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Integrated Multiphysics Simulation & Design Optimization

An Open Database Workshop for Multiphysics Software Validation

University of Jyväskylä, March 10-12, 2010

http://jucri.jyu.fi

UNIVERSITY OF JYVÄSKYLÄ

SCOMA CENTER

Tekes

Computation results for academic optimization test cases
are gathered from authorized contributors
and will be presented at the

An Open Database Workshop for Multiphysics Software Validation

**organized at the University of Jyväskylä, Agora
in March 10-12, 2010.**

Organized by **the SCOMA Center, University of Jyväskylä,**
in association with **CSC, VTT, Stanford / MIT
Consortium for Multidisciplinary System Design
and University of Houston, College of Technology**

Sponsored by **TEKES FIDIPRO PROGRAM**

More information about the test cases: **http://jucri.jyu.fi/**

More information about the workshop:
http://www.mit.jyu.fi/scoma/DBW2010/

Database Workshops

The Integrated Multiphysics Design Database was launched last March 2009 to provide a computational tool for the general evaluation of uncertainties and a reference with useful validation guidelines for future products in the area of multidisciplinary design optimization. The database makes possible the evaluation of both the efficiency and the robustness of innovative software via comparison of existing computational and experimental data.The database will incorporate optimization test cases from a variety of areas including telecommunications, aerospace, energy, environmental engineering, biomechanics and medicine, and computational science. The database is hosted by the University of Jyväskylä in Finland with a mirror site at the University of Houston.

Two events, one upstream and other more downstream, are scheduled on to engage and involve the worldwide scientific and technological community. The Preparatory Database Workshop held on December 3rd and 4th, 2009, in Jyväskylä, Finland was concerned with the presentation and analysis of academic optimization test cases. The second event which also will be held at the University of Jyväskylä is entitled the Industrial and Academic Database Workshop. This Workshop, held on March 10th–12th, 2010, will be concerned with the presentation and analysis of industrial as well as academic test cases.

Industrial and Academic test cases will be presented during the spring of 2010 in conjunction with a Tekes DESIGN event entitled "Database Workshop for Multiphysics Software Validation".

Objectives of the Database Workshop

- Propose to the scientific/industrial community involved in Design and Control problems, test case analysis and optimization problems for multiphysics software validation.
- Gather a forum of international experts for evaluating by comparison of computerized data the efficiency and robustness of existing and new multidiscipline optimization software without and with uncertainties on selected test cases installed on a synchronized Finnish and US Database.
- Provide industry and society reference test cases for validation of advanced software used to design their new digital complex products.
- Identify collaborative areas requiring additional R&D in Multi-criteria / Multidisciplinary Design Optimization.

The announcement introducing Database Workshop with the definition of optimization test cases is available on the website:

http://jucri.jyu.fi

Contributing to the Database

The Design Test Case Database is available at http://jucri.jyu.fi. A series of MDO test case descriptions provided by industrial and academic experts can be found on the site mentioned above. The definitions are prepared in such a way that interested parties can test their own tools and methods in solving these test cases.

If you are a researcher or a professional in the field of multidisciplinary optimization and interested in becoming a contributor to the database, please go to the website and follow the instructions. Your application will be processed by the administrators and you will be contacted shortly with further details, including specific details on requested data formats for the computational results as determined by the test case chairmen.

File Formats

We are planning to use **ParaView** as the primary tool for creating visualizations of data submitted to the database. Same tool is to be used in Workshop presentations. ParaView is an open-source, multi-platform data analysis and visualization application based on **Visualization Toolkit (VTK)**.

Due to choice of visualization software, we encourage using ParaView compatible file formats for your submissions. Especially the native XML-based VTK format is recommended. A detailed specification of the VTK file formats can be found at their website. Information on other supported 3D file formats are available in the **ParaView wiki**.

For simple data sets (intended for 2D plots etc.) submissions in CSV or whitespace delimited formats are recommended.

We also accept submissions in text format if the required information is provided:

- For mesh files, mesh node coordinates and element data values
- For data arrays, coordinates and values

Please use whitespace for separating values. Refer to example files at http://jucri.jyu.fi/?q=node/41 for details.

If your software produces other file formats or you have any questions please contact us (http://jucri.jyu.fi).

Related links:

- Paraview: http://www.paraview.org/
- VTK: http://www.vtk.org/
- VTK File Format specification: http://www.vtk.org/VTK/img/file-formats.pdf

NB: **The academic test cases are marked with TA and industrial test cases are marked TI.**

TA1 A numerical set-up for benchmarking and optimization of fluid-structure interaction

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Keywords:
Discretization techniques, robustness of solver, lift/drag optimization, FSI

Introduction:
The main purpose of this benchmark proposal is to describe specific configurations which shall help in future to test and to compare different numerical methods and code implementations for the fluid-structure interaction (FSI) problem which can be additionally coupled with an additional optimization procedure. In particular, the various coupling mechanisms, ranging from partitioned, weakly coupled approaches to fully coupled, monolithic schemes are of high interest for the FSI community. Moreover, the settings allow to examine the quality of different discretization schemes (FEM, FV, FD, LBM, resp., beam, shell, volume elements), and the robustness and numerical efficiency of the integrated solver components is a further aspect. This FSI benchmark is based on an older successful 'flow around cylinder' benchmark for incompressible laminar fluid flow. Similar to this older configuration we consider the flow to be incompressible and in the laminar regime. The structure is allowed to be compressible, and the deformations of the structure should be significant. The overall setup of the interaction problem is such that the solid object with elastic part is submerged in a channel flow. Then, self induced oscillations in the fluid and the deformable part of the structure are obtained so that characteristic physical quantities and plots for the time-dependent results can be provided in a rigorous way. Furthermore, these FSI configurations can be extended towards optimal control of body forces acting on and deformations of the elastic object in which case additional outer inflow/outflow regions control the optimal result.

Objectives:
Objective of this benchmarking scenario is to test and compare different numerical approaches for fluid-structure interaction and code implementations qualitatively and particularly quantitatively with respect to efficiency and accuracy of the computation and to extend these validated configurations to optimization problems such that minimum drag/lift of the elastic object, minimal pressure loss or minimal nonstationary oscillations through boundary control of the inflow, change of geometry or optimal control of volume forces can be reached.

Requirements:
Meshing, FSI solver and optimizer software, 2D, laminar regime

Computational domain:

The domain is shown in the figures below. Details can be found at the website : http://jucri.jyu.fi/?q=node/14.

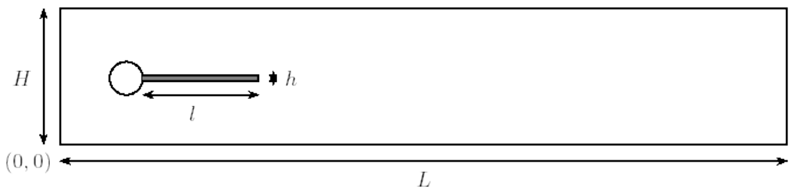
Geometry parameters:

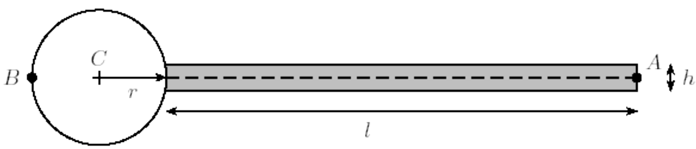
Table 1. Overview of the geometry parameters.

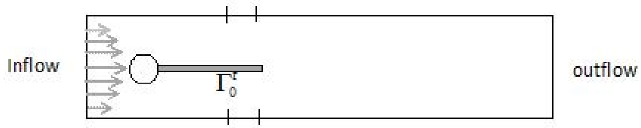
geometry parameters		value [m]
channel length	L	2.5
channel width	H	0.41
cylinder center position	C	(0.2, 0.2)
cylinder radius	r	0.05
elastic structure length	l	0.35
elastic structure thickness	h	0.02
reference point (at $t = \mathbf{0}$)	A	(0.6, 0.2)
reference point	B	(0.15, 0.2)

- The setting is intentionally non-symmetric to prevent the dependence of the onset of any possible oscillation on the precision of the computation.
- By omitting the elastic bar attached with the cylinder one can exactly recover the setup of the well known 'flow around cylinder' benchmark configuration which can be used for validating the CFD part.
- The control points are $A(t)$, fixed with the structure with $A(\mathbf{0}) = (\mathbf{0.6}, \mathbf{0.2})$, and $B = (\mathbf{0.15}, \mathbf{0.2})$.

Illustration of the computational domain:







Modeling: physical properties:
- incompressible Newtonian fluid (Navier-Stokes)
- elastic compressible solid (St. Venant-Kirchhoff material)
- see attached papers for more details at the website: http://jucri.jyu.fi/?q=node/14

Table 2. Material combination.

parameter	FSI1	FSI2	FSI3
$\beta = \frac{\rho^s}{\rho^f}\left[10^3 \frac{\mathrm{kg}}{\mathrm{m}^3}\right]$	1	1	1
ν^s	0.4	0.4	0.4
$Ae = \frac{E^s}{\rho^f \overline{U}^2}$	3.5×10^4	1.4×10^3	1.4×10^3
$Re = \frac{\overline{U} d}{\nu^f}$	20	100	200
$\overline{U}\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	0.2	1	2

Boundary and/or initial conditions for computations:

Boundary conditions:
- A parabolic velocity profile is prescribed at the left channel inflow

$$\nu^f(0, y) = 1.5\overline{U}\frac{y(H-y)}{\left(\frac{H}{2}\right)^2} = 1.5\overline{U}\frac{4.0}{0.1681}y(0.41-y)$$

  such that the mean inflow velocity is $\overline{U}$ and the maximum of the inflow velocity is $1.5\overline{U}$.
- The outflow condition can be chosen by the user, for example *stress free* or *do nothing* conditions.
- The *no-slip* condition is prescribed for the fluid on the other boundary parts i.e. top and bottom wall, circle and fluid structure interface Γ_t^0

Initial conditions:
Suggested starting procedure for the non-steady tests is to use a smooth increase of the velocity profile in time

Optimization:
Lift reduction under variation of geometrical design variables and boundary control.

Design parameters:
- Boundary control

Objective function definition:
minimize $(lift^2 + \alpha \| V^2 \|)$ (definition of lift see attached papers on the website: http://jucri.jyu.fi/?q=node/14) w.r.t V_1 velocity from top and V_2 velocity from bottom (parabolic), where $V = (V_1, V_2)$ is from $x \in (0.45, 0.6)$ and $\alpha = 1, 10^{-2}, 10^{-4}, 10^{-6}$ for tests.

Results:

Quantities of interest
- The results should be presented for three mesh levels in a table.
- The position of the end of the structure, displacement in x- and y- directons, drag and lift, V_1 and V_2 and additionally the number of equations, number of iterations, and CPU time.
- Forces exerted by the fluid on the whole body (lift and drag forces acting on the cylinder and the structure together).
- Frequency and maximum amplitude (for nonstationary tests)

1st step:
Stationary results without and with optimization:
- Produce results for CFD1, CSM1 (see attached pdf fileat the website: http://jucri.jyu.fi/?q=node/14).
- Calculate FSI1.
- CalculateFSI1+Opt, which tries to find a configuration with minimum lift value in case of optimization (see table of example 1 in ppt file attached at the website: http://jucri.jyu.fi/?q=node/14).

2nd step:
Nonstationary results without optimization:
- Produce results for CFD2/3, CSM2/3 (see attached pdf file at the website: http://jucri.jyu.fi/?q=node/14).
- Apply your code on FSI2 and FSI3.

Suggestions:
- Validate your code for CFD1-3, CSM1-3 without fluid structure interaction.
- Validate your code for FSI1and FSI1+Opt with optimization (see table of example 1 in ppt file attached at the website: http://jucri.jyu.fi/?q=node/14).
- Send us results for FSI1+Opt until fall.

Link: http://jucri.jyu.fi/?q=node/14

TA2 Inverse or optimization problems for multiple (ellipse) ellipsoid configurations

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Keywords: inverse problems, shape recovery, CFD, electromagnetics, acoustics

Introduction:
This academic test case was developed in order to study algorithmic convergence by splitting the inverse problem (recovery of target pressure on the surface) into smaller subproblems. It also provides a way to study the behaviour of algorithms with meshes of different quality. Finally, it can be expanded into a simple test platform for multiphysics optimization (computational fluid dynamics, computational electromagnetism, and aeroacoustics), both in 2D and 3D.

Objectives:
Aerodynamic reconstruction problem
Recovery of the original position of two ellipses (2D) or ellipsoids (3D) using potential, Euler, or Navier-Stokes flows for Re = 100 and Re = 500.

Radar wave problem
Reconstruction of the original position of the ellipses/ellipsoids using radar cross section with perfectly conducting material.

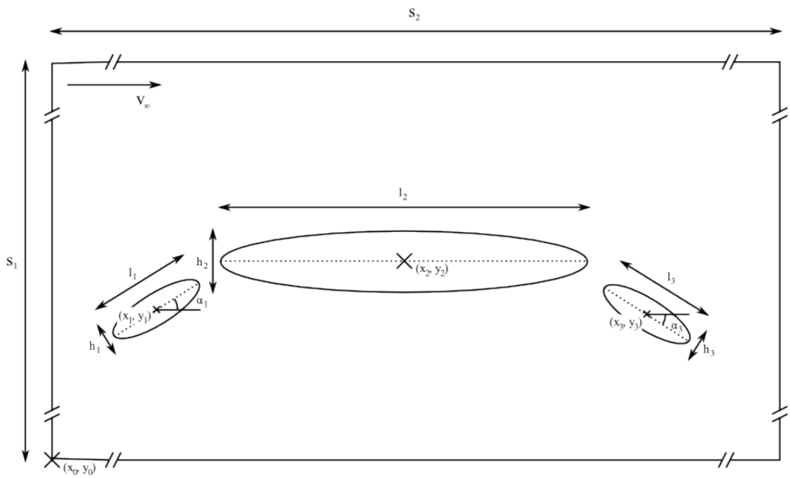
Acoustics problem:
Reconstruction of the original position of the ellipses/ellipsoids using acoustic waves.

Requirements: Navier-Stokes solver, Maxwell solver, acoustics solver, mesher

Computational domain: See the figure for the 2D case.

$s_1 = s_3$	=	**40**	height (and width) of the bounding box (aerodynamic reconstruction problem)
	=	**20**	height (and width) of the bounding box (radar wave problem)
s_2	=	**80**	length of the bounding box (aerodynamic reconstruction problem)
	=	**30**	length of the bounding box (radar wave problem)
(x_0, y_0, z_0)	=	**(–30, –20, –20)**	front lower left corner of the bounding box (aerodynamic reconstruction problem)
	=	**(–15, –10, –10)**	front lower left corner of the bounding box
l_1	=	**2.0**	length of the ellipse/ellipsoid 1
h_1, w_1	=	**0.5**	height (and width) of the ellipse/ellipsoid 1
(x_1, y_1, z_1)	=	**(–7.0, –0.5, 0,0)**	reference position of the ellipse/ellipsoid 1
α_1	=	**–30°**	reference angle of the ellipse/ellipsoid 1 (clockwise)
l_2	=	**10.0**	length of the ellipse/ellipsoid 2
h_2, w_2	=	**10**	height (and width) of the ellipse/ellipsoid 2
(x_2, y_2, z_2)	=	**(0.0, 0.0, 0.0)**	position of the ellipse/ellipsoid 2
α_2	=	**0.0°**	angle of the ellipse/ellipsoid 2
l_3	=	**3.5**	length of the ellipse/ellipsoid 3
h_3, w_3	=	**05**	height (and width) of the ellipse/ellipsoid 3
(x_3, y_3, z_3)	=	**(75–0500)**	reference position of the ellipse/ellipsoid 3
α_3	=	**30°**	reference angle of the ellipse/ellipsoid 3 (clockwise)

Illustration of the computational domain:



Modeling: physical properties:
Aerodynamic reconstruction problem

- Incompressible fluid (Navier-Stokes laminar flow).
- Kinematic viscosity $\nu = \dfrac{1}{10}$ or $\nu = \dfrac{1}{50}$.

Reynolds number $Re = \frac{v_\infty l_2}{\nu} \to Re = 100$ or $Re = 500$

Radar wave/acoustics problem
- density $\rho = 1$
- Radar wave $f = 0.6$ GHz => $\lambda = 0.5$ m
- Acoustics wave $\lambda = 0.5$ m

Boundary and/or initial conditions for computations:

Aerodynamic reconstruction problem
- Upstream entrance: $v_x = \cos(\alpha)$, $v_y = \sin(\alpha)$, angle of attack $\alpha = 5{,}0^{\circ}$
- Downstream exit: free boundary conditions
- Ellipse/ellipsoid surface: no-slip condition

Radar wave/acoustics problem
- Monostatic radar
- Angle of radar illumination $0°$
- Outer boundary: absorbing boundary condition at infinity (Enquist)
- Ellipse surface: perfectly conducting material

Material Parameters:

- Fluid

Optimization:

Aerodynamic reconstruction problem: Reconstruction of the target pressure on the surfaces of the ellipses.
Radar wave/acoustics problem: Recovery of the target radar cross section/scattering cross section.

The target vector is:
$x^* = \{x_1, y_1, \alpha_1, y_3, y_3, \alpha_3\} = \{\mathbf{-7.0, -0.5, -3.0}\,^{\mathbf{o}}, \mathbf{7.5, -0.5, 3.0}\,^{\mathbf{o}}\}$.

Design parameters:

−10.0	$\leq$	x_1	$\leq$	**−6,5**	position of the ellipse 1
−1.5	$\leq$	y_1	$\leq$	**0.0**	
−10.0 º	$\leq$	α_1	$\leq$	**0.0 º**	clockwise angle of the ellipse 1
7,25	$\leq$	x_3	$\leq$	**10.0**	position of the ellipse 3
−1,5	$\leq$	y_3	$\leq$	**0.0**	
0.0 º	$\leq$	α_3	$\leq$	**10.0 º**	clockwise angle of the ellipse 3

In addition, the ellipses/ellipsoids must not be overlapping.

Objective function definition:
Aerodynamic reconstruction problem

$$\min f = f_1 + f_2 + f_3$$

where f is the L^2 error norm of the surface pressure:

$$f_1 = \int_{\Gamma_1} | p_1 - p_1^* |^2$$
$$f_2 = \int_{\Gamma_2} | p_2 - p_2^* |^2$$
$$f_3 = \int_{\Gamma_3} | p_3 - p_3^* |^2$$

where p_i is the current pressure and p_i^* the target pressure on the surface of the ellipse i.

Radar wave problem:

$$\min \int_{\Theta} | u_\infty - u_\infty^* |^2 d\Theta$$

where Θ is the direction of the reflected wave, u_∞ and u_∞^* are the far field patterns for the computed case and the target, respectively.

Results:

- Target mesh and the mesh of the best solution in ParaView compatible format
- Target geometry compared to the best solution (list of boundary point coordinates)
- The optimized design variable values
- Aerodynamic reconstruction problem:
    - Pressure coefficient of the target compared to the best solution (list of points)
    - Pressure and velocity fields of the target and the best solution in ParaView compatible format
- Radar wave/acoustics problem:
    - Radar cross section/scattering cross section of the best solution compared to the target (list of values from 0° to 360°)
    - Scatter field of the target and the best solution (imaginary and real component) in ParaView compatible format
- For the tested algorithms the averaged convergence of the tested algorithms over 10 runs is required (a table of the increasing number of fitness evaluations on the first column, objective function values on the second column)
- In addition, the following information is needed:
    - Mean final value
    - Standard deviation of the final values
    - Minimum final value
    - Maximum final value
    - Average number of fitness calculations required

Link: http://jucri.jyu.fi/?q=node/5

TA3 Numerical investigation of two dimensional flow over Darrieus-type wind turbine

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Keywords: Darrieus, turbulent flow, turbine

Introduction:
Vertical axis wind turbines (VAWTs) offer an alternative way of exploiting wind energy over conventional horizontal axis wind turbines (HAWTs). Currently, HAWTs are regarded more efficient. However, aerodynamics of a VAWT differ considerably from those of a HAWT.

The goal is to solve the relevant flow equations in two dimensions when the turbine is rotating at a specified rpm in given wind conditions. Careful considerations must be made regarding the turbine operating conditions. At low tip speed ratios dynamic stall complicates the analysis. In cases A and B parameters are chosen such a way that the airfoil does not enter stall conditions. Optionally, variable blade pitch can be considered.

Objectives:
The main objective is to determine the torque and work done by a traditional, circular Darrieus-type turbine in conditions specified hereafter. An optional goal is to maximize the work done by the VAWT during a single revolution for fixed wind conditions (V), angular velocity ω, radius R and blade number N. For the optimization problem, airfoil thickness t and chord length c defining the airfoil geometry and pitching angle are used as design parameters .

Requirements:
Two dimensional Navier-Stokes flow solver with a turbulence model.

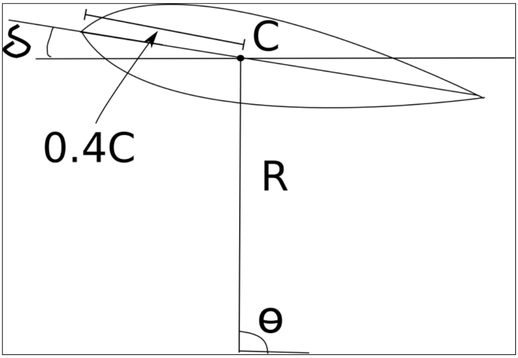
Computational domain:
The rectangular computational domain is illustrated below.

The coordinates of the turbine center (x2,y2) are
x2= 7.5 m
y2= 30 m

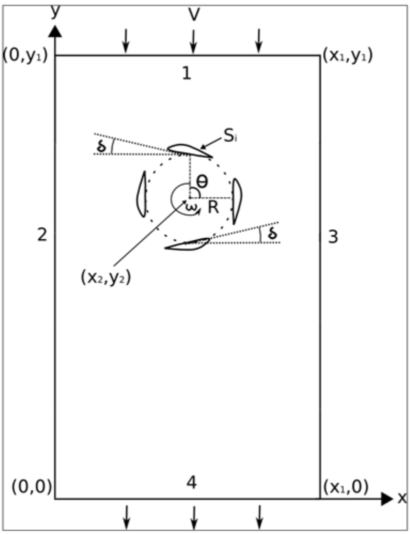
The coordinates specifying the domain size are
x1= 25 m
y1= 50 m

The airfoil used is a symmetric NACA00xx -series airfoil, a typical choice for Darrieus type turbines. The sinusoidally varying pitching angle δ defined negative inwards and positive outwards with respect to circle tangent. The radius tip from the origin to the airfoil is attached to a point 0.4 chord lengths from the blade tip to a point located on the chord line.

Illustration of computational domain:



Airfoil attachment



Computational Domain
Modeling: physical properties:

Incompressible turbulent flow of air.
Number of blades: 1 or 4 (symmetrical arrangement)

Airfoil: symmetric NACA00xx airfoil defined below:

$$y = c\frac{t}{0.2}\left[0.2969 \times \sqrt{\frac{x}{c}} - 0.1260\left(\frac{x}{c}\right) - 0.3516\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4\right],$$

xx = percentage of thickness to chord length.
y defines the airfoil upper surface equation.

c is the chord length.

t is the maximum airfoil thickness as a fraction of the chord *c*.

Property	Value A (Realistic)	Value B (default)	Value C (dynamic stall)
Kinematic viscosity (ν) [m^2/s]	1.3e-5	4.04e-5	4.04e-5
Chord length (c) [m]	0.120 m	0.120 m	0.120 m
Thickness (t)	0.12	0.12	0.12
Pitching amplitude a1,a2	0	0	0
Radius (R) [m]	2.5 m	2.5 m	2.5 m
Pressure (p) [atm]	1	1	1
Free stream velocity (V) [m/s]	(0,-7)	(0,-7)	(0,-7)
Angular velocity (w) [1/s]	16.8	18.76	8.4
Reynolds number ($Re=2RV/\nu$)	2.7e6	8.66e5	8.66e5
Tip speed ratio ($\lambda = \omega R/V$)	6	6.7	3

Boundary and/or initial conditions for computations:

No slip at blade surface:
(u=0,v=0)
V = (0, -7) m/s at boundaries 1, 2 and 3.
Outflow conditions at boundary 4

Initial condition: Steady state solution (θ= 0)

Material Parameters:
Fluid

Optimization:
Work maximization under variation of airfoil shape or pitching angle.

$max(\Sigma_i W_i)$

Design parameters:

Property	Minimum	Initial	Maximum
Chord length (c) [m]	0.100	0,120	0.140
Airfoil thickness (t)	0.09	0.120	0.26
Pitching angle (a1,a2)	0	0	10

Objective function definition:

$max(\Sigma_i W_i)$

Results:

Force exerted by the fluid on the airfoil i:

$$\vec{F}_i(\theta) = \oint_{S_i} p \cdot d\vec{S} + \oint_{S_i} \vec{\vec{\tau}} \cdot d\vec{S}$$

where $\vec{\vec{\tau}}$ is the shear stress tensor.

Forces F_T and F_N are defined as the components of $\vec{F}$ projected on the tangent and normal of the circular blade trajectory, respectively.

Torque by blade i is defined as $T_i(\theta)=RF_T(\theta)$

Work done by blade i is defined as

$$W_i = \int_0^{2\pi} T_i(\theta) d\theta.$$

Pitching function is defined as

$\delta = a_1 sin\theta (0 < \theta < \pi)$

$\delta = a_2 sin\theta (\pi < \theta < 2\pi)$

Quantities of interest

Optimal thickness to chord length ratio.

Optimal pitching amplitude a_1, a_2.

Normal force $F_N(\theta)$ for every blade

Tangential force $F_T(\theta)$ for every blade

Total torque $T(\theta)$

θ =90, 180, 270:

Velocity field

Pressure field

Vorticity patterns

Link: http://jucri.jyu.fi/?q=node/19

TA4 Optimization of beam profile in fluid-structure interaction

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Keywords: Fluid-structure interaction, Elastic beam, Optimization

Introduction:

The test case combines fluid-structure interaction with optimization in a simple but effective way. The cost function is well defined, has a definate global minimum and its evaluation requires the solution of a strongly coupled fluid-structure interaction problem. The individual problems are easily solved while the coupled problem sets requirements to the efficient coupling of the different subproblems.

The one biggest challenge of the case is to find a surface presentation that allows sufficient freedom in design and also enables the use of efficient optimization techniques. The test case may be used to provide a reference solution for the verification of software components for multiphysical optimization problems. Even though the case itself is not realistic it may help in the development and testing of tools needed for industrial fluid-structure interaction problems.

Objectives:

The aim is to optimize the geometry of an elastic beam so that it bends as little as possible under the pressure and traction forces resulting from viscous incompressible flow. The profile of the beam has an effect both on the flow and the structural stiffness of the beam, respectively.

The case includes three different variations. The first case is fully linear and involves only one-directional coupling between the models. The linearity is achieved by neglecting the inertial forces in the Navier-Stokes equation, and by setting the beam to be so stiff that its bending is so small that its influence on the flow does not need to be taken into account. This also means that there is no geometric nonlinearities in the problem. The second variation increases the Reynolds number but the coupling is still one-directional. The third variation includes geometric nonlinearities in the elasticity equation, and nonlinearity resulting from the fluid-structure coupling. The optimum profile of the linear problem will not depend on any of the material parameters while in the nonlinear case the optimum profile will be parameter dependent.

Requirements:

- Incompressible Navier-Stokes solver for laminar flow
- Elasticity solver for large displacement
- Method to extent elastic deformarmation of the to the geometry of the fluid mesh
- Capability to solve fluid-structure-interaction problems

Computational domain:

- Rectangular domain of size **10 X 2**
- Standing beam (height = 1, total area = 0.3), the tip of the beam located at x = **2.5**

Illustration of the computational domain:

A possible initial geometry for the case

Modeling: physical properties:

Property	Case A	Case B	Case C
Density of fluid	$0\ kg/m^3$	$10\ kg/m^3$	$10\ kg/m^3$
Viscosity of fluid	$1\ m/s^2$	$1\ m/s^2$	$1\ m/s^2$
Young's modulus of structure	$1e9\ Pa$	$1e9\ Pa$	$2e4\ Pa$
Poisson ratio of structure	0.3	0.3	0.3

Boundary and/or initial conditions for computations:

Boundary conditions:

- Left-hand side boundary: inlet with mean velocity 1 and a parabolic inlet flow profile, $v_x = \frac{3}{2}y\,(2 - y)$
- Right-hand side boundary: outlet which vanishing traction component
- FSI-boundary: force equality
- Other boundaries: no-slip boundaries

Material Parameters:

- Solid
- Fluid

Optimization:

The goal is to optimize the shape of the left-hand side wall of the beam so that its height and area stay fixed. The width at the bottom may freely vary as long as the other constraints are met.

Design parameters:
The standing beam: height = 1, total area = 0.3. The left and right walls may be assumed to be smooth.

Objective function definition:
$f = \max(|u|)$

Results:
The different solutions may be compared to each other using 0D, 1D and 2D data. Below the different data for comparison is defined.

Scalar values:
- Maximum displacement on the beam at optimum
- Maximum displacement on the beam at rectangular shape
- Displacement reduction factor
- Area of the optimized beam
- Parametrization of the left wall pro file

Ideally the results are saved in a format which enables that the results are studied with the same software. For line plotting the natural format is a table where the columns represent different fields and the rows different nodes.

- The shape of the left side wall as a $[y ; x]$ table
- The displacement on the left side wall as $[y ; u_x]$ table
- The pressure on the left side wall as $[y ; p]$ table

Contour plots:
Ideally the results are saved in a format which enables that the results are compared within the same visualization software. For 2D the contour plots this format could be the VTK format (or its newer XML generalizations) that enable visualization with all VTK derived software such as Paraview.

- Contour plot of absolute velocity
- Contour plot of pressure
- Contour plot of displacement

Additional information:
The results may also discuss the different numerical methods and optimization algorithms used. For successful comparison this information is however, not required.

Link: http://jucri.jyu.fi/?q=node/8

TA5 Shock control bump optimization on a transonic laminar flow airfoil

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Keywords: Shock control bump, transonic flow, natural laminar flow airfoil

Introduction:
Reducing aircraft drag has a huge impact on reducing aviation emission, therefore, for greener air transport. Shock control bumps are effective in reducing the wave drag, a component of the total drag, at high subsonic or transonic speed range.

The challenges are: (1) to assure good accuracy of aerodynamic force calculation; (2) to assure high quality and consistant meshes for all the designs; (3) to find the global optimum.

The Navier-Stokes equations are to be solved and there are a large number of flow solvers. Comparison of the solution for the original airfoil flow forms a good starting point.

Objectives:
Drag reduction for transonic wings is crucial for the aeronautical industry, for control of aviation emission and operational efficiency. Shock control bumps were found to be effective in reducing the wave drag and the total drag if installed on transonic airfoils or wings. However, their effectiveness relies on the position, height, and size of the bumps. In this test case, we will look into the optimal design parameters for a given laminar flow airfoil, i.e. RAE5243 airfoil, at the design Mach number and Reynolds number. It will be divided into two cases: (1) fully turbulent flow; (2) fixed transition at 45%. The optimization will be constrained by the given lift condition.

Requirements:
- Navier-Stokes flow solver with turbulence modelling
- Optimization method with lift constraint

Computational domain:
Figures 1 and 2 here show the airfoil, the bump and its parameterisation. The computational domain is suggested to be 20 chord length away from the airfoil in all directions.

Illustration of the computational domain:

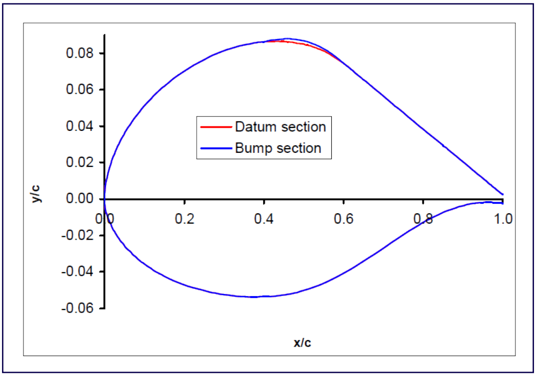

Figure 1. RAE5243 with shock control bump

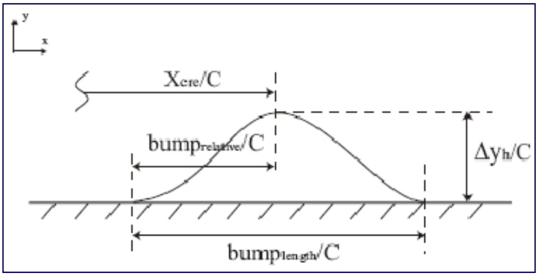

Figure 2. Bump design parameters

Modeling: physical properties:

- Air as perfect gas
- Laminar or turbulent flow (fixed transition)

Table 1. Test cases

Airfoil	M_∞	$Re_{c,\infty}$	C_1	Flow Condition
RAE5243	0.68	19 X 10^6	0.82	Fully turbulent
RAE5243	0.68	19 X 10^6	0.82	45% transition

Boundary and/or initial conditions for computations:

- Steady state solution
- No-slip boundary condition at wall and far field boundary condition
- Fully turbulent or fixed transition

Material parameters:
Fluid

Optimization:
Minimum total drag Min C_d for given C_l

Design parameters:
Bump height, position, length and crest position

Bounds of design parameters:

Bump crest position
$\mathbf{0} < X_{cre} / C < \mathbf{1}$

Bump starting point to crest
$\mathbf{0} < X_{bumprelative} / C < X_{bumplength} / C$

Bump total length
$\mathbf{0} < X_{bumplength} / C < \mathbf{0.4}$

Bump height
$\mathbf{0} < \Delta Y_h / C < \mathbf{0.05}$

Objective function definition:
Total drag of the airfoil $C_d = C_{d,pressure} + C_{d,friction}$

Results:

Results for datum airfoil:
Lift curve, drag polar and flowfield at the given C_l

Results for optimized airfoil:
- Bump shape and position parameters
- Lift, drag (both components) and pitching moment at the design condition
- Lift curve and drag polar for a range of lift around the design point

Data to be stored requested from Analysis
Flow field data

Link: http://jucri.jyu.fi/?q=node/4

TA6: 3D Shock Control Bump Optimisation

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Keywords: Shock control bump, transonic flow, natural laminar flow airfoil

Introduction:
When flying at transonic speeds, shock waves, terminating rejoins of supersonic flow on the upper surface of an aircraft's wings, generate drag. This drag component can represent a large proportion of overall drag for flight at high chord-wise Mach numbers and lift coefficients, and for airfoil profiles vulnerable to strong shocks such as natural laminar flow wings.

Shock control bumps are capable of significantly reducing wave drag by splitting a single shock wave into a number of weaker oblique compressions. Two dimensional bumps extending along a large proportion of a wing's span, although capable of good 'on-design' performance, are ineffective at reducing drag across a range of typical flight conditions.

Dividing 2D shock control bumps into a number of discrete 3D bumps can reduce the sensitivity of the device, whilst retaining the benefits of shock control.

The design and placement of 3D bumps on a transonic wing is however far from trivial. To limit the computational resource necessary, the optimisation of a 3D shock control device on a simplified geometry, representative of an infinite wing with a constant chord and fixed bump spacing, is proposed.

Objectives:
The aim of current optimisation problem is a multipoint minimisation of overall drag using 3D shock bump control applied to the natural laminar flow RAE5243 airfoil. Each case is given equal weighting, with a successful design aiming to minimise average overall drag. A typical flight condition range is simulated here using three flight Mach numbers, found to have a strong influence on shock Mach number and position, with all other flight variables held constant, as summarised in Table 1.

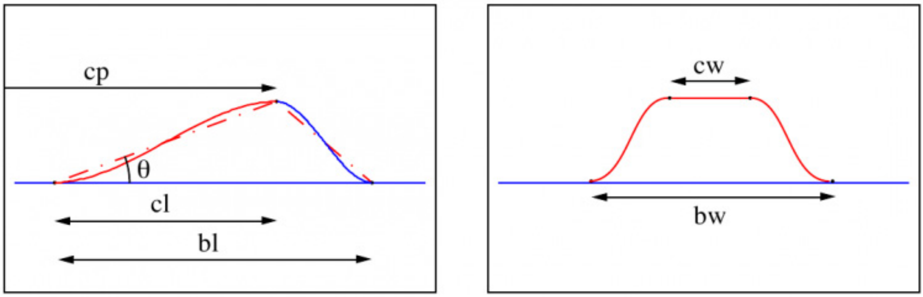
Requirements:

Reynolds averaged Navier-Stokes solutions using a turbulence model.

Computational domain:

Solutions should be carried out on high quality grids with: a far field boundary greater than 20 chord lengths away from the airfoil in all directions and a value of $y^+ \sim 1$ at the aerofoil surface.

Illustration of the computational domain:



(a) Chord-wise cross-section (b) Span-wise cross-section

Figure 1: Illustration of geometric parameters describing the 3D shock control bump.

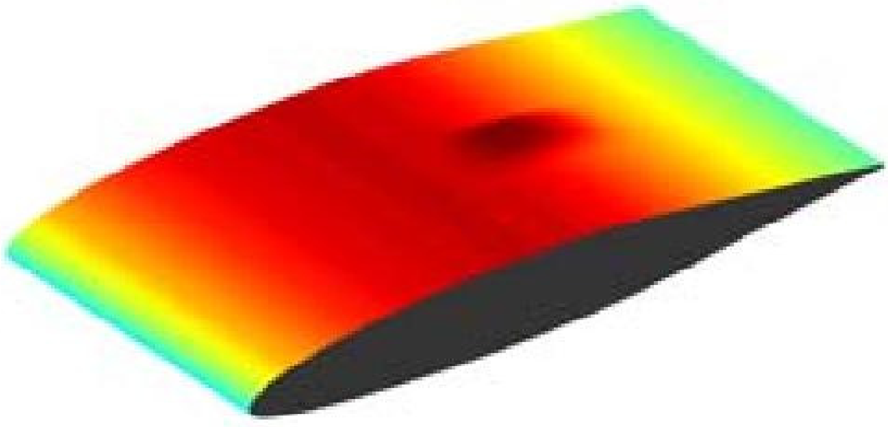


Figure 2: RAE5243 wing with 3D shock control bump.

Modeling: physical properties:

Table 1. Design cases

Case	M_{∞}	$\mathbf{Re}_{c,\infty}$	C_1	**Flow condition**
A	0.74	10×10^6	0.45	40% transition
B	0.75	10×10^6	0.45	40% transition
C	0.76	10×10^6	0.45	40% transition

Boundary and/or initial conditions for computations:

- Steady state.
- Non-slip at airfoil surface and far-feild at boundary edges.

Material Parameters:

Fluid

Optimization:

A single design minimising average overall drag for the three design cases,

$$\frac{1}{3}(C_{dA} + C_{dB} + C_{dC})$$

as outlined in Table 1.

Design parameters:

Specification of the 3D control bump geometry is achieved using the following six geometric parameters (Fig. 1):

- ramp angle, θ
- control position, cp
- bump length, bl
- crest position, $crest \equiv \frac{\text{control length}, cl}{\text{bump length}, bl}$
- aspect ratio, $AR \equiv \frac{\text{bump length}, bl}{\text{bump width}, bw}$
- crest ratio, $CR \equiv \frac{\text{crest width}, cw}{\text{bump width}, bw}$

Cubic splines define surfaces between the control points listed above, with tangential conditions applied between: the bumps edges and the aerofoil surface and the bump crest and the airfoil surface. Geometories generated on a flat surface, as illustrated in Fig. 1(b), are 'wrapped' onto the upper surface of the curved RAE5243 profile, as illustrated in Fig. 2. Span-wise, centre to centre, control bump spacing is fixed at 30% chord. It is suggested that, to take advantage of the problem's geometrical symmetry, solutions only be carried out over half the domain.

Bounds on Design Parameters

Optimisation is subject to the following six geometric constraints:

$$0 \geq \theta \leq 10$$

$$cp + (1 - crest)bl \leq 0.9$$

$$cp - crest\, bl \geq 0.3$$

$$\frac{bl}{AR} \leq 0.05$$

$$0.1 \geq crest \leq 0.9$$

$$0.1 \geq CR \leq 0.9$$

Objective function definition:

$$\min \ \tfrac{1}{3}(C_{dA} + C_{dB} + C_{dC})$$

Results:

- Drag polars of optimum design illustrating force coefficients at five lift coefficients spaced evenly between 04Cl05 for each design Mach number including comparison with datum 'no bump' case.
- Average overall drag of optimum design, including comparison with the datum 'no bump' overall average.

Link: http://jucri.jyu.fi/?q=testcase/34

TA7 Maximizing the Performance of SHM Systems by Robust Sensor Network Optimization

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Keywords: Structural Health Monitoring (SHM), Composite Structures, FEA, Evolutionary Computation, Uncertainty, Pareto solutions

Introduction:

Recent advanced design tools and material offers complex structures with composite materials. However, the impact on structures causes delamination between composite layers or crack on fiber-reinforced area which the current visual inspection is impossible to check. In addition, current visual inspection will take high time cost on large structures in engineering. This is why Structural Health Monitoring (SHM) system is introduced as a promising technology to maintain healthy structure in increasing engineering applications [1]. Ultimately, the use of SHM system will save both maintenance time and cost.

The main goal of this test case is to maximize the Probability of Detection (POD) by selecting an optimal number of sensors and also their locations with efficient optimization methods like Evolutionary Algorithms which will be part of a SHM system to handle complex models.

Objectives:

A SHM system determines the status of the structural health where and how much local or global stresses are applied. However, the efficiency of SHM system highly relies on the number of sensors and their locations on structure. An efficiency definition of SHM system can be expressed by the Probability of Detection (POD); a high POD value represents a high efficiency of SHM system.

The main objectives of this test case are to maximize mean value of POD by optimizing number of sensors and their locations. Two test cases are considered; the first test case is to maximize POD at given number of sensors and global load. The second test case uses an uncertainty design technique [2] to maximize POD while minimizing sensitivity of POD at the variability of global load cases.

1. Single objective SHM system design optimization
2. Robust multi-objective SHM system design optimization.

Required software for optimization :

- FEA analysis tools.
- A mesh generator and the number of nodes of the discretized structure
- Multi-Objective Evolutionary Algorithms (MOEAs).

Model and Materials:

The test model is shown in Figures 1
and 2. The composite material properties are described in Table 1.

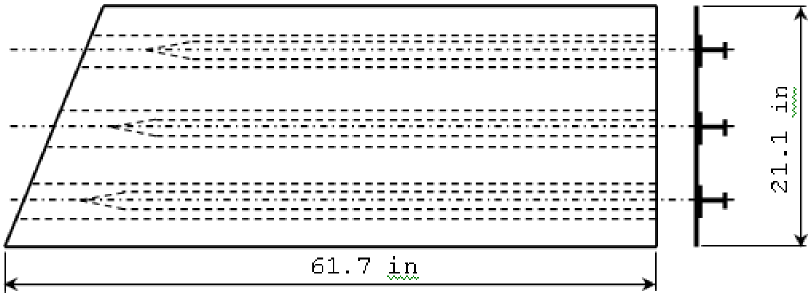

Figure 1. Test model: Stiffened panel [Ref. 2].

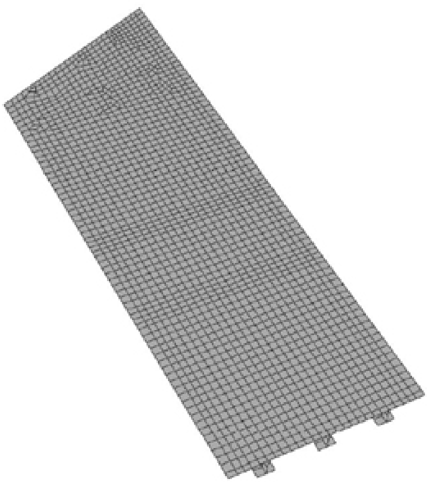

Figure 2. Example - 3D view of test model mesh [Ref. 2].

Table 1. Test material properties [Ref. 2].

Material Properties	Symbol [units]	Value
Longitudinal Young's modulus	E_{11} [msi]	23.2
Transverse Young's modulus	E_{22} [msi]	1.30
Transverse Young's modulus	E_{33} [msi]	1.30
Poisson's ratio	ν 12	0.28
Poisson's ratio	ν 13	0.28
Poisson's ratio	ν 23	0.36
In-plane shear modulus	G_{12} [msi]	0.90
Out-of-plane shear modulus	G_{13} [msi]	0.90
Out-of-plane shear modulus	G_{23} [msi]	0.50

Note: Contributor can choose one of the two test cases 6.1 or 6.2 or both for computation

Test Case 7.1: Single-Objective SHM System Design Optimization

Fitness Functions:

The discrete optimization problem considers robust multi-objective design for SHM system under considering variability of global load cases. The fitness functions are shown below;

$$f_1 = \left(\frac{1}{\overline{POD}}\right) = \frac{1}{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{1}{n}\sum_{j=1}^{n} POD_{ij}\right)}$$

Subject to

$$POD_{jk} = \begin{bmatrix} 0 & if & \varepsilon_j(x_k) \leq \varepsilon_{min} \\ 1 & if & \varepsilon_j(x_k) \geq \varepsilon_{min} \end{bmatrix}$$

where m, n represent number of local impact forces and number of sensors respectively. $\overline{POD}$represents mean value of POD.

Design Parameters:

- Number of sensors (N_{Senor}), and location of Sensor (L_{Senor}).
- Note: location of sensor will be same as nodal point of mesh.

Design Bounds:

- Number of sensors (N_{Senor}) is given: 10
- Location of sensors: $1 \leq L_{Senor} \leq N_{NodalPoint}$
  Note: $N_{NodalPoint}$ represents the maximum nodal points of mesh.
- Global load case is given: 500 *lb*

Results:
- Mean value of POD.
- Locations of given number of sensors.
- POD comparison between uniformly distributed sensors and optimal sensors at given global load case.
- Convergence plot of the optimizer

Test Case 7.2: Robust Multi-Objective SHM System Design Optimization

Fitness Functions:

The discrete optimization problem considers robust multi-objective design for SHM system under considering variability of global load cases. The fitness functions are shown below;

$$f_1 = min(\frac{1}{\overline{POD}}) = \frac{1}{\frac{1}{l}\sum_{i=l}^{l}(\frac{1}{m}\sum_{j=l}^{m}(\frac{1}{n}\sum_{k=l}^{n} POD_{ijk}))}$$

$$f_1 = min(POD_{sd}) = \sqrt{\frac{1}{l-1}\sum_{i=l}^{l}(\frac{1}{m}\sum_{j=l}^{m}(\frac{1}{n}\sum_{k=l}^{n} POD_{ijk}) - \overline{POD})^2}$$

subject to

$$POD_{jk} = \begin{bmatrix} 0 & if & \varepsilon_j(x_k) \leq \varepsilon_{min} \\ 1 & if & \varepsilon_j(x_k) \geq \varepsilon_{min} \end{bmatrix}$$

where l, m, n represent number of global load cases, number of local impact forces, number of sensors respectively. $\overline{\text{POD}}$ and POD_{sd} represent mean and standard deviation values of POD.

The first and second fitness functions aim to maximize the mean value of POD and to minimize standard deviation (sensitivity) of POD at the variability of global load cases.

Design Parameters:
- Number of sensors (NSenor), and location of Sensor (LSenor).
- Note: location of sensor will be same as nodal point of mesh.

Design Bounds:
- Number of sensors: 1 ≤ NSenor ≤ 30
- Location of sensors: 1 ≤ LSenor ≤ NNodalPoint
  Note: NNodalPoint represents the maximum nodal points of mesh (to be defined).
- Variability of global load cases (lb): [200, 500, 800]

Results:

- Pareto non-dominated solutions in terms of mean and standard deviation of POD.
- Number of optimal sensors and locations.
- Histogram of POD comparison between uniformly distributed sensors and optimal sensors at the variability of global load cases.
- Convergence plot of the optimizer.
- Data obtained by Test 6.1 and Test 6.2 to be stored:
- Solutions obtained by optimization.
- Number of optimal sensors and their locations in the structure.

References:

[1] Johannes F.C. Markmiller, Fu-kuo Chang, Sensor Network Optimization for A Passive Sensing Impact Detection Technique. Structural Health Monitoring, Vol. 9, No.1, pp. 25-39, 2010.

[2] D.S. Lee, L.F. Gonzalez, J. Periaux and K. Srinivas. Evolutionary Optimisation Methods with Uncertainty for Modern Multidisciplinary Design in Aeronautical Engineering, Notes on Numerical Fluid Mechanics and Multidisciplinary Design (NNFM 100), 100 Volumes NNFM and 40 Years Numerical Fluid Mechanics. Pages 271-284, Ch. 3., Heidelberg: Springer-Berlin, ISBN 978-3-540-70804-9, 2009.

Link: http://jucri.jyu.fi/?q=testcase/35

TI1 MDO of Mobile Phone: Antenna, SAR, HAC and Temperature

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Keywords: Mobile phone, antenna, Specific Absorption Rate (SAR), Hearing Aid Compatibility (HAC), Temperature

Introduction:
The purpose of this test case is to test tools, methods and new ideas to solve everyday design challenges in mobile phone industry. There are no single, right, solution for the problem. It may also be so that some of the goals can't be reached. That is also true in real product design process. Designers have to accept compromises. The challenge for test case contributors will be to define multi-objective goals in such a way that optimization code can make a decision if there are no ways to achieve the objective function. There are three different possibilities to contribute.

The first option is to optimize the antenna geometry according to objective function defined later. There is a reference model that can be used to check that your model is constructed correctly. The second option is to combine antenna performance and temperature on keyboard and display area. The third, and most challenging, is to optimize the design according the all objectives given (antenna, temperature, SAR and HAC)..

Objectives:
Option 1: Maximize transmitted power of two GSM bands and minimize scattering parameters (S11) on antenna feed point.

Option 2: Maximize transmitted power of two GSM bands and minimize scattering parameters (S11) on antenna feed point and minimize temperature at keyboard and dT on display between any two points.

Option 3: Maximize transmitted power of two GSM bands and minimize scattering parameters (S11) on antenna feed point and at the same time minimise E-fields around ear piece for hearing aid compatibility. Also minimize SAR values to human head.

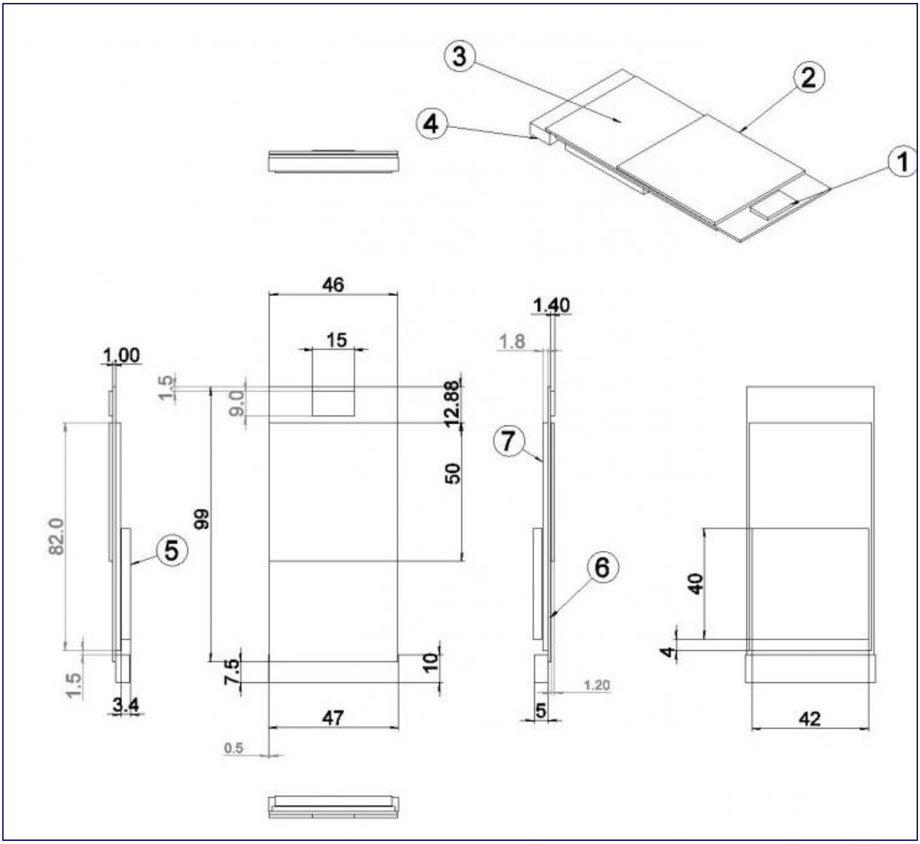
Requirements:
Realistic phone model (template given, size and "must" use modules, as display, battery, antenna volume, etc.) with realistic materials.
Outer dimensions for the phone (w * l * h): 50mm * 110m * 10mm
Size of the antenna volume: 47mm * 10mm * 5mm

Computational domain:
- Simplified mobile phone
- Sources
- Boundaries

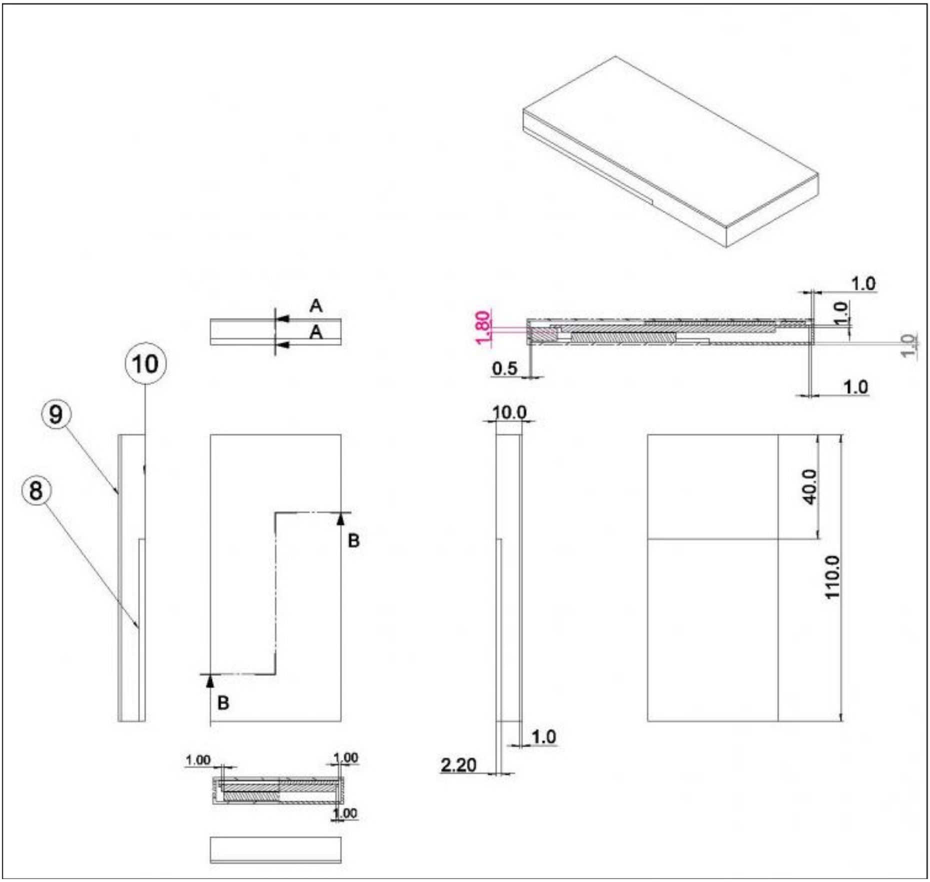
Parts to be included to the model:

1. Ear piece - copper
2. Display module - stainless steel
3. Key pad - ABS/PC plastic
4. Antenna support - ABS/PC
5. Battery - aluminium
6. Printed wired board - copper
7. Shield can - stainless steel
8. Battery cover - ABS/PC
9. A-cover - ABS/PC
10. B-cover - ABS/PC

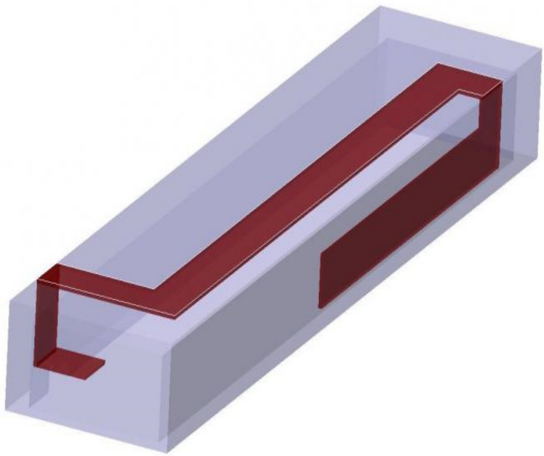
Illustration of the computational domain:



Dimensions for the PWB and other components of the phone:

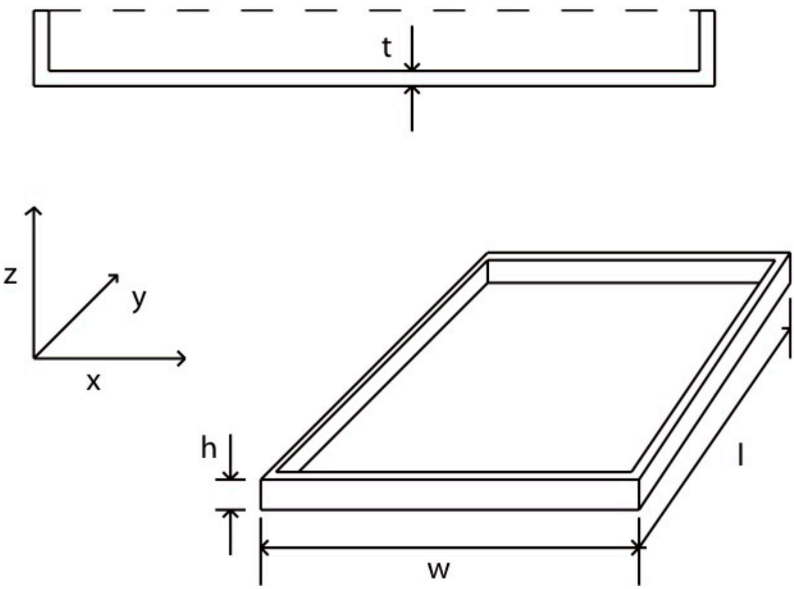


Dimensions for the phone



Name	w [mm]	l [mm]	h [mm]	t [mm]	material	pwr dissip. [mW]	Note
Ant. Volume	47	10	5	-	Air	-	
Battery	42	40	3.4	-	Al	-	V_{bat}=3.7V, ESR 100 mΩ
BB shield	42	65	1.8	0.2	Stainless steel	-	
Covers	50	110	10	1	ABS/PC	-	
Display	46	50	1	0.3, 0.7	Stainless + glass	-	t1 for stainless steel and t2 for glass
Ear piece	15	8	1.4	-	Cu	-	
PWB	46	99	1	-	FR4+copper	-	
RF PA	6	6	0.1	-	Cu	eff. 50%	power dissipation depends on other losses
RF shield	42	14	1.8	0.2	Stainless steel	-	
µP1	20	20	0.1	-	Cu	200	
µP2	15	15	0.1	-	Cu	150	
µP3	10	8	0.1	-	Cu	50	

Table 1 - Parameters for used modules



Coordinates and directions for the model

Material	ε_r	μ_r	ρ [Ω m]	k [W/(m*K)]	Density [kg/m^3]	C_p [J/(kg*K)]	Note
ABS/PC	3.5	1	-	0.33	1100		
Air	1	1	-	0.026	1.205	1.005	@20ϒC
Al	1	1	2.65E-08	160	2700	900	
Cu	1	1	1.68E-08	385	8920	385	
Cu+FR4	1	1	1.68E-08	38.4	2350	969	Use Cu resistivity for PWB
Glass	5.5	1	-	1.05	2500	840	
Stainles steel	1	1	6.90E-07	16	8030	475	

Table 2 - Material parameters for EM and thermal simulations

Modeling: physical properties:
- Antenna performance:
  - Antenna matching
  - Total Radiated Power (TRP)
- Hearing Aid Compatibility (HAC - Category M3)
  - E-fields above earpiece from specified height and area
- SAR (human head)
- Surface temperature of keypad

Boundary and/or initial conditions for computations:
- Case 1:
  - Antenna and HAC optimisation
- Case 2:
  - Antenna, HAC, SAR and Thermal optimisation

Material Parameters:
Solid

Optimization:
- Antenna bandwidth in 850/900MHz and 1800/1900MHz bands
- S_{11} of antenna feed
- Minimise E-field for HAC
- Minimise SAR values
- Minimise temperature on keypad

Design parameters:
- Antenna element dimensions
- Grounding points of mechanical structure
- Dimensions and groundings of thermal conductor

Objective function definition:
- $S_{11} < -6dB$ with in each band, $\mathbf{824{-}960}MHz$ and $\mathbf{1710{-}1990}MHz$

According to ANSI C63.19-2006 standard
- $E{-}field < \mathbf{266{,}1}\ V/m$ @ $GSM\ \mathbf{850}\ MHz$ and $E{-}field < \mathbf{84{,}1}\ V/m$ @ $GSM\ \mathbf{1900}\ MHz$ on the earpiece area
- $H{-}field < \mathbf{0{,}8}\ A/m$ @ $GSM\ \mathbf{850}\ MHz$ and $H{-}field < \mathbf{0{,}25}\ A/m$ @$GSM\ \mathbf{1900}\ MHz$ on the earpiece area

- $SAR < \mathbf{1{,}6}\ W/kg$ in human head (CTIA standard head model/TBD)

Conformity level
- Temperature of keypad $< \mathbf{60}\ ^{o}C$ (ABS/PC)
- Temperature difference on display between any two points $< \mathbf{10}\ ^{o}C$

Results:

Geometry:
Mesh of the optimized geometry.
Antenna performance:
Total radiated power (TRP) in dBm and antenna efficiency in percentage.
Antenna matching:
2d-plot; x-axis for frequencey from 800MHz to 2000MHz, y-axis for S_{11} from -30 to 0 dB.
Temperature
Color map of the static temperature on geometry
HAC
E- and H-fields on earpiece area 5mm above the surface of phone
SAR
Maximum SAR values in 3D-plot.

Link: http://jucri.jyu.fi/?q=node/6

TI2 Patria AST
Test Case 2.1

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Keywords: Structural mechanics, Shape optimization

Objectives: Optimization of a generic aircraft control surface

Requirements: Structural analyzer, Optimizer

Computational domain:

Control Surface Dimensions (figure 1):
- Rectangular plan form with 3000mm x 1000mm dimensions
- Triangular cross section with 1000mm chord and 200mm height

Cross Section (figure 2):
- Uniform cross section along the span
- The maximum number of the internal spars is limited to 10 spc
- Spar locations and tilting to be freely chosen
- Skin and spar thicknesses to be freely chosen
- Fittings not included in the optimization, supports can be assumed ideally rigid
- The control surface structure is closed with inner and outer end ribs

Fittings (figure 3)

Illustration of the computational domain:

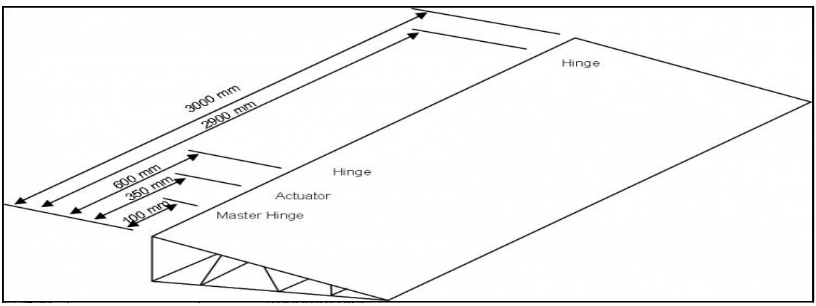

Figure 1. Control Surface Dimensions

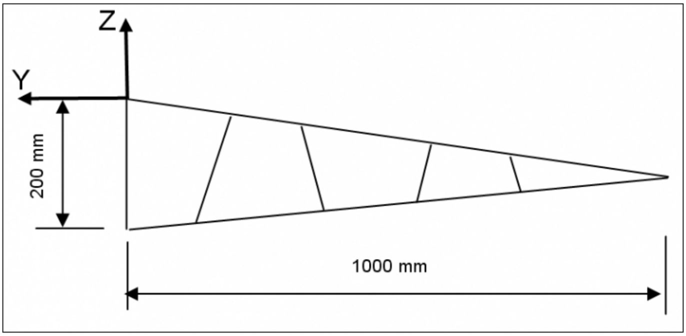

Figure 2. Cross Section

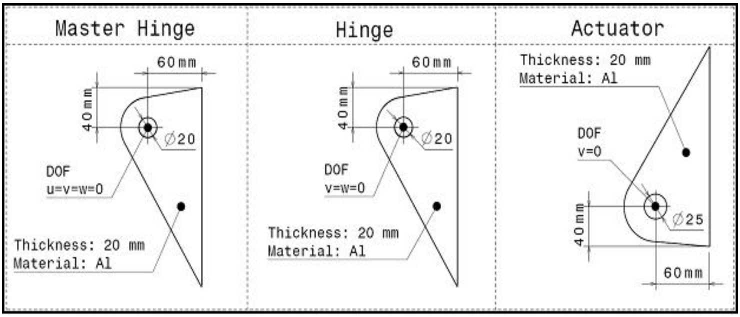

Figure 3. Fittings

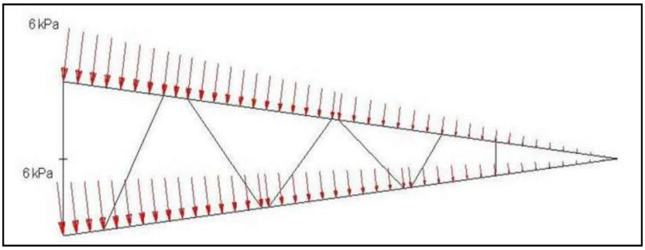

Figure 4. Aerodynamic loading

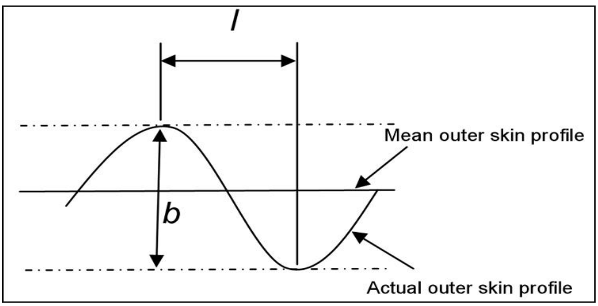

Figure 5. Surface waviness parameters

Modeling: physical properties:
Material Data for aluminium:

Density (kg/m^3)	2795

Elastic modulus

E (GPa)	71
Poisson's v	0.3

Loads:
The aerodynamic loading is assumed to follow triangular shape on both the upper and lower surfaces as shown in the figure 4.

Boundary and/or initial conditions for computations:
See Fig 3, Fig 4

Material Parameters:
Solid

Optimization:
Objective is to minimize the mass.

Design parameters:
$\mathbf{x} = [t_1\ t_2\ t_3\ \ldots\ t_n]^T$

Objective function definition:

Minimize	$F_{mass}(x)$		Objective is to minimize the mass
Subject to	$\delta_{\max}(\mathbf{x})$	≤ 10 mm	Constraint for maximum displacement
	n_{buck}	≥ 1.1	Constraint for minimum buckling factor
	$\sigma_{VonMises}$	≤ 260 MPa	Constraint for max Von Mises stress
	$\dfrac{b(\mathbf{x})}{l(\mathbf{x})}$	≤ 0.005	Constraint for surface waviness (see figure 5)
	$b(\mathbf{x})$	≤ 3 mm	Constraint for wave amplitude
	$\mathbf{x}$	$= \left[t_1\ t_2\ t_3 \cdots t_n\right]^T$	Thickness design variables (considered as continuous)

Note: Material thickness of each skin, spar and end rib has to remain constant along its surface area.

Results:

- Final cross section geometry incl. thickness of spars and skins used (mm)
- Optimal mass complying to requirements
- Optimization convergence curve (iteration #, best $min(F_{mass}(x))$)

Link: http://jucri.jyu.fi/?q=node/11

TI2 Patria AST
Test Case 2.2

Chairman: Petri Hepola, petri.hepola@patria.fi
Organization: Patria Aerostructures Ltd.
Country: Finland
Jyväskylä contact: Tero Tuovinen, tero.tuovinen@jyu.fi

Keywords: Composite laminates, Structural mechanics, Shape optimization

Objectives: Optimization of a generic aircraft control surface
Requirements: Structural composite analyzer, Optimizer

Computational domain:

Control Surface Dimensions (figure 1):
- Rectangular plan form with 3000mm x 1000mm dimensions
- Triangular cross section with 1000mm chord and 200mm height

Cross Section (figure 2):
- Uniform cross section along the span
- The maximum number of the internal spars is limited to 10 spc
- Spar locations and tilting to be freely chosen
- Skin and spar thicknesses to be freely chosen
- Fittings not included in the optimization, supports can be assumed ideally rigid
- The control surface structure is closed with inner and outer end ribs

Fittings (figure 3)

Illustration of the computational domain:

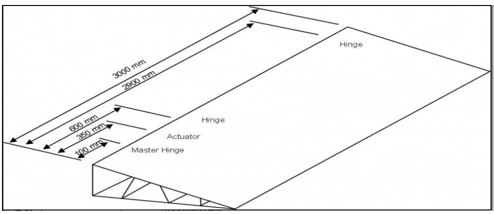

Figure 1. Control Surface Dimensions

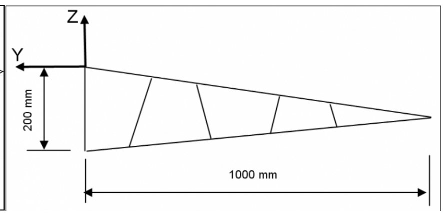

Figure 2. Cross Section

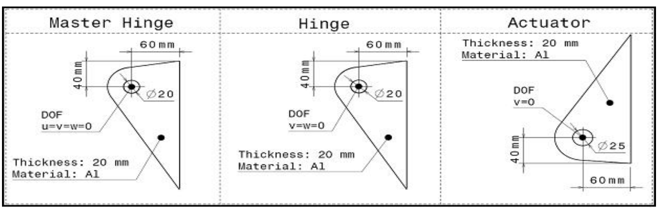

Figure 3. Fittings

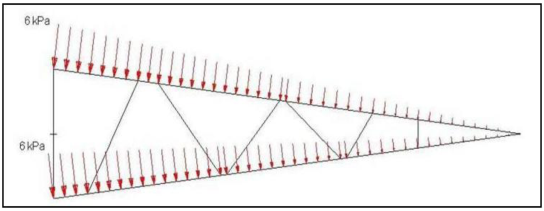

Figure 4. Aerodynamic loading

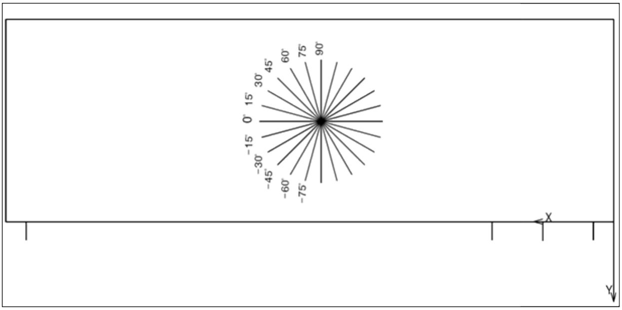

Figure 5. Allowed fiber orientations

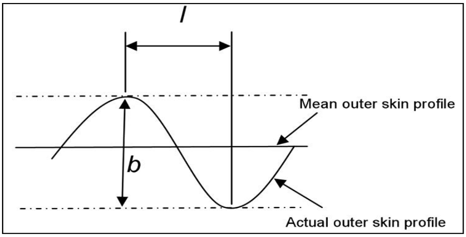

Figure 6. Surface waviness parameters

Modeling: physical properties:

Material Data for UD Tape:

Density (kg/m^3)	1 600
Layer thickness (mm)	0.15 - 10.0

Elastic modulus

E_1 (GPa)	125
E_2 (GPa)	4.5
$G_{1}2$ (GPa)	4.5
Poisson's v	0.35

Allowable strengths

σ_{1T} (MPa)	1300
σ_{1C} (MPa)	-800
σ_{2T} (MPa)	60
σ_{2C} (MPa)	-120
τ_{12} (MPa)	70

Material Data for aluminium:

Density (kg/m^3)	2795

Elastic modulus

E (GPa)	71
Poisson's v	0.3

Loads:
The aerodynamic loading is assumed to follow triangular shape on both the upper and lower surfaces as shown in the figure 4.
- The stacking sequence to be freely chosen
- Allowed fiber orientations are shown in the figure 5

Boundary and/or initial conditions for computations:
See Fig 3, Fig 4

Material Parameters:
- Solid

Optimization:
Objective is to minimize the mass.

Design parameters:
$\mathbf{x} = [t_1\ t_2\ t_3\ \ldots\ t_n]^T$

Objective function definition:

Minimize	$F_{mass}(x)$		Objective is to minimize the mass
Subject to	$\delta_{\max}(\mathbf{x})$	≤ 10 mm	Constraint for maximum displacement
	n_{buck}	≥ 1.1	Constraint for minimum buckling factor
	$\left(\frac{\sigma_1(\mathbf{x})}{X}\right)^2 + \left(\frac{\sigma_2(\mathbf{x})}{Y}\right)^2 + \left(\frac{\tau_{12}(\mathbf{x})}{S}\right)^2 - \left(\frac{\sigma_1(\mathbf{x}) \cdot \sigma_2(\mathbf{x})}{X^2}\right)^2$	≤ 1	Constraint for failure criterion
	where X is the fibre direction tensile or compressive allowable Y is the tensile or compressive allowable transverse to fibres S is the shear allowable n.b. For further details see Tsai-Hill criterion		
	$\frac{b(\mathbf{x})}{l(\mathbf{x})}$	≤ 0.005	Constraint for surface waviness (see figure 6)
	$b(\mathbf{x})$	≤ 3 mm	Constraint for wave amplitude
	$\mathbf{x}$	$= [t_1\, t_2\, t_3 \cdots t_n]^T$	Thickness design variables (considered as continuous)

Note: Material thickness of each skin, spar and end rib has to remain constant along its surface area.

Results:
- Final cross section geometry incl. thickness of spars and skins used (mm)
- Optimal mass complying to requirements
- A table of fiber orientation in skins and spars
- Optimization convergence curve (iteration #, best $min(F_{mass}(x))$)

Link: http://jucri.jyu.fi/?q=node/12

TI2 Patria AST
Test Case 2.3

Chairman: Petri Hepola, petri.hepola@patria.fi
Organization: Patria Aerostructures Ltd.
Country: Finland
Jyväskylä contact: Tero Tuovinen, tero.tuovinen@jyu.fi

Keywords: Composite laminates, Structural mechanics, Shape optimization

Objectives: Optimization of a generic aircraft control surface
Requirements: Structural composite analyzer, Optimizer

Computational domain:

Control Surface Dimensions (figure 1):

- Rectangular plan form with 3000mm x 1000mm dimensions
- Triangular cross section with 1000mm chord and 200mm height

Cross Section (figure 2):

- Uniform cross section along the span
- The maximum number of the internal spars is limited to 10 spc
- Spar locations and tilting to be freely chosen
- Skin and spar thicknesses to be freely chosen
- Fittings not included in the optimization, supports can be assumed ideally rigid
- The control surface structure is closed with inner and outer end ribs

Fittings (figure 3)

Illustration of the computational domain:

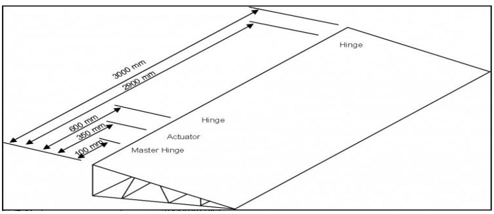

Figure 1. Control Surface Dimensions

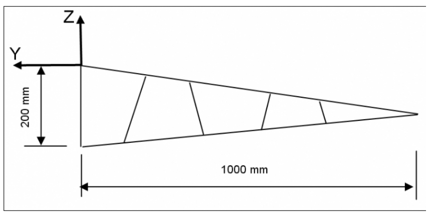

Figure 2. Cross Section

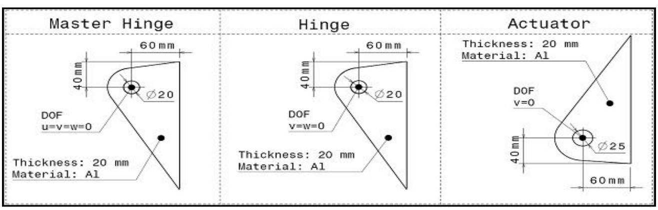

Figure 3. Fittings

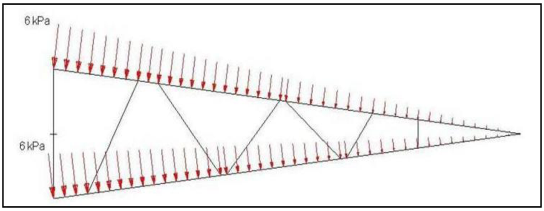

Figure 4. Aerodynamic loading

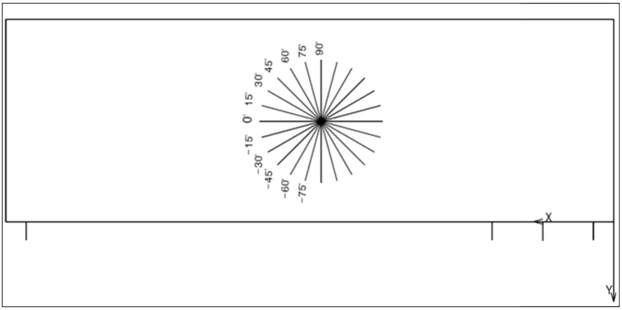

Figure 5. Allowed fiber orientations

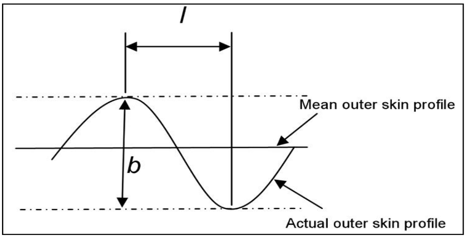

Figure 6. Surface waviness parameters

Modeling: physical properties:

Material Data for UD Tape:

Density (kg/m^3)	1 600
Layer thickness (mm)	0.15

Elastic modulus

E_1 (GPa)	125
E_2 (GPa)	4.5
G_12 (GPa)	4.5
Poisson's v	0.35

Allowable strengths

σ_{1T} (MPa)	1300
σ_{1C} (MPa)	-800
σ_{2T} (MPa)	60
σ_{2C} (MPa)	-120
τ_{12} (MPa)	70

Material Data for aluminium:

Density (kg/m^3)	2795

Elastic modulus

E (GPa)	71
Poisson's v	0.3

Loads:
The aerodynamic loading is assumed to follow triangular shape on both the upper and lower surfaces as shown in the figure 4.

- The stacking sequence to be freely chosen
- Allowed fiber orientations are shown in the figure 5

Boundary and/or initial conditions for computations:
See Fig 3, Fig 4

Material Parameters:

- Solid

Optimization:
Objective is to minimize the mass.

Design parameters:
$\mathbf{x} = [t_1\ t_2\ t_3\ \ldots\ t_n]^T$

Objective function definition:

Minimize	$F_{\text{mass}}(\mathbf{x})$		Objective is to minimize the mass
Subject to	$\delta_{\max}(\mathbf{x})$	≤ 10 mm	Constraint for maximum displacement
	n_{buck}	≥ 1.1	Constraint for minimum buckling factor
	$\left(\frac{\sigma_1(\mathbf{x})}{X}\right)^2 + \left(\frac{\sigma_2(\mathbf{x})}{Y}\right)^2 + \left(\frac{\tau_{12}(\mathbf{x})}{S}\right)^2 - \left(\frac{\sigma_1(\mathbf{x}) \cdot \sigma_2(\mathbf{x})}{X^2}\right)^2$	≤ 1	Constraint for failure criterion
	where X is the fibre direction tensile or compressive allowable Y is the tensile or compressive allowable transverse to fibres S is the shear allowable n.b. For further details see Tsai-Hill criterion		
	$\frac{b(\mathbf{x})}{l(\mathbf{x})}$	≤ 0.005	Constraint for surface waviness (see figure 6)
	$b(\mathbf{x})$	≤ 3 mm	Constraint for wave amplitude
	$\mathbf{x}$	$= [t_1\, t_2\, t_3 \cdots t_n]^T$	Thickness design variables (considered as discrete)
	$x_i = [0\ 0.15\ 0.30\ 15.00]$ mm		

Note: Composite laminate of each skin, spar and end rib is allowed to vary freely along its surface area.

Results:

- Final cross section geometry incl. thickness of spars and skins used (mm)
- Optimal mass complying to requirements
- A table of fiber orientation in skins and spars
- Optimization convergence curve (iteration #, best $min(F_{mass}(x))$)

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