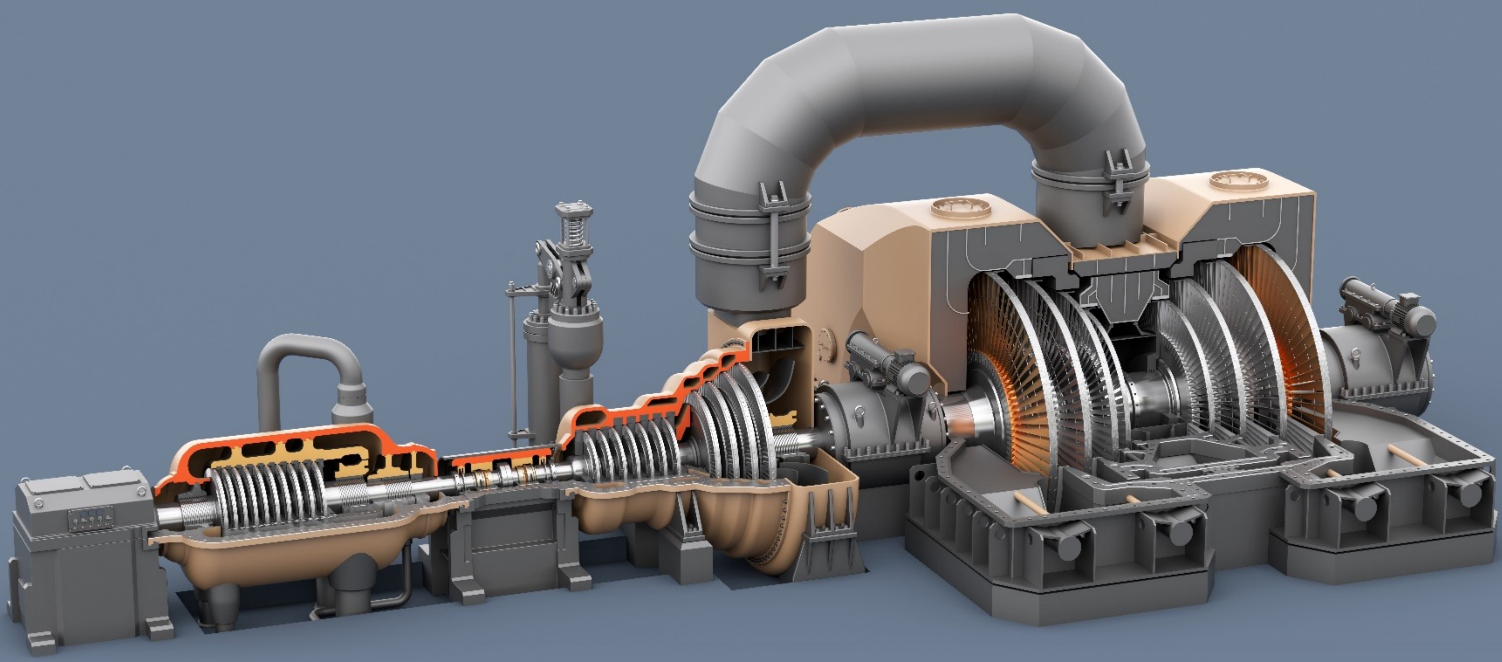
PIPING LOAD OPTIMIZATION ON TURBINE CASINGS

An efficient method for solving an optimization problem of pipe forces on machinery with the use of Finite Element Methodology and Monte Carlo Simulation Techniques



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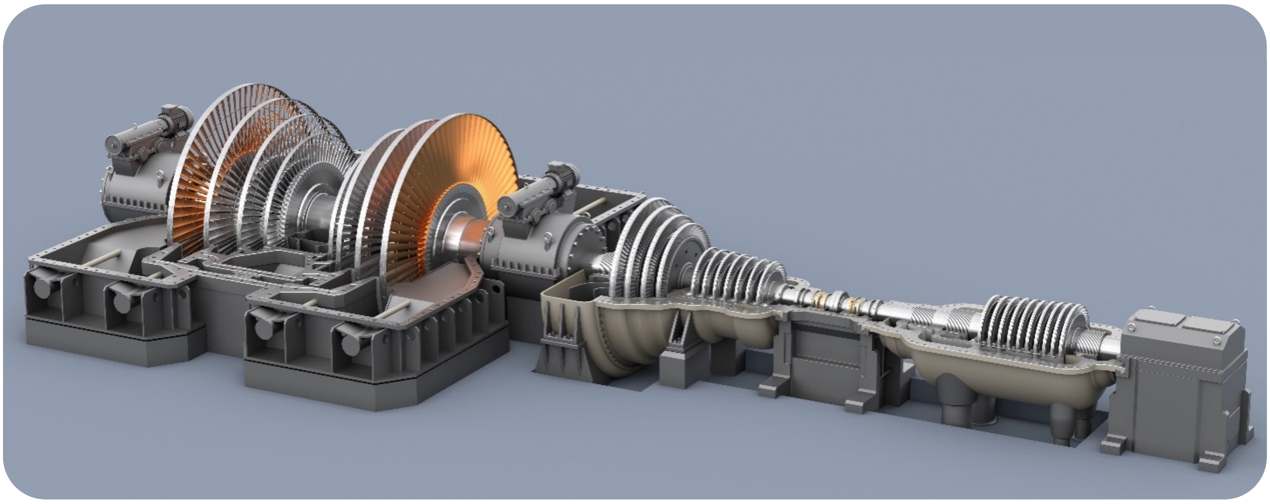
Abstract

In engineering design projects, components are often outsourced to contractors. For steam turbines, this includes piping system, which must not distort the turbine casing due to forces and moments applied at the flanges. Given the complex forces in multiple directions, determining critical load cases analytically poses significant challenges. To address this, a statistical approach defines allowable force limits, ensuring structural integrity. A transfer function for casing displacements was developed by analyzing unit forces and moments on each pipe, enabling the combined response to mixed forces using a spreadsheet model based on linear elastic behavior. This tool validated through finite element analysis (FEA), was further optimized with Monte Carlo simulations, offering a fast and cost-effective alternative to traditional deterministic FEA approach. The approach maximizes permissible loads while maintaining casing integrity, streamlining analysis and design processes.

Introduction

Piping is an integral element in steam turbine power plants, transporting steam from boilers to turbine inlets and redirecting it from outlets to re-heaters, condensers and other equipment. These pipes exert significant forces and moments on the turbine casing in 3 principal directions. It is the turbine designer's responsibility to define allowable limits for these forces and moments, ensuring they do not cause excessive distortion and stress to the casing and joints.

When piping systems are outsourced to third-party contractors, these limits must be clearly communicated. Forces and moments imposed on turbine casing by external piping systems are constrained by turbine distortion limits, and in some cases, stress thresholds. Distortions in the casing can misalign the rotor, both during cold and operational conditions. The shell distortion has to be maintained within the specific limits by limiting the piping forces. Appropriate analysis can help maximize these limits, enabling third-party suppliers to design compliant piping systems without compromising turbine performance.



Theory

Due to the complexity of forces and moments generated by multiple large pipes in three principal directions, calculating the maximum allowable pipe forces analytically is impractical. A statistical method is therefore required to define the permissible range of forces while preventing casing distortion.

A transfer function for casing displacements was developed by analyzing the effect of unit forces and moments on each pipe. Axial, vertical, and, transverse deflections from these unit loads were tracked at key points on the casing. Assuming linear elastic behavior, these deflections were used to create a load/deflection transfer function in a spreadsheet, enabling quick calculations for combined forces. Microsoft Excel was employed for this analysis and henceforth be referred to as “the spreadsheet”.

Principle of Superposition

The principle of superposition, a foundational concept in mechanics, states that the resultant deflection from multiple simultaneous loads can be determined by summing the deflections caused by each load individually. This principle applies to linear systems where deflections and rotations remain small, ensuring that Hooke’s law holds and the load-deflection relationship remains linear.

In the context of piping load analysis, the principle allows for the decomposition of complex loading scenarios into simpler cases. These individual deflections are calculated and then superimposed to obtain the total deflection. For example, in a cantilever beam subjected to multiple loads, the resultant deflection is the algebraic sum of the deflections caused by each load, provided the loads and their effects remain within the linear elastic range. The illustration below further sheds light on the use of the principle of superposition for calculating the deflections of beams. For instance, let us assume a beam subjected to loads P1 and P2 simultaneously as shown below figure (1)

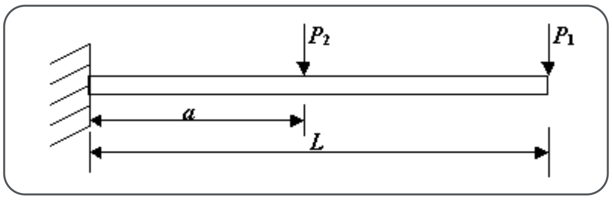


Figure1: A simple cantilever beam with two-point loads

From the principle of superposition, we can split the combined load on beam into two individual loads as shown below figure (2).

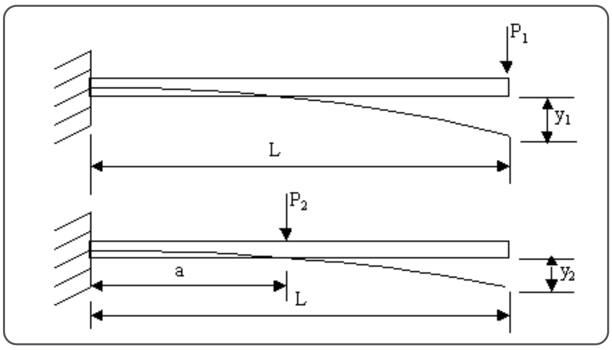


Figure2: Deflections due to individual loading

We can then calculate the deflection at the free end of the beam due to load P1 alone as

$$\boxed{y_1 = \frac{P_1 L^3}{3EI}}$$

And deflection at free end due to load P2 alone as

$$\boxed{y_2 = \frac{P_2 a^2 (3L - a)}{6EI}}$$

And the method of superposition says that the resultant deflection from these two individual loads is simply the algebraic sum of individual loads, as shown in below figure (3). Resultant deflection due to combined loads is given below

$$y = y1 + y2 = \frac{P_1 L^3}{3EI} + \frac{P_2 a^2 (3L - a)}{6EI}$$

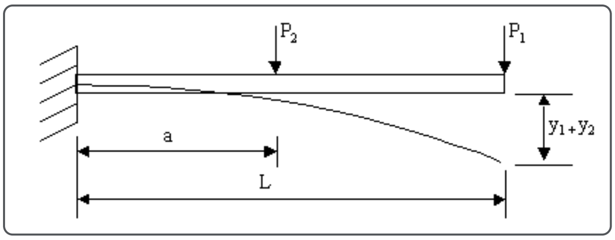


Figure3: Deflection due to combined loading

Procedure

To analyze the turbine casing, unit forces and unit moments were applied independently on each pipe. The total number of unit load cases equals 6 (Number of pipes), representing three forces and three moments for each pipe in the principal directions. The following values were used for unit loading:

- Unit Force Load = 10000 lbs.
- Unit Moment Load = 420000 lb-ft

The following figure (4) shows a typical casing with pipe and the application of unit loading on a casing with the help of rigid links created at the center of the pipe.

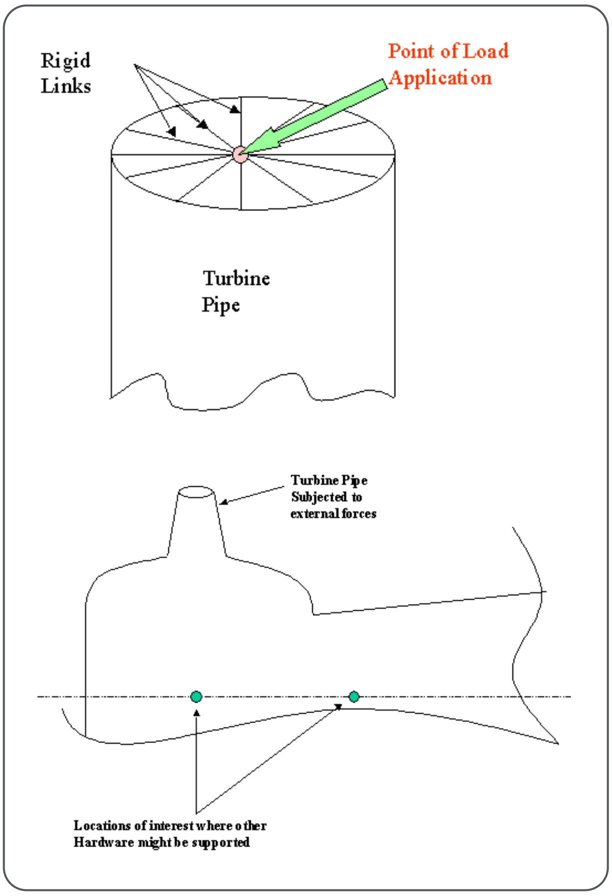


Figure4: Casing with a pipe and application of load on a pipe

The casing was analyzed under these unit loads, and the resulting axial, vertical and transverse deflections were measured at predefined points using FEA. Assuming linear elastic behavior, these results were used to construct a load / deflection transfer function in the spreadsheet. This transfer function enables rapid calculation of casing deflections for any combination of forces and moments.

The following equation shows the load/ deflection transfer function at any point "A" for one pipe.

$$\Delta_A = F_X \times \delta_A^{UF_X} + F_Y \times \delta_A^{UF_Y} + F_Z \times \delta_A^{UF_Z} + M_X \times \delta_A^{UM_X} + M_Y \times \delta_A^{UM_Y} + M_Z \times \delta_A^{UM_Z}$$

Where, Δ_A	Total Deflection at Point A
F_X, F_Y, F_Z	*Forces in 3 principal directions*
M_X, M_Y, M_Z	*Moments in 3 principal directions*
$\delta_A^{UF_X}, \delta_A^{UF_Y}, \delta_A^{UF_Z}$	*Deflections at point A due to unit forces in X, Y, Z directions*
$\delta_A^{UM_X}, \delta_A^{UM_Y}, \delta_A^{UM_Z}$	*Deflections at point A due to unit moment loads in X, Y, Z directions*

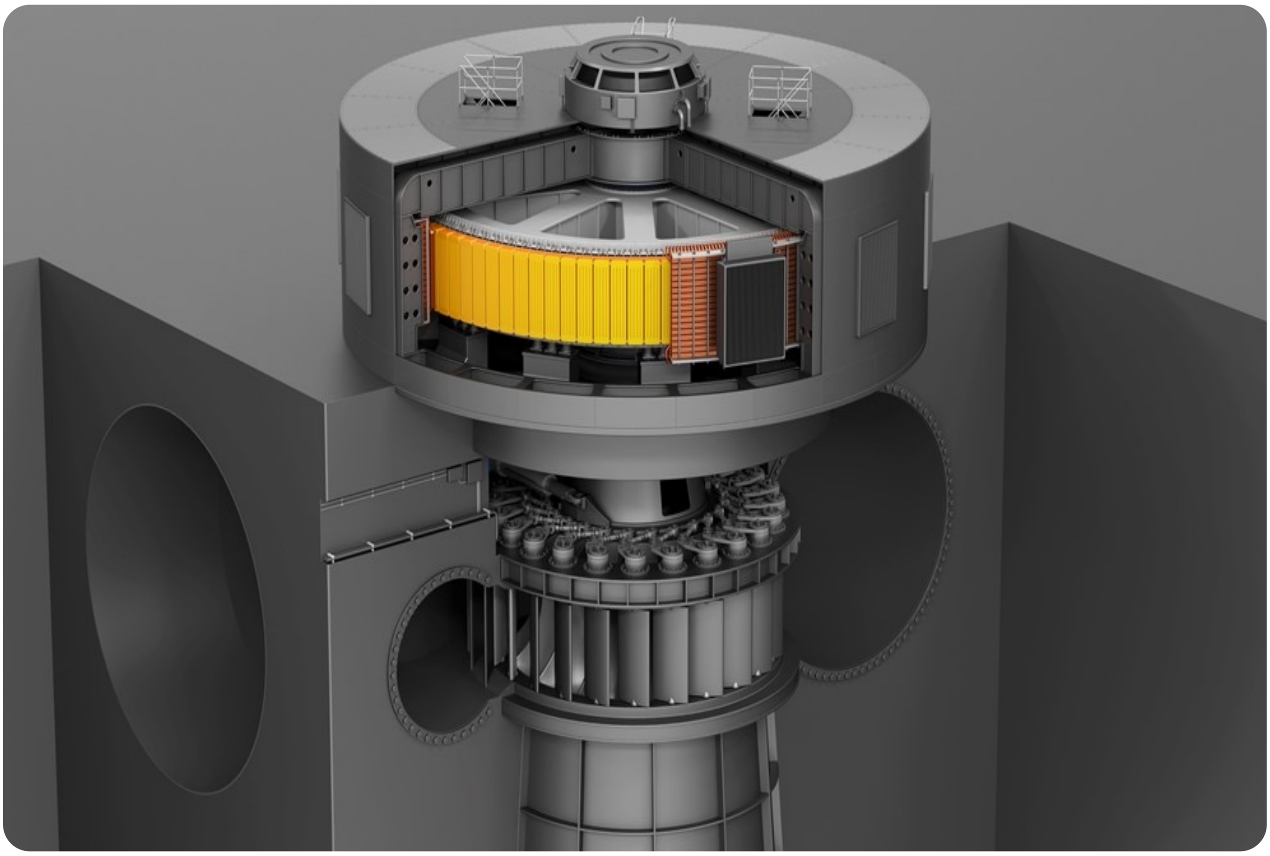
Number of terms in the load/deflection transfer function depends on the number of nozzles the turbine has i.e. 6 Number of nozzles.

Validation runs confirmed that the spreadsheet's predictions aligned closely with FEA results, typically showing errors of less than 1%. This accuracy ensures that the spreadsheet tool is a reliable and efficient method for calculating deflections under complex loading scenarios.

INPUT				
Load	Nozzle-1	Nozzle-2	Nozzle-3	Nozzle-4
fx	13456	12000	9807	1000
Fy	7900	5200	7658	12000
Fz	7500	3456	5678	9000
Mx	25125	23653	50000	32561
My	42000	4567	1258	25412
mz	5678	7689	42000	8963

OUTPUT		
Location on the Shell	**Vertical Deflection**	**Transverse Deflection**
Location 1	0.0011	0.0016
Location 2	0.0017	0.0019
Location 3	0.0019	0.0023
Location 4	0.0020	0.0031
Location 5	0.0010	0.0013
Location 6	0.0009	0.0011

Figure5: Input and output for a typical Spreadsheet tool.



Monte Carlo Simulations

Monte Carlo simulations were employed to address uncertainties in force and moment ranges, providing a robust statistical framework for optimization. Unlike deterministic analysis, which evaluates a single scenario, Monte Carlo simulations generate thousands of random scenarios to assess the impact of uncertain variables on the system.

Monte Carlo simulation derives its name from Monte Carlo, Monaco, famed for its casinos and games of chance. Games such as roulette wheels, dice, and slot machines exhibit random behavior. This randomness mirrors how Monte Carlo simulation selects values for variables at random to simulate a model. For example, when rolling a die, the outcome is always one of six possibilities, but the specific result is unpredictable. Similarly, variables with defined ranges but uncertain exact values behave in a comparable way in the simulation.

Crystal Ball:

Crystal Ball Standard is an intuitive simulation program that helps analyze risks and uncertainties in Microsoft Excel spreadsheet models. Excel models are inherently deterministic, meaning inputs are fixed to single values per cell, allowing only one solution to be viewed at a time. For alternative results, manual changes to inputs are required.

Crystal Ball extends Excel's capabilities by enabling rapid simulations of numerous potential outcomes. While Excel cannot run on simulations without extensive macro coding, Crystal Ball provides an efficient alternative. It allows for hundreds or even thousands of simulation trials to be conducted in minutes.

During a single trial, Crystal Ball randomly selects values for uncertain variables – such as forces and moments - based on their defined range and probability distribution. The spreadsheet then recalculates results for the chosen scenario, providing a comprehensive analysis of potential outcomes.

Defining Assumptions:

The first step in using Crystal Ball is identifying uncertain model inputs and assigning profitability distributions to them. For each uncertain variable, such as forces or moments, the possible range (of values is defined.. The type of probability distribution is selected based on the variable's conditions.

Distribution types include:

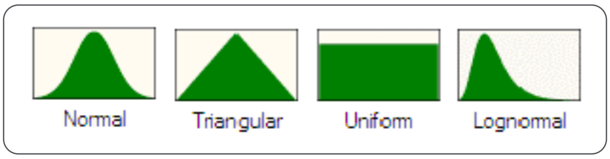


Figure 6: Types of distributions for uncertain variables

In this analysis, a uniform distribution was chosen, where all values between the minimum and maximum are equally likely to occur. Uniform distribution, assumes the following:

- The minimum value is fixed.
- The maximum value is fixed.
- All values within the range are equally likely .

This assumption simplifies the modeling process while ensuring accurate representation of input variability.

Defining Target Forecasts:

A forecast is a formula cell in the spreadsheet representing the output to be analyzed – such as the deflection at a specific point of interest. The coded load / deflection transfer function in spreadsheet calculates these values dynamically.

Multiple assumptions (uncertain inputs) and forecasts (outputs) can be defined. Once these parameters are set, the number of simulation trials is chosen, ranging from hundreds to several thousand, depending on the required accuracy and computational resources.

Simulation Results

The simulation was run for **50,000 trials;** resulting in 50,000 forecasts. Results were displayed in the form of interactive histograms(frequency charts), providing a clear visualization of deflection distributions. The below figure shows the results of 50,000 trials of our piping analysis at one of the targets forecast.

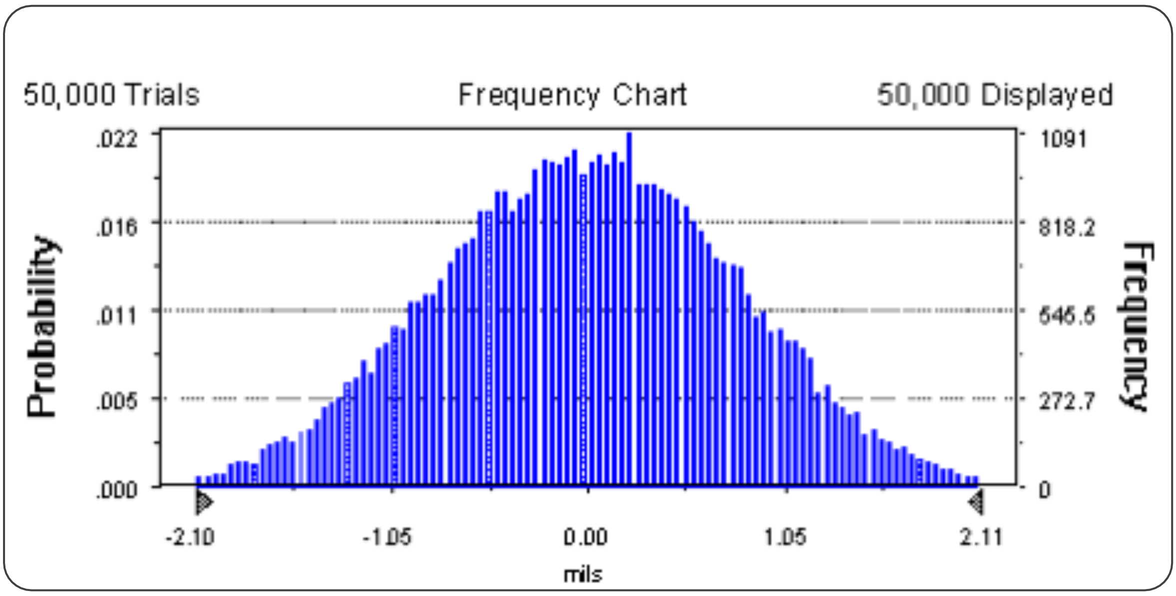


Figure 7: Simulation results after 50000 trails

Figure 7 showed a deflection range of–2.10 mils to 2.11 mils, based on the assumed forces and moment ranges. This range of distortion can be fine-tuned by adjusting input assumptions. To do so, sensitivity analysis identifies the most influential forces and moments affecting deflections.

The sensitivity chart ranks input variables based on their impact, providing insight into which forces or moments require tighter controls. Figure 8 demonstrates a typical sensitivity chart from the analysis.

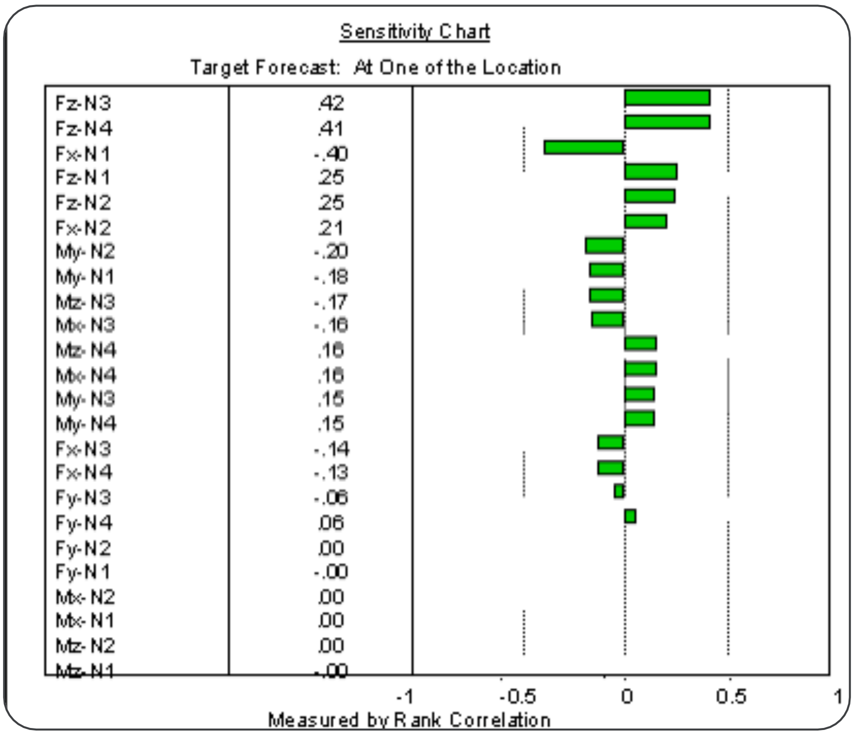


Figure 8: Sensitivity chart for one of the targets forecast

Cyient's Approach to Optimizing Turbine and Piping Load Challenges

Cyient has the capability to derive the transfer function between load and deflection, which can then be input into the Crstalball tool to perform iterations and determine the most probable distribution. This approach is not only applicable to steam turbine casings but can also be utilized to identify optimal loads for heavy machinery. We would be proposing this solution to both existing and potential customers in the energy sector to drive business opportunities in this domain.

Both turbine and piping manufacturers benefit from the analysis: turbine manufacturers gain clarity on design-impacting forces, while piping suppliers have definitive, justified design criteria.

The methodology is well-defined and applicable to similar scenarios where external systems influence design integrity.

The approach optimizes (maximizes) allowable piping loads, offering clear design criteria for third-party suppliers.

The spreadsheet tool predicts individual scenarios, while Crystal Ball facilitates rapid exploration of multiple scenarios, saving time and effort.

The need for exhaustive FEA simulations is minimized, resulting in significant time and cost savings

Both turbine and piping manufacturers benefit from the analysis: turbine manufacturers gain clarity on design-impacting forces, while piping suppliers have definitive, justified design criteria.

About the Author

Sadasiva Reddy Challa holds a Master's degree in Mechanical Engineering with a specialization in Solid Mechanics and Design from IIT Kanpur. With over 25 years of experience in Finite Element Analysis and Engineering Design, he has developed expertise in design optimizations, data-matched simulations, and hand calculations. His extensive experience spans multiple industries including automotive, heavy engineering, white goods, HVAC, aerospace, oil & gas, and rail. Sadashiva possesses a comprehensive understanding of various engineering service quality standards, ensuring excellence in all his professional endeavors.

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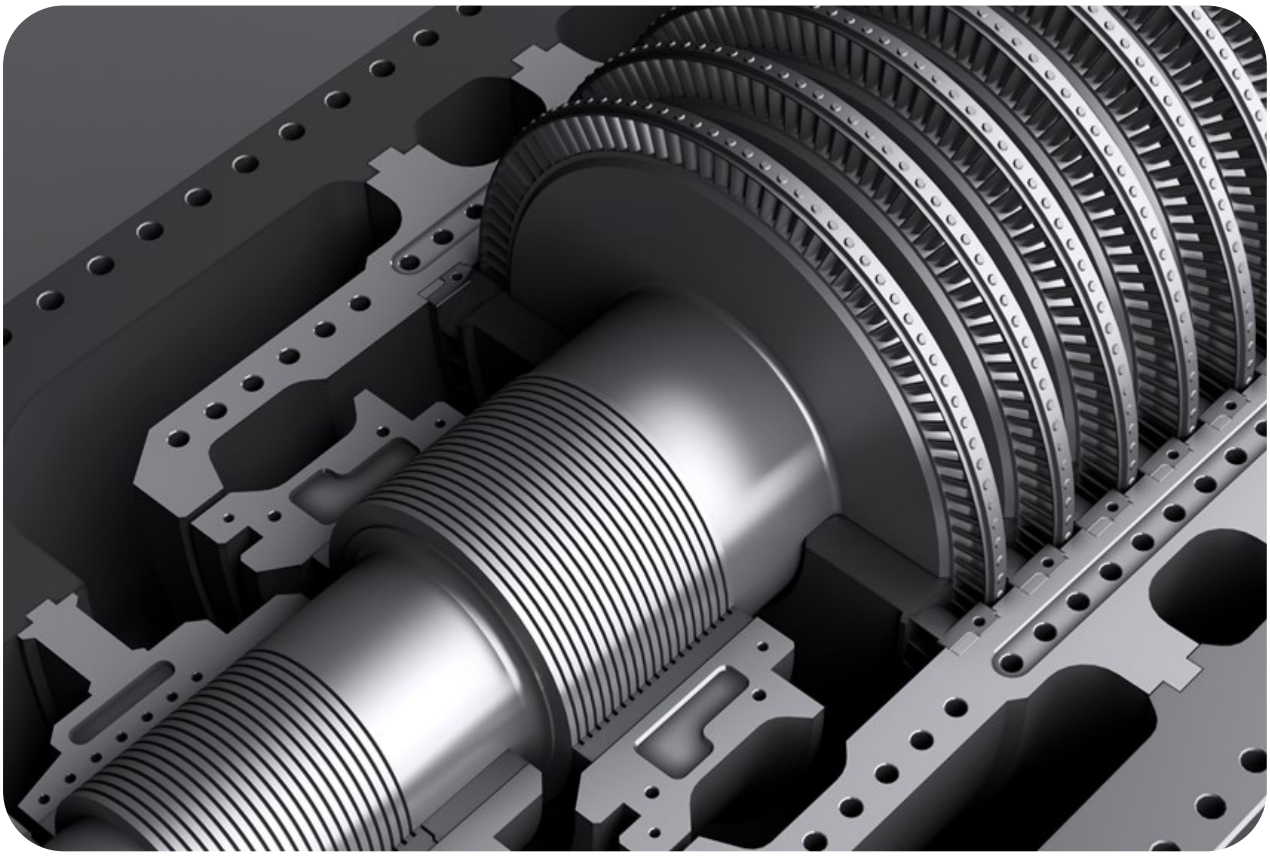
ANSYS V18.0 Software and Analysis Help Manuals



About Cyient

Cyient (Estd: 1991, NSE: CYIENT) partners with over 300 customers, including 40% of the top 100 global innovators of 2023, to deliver intelligent engineering and technology solutions for creating a digital, autonomous, and sustainable future. As a company, Cyient is committed to designing a culturally inclusive, socially responsible, and environmentally sustainable Tomorrow Together with our stakeholders.

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