Finite Element Analysis of the Vertical Tailplane of PZL-106BT Aircraft with a CAD/CAE Based Multidisciplinary Process

Péter Deák
Warsaw University of Technology
Warszawa, Poland
ddeakpeti@gmail.com

Abstract. The work describes a finite element analysis of a vertical stabilizer of a Polish agricultural aircraft (PZL-106BT) with the possibility of an automated approach. The aim was to compare two models, a reduced top section of the vertical tailplane with the original structure model.

The first part of the presented work provides an introduction to the Multidisciplinary CAD/CAE based aircraft design optimization. After the theoretical introduction of the vertical tail, the multidisciplinary process for the structural analysis follows. The geometry model creation together with aerodynamics calculations were performed using PANUKL software. Moreover, CalculiX was used for post-processing in the Finite Element Analysis.

The final part deals with the results of the structural analysis which compares the two analyzed models from structural point of view and other conclusions that can be drawn from the analyses. It focuses on the nodal displacements, Von-Mises stresses arising at the aft spar and at the ribs. A frequency analysis was also performed to determine structural eigenmodes. Finally, buckling factors are determined to analyze the models for buckling.

Keywords. Aircraft Design Optimization, PZL-106BT, Vertical Stabilizer, Multi-disciplinary Process, MDCAD, FEM analysis

1 Introduction

In today's developing and growing aircraft industry, manually performing the state-of-the-art aircraft design phases is not practical, therefore a fast and accurate automated analysis and data exchange are crucial. A Multidisciplinary CAD/CAE based concept assessment and design is already widely used in major aircraft designing companies to automate the optimization process in case of weight estimation, structural modifications or even other time consuming analysis. The idea of MDCAD is to allow any software to be used if the output files are compatible with certain software. The main goal of the work was to compare two models of PZL-106BT (Kruk) agricultural aircraft's vertical tail, using a Finite Element Approach and to give an idea of an automated approach in design.

1.1 Multi-Disciplinary Concept Assessment and Design (MDCAD)

Multi-disciplinary aircraft design optimization is a novel concept in today's preliminary aircraft design phase. The main motive for its application is to understand the impact of early stage design decisions on a deeper level. Advantages of MDCAD include; reduction in development time to access the benefits, cost and easier data exchange between different software by using standardized software tools and data formats.

The main disadvantages are those that drastically limit the practicability of the CAD/CAE-based approach. They include; fixed and recurring license costs, low computational efficiency (1 hour is required for the automated generation of models) and finally, use of composite materials is not available in recent software versions of the CAD/CAE-based mass estimation process. The last argument is especially important as aircraft design is a multidisciplinary process that combines teams of different disciplines such as flight dynamics, aerodynamics and structural mechanics on a high degree of collaboration. [1]

1.2 Compatibility of MDCAD application

The MDCAD could be used with other software analogy. The idea allows any software to be used if the output files are compatible with certain software. To automate the process, the multidisciplinary process is used. In the presented work, the following architecture of software application is used.

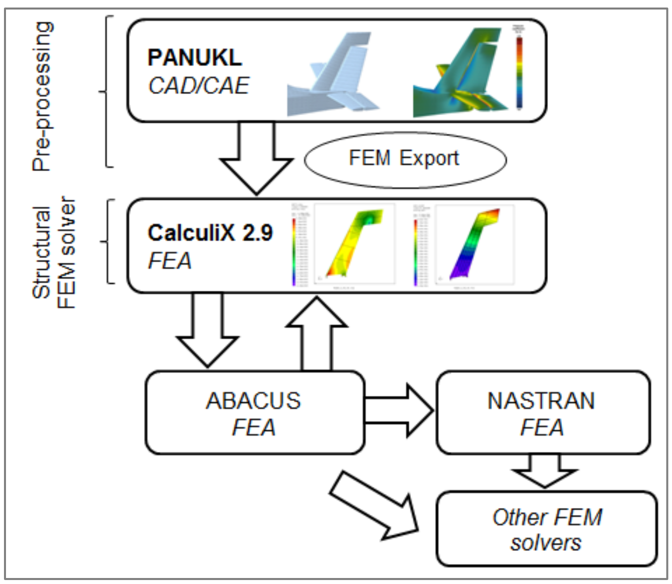


Figure 1. Flowchart of software compatibility

Figure 1. gives an overview of the used software and their compatibility for further applications of the results. The generated PANUKL results can be exported for finite element analysis with the help of a built-in option of the program. This step is explained in more details in Section 2.2. The converted data is now in a format that is sufficient to be loaded in CalculiX CGX, where the pre- and post-processing are performed. The file extensions used for naming conventions and input style formats are based on

those used by ABAQUS. Any further analysis of more complex calculations is possible through other advanced FEA programs as shown.

A flowchart of the multidisciplinary process is presented in Figure 2. The input part contains the definition of the real aircraft, includes data taken from original drawings and their simplifications for the analyzed model. The multidisciplinary process is the core of the chart. The models derived from PANUKL are then transferred theoretically to the load generation part. Both aeroelastic and sizing loop are within this field. The convention of the pre-processing stage is taking place inside the sizing loop. The transferred data files can then be loaded by CalculiX FEA program.

Although, the thesis was not made with the help of the automated process, it is possible within the framework of MDCAD.

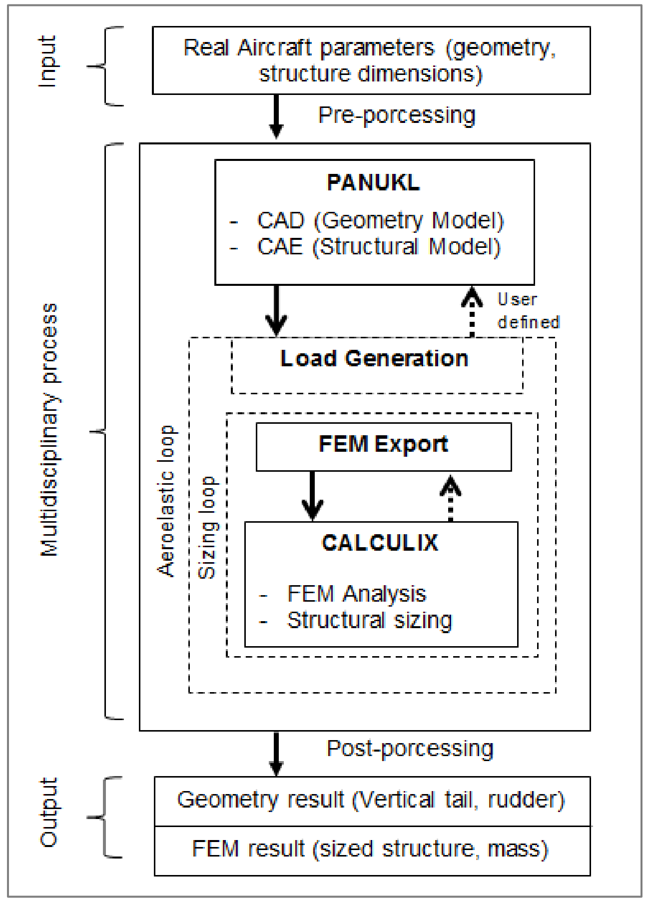


Figure 2. Multidisciplinary process

2 Descriptive definition of aircraft and the vertical tail

2.1 PZL-106BT aircraft vertical tail

The main motive of the thesis came from PZL Warszawa – Okęcie. As far as the history of the plane is concerned: during a long distance flight from Argentina to the Ecuador, the pilot experienced excessive loads in control of the aircraft, which made him exhausted. Similar results were told by pilots during day-long agricultural flights. Some of the owners of the airplanes decided to cut the vertical tail at the position of Rib #7, which become the tip rib, instead of the previous Rib #8. The reduced tail area creates less directional stability but at the same time better yawing maneuverability. This reduced tail can be seen on Figure 3.

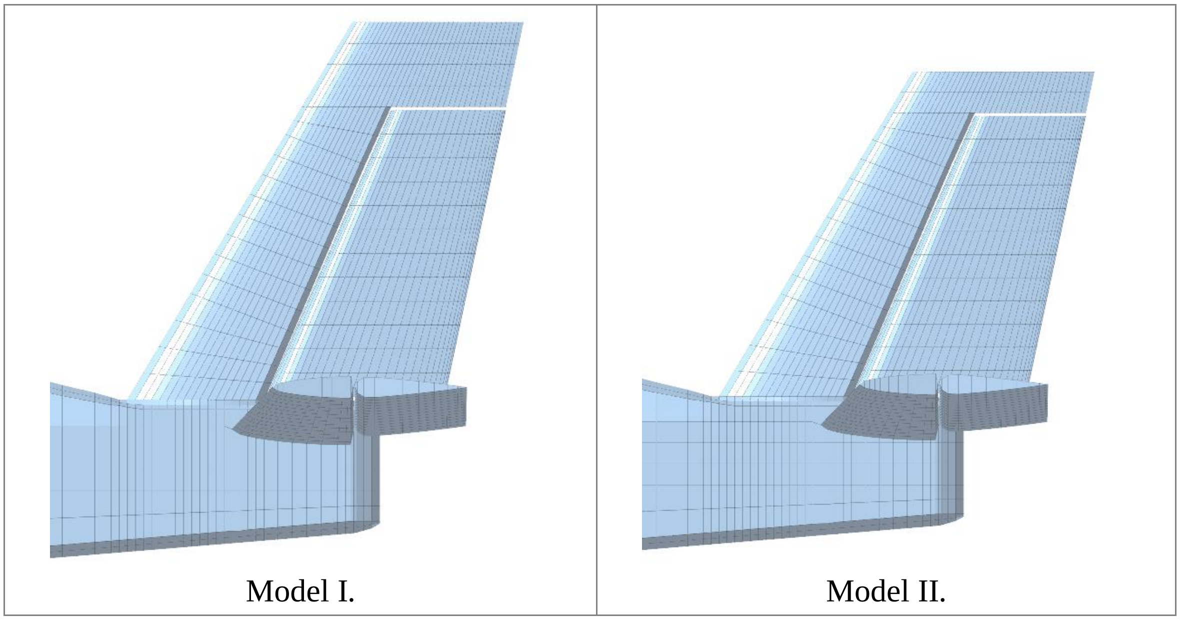


Figure 3. Geometry models in PANUKL before and after the cut

The vertical tailplane comprises a main box with a leading edge, a top part called as a tip and a single unit rudder. The fin is made up of front and aft spar, 7 ribs, and 4 stringers. The local reinforcements of the tail were not included in the calculation due to the functionality of the used software. For a more detailed local analysis, more advanced software shall be used.

2.2 Geometry model (CAD/CAE)

PANUKL is a software developed at the Faculty of Power and Aeronautical Engineering at Warsaw University of Technology. It has multiple functions that include; fuselage, wing and stabilizers creation, aerodynamic characteristics of an aircraft such as; vortex distribution and pressure coefficient distribution, using low-order panel method. Aerodynamic loads, such as lift force, drag force and pitching moment can be obtained. It enables to convert the meshed geometry file and calculated results for further analysis. The distribution of the tail components, shown on Figure 4., were necessary to generate the model using PANUKL.

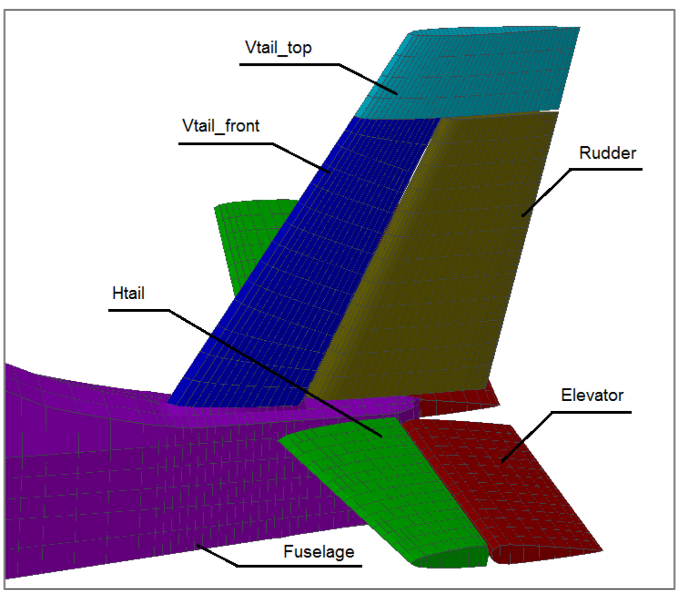


Figure 4. Components of CAD model in PANUKL

FEM Export tool is an in-built function of PANUKL for data export. It also defines FEM analysis case of an airplane for further use in CalculiX. Pre-processing definitions such as boundary conditions, material selection, leading edge or trailing edge cuts, selection of ribs and output file extension parameters are set using the software.

2.3 Material properties

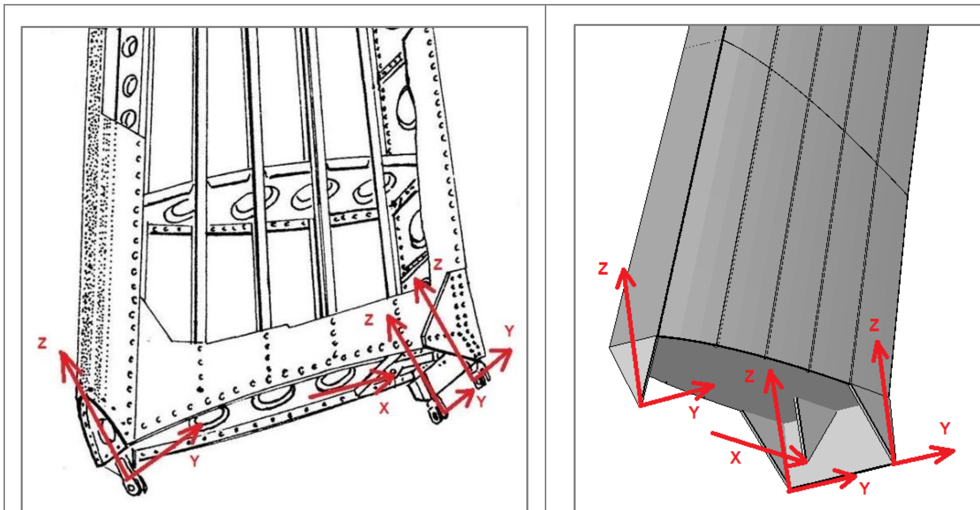
The vertical tail is manufactured from (PA-7) duralumin; 2024-T351 type sheet elements with internal ribs of the same materials riveted together.

Table 1. Material properties [2]

Type of Aluminum: (PL-7 duralumin)	**2024-T351**
Young's modulus E [MPa]	73100
Poisson's ratio ν	0.3
Density ρ [kg/m^3]	2780
Yield strength σ_{yield} [N/mm^2]	324
Ultimate (tensile) strength $\sigma_{ultimate}$ [N/mm^2]	469

2.4 Boundary conditions

The main box attachment fitting is made up of 4 attachment points to the fuselage: 3 main attachment fittings, in the form of lugs, secured with a horizontal pin to the fuselage. An additional, 4th fitting is a transverse load one, located at the root of the tail. The main attachment fittings are fixing the tail in Y and Z direction, while the transversal one is only in X direction. Figure 5. shows the original schematic drawing of the lugs and the created equivalent model for FEA.



Original model | CalculiX model

Figure 5. Vertical tail fittings with boundary conditions

2.5 Load generation

The aerodynamic loads applied on the rudder were estimated for the case of aerodynamic loads due to maximum rudder deflection at high maneuvering speeds – V_A. The value of V_A was taken from the load envelope plot (corner A). These loads act normally on both rudder side surfaces and induce bending and torsion of the rudder structure. In the FEM model, these aerodynamic loads are represented by concentrated force vectors. The boundary conditions are set as follows: the lower hinge transmits translational DOFs in all directions and one rotational DOF in direction of the hinge axis (z direction) to simulate the rudder moment. The upper hinge only transmits translational DOFs in x and y directions but not in direction of the hinge axis.

The rudder is designed as a single unit. Its maximum deflection is 35° to each side. It is attached to the fin by two hinges, one connected to the 4^{th} rib and another one at the root, attached to the fuselage.

In order to find the corresponding angle of attack for which aerodynamic calculation was to be performed in PANUKL, the lift coefficient was needed to be determined. After obtaining the lift coefficient, the corresponding angle of attack can be determined from the lift curve slope for the whole aircraft (with NACA-2415 airfoil). The lift force distribution can be calculated and plotted along the rudder in height-wise direction. The following step is to calculate a point load from the non-uniformly distributed loads on the rudder. The rudder is then modeled as a simple beam with a fixed support at its root fitting and with a pin support on the upper mounting point, as shown on Figure 6. The resulting geometry will require calculating the reaction at point B that is going to be equivalent to that sought point load.

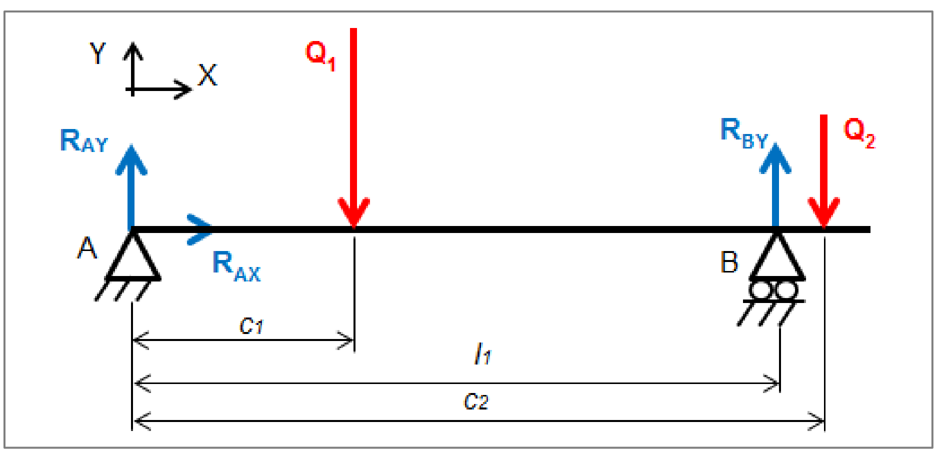


Figure 6. Free body diagram of the rudder

After writing the balance of forces for the above free body diagram, the reactions at the supports can be calculated. The reaction of the rudder at point B is taken as a concentrated point load on the vertical tail. This load is set to the model at the position of the hinge, in Y direction.

2.6 Finite element analysis (CalculiX)

CalculiX 2.9 is a three-dimensional, open source, structural finite element program that is compatible to use with ABACUS (FEM software). The program can be divided into two subparts: Calculix GraphiX (CGX) – Pre/Post-processing, and Calculix CrunchiX (CCX) – FEM solver part. An advantage of CalculiX over other similar FEA software is the GPL source code layout – available for free public use. This allows the user to automate the analysis in a multidisciplinary way. Similarly to other FEM programs, CalculiX does not use units. The user must be consistent when selecting the proper units and when providing the values to the input file.

For the FEA, the thickness of each component and the element types were defined in CalculiX CGX. For further information about the calculation methods, the documentation of CalculiX is at hand.

3 Results of analysis

3.1 Results of aerodynamic calculations

On Figure 7. the pressure coefficient distribution of the two empennage models of PZL-106BT aircraft can be seen, after performing the aerodynamic calculation in PANUKL. The figures include the vortex lines leaving the panels at the trailing edges. The one can notice how, for a deflected rudder the pressure is distributed along the rudder's airfoil. On the deflected side, there is a higher pressure region (in blue), while on the other side, is the lower pressure part (in red). This generates the lift force, pointing to the right in the yawing plane, causing the turn to the left of the aircraft. Other figures are the imported models from PANUKL into CalculiX. At this stage the models from both software must show the same distribution. In CalculiX the pressure sign had to be inverted for proper analysis.

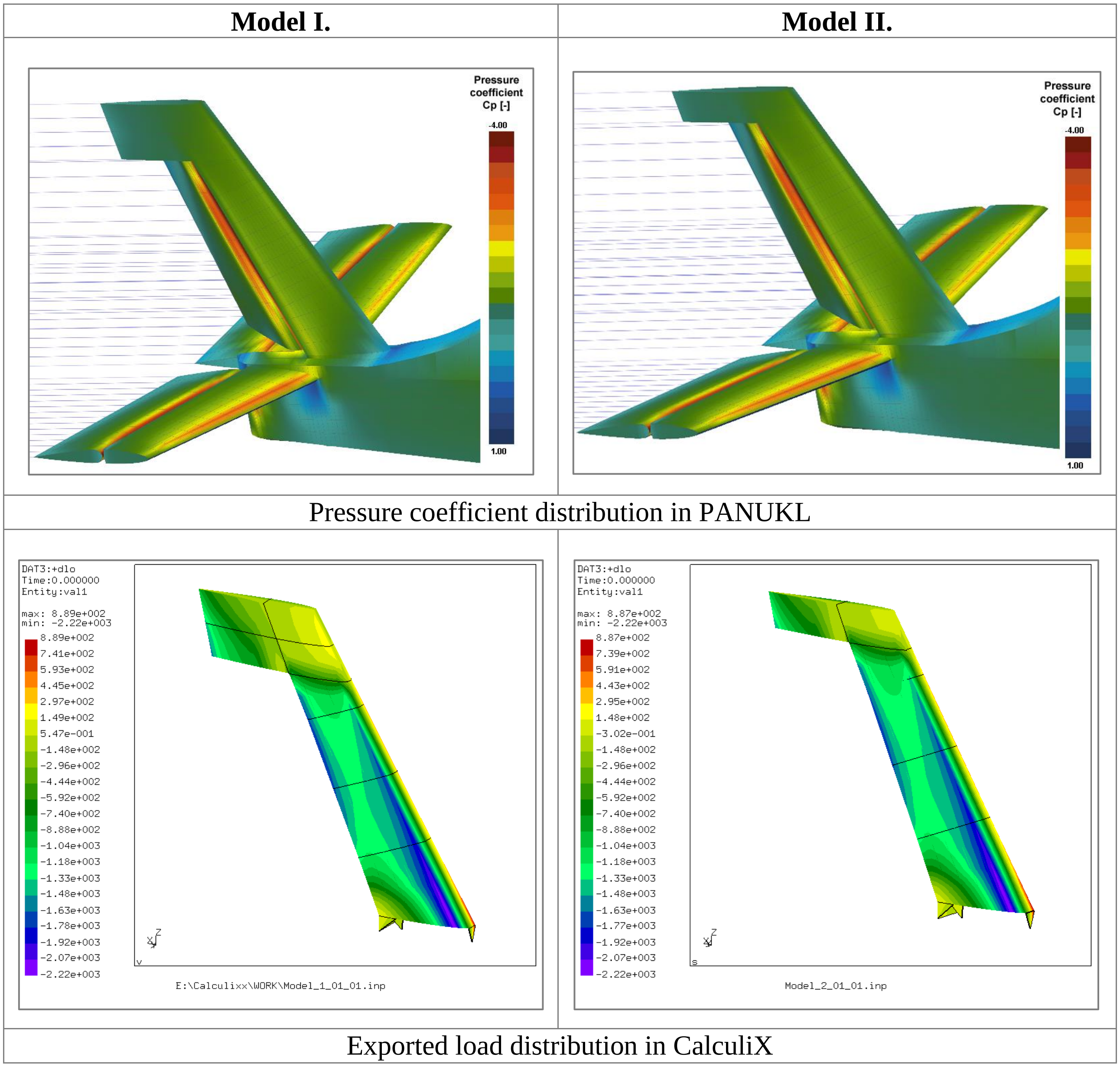


Figure 7. Aerodynamic load distribution of vertical tail

3.2 Frequency analysis

To determine corresponding eigenmodes and eigenfrequencies of the tail structure, modal analysis was carried out. This was done with the help of "*FREQUENCY" flag, for the 10 lowest eigenfrequencies to be determined.

Iterative numerical techniques are used to find the limited number of eigenvalues (natural frequencies) within the interesting range. In FEM modal analysis, good accuracy of the results (frequencies, mode shapes) can be obtained even for rough meshing.

3.3 Buckling criterion

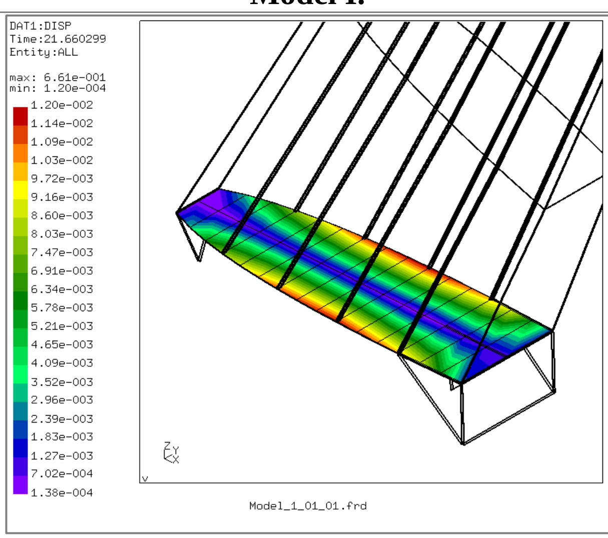
Buckling is a characteristic phenomenon of structures that are having tension in their axidirection. For a column type of elements, if the applied axial load at its ends is monotonously increases, the column will deflect until reaching its critical bending state. Further increasing the load will cause plastic deformation and finally cause failure. Because many of the components are thin riveted sheet metals, there is a strong likelihood of buckling taking place. This is why a buckling analysis was necessary to be performed.

In order to decide at what value of the buckling load the system will collapse, the buckling factor is used. For this reason, the buckling load system is scaled with a factor λ. The value of λ, at which the lowest eigenvalue of the system will be equal to zero, is to be determined. If this factor is less than or equal to 1, buckling will occur, if it is greater than one, no significant effect will take place. [3] In order to determine the buckling load, the one can increase the compressive load up to the point that the lowest buckling factor equal to 1. [4]

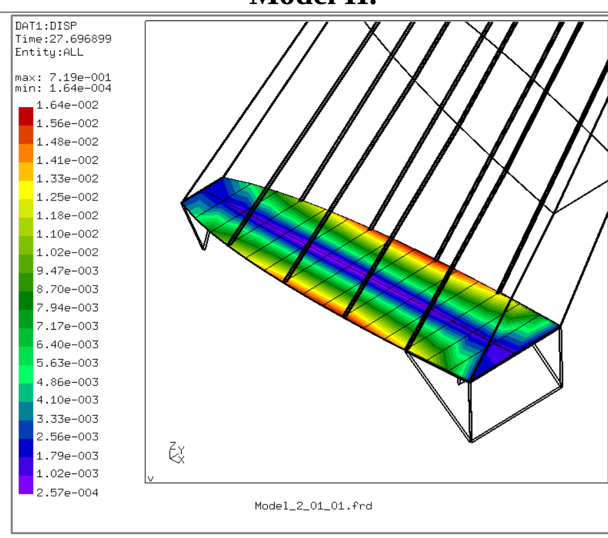
3.4 Results of finite element analysis

The following results on Figure 8-9. are presenting the nodal displacements and the Von-Mises stress distributions for the two models for the first mode of vibrations only. Presenting further modes were excluded from this article. The results are shown only for the mostly interested regions: for the root rib and for the aft spar, following then a complete distribution for the entire model.

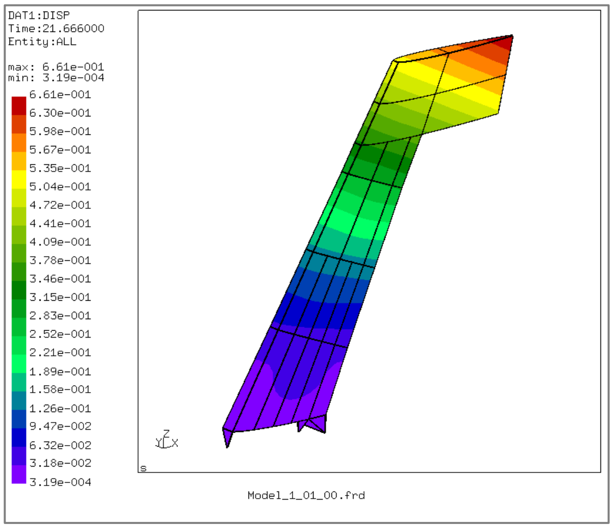
Model I.

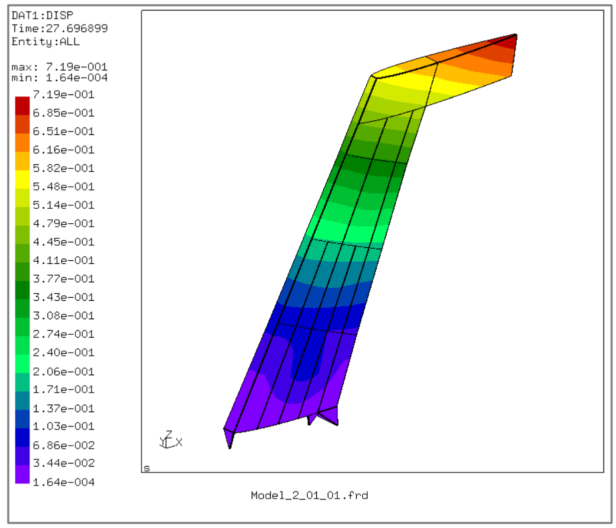


Model II.



Nodal displacements for Rib #1.

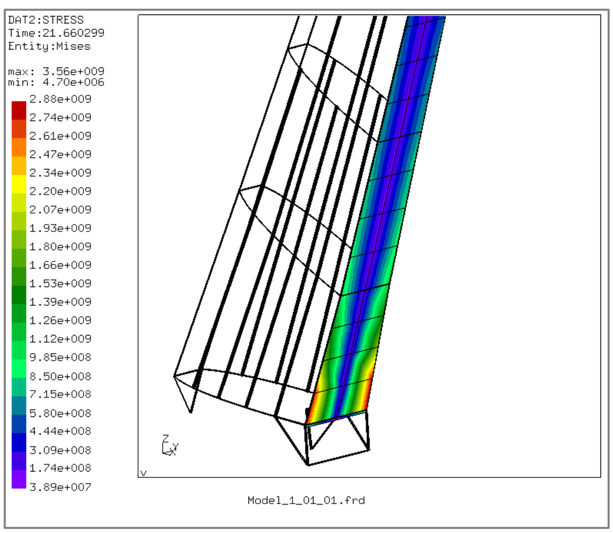


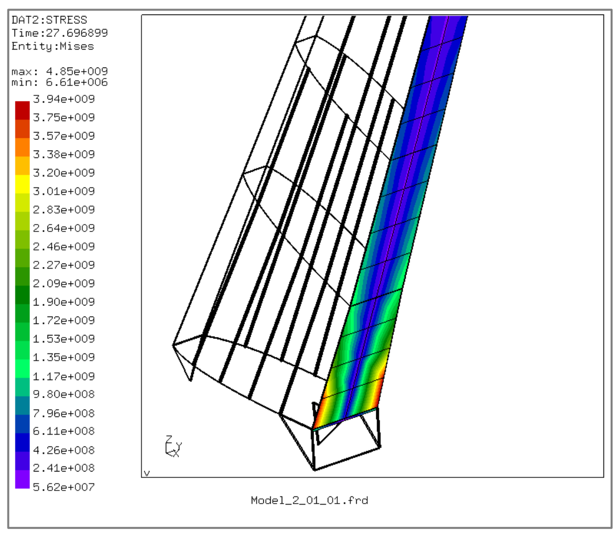


Nodal displacements for vertical tail

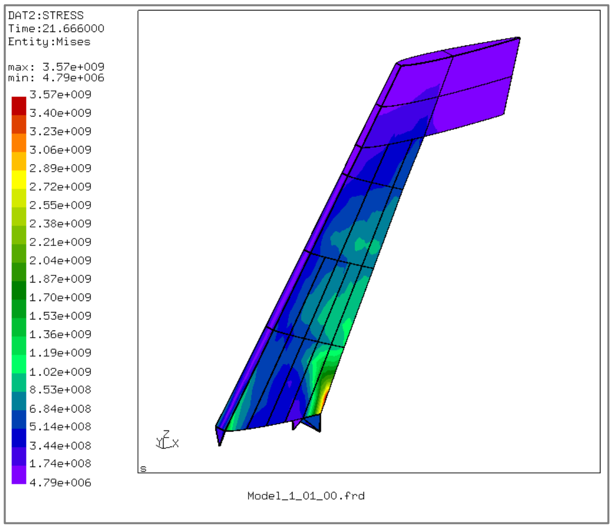
Figure 8. Nodal displacements

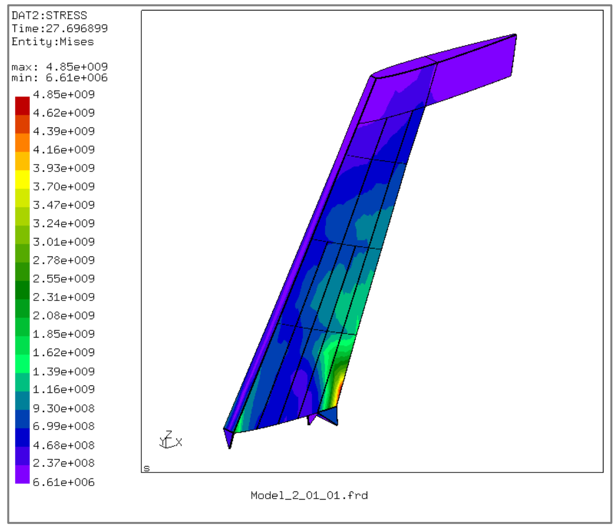
Model I.	**Model II.**





Von-Mises stresses for aft spar





Von-Mises stresses for vertical tail

Figure 9. Von-Mises stresses

To get correct validity of the computed results, buckling analysis for a stringer element was performed. The stringer was taken as a simple beam supported at both of its ends by ribs and was calculated by Euler's formula for buckling. This was then compared with the analytical results from CalculiX.

4 Conclusions

One of the main reasons why the cut has been made on the vertical tail was to gain more maneuverability for side turns, in yawing motion. The characteristics of stability however should be concluded in more details after a trade-off study of the static and dynamic analysis.

For both models, the buckling factor was more than the limit value for buckling therefore the one can conclude that no buckling occurs to the structure with the defined loadings and boundary conditions.

The FEA revealed that the nodal displacements compared to each other have very small difference in case of the two models. The displacements for the model with smaller surface area (Figure 8.) are higher. The same can be said about the stresses, the Von-Mises stress distribution shows slightly higher values for Model II (Figure 9.). This is due to the fact that the shorter tail has to withstand the same loading as for Model I.

The second model, after the shortening of the vertical tail has been made, appeared to be safe from structural point of view. Further static and dynamic analysis of the vertical tail is suggested to be performed. Although the analysis was completed manually, the study shows a possible example of how a multidisciplinary technique can be used for the preliminary design of vertical tail-box structure.

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