ANALYSIS OF BUCKLING AND STRUCTURAL OPTIMIZATION OF LOW-PRESSURE TURBINE CASING FOR A CIVIL AIRPLANE ENGINE

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The low-pressure turbine casing

Example of turbofan engine

Low-pressure turbine casing
Casing properties and functions

The casing is a large complex part, realized by forging or casting, followed by a machining to realize the particular shape of the inner profile.

Among its functions, the main ones are:
- to **Maintain** the stators and the shrouds in correspondence of the rotors by inner circular rails;
- to **Contain**: it must not fracture in case of blade detachment, hurled from the turbine centrifugal force towards the outside;
- to **Withstand** engine thermal stresses and to **Transmit** thrust-loads to the flanges that fixed it to other turbine parts (Center-Frame and Rear-Frame).
The buckling collapse

- The low-pressure turbine casing is a thin curved wall structure constituted by a single material. Given the possible distributed load presence on the thin wall, the buckling analysis is therefore necessary. The buckling is a particular type of collapse immediate and catastrophic.

Examples of buckling collapse of a cylindrical shell under simple load-cases: distribution of axial load and torsional moment.
The chosen material

- We assume the material linear, homogeneous and elastic

- We simplify the problem supposing null the gradient of axial and radial temperature, reporting us to the characteristics of Waspalloy material at the temperature of 1000°F:

We will work only searching THE LINEAR SOLUTION OF FIRST ORDER BUCKLING COLLAPSE, that linearly depend on the module of elasticity.

<table>
<thead>
<tr>
<th>Material: WASPALLOY 4455</th>
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</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>$E = 2.69E+07$ psi</td>
</tr>
<tr>
<td>$\nu = 0.3$</td>
</tr>
<tr>
<td>$\rho = 0.298 \text{ lb/inch}^3$</td>
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</tbody>
</table>
Principal aims of this work

- Develop the FEM-model in MSC-PATRAN and calculate, with the working load condition, the collapse buckling factor defined by:

\[
buckling \text{ collapse factor } f = \frac{\text{critical buckling load}}{\text{effective load applied}}
\]

- Discretize and parameterize the shape of the casing cross-section, choosing the thickness variables to define the complete geometry and run the optimization process. The multi-objectives optimization is aimed to:
  - minimize the casing weight;
  - maximize the collapse buckling factor.

- Implement a Robust Design process to include the manufacturing tolerance effect on the structural optimization.
FEM-model choices

Starting from the cross section geometry, attention has been focalized on a casing portion:

The external shell has been meshed by bi-dimensional elements SHELL Quad4 revolving the cross-section centre line; we choose an uniform mesh for all the SHELLs of the structure;

Each rail has been meshed by one-dimensional BEAM elements CBAR, on the circle born from the complete revolution of barycentre around the engine-axis;

The connection between BEAM and SHELL has been simulated by MPC elements that reproduce the rigid link between every node of beam and it’s correspondent image of the shear centre on external shell.

After the parameterization of the cross-section by fillet approximations, we cut to separate the rails (BEAMs) from the SHELL, and then we discretize it and trace the casing centre-line.
**FEM-model choices and load-case**

We resume the peculiarities of FEM-model in the following figure:

We have also modelled the TCF, to simulate the stiffness of the part and to assure the circularity.

The rear flange of the casing has been considered fixed.

The worst working load case has been applied on the front flange of the casing by elements MPC to allow the distribution of the load from a node put on engine axis.

The connection between TCF and casing flanges has been obtained merging the corresponding nodes.
1. Preliminary statistical analysis by DOE (Design of Experiment)

2. First optimization by Multi-Objective Genetic Algorithm (MOGA)

3. Refining optimization by mathematical (gradient) algorithm (BFGS)

The hybrid optimization process chosen is subdivided in 3 steps:

1. Post processing
2. Pareto Frontier visualization and choice of optimized "best designs"
3. Selection of "best designs" for beginning Population of successive optimization

We obtain the final solution: Optimum of Pareto

The principal aim of this work is the optimization of the casing geometry in order to reduce the structural weight, increasing the resistance to the buckling collapse.

We will use the FEM model choosing opportune some geometric parameters, to define the design-space of possible geometric cross-section shapes.

We operate the optimization under the worst load case chosen between the estimated work conditions.

FEM-MODEL: worst load case
NASTRAN-PATRAN results:
Buckling collapse factor = 1,772
Weight = 269,4 lb

We operate the optimization under the worst load case chosen between the estimated work conditions.
The casing parameterization

The shape of cross-section is parameterized by the 7 thicknesses of the casing zones in correspondence of the rotors; in order to guarantee the containment, the stator zones thicknesses must be equal to the maximum between the 2 value of contiguous rotor zone thicknesses.
**INPUT DATA:**
- Variables—thicknesses to parameterize all the casing shape

**Choice of successive input design by optimizing algorithm or random sequence**

**NASTRAN analysis execution**

**Objectives evaluation**

**OUTPUT variables:**
- Buckling collapse factor and casing weight

**Optimization process on the Mode-Frontier flow chart**

**Optimization core engine:**
- SCRIPT-UNIX able to:
  - export to the CLUSTER-AVIO the input files;
  - run NASTRAN analysis;
  - import the output files.

**SCHEDULER:** to choose optimization algorithm

**DOE:** Design Of Experiment:
- Beginning Population of the entire optimization process

**Input-files**

**First level parameters (VARs):** rotor-zones thicknesses

**Second level parameters (VARSTATs):** stator-zones thicknesses

**Other parameters:** guarantee all the geometric boundaries due to interfaces geometric limitation

Young Modulus: here considered constant; knowing the thermal-map we could change them to simulate the dependence by temperature
1. Preliminary statistical analysis by DOE (Design of Experiment)

DOE (Design Of Experiment)

By the initial geometry, represented by a point of the DESIGN SPACE, we obtain a couple of values (factor and weight) or a point of FEASIBLE REGION. The aim of the hybrid optimization process is to identify the best casing geometry that minimizes the weight and maximizes the buckling collapse factor. The point which represents the couple of solution will move toward the Pareto Frontier.

The DOE start from a random design distribution and spreads the solution on the FEASIBLE REGION. Solutions chosen to take part to the MOGA Beginning Population.
2. First optimization by Multi-Objective Genetic Algorithm (MOGA)

MOGA (Multi-Objective Genetic Algorithm)

Weight history chart

Buckling collapse factor history chart
The BFGS is a mathematical gradient algorithm of Quasi-Newtonian type that optimize only one objective. We impose as a constraint the objective to maximize the Buckling collapse factor.

Refining optimization by mathematical (gradient) algorithm (BFGS)

Broyden Fanno Fletcher Goldfarb Shanno algorithm

Lower limit of admitted buckling factor: the BFGS solutions under that value are unfeasible.

Value choice: 1,845
Evolution of optimization on the Correlation Matrix and on the Pareto Chart

The Correlation Matrix is a measure of dependence between 2 variables: if $r = 1$ it means that 2 variables are perfectly correlated, with correspondence of module and sign. We see on the DOE Correlation Matrix the high dependence between buckling collapse factor and THICK2. During the MOGA the dependence of weight from variables-thicknesses is more sensible. The BFGS algorithm operate to minimize the weight, maintaining the buckling collapse factor over a constraint value. On Correlation Matrix we can see the increasing influence of THICK8, THICK10 and THICK16 values on weight solution.
Optimizing solution

<table>
<thead>
<tr>
<th></th>
<th>THICK1</th>
<th>THICK2</th>
<th>THICK4</th>
<th>THICK8</th>
<th>THICK10</th>
<th>THICK12</th>
<th>THICK16</th>
<th>factor</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>before optimization</td>
<td>0.144</td>
<td>0.080</td>
<td>0.080</td>
<td>0.068</td>
<td>0.109</td>
<td>0.104</td>
<td>0.080</td>
<td>1.77187</td>
<td>286.4002</td>
</tr>
<tr>
<td>after optimization</td>
<td>0.140</td>
<td>0.113</td>
<td>0.065</td>
<td>0.085</td>
<td>0.100</td>
<td>0.065</td>
<td>0.065</td>
<td>1.85629</td>
<td>285.4165</td>
</tr>
<tr>
<td>delta</td>
<td>-0.004</td>
<td>0.033</td>
<td>-0.015</td>
<td>-0.013</td>
<td>-0.009</td>
<td>-0.039</td>
<td>-0.015</td>
<td>0.08442</td>
<td>-3.9837</td>
</tr>
<tr>
<td>delta %</td>
<td>-2.857</td>
<td>29.20354</td>
<td>-18.75</td>
<td>-13.2653</td>
<td>-8.25688</td>
<td>-37.5</td>
<td>-18.75</td>
<td>4.547781</td>
<td>-1.50092</td>
</tr>
</tbody>
</table>

The optimization has increased THICK2: this variable governs the geometry of the casing cross-section in the zone where is observable the calculated and visualized buckling collapse by NASTRAN-PATRAN.

After the hybrid optimization we find a solution that increase the factor of 4.55% and diminish the weight of 1.5%.
ROBUST DESIGN

- The optimization obtained without considering the working tolerances furnishes an ‘IDEAL’ optimal cross-section shape.

- During this work we have coupled an analysis that considers the working tolerances conditioning the part feasibility to the proposed process of structural optimization: such search process aimed to obtain the casing OPTIMAL FEASIBLE CONFIGURATION, or Robust Design.

- The working tolerances have been chosen in conservative way by symmetrical deviation of:

  \[ toll = \pm 0.005 \text{ inch} \]

- From a qualitative point of view, we will assume that the casing working methods are so precise to realize 95.46% of production with thicknesses values comprised around the nominal value by an interval of amplitude:

  \[ 0.0025 \text{ inch} \]

- The condition over described produced the application to the working process of a quality level equal to:

  \[ 2 \sigma \text{-level} \]
Robust Design on Response Surfaces

- Given an input parameters system perturbed near a chosen configuration, we obtain a series of output values. If we impose a statistic distribution to the values taken around of each input variable, estimating the answers we obtain a series of output values characterized also by a statistic distribution.
- Analyzing the mean and the standard deviation we will be able to measure the robustness of the solution.

Distributions evaluated on a virtual output variables space, APPROXIMATED by RESPONSE SURFACES (build by the Kriging algorithm)

DISTRIBUTION of solutions of buckling collapse factors

DISTRIBUTION of solutions of casing weight
1° Robust Design strategy: MONTE CARLO SAMPLING

- We leave from the solution, coming from the previous optimization and perturb its thickness configuration by a Monte Carlo distribution of standard deviation 0.0025 inch. So we search a more robust solution on the mean values of results.

- We obtain the following distributions:

<table>
<thead>
<tr>
<th>factor</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>before optimization</td>
<td>1.77187</td>
</tr>
<tr>
<td>after optimization: beginning of Robust Design Monte Carlo</td>
<td>1.85629</td>
</tr>
</tbody>
</table>

mean value at the end of Robust Design Monte Carlo: 1.8451, 268.59

std. deviation at the end of Robust Design Monte Carlo: 0.02661, 6.3642

delta respect the solution before optimization: 0.07323, -0.8102

delta % respect the solution before optimization: 3.944965, -0.30526
Robust Design strategy: MORDO

(Multi Objective Robust Design Optimization)

- We leave perturbing the entire domain of the first level variables, allowing the algorithm to converge towards the solution that assures:
  - Maximum mean value of the buckling collapse factor
  - Minimum mean value of the weight
  - Minimal standard deviation

The standard deviations are less than the others obtained by Monte Carlo Robust Design: the MORDO solution is the most robust.

The solution will be the output distribution nearest of the Pareto Frontier.

Results after MORDO

<table>
<thead>
<tr>
<th></th>
<th>factor [b]</th>
<th>weight [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>before optimization</td>
<td>1.77187</td>
<td>269.4002</td>
</tr>
<tr>
<td>after optimization</td>
<td>1.85029</td>
<td>265.4165</td>
</tr>
</tbody>
</table>

Mean value at the end of MORDO: 1.85813 266.682
Conclusions

Purposes of the optimization procedure:

- The FEM MODEL was created in a semi-automatic way, discretizing the casing and mapping its cross-section envelope of thicknesses.

- The same procedure will be applied to more complicate buckling problems: the versatility of chosen FRONTIER inputs let to introduce the elastic modulus at working temperature on rails, and in the future the stator blades forces.

- This process is satisfactory elastic in the choice of parameters and immediate in the transmission of data results from other optimization procedures, and so it’s possible to use it to generate automatically computational models, for simultaneous uses for many disciplines involved.

- The process of optimization realized, guarantees an ELEVATE LEVEL OF ACCURACY, and want to take a part in a MULTI-DISCIPLINARY optimization context.
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THANKS FOR YOUR ATTENTION.

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