Process improvement in the Design and Development of Gas Turbine Rotor Disk

Subhash Gopi[1], Maharshi Reguri[2], HarshaVardhan Yeruva[3], Omprakash Adalam[4]

[1]Subhash Gopi, Division Manager, Cyient Ltd, Manikonda, Hyderabad, India.
[2]Maharshi Reguri, Senior Design Engineer, Cyient Ltd, Manikonda, Hyderabad, India.
[3]HarshaVardhan Yeruva, Senior Design Engineer, Cyient Ltd, Manikonda, Hyderabad, India.
[4]Omprakash Adalam, Division Manager, Cyient Ltd, Manikonda, Hyderabad, India.

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Abstract - *Turbine and compressor disks with Airfoil blades are the critical components of Gas turbine engines as they play a vital role in engine performance. Structural strength and integrity at different rotating speeds and temperatures in operating conditions are essential for the better service life of these disks. The first step in the Design and Development of a Rotor Disk is an iterative concept design phase using CAD (Computer-Aided Design) software followed by a validation process with FEA (Finite Elemental Analysis) software to meet its structural integrity requirements. The paper aims to demonstrate the process improvement using a less iterative automation approach over the mentioned conventional approach in developing the final CAD geometry concept that is structurally and thermally viable.*

The automation tool interpolates the intermediate radial points (also referred to as radial stations) from the given input design parameters required for precise mapping of the elastic stresses developed in the disk. It calculates elastic tangential and radial stresses in the disk using the inbuilt mathematical equations at each radial station. All the governing equations for elastic stresses are taken from the classic "Manson method" [1] to calculate elastic stresses in the rotating disk. Design iterations are carried out using the tool by changing the input design parameters to validate the stresses at each radial station and finalize the design concept. The validated input geometrical parameters are exported to CAD to build a final optimized design concept. Final stress variation contour plots and critical results are generated in the tool dashboard. It saves almost 80% of design and developmental efforts as compared to the conventional approach.

***Key Words*: Rotor Disk, Gas turbine engine, Elastic stresses, Automation, Design Concept, CAD, FEA**

1. INTRODUCTION

In product development, CAD geometry for the Gas turbine Rotor Disk part is derived through an iterative concept design process. It needs a detailed structural and thermal evaluation to freeze the design concept that can withstand all the induced stresses in the component during field operation. The paper aims at bringing out an alternative efficient option to reduce the lead time in the concept development of the Gas turbine disk.

Firstly the geometrical and design parameters of the compressor or turbine disk are populated in the Automation tool that generates several interpolated points. The tangential and radial stresses are calculated using the "Manson equations" [1] at each interpolated radial point also called the Radial stations. The resultant stress at each Radial station is validated with allowable stress criteria for the Structural and Thermal integrity of disks from the inbuilt equations. Once all the interpolated points are validated, the finalized geometrical parameters related to the validated interpolated points are further taken as inputs to generate the CAD model from the Automation tool. It eliminates the iterative process of modeling and analyzing using CAD and FEA software, thus reducing overall turnaround time, cost and making it more productive.

Figure 1 shows the conventional and current improvised process approach of Rotor Disk concept design to generate the CAD Geometry.

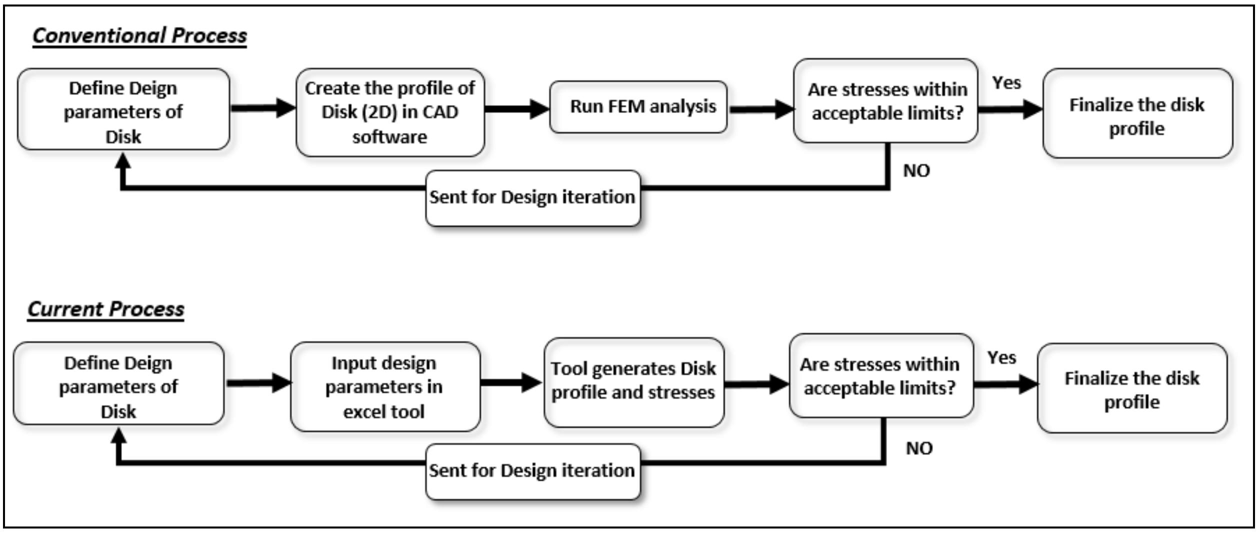


Figure 1: Conventional and Current improvised process approach of Disk Concept Design

2. METHODOLOGY

Turbine and compressor disks of a Gas turbine need to be structurally viable as their failure in service could result in severe engine damage. So determination and validation of stresses in the disk under operating conditions play an important role in the design of disks. The concept building stage in disk design requires numerous iterations and may consume a lot of time in extracting the results for each iteration. The Automation tool developed can calculate the stresses in the disk at various radial locations from bore to rim. So let's understand the Disk configurations, Design parameters, and the Governing equations used from the Manson method [1] of elastic stresses calculation for Disks. In the later section, we will look into the results and validation to build an optimized Disk concept.

Disk design configurations as shown in Figure 2 are of three major types [2], which are also considered in designing the tool:

1. Web disk
2. Hyperbolic disk
3. Ring disks

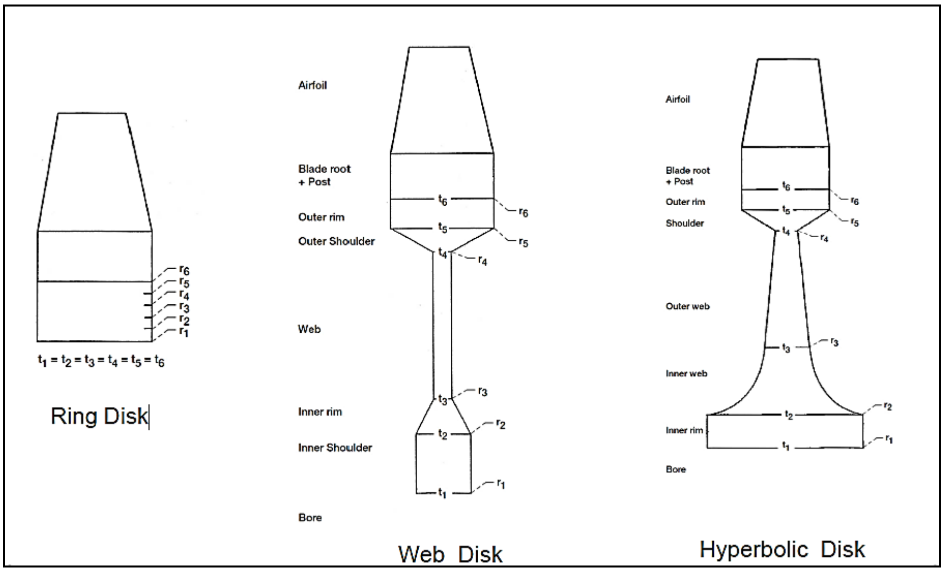
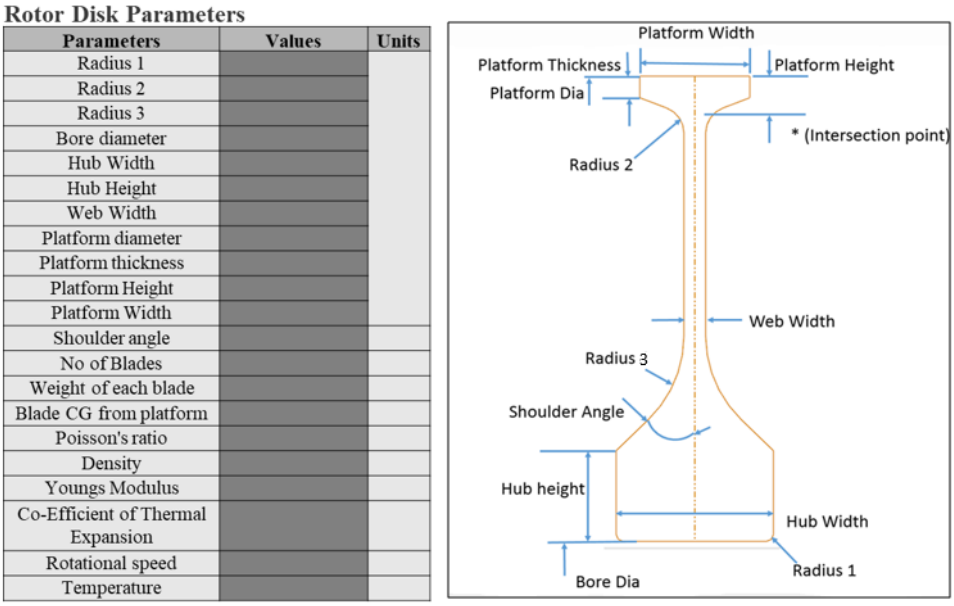


Figure 2: Disk configurations used for the tool

The developed automation tool has an inbuilt baseline disk geometry selection option as per Figure 2. All the Geometric design parameters and Dimensions are reflected as input fields in the tool based on the disk type selection as shown in Figure 3. Users can pick the disk type and give the necessary designer inputs as per the Design requirement.

Figure 3 shows all the primary inputs with the feasibility of picking the necessary units. The parameters are related to the disk critical dimensions, blade parameters, material properties, rotational speed, and temperatures. All the Disk design parameters fed here in turn feed the governing equations as inputs in Figure 4 which calculates the Radial (σ_r) and Tangential stresses (σ_t) at each radial station location (n). The station location (n) is derived from interpolated data using trigonometric functions and the baseline geometric parameters. The tool also has the option to give temperature inputs at each station location shown in Figure 3 which helps in building not only structural but even a thermally viable Disk design concept.


Rotor Disk Parameters

Parameters	Values	Units
Radius 1		
Radius 2		
Radius 3		
Bore diameter		
Hub Width		
Hub Height		
Web Width		
Platform diameter		
Platform thickness		
Platform Height		
Platform Width		
Shoulder angle		
No of Blades		
Weight of each blade		
Blade CG from platform		
Poisson's ratio		
Density		
Youngs Modulus		
Co-Efficient of Thermal Expansion		
Rotational speed		
Temperature		

Figure 3: Design input parameters for Disk Creation

The tool uses the Manson method [1] governing equations which are finite-difference formulations to calculate the Tangential and Radial stresses in a rotating disk. In a thin rotating disk of variable thickness, the state of stress at any radius can be completely defined by the two principal stresses, the Radial (σ_r) and Tangential (σ_t) stresses. Below are the two fundamental governing equations used to derive the two unknown stresses from the Manson approach [1].

$$\frac{d}{dr}(rh\sigma_r)-h\sigma_t+\rho\omega^2 h*r^2=0$$

$$\frac{d}{dr}\left(\frac{\sigma_t}{E}\right)-\frac{d}{dr}\left(\frac{\mu\sigma_t}{E}\right)+\frac{d}{dr}(\alpha\Delta T)-\frac{(1+\mu)(\sigma_r-\sigma_t)}{Er}=0$$

Note: See the Details of the Symbols used above in Figure 4

The first of these above equations can be obtained from the conditions of equilibrium of an element of the disk; the second is from the compatibility conditions, which are mathematical statements of the interrelation between the radial and tangential strains in a symmetrical disk. The equilibrium and compatibility equations result in differential form defining relations between the stresses at disk radius r and those at a radius infinitesimally removed from r. To facilitate a solution, the differential equations are rewritten in the finite-difference equations shown in Figure 4 to arrive at the elastic stresses at each radial location r (also referred to as radial stations in the tool).

To derive these radial locations and use the governing finite-difference equations in the tool, the baseline geometric 2D profile of the disk is divided into several incremental interpolated radial points. These “n” number of points at incremental radial heights are used as inputs to the governing Manson’s finite-difference equations to calculate the stresses at each radial location.

Now all governing finite-difference equations are used in the Automation tool to calculate elastic Radial and Tangential stresses as shown in Figure 4 at all the "n" radial stations. These stresses with interpolated points are mapped as results by the tool which would be explained in the next result section.

Description	Symbols (as per Manson Method)	Input Details (Description & Derived Finite-difference Equations)
Primary Inputs	n	n^{th} Radial Station
	a	Station Location at Bore (first radial station)
	b	Station Location at Platform or Rim (last radial station)
	r_n	Radius @ n^{th} radial station
	h_n	Width @ n^{th} radial station
	$\rho_n \omega^2$	Density x (Angular speed)^2
	μ_n	Poissons ratio
	E_n	Youngs Modulus
	α_n	Co-efficient of Thermal Expansion
	ΔT_n	Temperature Difference
Derived Inputs from Mathematica Equations @ each station loaction (from Manson method)	C_n	$r_n h_n$
	D_n	$(1/2)*(r_n-r_{n-1})h_n$
	F_n	$r_{n-1}*h_{n-1}$
	G_n	$(1/2)*(r_n-r_{n-1})h_{n-1}$
	H_n	$(1/2)*\omega^2*(r_n-r_{n-1})(\rho_n h_n r_n^2+\rho_{n-1}h_{n-1}r_{n-1}^2)$
	C'_n	$((\mu_n)/E_n)+((1+\mu_n)(r_n-r_{n-1}))/2E_n r_n$
	D'_n	$(1/E_n)+((1+\mu_n)(r_n-r_{n-1}))/2E_n r_n$
	F'_n	$((\mu_n-1)/(E_n-1))+((1+\mu_{n-1})(r_n-r_{n-1}))/(2E_{n-1}r_{n-1})$
	G'_n	$(1/(E_{n-1}))-((1+\mu_{n-1})(r_n-r_{n-1}))/(2E_{n-1}r_{n-1})$
	H'_n	$(\alpha_n \Delta T_n)-(\alpha_{n-1}\Delta T_{n-1})$
	K_n	$((F'_n D_n-F_n D'_n)/(C'_n D_n-C_n D'_n)$
	L_n	$(-(G'_n D_n+G_n D'_n)/(C'_n D_n-C_n D'_n))$
	K'_n	$((F'_n C_n-F_n C'_n)/(C'_n D_n-C_n D'_n)$
	L'_n	$(-(C'_n G_n+C_n G'_n)/(C'_n D_n-C_n D'_n))$
	M_n	$(H'_n D_n+H_n D'_n)/(C'_n D_n-C_n D'_n)$
	M'_n	$(C'_n H_n+C_n H'_n)/(C'_n D_n-C_n D'_n)$
	$A_{r,n}$	$(K_n*A_{r,n-1})+(L_n*A_{t,n-1})$; *where* $A_{r,a}=0, A_{t,a}=1$
	$A_{t,n}$	$(K'_n*A_{r,n-1})+(L'_n*A_{t,n-1})$
	$B_{r,n}$	$(K_n*B_{r,n-1})+(L_n*B_{t,n-1})+M_n$; *where* $B_{r,a}=B_{t,a}=0$
	$B_{t,n}$	$(K'_n*B_{r,n-1})+(L'_n*B_{t,n-1})+M'_n$
	$\sigma_{t,a}$	$(\sigma_{r,blades}-A_{r,b})/(B_{r,b})$

Where: $\sigma_{r,blades}$ =Radial stress due to blade load
=Centrifugal force due to mass of Blades/Peripheral area of Rim
=(M*Rcgb*ω^2)/(2*PI()*Thickness of Rim *Radius of Rim)

M=Total Mass of blades.
Rcgb=Center of Gravity of blades in radial direction from center line.
ω= Angular speed of rotation of blades.

Final Stress Results @ each Station location	
Radial Stress (σ_r)	$A_{r,n}\sigma_{t,a}+B_{r,n}$
Tangential/Hoop stress (σ_t)	$A_{t,n}\sigma_{t,a}+B_{t,n}$

Figure 4: Radial and Tangential (Hoop) Stress derivation at each Station location

3. RESULTS AND DISCUSSIONS

The derived interpolated points at each radial location (n) play a critical role in building the optimized final design concept. The tool calculates stresses at each radial station and validates them against baseline allowable stress limits. Multiple iterations can be carried out with a click by changing the basic geometrical parameters earlier shown in Figure 3, which in turn generates a new set of interpolated coordinates with stress results. This flexibility to change the design parameters to get the results in a quick turnaround makes the process effective. The output Disk coordinates are captured and the stress magnitude is mapped across the radial stations as shown in Figure 5. The magnitude of the stress plots is checked for the allowable stress margin before finalizing the design. Once the designer meets the targeted geometrical and stress margins he could freeze the concept and export the geometric parameters to CAD Software for building the final CAD model.

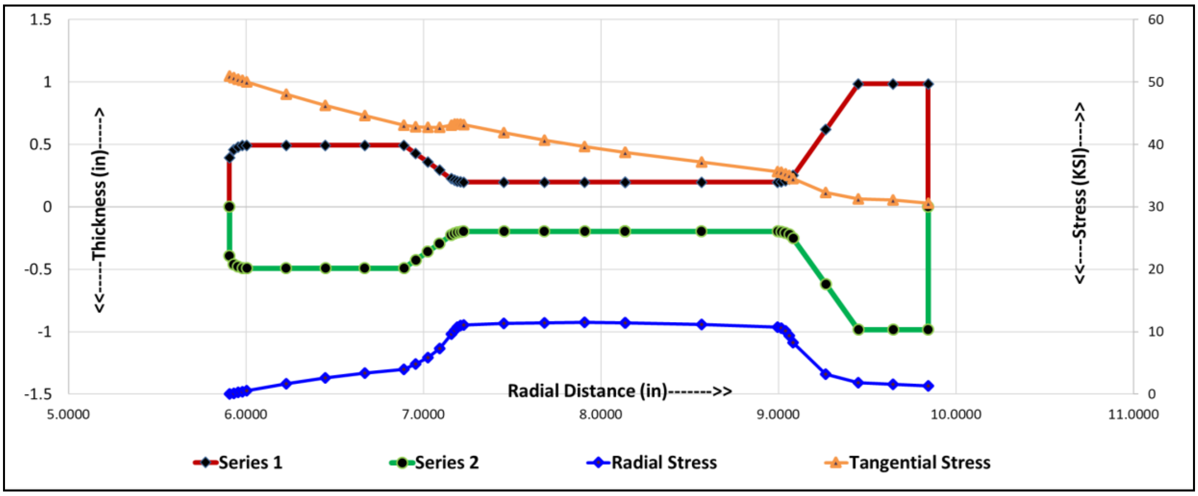


Figure 5: Interpolated Disk Radial stations (points) with Radial and Tangential Stress plots

Critical stress results are extracted from the stress contour in Figure 5. Along with the profile, the weight of the disk is also generated by the tool which is also a necessary attribute to freeze the concept. The consolidated report enables the designer to make a final decision on freezing the concept before exporting it to CAD to build an optimized concept model.

3.1 Final Concept Building in CAD

Once we are good with the geometry and the stress margins next step is to derive the CAD geometry using the finalized geometric parameters. NX CAD sketch followed by final design 3D concept generated by importing finalized design parameters from the tool as expression as shown in Figure 6 and Figure 7. As you notice that it is just a few clicks and one time job after the tool validation is completed.

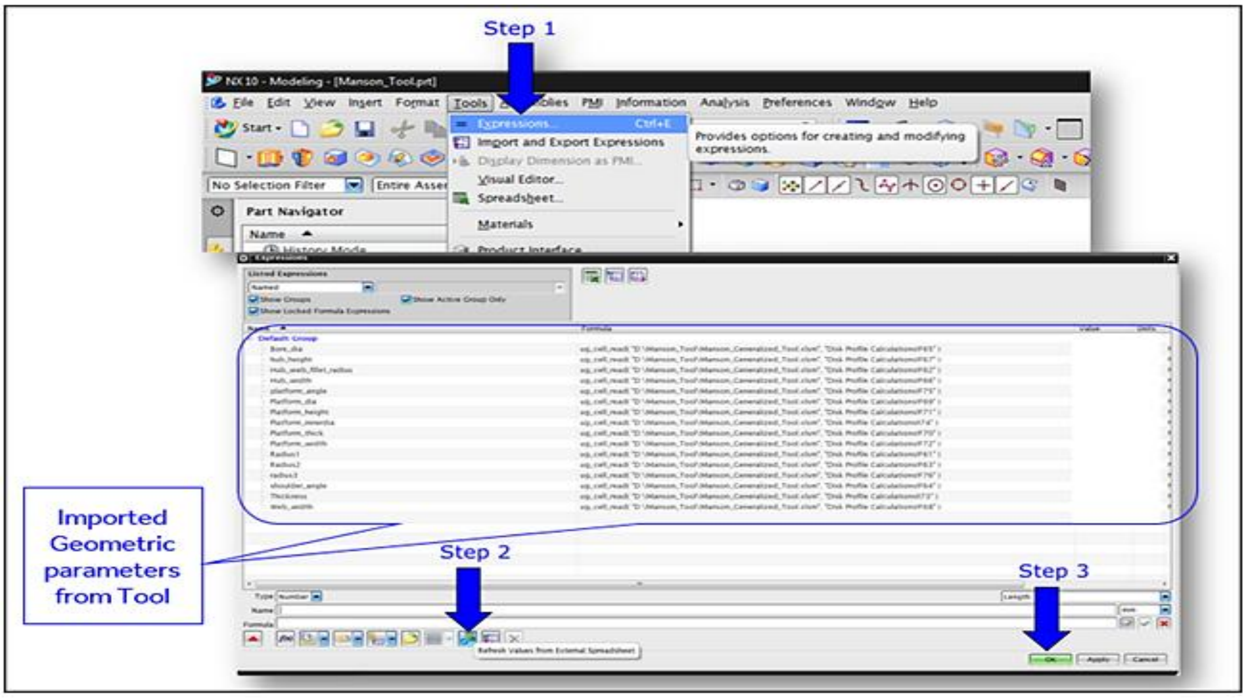


Figure 6: Importing of finalized Tool Geometric Parameters (Dimensions) to CAD (NX) Software

Expression Import: open NX file → Tools → Expressions → Refresh values from the external spreadsheet

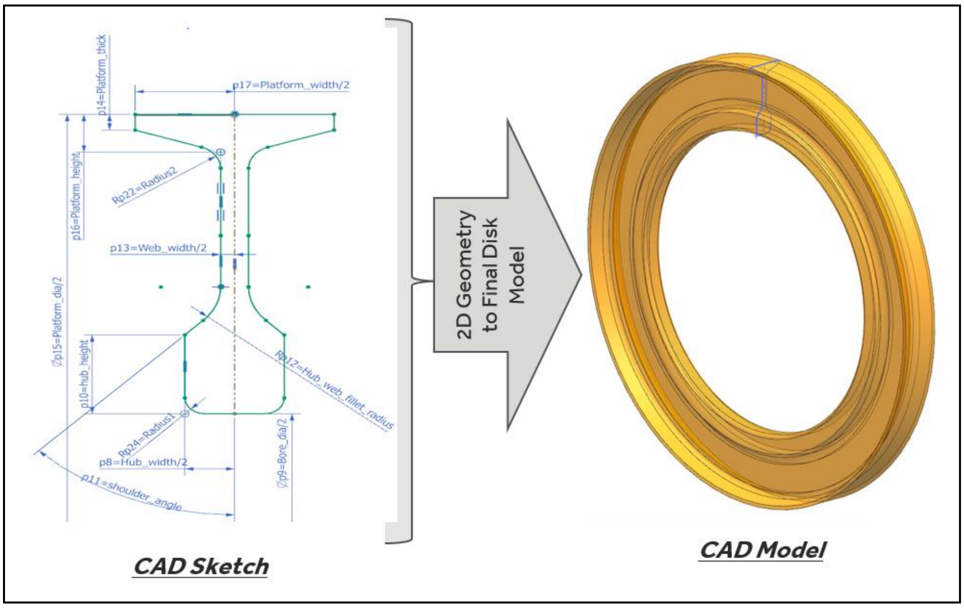


Figure 7: Derived CAD (NX) Geometry from imported tool Design Geometric Dimensions

3.2 Resultant Process Improvement and Value addition

As a result of the new process, we could now improve productivity by approximately 80% compared to the conventional design process. Figure 8 shows the detailed comparison of improvised process steps over the conventional approach. The given process is for one iteration and in real-time disk concept design, number of iterations have to be performed to finalize the design parameters which adds further cost savings and productivity.

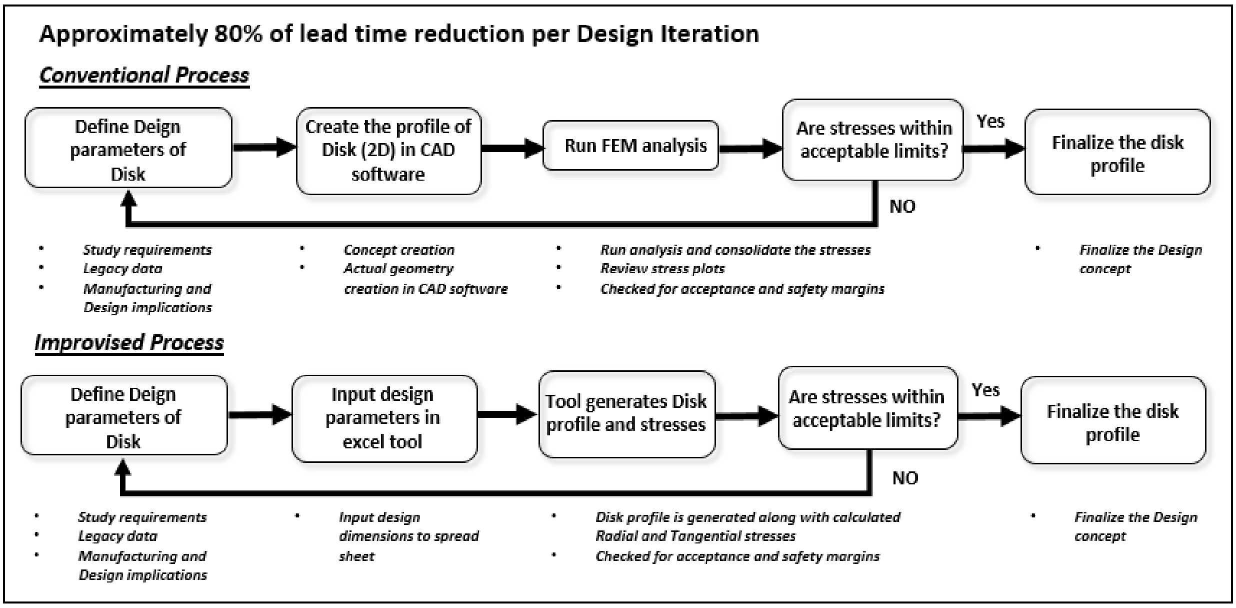


Figure 8: Productivity savings of Approx. 80% with improvised process

4. CONCLUSION

Automation of design process flow brings up great productivity for the Design engineers. The paper has attempted to bring one such automation of the Gas turbine Disk Design that could generate approx. 80% of productivity savings for each design iteration. As the design process is iterative in nature the total productivity savings multiply with each design iteration. The automation gives great flexibility to Designers for a better solution in quick turnaround time and increases productivity.

By viewing the output stresses across the radial station and critical stresses in the Dashboard, the designer can make quick decisions about finalizing the design concept. CAD models are built without switching from FEA to CAD software each time. Once the designer is satisfied with the output of the tool, he can use the geometric parameters to generate the final baseline CAD model in just a few clicks.

The tool is validated by comparing the results with actual structural analysis results and both are almost matching with a negligible 2% deviation which is within the allowable Margin Of safety (MOS) requirements for the Disk design. The automation tool makes the Disk design simple, economic, productive, and designer-friendly.

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BIOGRAPHIES

Overall 17+ years of experience in the field of Engineering Design and development of Commercial Gas Turbine, Industrial gas turbines, Aero Engine Test Rigs, Aero structure assemblies & Reverse Engineering projects.

10.5 years of experience in detail design and engineering of commercial aero engines. Creating component Manufacturing drawings, Assembly drawings and Layout drawings.

Having 5.5 years of experience in the field of Engineering Design and development involving in Design, Modeling, Assembly and Drafting of Gas Turbine Engine Components.

Overall 17+ years of experience in the field of Engineering Design and development of Commercial Gas Turbine, Industrial gas turbines, Aero Engine Test Rigs, Aero structure assemblies & Reverse Engineering projects. Experience in Automation using ML,AI, NLP, Artificial neural networks with PYTHON programming language.