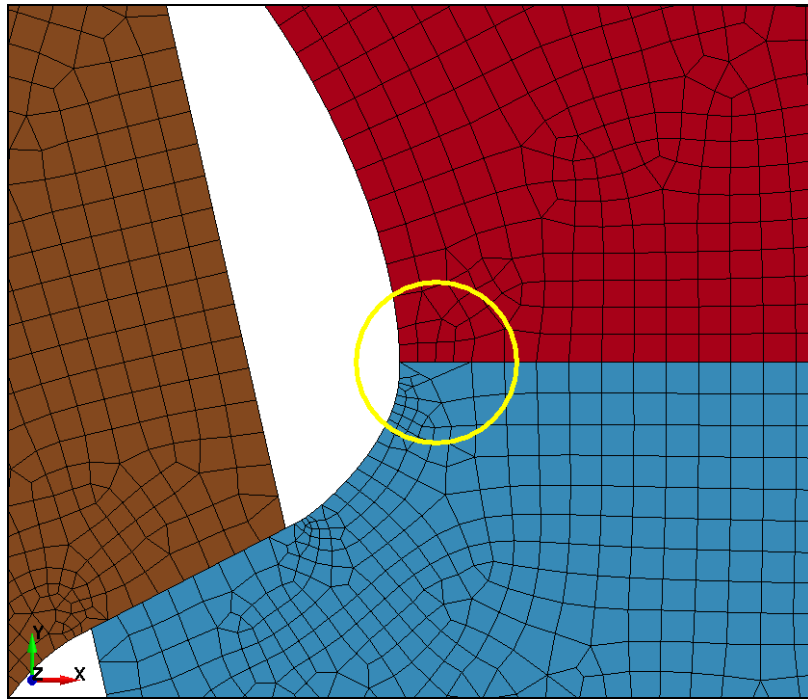


Fig.6: For some geometry configuration inconsistent mesh was generated by VSM – thus a need for mesh check appeared

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$ --- cross-section creation: ---
KEYWORD INPUT
*DATABASE_CROSS_SECTION_PLANE_ID
$#   csid                                     title
     301 1st-neck-blade
$#   psid   xct   yct   zct   xch   ych   zch   radius
     310   0.000  &Y_L55  0.000  0.000  &Y_L1  0.000  0.000
$#   xhev   yhev   zhev   lenl   lenm   id   itype
     &X_L17  &Y_L17  0.000  0.000  0.000  301    2
*END
keyword updatekind
DATABASE_CROSS_SECTION_PLANE_ID

```

Fig.7: Keyword card definition using LS-Prepost parameters in cfile-mode.

4.3 Some important keyword parameters

The following parameters of LS-DYNA keywords were important for the proper solving of this FE-analysis.

- CPCHK = 1 in *CONTROL_IMPLICIT_SOLUTION for a better convergence of the problem.
- ISYM = 1 in *CONTROL_CONTACT for using proper segments in contact.
- SLSFAC = 1 in *CONTROL_CONTACT for using proper contact stiffness in contact.
- NINTSLD = 8 in *DATABASE_EXTENT_BINARY to have more accurate stress results (from integration points) in solid elements, which can be extrapolated.
- IEVERP = 1 in *DATABASE_EXTENT_BINARY to have possibility keep results only from the first and last timestep (after deleting d3plot files of timesteps between them).
- ELFORM = 2 in *SECTION_SOLID for fully integrated S/R solid elements.

5 Evaluation results from an analysis

There is a need to obtain several responses from the LS-DYNA analysis. Maximal principal stress has to be determined using LS-Prepost. Average normal stress, average shear stress and average contact pressure can be determined using mathematical operations with parameters obtained from the LS-DYNA result files.

5.1 Analysis results from LS-Prepost

Minimization of Maximum principal stress (P1 = first principal stress) is required in the optimization process of the fir-tree root. The extrapolated value of this response can be currently obtained solely from the LS-Prepost program, not from any LS-DYNA ASCII result file. In Fig.8 there is the LS-Prepost cfile-command sequence for obtaining extrapolated maximal first principal stress of a particular part. The LS-Prepost cfile-command "extrapolate 4" ensures the usage of nodal stresses extrapolated from integration points. The value of maximal P1 can be obtained then from the saved ASCII file using any text-extraction utility (e.g. utility GenEx of LS-OPT).

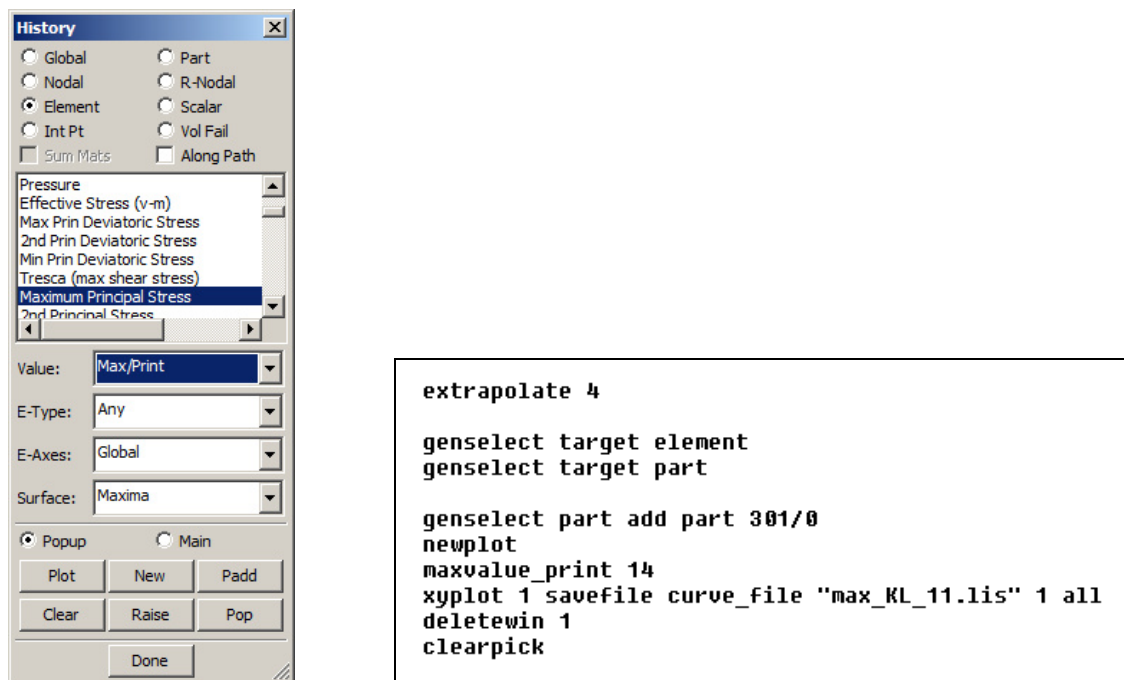


Fig.8: LS-Prepost GUI and cfile-command sequence for determining maximal P1 stress in post-processing.

5.2 Analysis results from LS-DYNA result files

The average normal stress in necks and average shear stress in teeth are obtained using mathematical operations with values from the *secforc* LS-DYNA result file. In this file there are written sectional forces in a particular coordinate system and the area of cross-section. The particular forces are divided by corresponding areas and thus the stresses are determined.

The average contact pressure in contact zone is obtained using mathematical operations with values from the *rcforc* LS-DYNA result file. Particular resulting forces are divided by the area of tooth contact zone.

6 Optimization problem in LS-OPT

Mathematically defined optimization task

$$\begin{aligned} & \min f(\mathbf{x}) \\ & \text{subjected to:} \\ & g_j(\mathbf{x}) \leq 0; j = 1, 2, \dots, m \\ & h_k(\mathbf{x}) = 0; k = 1, 2, \dots, l \end{aligned}$$

was solved using the LS-OPT [2] optimization software.

The chosen optimization strategy was the SRSM (Sequential response surface method). Optimization algorithm was the Hybrid ASA (Adaptive simulated annealing) and the selection of design points was conducted using D-Optimal design criterion. The optimization job was run for 10 iterations utilizing 3 CPUs. In case of using 50 free parameters, 77 design points were analyzed in each iteration.

The LS-Prepost was run as a pre-processor from the LS-OPT program (see Fig.9) to parametrically generate FE-models for the implicit solver of LS-DYNA program. The LS-OPT capability to recognize the LS-Prepost parameters in the specified cfile and use them as design variables was successfully utilized.

Determination of maximal first principal stresses (value of P1 peak stress) of a particular part was conducted using LS-Prepost and by consequent usage of LS-OPT utility GenEx. This is illustrated in Fig.10 and Fig.11.

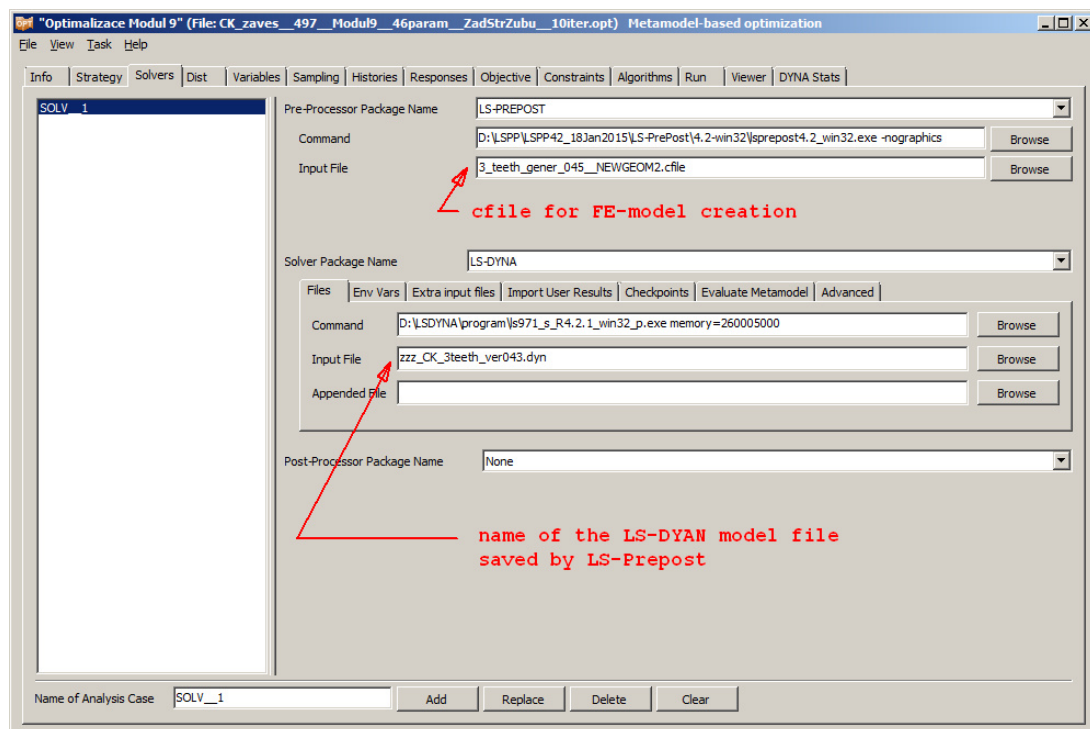


Fig.9: LS-Prepost specified as a pre-processor in LS-OPT.

7 Used programs

For solving the optimization task the following program versions were used:

- LS-Prepost: version 4.0, 4.1 and 4.2
- LS-DYNA: version 971, release 4.2.1
- LS-OPT: version 4.2, revision 75641

During the project solving the last developed version of LS-Prepost was always used, mostly released after incorporating any functionality necessary for the model generation.

Version 4.2 of LS-OPT was preferred rather than 5.x version to run optimization process, because LS-Prepost can be easily run in a “visible” mode compared to LS-OPT 5.x which default runs LS-Prepost in “-nographics” mode. Especially in the phase of tuning the optimization runs it is better to find out where LS-Prepost geometry generation had problems and caused hanging the LS-Prepost and thus pausing the whole optimization process.

In analyzing the design points in the LS-OPT Viewer there is an icon (Fig. 12) to open result files of selected design point in LS-Prepost. The recent versions of LS-OPT use an older version of LS-Prepost (located in installation directory of LS-OPT) for opening the result files. And this old version is not able to show extrapolated stresses of solid elements. Therefore own program was built, which opens selected results (design point) using the user specified LS-Prepost version (see Fig.13). The program was renamed to *lsprepost.exe* and placed into LS-OPT installation directory. Thus it is possible to explore extrapolated nodal results, which are important for solving the problem.

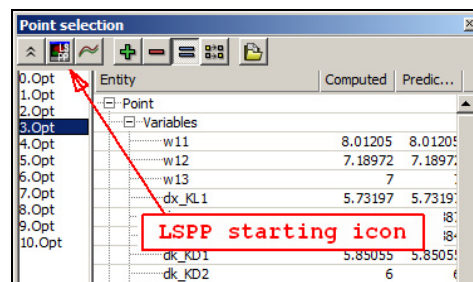


Fig. 12: LS-Prepost starting icon in LS-OPT Viewer.

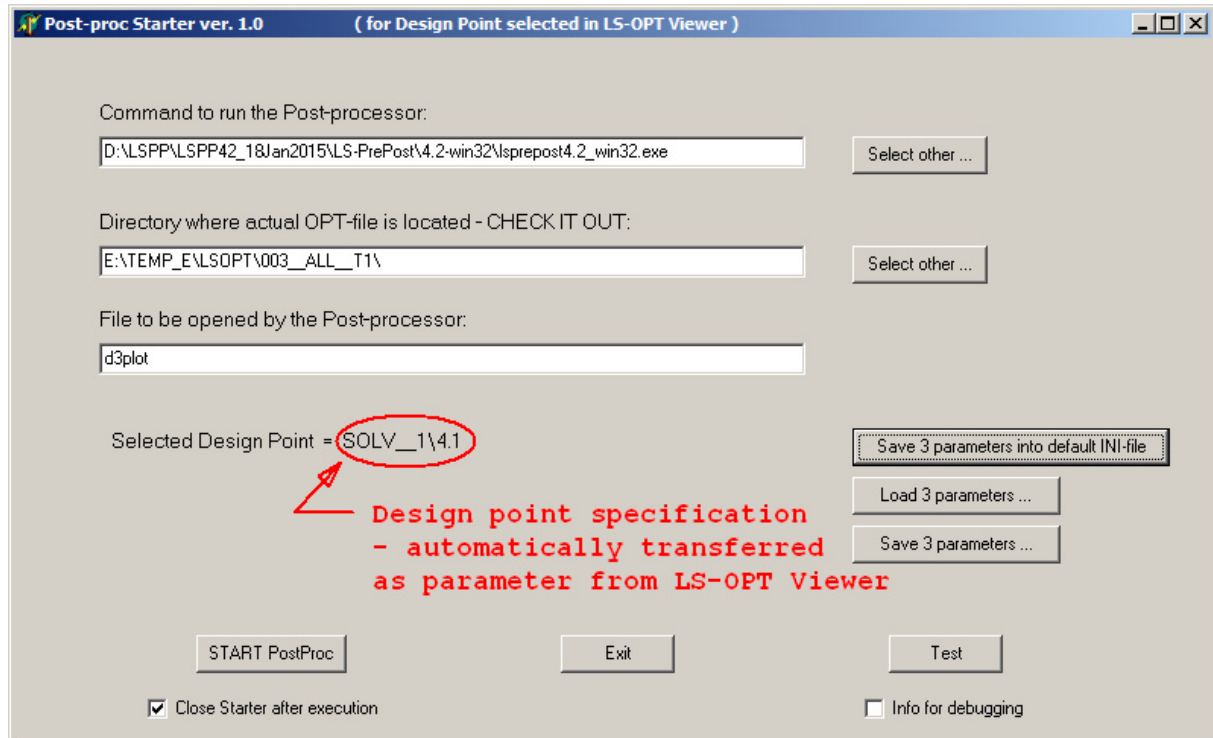


Fig.13: User interface of program for starting LS-Prepost to analyze results of selected Design Point.

In some cases (model configurations) the implicit LS-DYNA solver was unable to converge and crashed with showing a message window (see Fig.14), which required the user interaction to close this window and to enable to continue the calculation. Therefore own program was built to automatically close any error-message window of LS-DYNA. This program was incorporated into each post-processing command sequence. Naturally this approach is meaningful only when multiple Concurrent Jobs are run from LS-OPT.

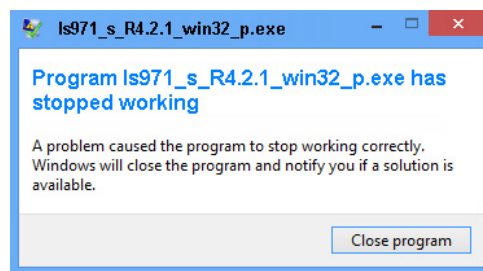


Fig.14: System message requiring user interaction.

8 Summary

Usage of LS-Prepost for turbine blade fir-tree root shape optimization was demonstrated in this paper. Some problems occurring during creation of parameterized scripting command file and their solutions were presented. Some problems required workaround and some of them were helpfully solved by LS-Prepost developers adding new features or functionalities.

The conducted optimization task has shown that also problems involving geometry parameterization and modification can be solved only using software tools from LSTC (LS-Prepost, LS-DYNA and LS-OPT) and that there is not necessary to incorporate another commercial pre-processor for the geometry parameterization.

9 Literature

- [1] LS-Prepost 4.2 Help Document, <ftp://ftp.lstc.com/outgoing/lsprepost/4.2/doc/win/Document.chm>, 2015
- [2] LS-DYNA Keyword User's Manual, Version 971, Release 4, Livermore Software Technology Corporation, Livermore, 2009
- [3] LS-OPT User's Manual, Version 4.2, Livermore Software Technology Corporation, Livermore, 2012
- [4] Ou, H.: "A direct shape optimization approach for contact problems with boundary stress concentration", Journal of Mechanical Science and Technology, Volume27, Issue 9, 2013, pp 2751-2759
- [5] Song, W: "Turbine blade fir-tree root design optimisation using intelligent CAD and finite element analysis", Computers and Structures 80, 2002, pp 1853–1867
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