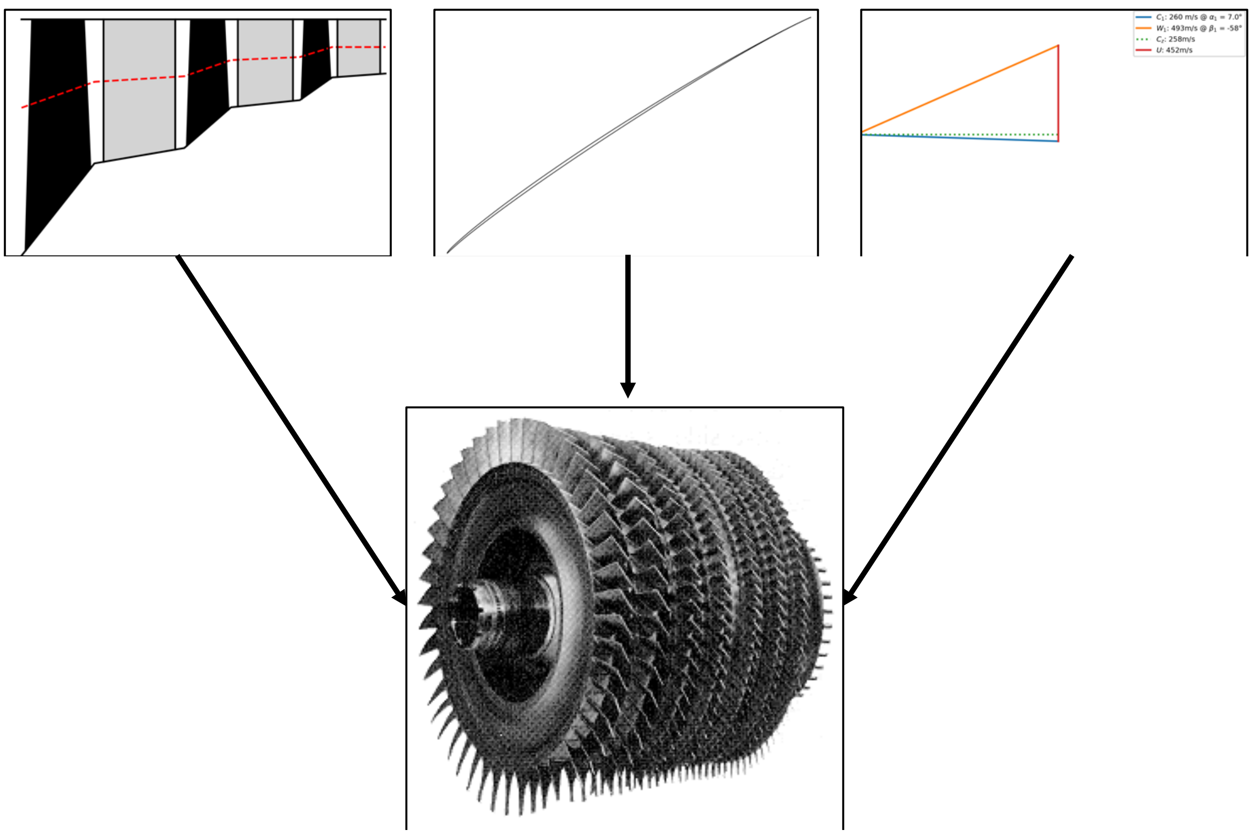
Turbomachinery prEliminary Design (TED)
User Manual



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How to run the program:

TED was originally written in MATLAB but was adapted to Python 3 for the public release. This was done so that the program can be open source and accessible to anyone for free. The current version is TED 1.0. This release only features compressor design infrastructure. Future versions may include disk design and turbine design infrastructure. The only requirements to run TED is python and a text editor. I recommend using the "Spyder" IDE that comes with the anaconda installation.

Designing a compressor:

To design a compressor a vars list must be created in order to outline some of the basic inlet conditions and requirements of the compressor.

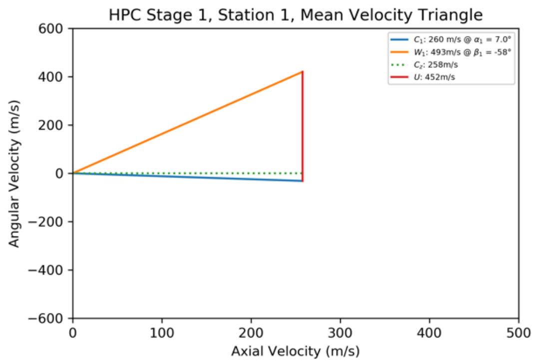
Variable Name	Allowed inputs	Description
radius_config	"TIP", "MEAN" or "HUB"	Which radius is held constant during design
IGV_config	"YES" or "NO"	Does the compressor have an IGV
turbo_type	"Fan", "LPC" or "HPC"	Type of compressor
free_vortex	"YES" or "NO"	Would you like the program to conduct a free vortex design to get blade design across the blade height?
units	"SI" or "ENGLISH"	Output figure and file units
n_stage	Any integer	Number of stages
gamma	Any integer	Specific heat ratio, typically 1.4 for air at SLS
R	Positive float	Gas constant, typically 287.05 for air
m_dot_in	Positive float	Entrance mass flow
Pt_in	Positive float	Entrance total Pressure
Tt_in	Positive float	Entrance total Temperature
PR_req	Positive float	Compressor pressure ratio requirement

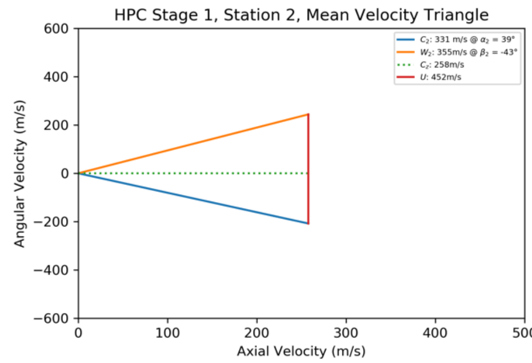
In addition to the inlet conditions and requirements, a few design choices must be made. To simplify the design, only the first and last stage design choices are required. The program will generate a linearly space vector based on these choices and the number of stages. This allows TED to estimate the design choices for each stage.

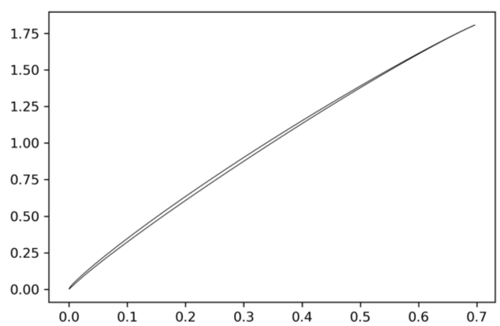
Variable Name	Allowed inputs	Description
hub_tip_ratio	0< float < 1	Inlet hub/tip ratio, typically around 0.3 for fans and 0.5 for HPC
M_in	0< float < 1	Inlet Mach Number, typically ~0.5
IGV_exit_angle	-30< float < 30	If no IGV this should equal 0
last_stage_exit_angle	-30< float < 30	Last stage exit angle, typically this should equal 0
deHaller_first_stage	0< float < 1	De Haller Number, typically >0.72
deHaller_last_stage	0< float < 1	De Haller Number, typically >0.72
diff_factor_rotor_first_stage	Positive float	1st stage rotor Diffusion Factor, typically around 0.45
diff_factor_rotor_last_stage	Positive float	Last stage rotor Diffusion Factor, typically around 0.45
diff_factor_stator_first_stage	Positive float	1st stage stator Diffusion Factor, typically around 0.45
diff_factor_stator_last_stage	Positive float	Last stage stator Diffusion Factor, typically around 0.45
reynolds_rotor_first_stage	Positive float	1st stage rotor Reynolds Number, typically greater than 5 E5
reynolds_rotor_last_stage	Positive float	Last stage rotor Reynolds Number, typically greater than 5 E5
reynolds_stator_first_stage	Positive float	1st stage stator Reynolds Number, typically greater than 5 E5
reynolds_stator_last_stage	Positive float	Last stage stator Reynolds Number, typically greater than 5 E5
w_r	Positive float	Loss Factor for Rotor
w_s	Positive float	Loss Factor for Stator

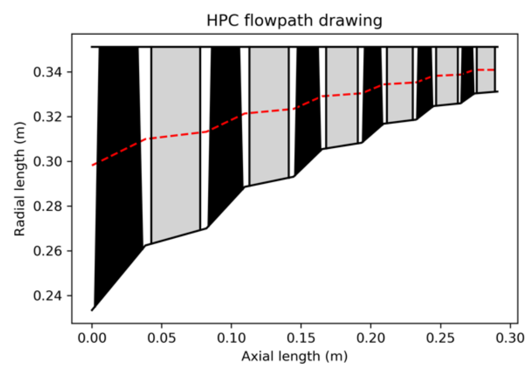
Once the vars list is set up with all of the variables above, change line 11 in the "compressor_test.py" and run "compressor_test.py". The program will iterate the compressor rpm until the compressor PR matches the required PR. The output of the program will be an excel file detailing the compressor parameters, dimensions, angles, etc.

Additionally, TED will generate and output the velocity triangles at station 1 and 2 of the compressor, a drawing of the mean line rotor airfoil section as well as a 2D flow path drawing. Examples of all 3 figures are shown below.

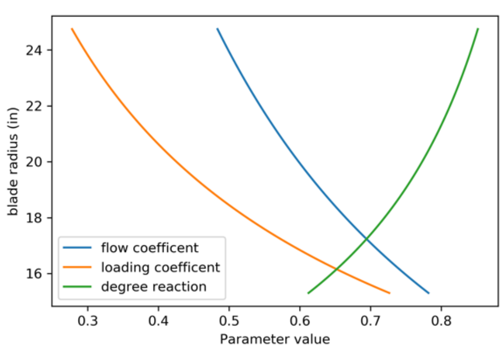


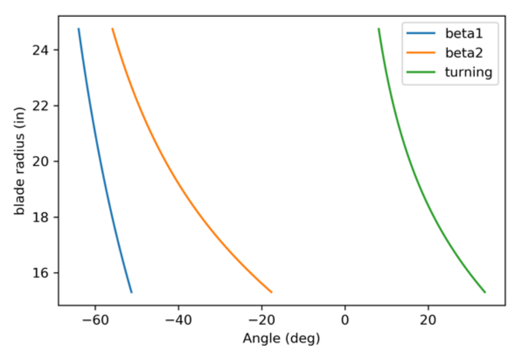






In addition, if the user specifies they want a free vortex design, TED will output figures showing the aerodynamic coefficients across the blade height and the rotor flow angles and turning for each stage. Examples of these figures are shown below.





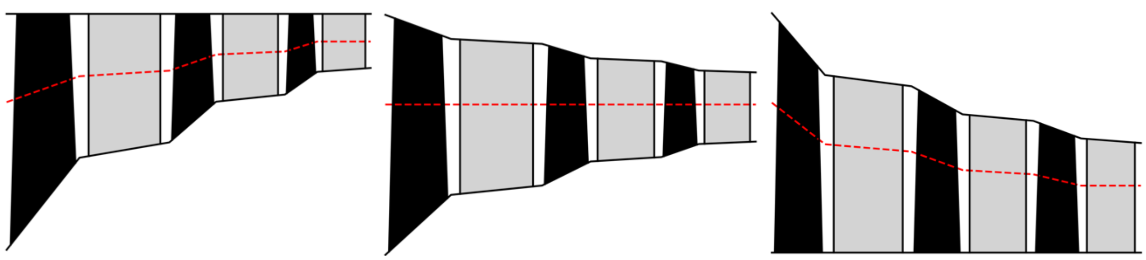
Calculations

TED deigns the compressor stage using the following inputs: γ, R, radius config, A_{in}, r_{in}, N_{rpm}, C_z, α_1, de Haller (DH), $T_{t\,in}$, α_3, df_r, df_s, $P_{t\,in}$, m_dot, Re_r, Re_s, V_trinangles, n_stage,turbo_type, units, w_r, w_s, free_vortex_input)

First, TED calculates the specific heat of the fluid based on γ and gas constant inputs:

$$c_p = \frac{R * \gamma}{\gamma - 1}$$

For an axial compressor design, there are typically 3 different configurations that may be chosen. Constant tip, constant mean and constant hub. They are shown below.



A user specifies the configuration and using the inlet area and a radius input, TED will calculate the remaining two radii using a variation of the equations below. The mean radius calculation is area based (the area from mean to tip is the same as the area from hub to mean).

$$A_n = \pi\left({r_{tip}}^2 - {r_{hub}}^2\right)$$

$$r_{mean} = \sqrt{\frac{({r_{tip}}^2 + {r_{hub}}^2)}{2}}$$

With the rotor entrance radii determined, the rotor hub to tip ratio, rotor blade height and stage mean line blade speed may be calculated from using the equations below.

$$h/t = \frac{r_{hub}}{r_{tip}}$$

$$h_{blade} = r_{tip} - r_{hub}$$

$$U_{blade} = r_{mean}\frac{\pi}{30}N_{rpm}$$

Using these calculations, the stage velocity triangles and aerodynamic coefficients may be calculated if α_1, α_3 and De Haller number are provided.

$$\phi = \frac{C_z}{U_{blade}}$$

$$\psi = 1 - \phi(\tan\beta_2 - \tan\alpha_1)$$

$$°R = \frac{1}{2} - \frac{\phi}{2}(\tan\beta_2 + \tan\alpha_1)$$

$$DH = \frac{W_2}{W_1} = \frac{C_z/\cos\beta_2}{C_z/\cos\beta_1} = \frac{\cos\beta_2}{\cos\beta_1}$$

$$W_x = C_z/\cos\beta_x$$

$$C_x = C_z/\cos\alpha_x$$

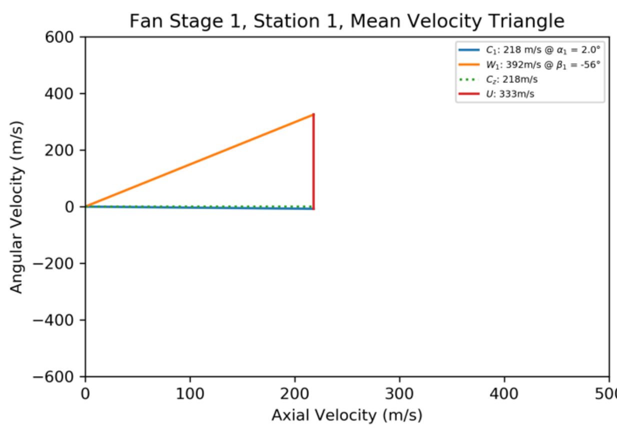
$$C_{\theta x} = C_z\tan\alpha_x$$

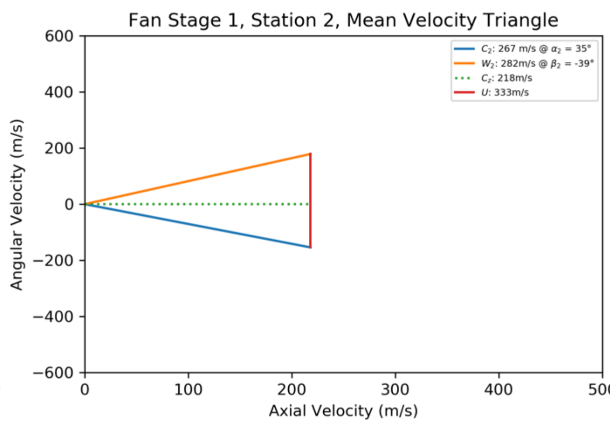
$$W_{\theta x} = C_z\tan\beta_x = C_{\theta x} - U_{blade}$$

$$\beta_1 = \tan^{-1}\left(\tan\alpha_1 - \frac{1}{\phi}\right)$$

$$\alpha_2 = \tan^{-1}\left(\tan\beta_2 + \frac{1}{\phi}\right)$$

Using the results from these calculations, TED will output figures showing the stage velocity triangles at the mean line for station 1 (rotor entrance) and station 2 (stator entrance).





The next step in the calculations is to determine the flow properties across the stage and determine the stage pressure ratio. Using the following equations, the relative and absolute frame MNs may be found. Additionally, the static and absolute stagnation temperatures are found.

$$T_{s1} = T_{t1\,abs} - \frac{{C_1}^2}{2c_p}$$

$$T_{t2\,abs} = T_{t1\,abs} + \frac{U^2\psi}{c_p}$$

$$T_{s2} = T_{t2\,abs} - \frac{{C_2}^2}{2c_p}$$

$$T_{t3\,abs} = T_{t2\,abs}$$

$$T_{s3} = T_{t3\,abs} - \frac{{C_3}^2}{2c_p}$$

$$a_1 = \sqrt{\gamma R T_{s1}}$$

$$MN_{abs\,1} = \frac{C_1}{a_1}$$

$$MN_{rel\,1} = \frac{W_1}{a_1}$$

$$a_2 = \sqrt{\gamma R T_{s2}}$$

$$MN_{abs\,2} = \frac{C_2}{a_1}$$

$$MN_{rel\,2} = \frac{W_2}{a_1}$$

The MNs and loss factors may be used to find the pressure at different stations using the equations below:

$$P_{s1} = \left(1 + \frac{\gamma - 1}{2} {MN_{1\,abs}}^2\right)^{\frac{-\gamma}{\gamma-1}} P_{t1}$$

$$P_{s2} = \left(1 + \frac{\gamma - 1}{2} {MN_{2\,rel}}^2\right)^{\frac{-\gamma}{\gamma-1}} P_{t2\,rel}$$

$$P_{t1\,rel} = \left(1 + \frac{\gamma - 1}{2} {MN_{1\,rel}}^2\right)^{\frac{\gamma}{\gamma-1}} P_{s1}$$

$$P_{t2} = \left(1 + \frac{\gamma - 1}{2} {MN_{2\,abs}}^2\right)^{\frac{\gamma}{\gamma-1}} P_{s2}$$

$$\varpi_{rotor} = \frac{P_{t2\,rel} - P_{t1\,rel}}{P_{t1\,rel} - P_{s1}}$$

$$\varpi_{stator} = \frac{P_{t3} - P_{t3}}{P_{t2} - P_{s2}}$$

$$P_{t2\,rel} = (P_{t1\,rel} - P_{s1})\varpi_{rotor} + P_{t1\,rel}$$

$$P_{t3} = (P_{t2} - P_{s2})\varpi_{stator} + P_{t2}$$

We could stop now since we have determined the stage pressure ratio but that is no fun. Let's define some more parameters of our compressor. We can determine the rotor and stator solidity using the flow angles and a diffusion factor choice

$$Rotor\ Diff\ factor = 1 - \frac{W_2}{W_1} + \frac{1}{\sigma_r}\frac{|W_{\theta 2} - W_{\theta 1}|}{2W_1} = 1 - \frac{\cos\beta_1}{\cos\beta_2} + \frac{1}{\sigma_s}\frac{\cos\beta_1}{2}(\tan\beta_2 - \tan\beta_1)$$

$$Stator\ Diff\ factor = 1 - \frac{C_3}{C_2} + \frac{1}{\sigma_s}\frac{|C_{\theta 3} - C_{\theta 2}|}{2C_2} = 1 - \frac{\cos\alpha_2}{\cos\alpha_3} + \frac{1}{\sigma_s}\frac{\cos\alpha_2}{2}(\tan\alpha_2 - \tan\alpha_3)$$

By assuming a Reynolds number for the rotor and stator, it is also possible to determine the mean line chord length for the blades as follows:

$$Re_r = \frac{W_1 \rho_1 b_r}{\mu}$$
$$Re_r = \frac{C_2 \rho_2 b_s}{\mu}$$

Density can easily be calculated using the static pressures and temperatures found above. Dynamic viscosity is a function of temperature:

$$\mu = \frac{0.000001458 * T^{3/2}}{(T + 110.4)}$$

In addition, the stator entrance and stator exit radii and areas may be found using conservation of mass and the equations above.

$$\dot{m} = \rho C_z A_n$$

Using the definition of solidity and the values for solidity and chord length we calculated earlier allows us to determine the number of rotor and stator blades.

$$\sigma = \frac{b}{s}$$
$$N_{rotor\ blades} = ceil(\frac{2\pi r_{m,1}}{s_r})$$
$$N_{stator\ blades} = ceil(\frac{2\pi r_{m,2}}{s_s})$$

Aspect ratio of the blades is simply the blade height over the blade chord:

$$AR = \frac{h}{b}$$

To be continued….