Engineering Analysis using the Finite Element Method

University of California, Berkeley, Spring 2019
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Lab 4 (2 weeks)

This week's lab is concerned with the 2D thermal analysis of a gas turbine fin in Ansys. Based on the 2D geometry provided to you, you will examine

- the temperature distribution under steady-state conditions, with the goal of keeping the maximum temperature below 300 °C
- the duration needed to cool down the fin (from steady state condition to below 50 °C upon switching off the turbine)
- the maximum temperature of the blade as a function of time if the turbine is loaded sinusoidally

As is the case in engineering practice, there is no "correct" solution. You will prepare a short report laying out your reasoning for the parameters and boundary conditions you choose.

1 Overview

Gas turbines are employed for two opposing purposes. Firstly, they are used to generate thrust such as in jet engines. Secondly, they can drive a generator that in turn produces electricity.

In the former, a sequence of rotors and stators (blades that rotate and those that remain fixed) are primarily tasked with sucking in and compressing ambient air to be burnt with fuel. In the latter, superheated steam from a nuclear reactor or coal plant is forced through a maze of rotors and stators in order to drive a shaft.

Electricity-generating gas turbines operate more efficiently the hotter the steam is. As a result, the efficiency of today's turbines is often limited by the temperatures (combined with the immense centripetal forces) that the turbine blades can carry. So for obvious economic and environmental reasons, vast investments have been made into

- the development of more heat-resistant materials
- intricate cooling systems for stators and rotors

The following images show examples of a complete gas turbine and a (possibly inaccurate) CAD model of an array of stator blades.

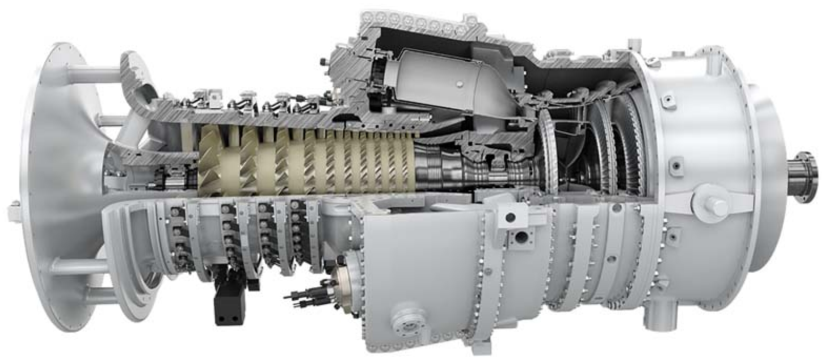

Figure 1: A small (5.4 MW) fuel-driven industrial gas turbine, courtesy of Siemens.

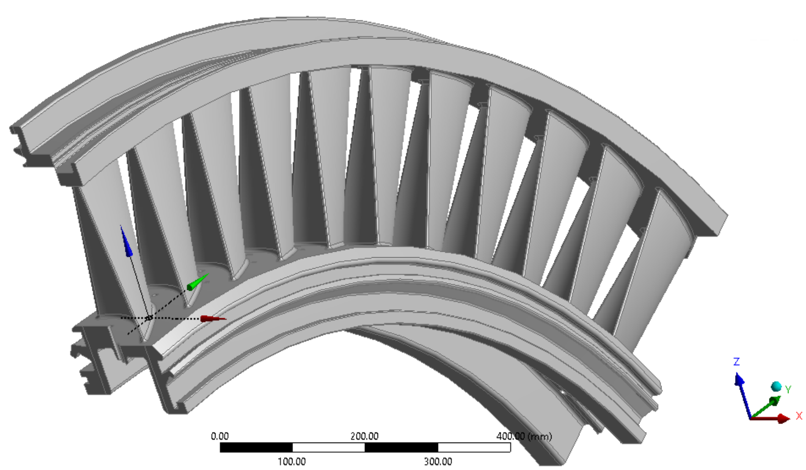

Figure 2: A CAD model of a section of stator blades.

To simplify our analysis we examine only a cross-section of a single blade. The following images show the 3D blade geometry as well as the 2D cross-section we'll use in this lab.

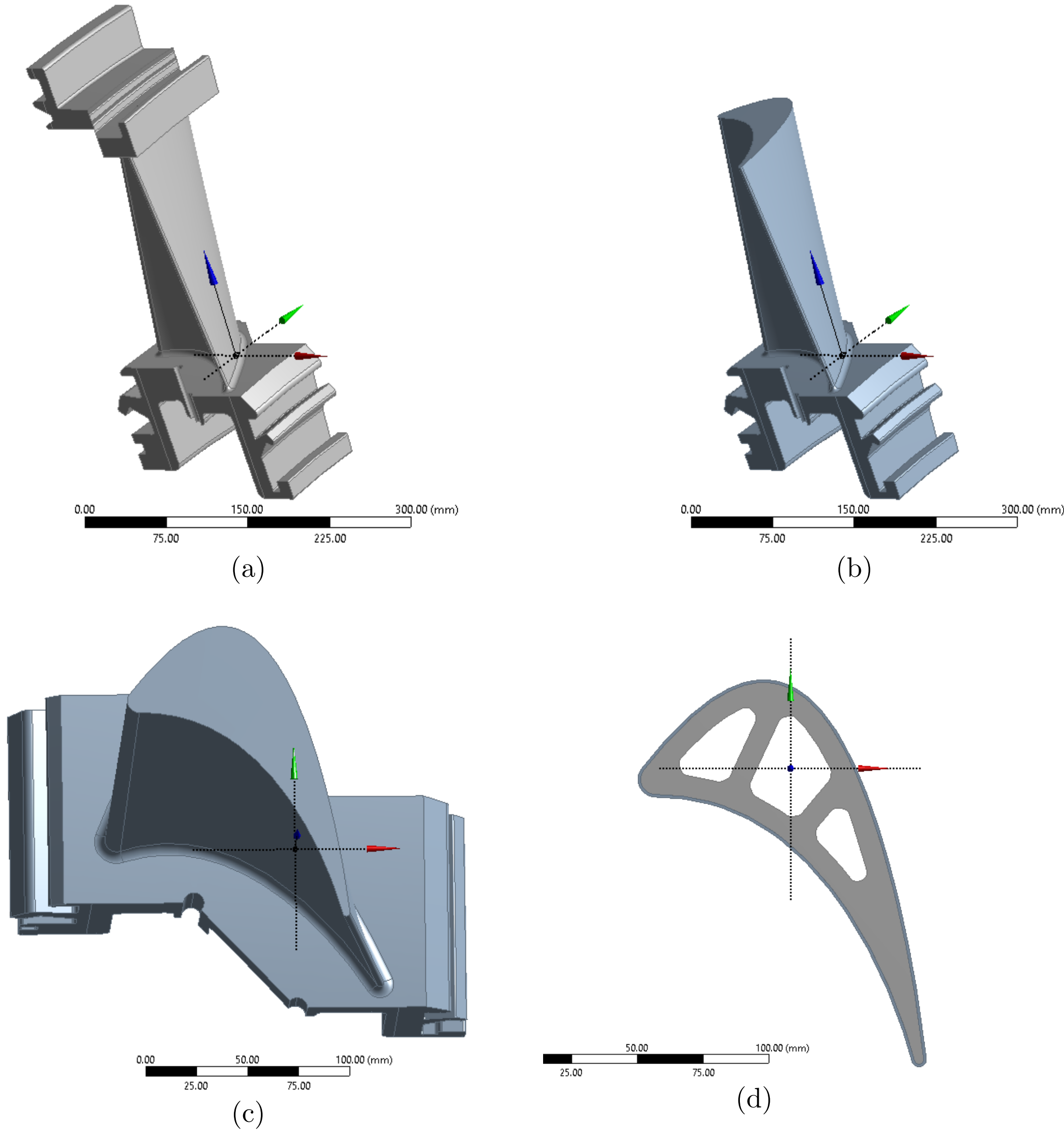

Figure 3: Close-ups of the CAD model

Note that the 2D model contains "holes" you can use for cooling by gas or liquid. Also notice that the 2D model consists in fact of two bodies - the main part as well as a thin "coating" that you can play with by assigning different thermal properties. The coating is "fused" with the bulk material underneath - you do not need to assume an additional film coefficient for the heat transfer between coating and bulk material.

2 Simulations

Your tasks are outlined in the following sections. Use the geometry provided in the DesignModeler file `Lab04Geometry2D.agdb` as basis for your work. *General hint: In order to be able to apply convection boundary conditions to a 2D body, you need to switch the geometry property to 2D (as in Lab 1).* Briefly comment on each of the following questions in your report.

2.1 Part 1: Steady state

Assume steam is passing the blade at high velocity at 1000 °C. For the bulk material of the fin choose a metal alloy. Examples are Inconel (a chromium-nickel alloy for high temperatures), titanium or other steel alloys. Find a combination of active cooling (assuming a steady supply of air or water at room temperature through the cooling channels) and coating material (a ceramic, perhaps[1]), such that the maximum temperature of the blade remains below 300 °C under *steady-state* conditions. You can find estimates for the film coefficient under various conditions on the internet[2].

- What are the film coefficients you used (and why)? Do you require water cooling or is air sufficient?
- How does the coating affect the temperature, as opposed to using steel everywhere?
- How many elements did you use? Verify, by means of mesh refinement, that your solution is accurate.
- In your opinion, is the 2D model a fair approximation for the 3D situation or not? Under what conditions is the 2D model inadequate?
- Recall that we claimed that for the solution to be unique, we require at least one essential (i.e. fixed temperature) boundary condition. Here, we only applied convection. Why is convection sufficient for uniqueness of the solution? (Perhaps try to find the structural / mechanical boundary condition, that is equivalent to a convection boundary condition in thermal analyses.)
- Provide a plot of the steady-state temperature distribution.

2.2 Part 2: Cooling down

Starting from the previously computed steady-state temperature distribution, estimate the time required for the fin to cool down to below 50 °C, assuming that the active cooling found in Part 1 continues to circulate.

[1] Several metal alloys and ceramics are available in the *thermal materials* section of the material library. You can also search for the thermal properties of other alloys online.

[2] Heat transfer coefficients can be found for example here.

Hint 1: If you click-and-drag a transient thermal model onto the *solution* field of the solution of the previous steady-state thermal model, this solution will automatically be adopted as initial condition.

Hint 2: Play with the time stepping parameters in *analysis settings* → *auto time stepping on/off* → define *initial/min/max time step*.

Hint 3: If your time steps are small the output result file may become very large. In that case, you can go to *output controls* → *store results at* → *N equally spaced points*.

- How long does it approximately take for the fin to cool down?
- What time step size did you use? Verify, by altering the time stepping, that your solution is accurate.

2.3 Part 3: Cyclic load

Assume that, for whatever reason, the temperature of the steam inflow varies over time as follows:

$$T_{in}(t) = T_0 + \Delta T \sin\left(\frac{2\pi t}{D}\right) \tag{1}$$

where $T_0 = 800\,°\text{C}$, $\Delta T = 200\,°\text{C}$ and $D = 100\,\text{s}$. Hint: The *convection* boundary condition allows for the ambient temperature to be specified as a function of time. Use `time` to denote the time variable and `4*atan(1)` for the variable pi. Be careful that your input is consistent with the units of your simulation.

- What is the maximum temperature experienced by the bulk steel portion of the fin?
- What is the amplitude of the temperature variation over time?