Flutter Analysis of Last Stage Steam Turbine Power Plant Blade Through Transient Blade Row Simulation

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Abstract. Flutter phenomena becomes significant in response with turbomachinery design trends that prioritize efficiency. Especially in later stages of steam turbines, the slender profile of the blade becomes more prone to unstable dynamic aeroelasticity. Predicting the potential of flutter on a turbine blade can be done by constructing aeroelastic stability curve with evaluation of aerodynamic damping value under different rotor blade position, relative to the stator blade (inter blade phase angle). In this study, combination of steady Computational Fluid Dynamics (CFD), structural Finite Element Analysis (FEA) and transient blade row CFD was carried out using ANSYS 2019 R2 with the end goal of constructing aeroelastic stability curve and analysing the flutter risk of a 350 MW last stage steam turbine blade. At inter blade phase angle position of -180°, -70°, 0°, 77° and 180°, the system are exhibits positive aerodynamic damping values which indicates low to none flutter potential.

1. Introduction
Flutter is one of the phenomena under the field of aeroelasticity, in which unstable dynamic aeroelasticity occurs in the form of oscillation or continuous vibration on a structure as a product of the interaction between elastic, inertial, and aerodynamic forces. The application of aeroelasticity is not only confined to cases on aircraft designs, but also on other flexible structures that interacts with aerodynamic forces, steam turbine blades being one of them [1,2,3,4,5,6,7,8,9]. This study was conducted on last stage steam turbine blade (low pressure section) of unit 2 at Tanjung Awar-Awar 350 MW coal-fired power plant (CFPP) which operates at 3000 rpm (50 Hz). The model used was from reverse engineering process through 3D laser scanning, manual measurement and reference from original equipment manufacturer (OEM) drawing, that was conducted by Metal Industries
Development Centre (MIDC) [5] during 2019 overhaul. The mentioned reference managed to produce a suitable model, with a deviation of -0.1 to +0.1 mm for the blade, to be used in further flutter analysis. Analysis of transient blade row feature at transient CFX software, has been utilized for flutter analysis in various cases. This study focuses on the flutter of Tanjung Awar-Awar last blade where face wire contributes to the harmonic deformation characteristics of the blade surface. To correctly modelled this characteristic, steady CFD and harmonic deformation analysis were conducted before the transient blade row Fourier Transformation method [10] were utilized for the flutter analysis.

2. Methodology
A typical aeroelastic stability curve is shown in figure 1. Values of aerodynamic damping are plotted in respect with the rotor blade position with the stator blade. Inter blade phase angle (IBPA) of -180° indicates the position in which rotor blade start to approaches a stator blade, while 180° IBPA coincides with the position in which the rotor blade exits the next stator blade. If the blade has a positive damping value, the vibration that may occurs from unstable dynamic aeroelasticity, or flutter, has low to none potential of happening. On the contrary, a negative damping value indicates potential of flutter to occurs.

![Figure 1. Typical aeroelastic stability curve for a turbine blade [11].](image)

This analysis combines different engineering tools and necessitates more than one data point to be evaluated. Figure 2 maps the analysis process in a flowchart starting from turbine modelling until the construction of aeroelastic stability curve. From the reverse-engineered model, fluid domains are constructed with revolved model and was emphasized for CFD analysis using rotational periodicity sectioning. The first rotor position is evaluated at around 77° IBPA. Steady CFD simulation was conducted resulting in boundary conditions at last blade surface and fluid domain for transient blade row simulation. With this blade surface pressure loading from steady CFD, FEA harmonic analysis was carried out to obtain blade deformation vibration modes and frequency. Lastly, transient blade row CFD analysis was executed on a different lofted model that only involves the last blade with data obtains from preceding steps. This results in aerodynamic damping values to construct the aeroelastic stability curve. The process repeats until the number of data points suffice.
Figure 2. Flutter analysis methodology flowchart.

3. Model
Reverse engineering conducted on low pressure (LP) turbine unit 2 at Tanjung Awar-Awar power plant produce 3D CAD model of LP rotor, LP stator, LP inlet and outlet, also LP inner and outer casing as shown in figure 3. Tanjung Awar-Awar LP turbine has two outlets on each end, governor and generator end, as pictured in figure 3(a). For the most part, both sides are mirrored symmetry of the other. Because of this configuration, simulation will only be conducted at governor end side of the LP turbine. Figure 3(b) shows five last stage blade configurations with a single lace wire (highlighted in orange) that will be the scope of the flutter analysis. Red arrow points the position of the governor end’s last stage blade on the assembly.

Figure 3. Model from reverse engineering: (a) full assembly and (b) last stage blade.
3.1. Steady CFD model

Figure 4 shows the steady CFD model used that were designed from the reverse-engineered model. This model facilitates the actual design and operating condition of LP turbine at Tanjung Awar-Awar from the diaphragm inlet, extraction chambers until the diffuser outlet. Each regions of fluid domains, indicated by different colors, have different span angle and segment multiplication factor for the whole circle.

Table 1 list the fluid domains used in the model with description of number of blades for each turbine stages, span angle of the periodic interfaces, and the multiplication factor for each segment.

Table 1. Fluid domains description for steady CFD

| Region Name      | Number of blades | Segment multiplication factor | Interface span angle |
|------------------|------------------|-------------------------------|----------------------|
| Inlet            | -                | 38.4                          | 1.875° x 5           |
| Stator 1         | 192              | 38.4                          | 1.875° x 5           |
| Rotor 1          | 192              | 38.4                          | 1.875° x 5           |
| Stator 2         | 176              | 35.21                         | 2.045° x 5           |
| Rotor 2          | 190              | 38                            | 1.895° x 5           |
| Stator 3         | 192              | 38                            | 1.875° x 5           |
| Rotor 3          | 190              | 38                            | 1.895° x 5           |
| Stator 4         | 208              | 41.62                         | 1.73° x 5            |
| Rotor 4          | 132              | 44                            | 2.727° x 3           |
| Stator 5         | 96               | 48                            | 3.75° x 2            |
| Rotor 5          | 118              | 39.33                         | 3.051° x 3           |
| Stator 6         | 62               | 31.00                         | 5.806° x 2           |
| Rotor 6          | 103              | 34.33                         | 3.495 x 3            |
| Stator 7         | 68               | 34.00                         | 5.294° x 2           |
| Rotor 7          | 120              | 30                            | 3° x 4               |
| Diffuser Outlet  | -                | 30                            | 3° x 4               |
Furthermore, a slight surface edit was executed on the model were used in steady CFD analysis. It was split to produce surfaces that correspond with inlet and outlet of the lofted model used in transient blade row. Figure 5(a) and (b) shows the surfaces for inlet and outlet, respectively, that was done on the steady CFD model to accommodate boundary condition extraction for transient blade row simulation purpose.

![Figure 5. Surface edit on steady CFD model: (a) single passage and (b) overlaid with other models on the same coordinate.](image)

3.2. Harmonic FEA Model
The model used in harmonic FEA was taken directly from the reverse-engineered solid model and resembles closely with the model shown in figure 3(b). The model shows a five blades configuration with fixed support on the root part of the blade, one lace wire, and zero normal displacement boundaries at the shroud to model the contact with adjacent blades.

3.3. Transient blade row CFD model
3.3.1 Lofted fluid domain.
To accommodate the need of transient blade row analysis with Fourier Transformation Method, a new lofted fluid volume model was used. Figure 6(a) shows the model mentioned, while figure 6(b) illustrates the revolved fluid model for steady CFD, lofted fluid model for transient blade row and solid model for structural FEA under the same coordinate.
3.3.2 Rotor position and IBPA.

To determine the rotor position in our model, we can measure and calculate the IBPA through figure 7(a) and (b).

\[
\text{Inter Blade Phase Angle (first position)} = \frac{56.745}{79.177} \times 360^\circ - 180^\circ \approx 77^\circ
\]

From the calculation above, it is known that the first rotor position is at 77° IBPA. Knowing this fact is important to ease the process of gathering other data points described in figure 2. Rotational offset in ANSYS CFX is the tool that can be utilized to conduct several steady CFD analyses without changing the CAD model.
4. Simulation and Analysis Process

4.1. Steady CFD analysis

The first analysis that were conducted after modelling is steady CFD with ANSYS CFX. Utilizing the model in figure 4, the following setup described in Table 2 were used.

Table 2. Steady CFD analysis setup

| Parameter            | Value                                      |
|----------------------|--------------------------------------------|
| Boundary Condition   |                                            |
| Inlet                | 0.96 MPa (gauge), 358°C                   |
| Outlet               | -90.7 kPa (gauge)                         |
| Extraction 1         | 0.30 MPa (gauge)                          |
| Extraction 2         | -48.7 kPa (gauge)                         |
| Extraction 3         | -71.62 kPa (gauge)                        |
| Domain Interface     |                                            |
| Frozen rotor         | At interface rotational span per domain.  |
| Rotational periodicity | At connections between stationary and moving domain. |
| General connection   | At connections between stationary domain.  |

From this steady CFD analysis, the results are pressure data of blade surface to be used in harmonic analysis and boundary data for transient blade row simulation, both in .csv (comma separated value) format.

4.2. Harmonic finite element analysis

Next step is harmonic finite element analysis with ANSYS Harmonic Response by utilizing the model in figure 3(b). End results selection is done by evaluating the maximum deformation, maximum stress and maximum stress location at the lace wire that occurs at harmonic order of 1, 3, and 5. This is because harmonic excitation order of 3x and 5x is the ratio line that crosses the vibration modes curve at operating range of 50 Hz, which is between 2500-3000 rpm, when the system Campbell diagram was evaluated. Due to the turbine operation of 50 Hz, results from 50 Hz, 150 Hz (50 Hz x 3) and 250 Hz (50 Hz x 5) were compared in Table 3. 150 Hz was deemed to be the critical case and was chosen due to the result that coincides with location of recent failure of lace wires, high deformation, and moderate stress.

Table 3. Comparison of parameters at lace wire for different frequencies

| Parameter                      | 50 Hz Frequency | 150 Hz Frequency | 250 Hz Frequency |
|--------------------------------|-----------------|------------------|------------------|
| Maximum Total Deformation (mm) | 0.052336        | 0.15088          | 0.124            |
| Maximum Principal Stress (MPa) | 11.785          | 22.435           | 40.68            |
| Max Stress Location            | Around lace wire weld area | Around lace wire weld area | Middle of lace wire |

Figure 8 shows the end results, which are blade deformations in X, Y and Z direction for 2 blades at 150 Hz vibration. The two blades correspond with the two passages simulated in transient blade row CFD. This deformation data will be extracted to .csv files and applied for transient blade row CFD simulation.
4.3. Transient blade row CFD
The last step of analysis is transient blade row CFD with ANSYS CFX to obtain the aerodynamic damping value and constructing aeroelastic stability curve. Utilizing the model in figure 6(a) the following setup described in Table 4 were used. Before transient blade row simulation is conducted, steady state CFD was conducted to provide value initialization for the transient analysis process.

**Table 4. Transient blade row CFD analysis setup**

| Parameter                     | Value                                                                 |
|-------------------------------|-----------------------------------------------------------------------|
| Mesh Deformation              | Regions of motion specified with displacement diffusion motion model. |
| Boundary Condition            | From steady boundary .csv file: **Inlet R7 Lofted Models**, figure 5(a). |
| Inlet                         | • Mass and Momentum: Cartesian Velocity Components and Relative Pressure |
|                               | • Heat Transfer: Static Temperature                                   |
| Outlet                        | From steady boundary .csv file: **Outlet R7 Lofted Models**, figure 5(b). |
| Blade Displacement            | Periodic displacement with harmonic analysis blade deformation .csv files at 150 Hz, figure 8. |
| Interface                     | Rotational periodicity at interface rotational span.                  |
| Transient Blade Row Settings  | Fourrier Transformation                                                |
| Model                         | Between the two passages.                                             |
| Sampling Plane                |                                                                        |

**Figure 8.** Blade deformation (from left to right, respectively) at X, Y and Z direction for frequency of 150 Hz.
Phase Angle Multiplier (PAM) or Nodal Diameter

Multiple of integer of \( \frac{\text{Number of blades}}{\text{PAM}} \) = 30.

Prioritized to have relation with number of blades.

Timestep/Period

30 \times 8 = 240, equals 2 times of number of blades.

240 chosen as \( \frac{\text{timestep}}{\text{period}} \).

Time Period

\( \frac{1}{\text{Frequency}} = 0.02 \text{ s} \)

Timestep

\( \frac{\text{Time Period}}{\text{Period}} = 8.333\times10^{-5} \text{ s} \)

Number of Periods per run

10 periods or 2400 timesteps

Max. Coefficient Loop

15

Figure 9(a) to (d) shows transient blade row model setup that includes boundary conditions and other important physical profiles. Figure 9(a) shows inlet contour and vector, while (b) shows outlet contour. Purple circles indicate rotational periodicity interfaces. Other important profiles in the setup are shown in figure 9(c), which shows blade surface with deformation data from harmonic analysis and 9(d) showing the sampling plane.

![Figure 9(a) to (d)](image)

Figure 9. Transient blade row CFD setup and profiles: (a) inlet, (b) outlet, (c) blade deformation and (d) sampling plane.

4.4. Analysis for other data points

For other data points with different IBPA position, frozen rotor interface between last stage stator and rotor (stage 7) have to be modified with a rotational offset. The rotational offset setting in ANSYS CFX, that have to be filled with other IBPA values after being normalized with stator 7 pitch, or 360° divided by 68 equals to 5.2941°. Table 5 lists the data points that were evaluated in this study.

| Table 5. Rotational offset setting for different data points |
|------------------------------------------------------------|
| Inter blade phase angle (IBPA) | b   | c   | d (1st pos.) | e   |
| Inter blade phase angle (IBPA) | -70° | 0°  | 77°       | 180° |
| Rotational offset setting     | -2.162° | -1.132° | 0°       | 1.515° |
5. Result and Discussion
The validation used in this study is a comparison between the calculation of the power generated by LP steam turbine with the CFX model and the thermodynamic calculation based on actual operating data. Can be seen in table 6 the calculation of the power turbine LP power from the CFX model is 152 MW. The separate calculation of turbine power from the actual operating data is 146 MW, so the difference is 4.1%.

Table 6. Calculation of Torque and Power CFD Model.

| No | Domain  | Multiplier | Torque 1 Segment (Nm) | Total Torque 360° (Nm) |
|----|---------|------------|-----------------------|------------------------|
| 1  | Rotor 1 | 38.4       | 304.03                | 11674.752              |
| 2  | Rotor 2 | 38         | 954.463               | 36269.594              |
| 3  | Rotor 3 | 38         | 943.856               | 35866.528              |
| 4  | Rotor 4 | 44         | 615.213               | 27069.372              |
| 5  | Rotor 5 | 39.333     | 1259.92               | 49556.853              |
| 6  | Rotor 6 | 34.333     | 1141.49               | 39191.157              |
| 7  | Rotor 7 | 30         | 1421.41               | 42642.3                |

Total All Stage 360° 242270.56 Nm
Rotational Speed 3000 rpm
LP Turbine Power 1 Side 76.11 MW
LP Turbine Total Power 152.22 MW

Simulation results used for flutter analysis is at accumulated time step of 2400, or 10 periods, shows a convergent trend for all mass and momentum, heat transfer, turbulence, also wall and boundary scale RMS parameters. All of mentioned RMS values converge below 1.0E-4. Using full period integration, aerodynamic damping values were calculated and also shows a convergent trend. Figure 10 to 13 shows two monitor windows of aerodynamic damping at different IBPA positions. Red graph shows aerodynamic damping 1, or corresponds to the main blade that was under study. Green graph shows aerodynamic damping 2, which corresponds to the second passage that was constructed to utilize the transient blade row with Fourier Transform model.

Figure 10. Aerodynamic damping simulation monitor at 77°
Figure 1. Aerodynamic damping simulation monitor at 180°.

Table 7 summarize the aerodynamic damping value at different IBPA positions. On data point a (-180°) the value was taken from data point e (180°) due to the periodic nature of the stator-rotor interactions.

Table 7. Aerodynamic damping at different positions

| Inter blade phase angle (IBPA) | a    | b    | c (1st pos.) | d    | e    |
|-------------------------------|------|------|--------------|------|------|
| Aerodynamic damping           | 2.336E-04 | 4.98E-05 | 2.049E-04 | 2.336E-04 | 2.336E-04 |

From these results, the aeroelastic stability curve can be constructed as shown in figure 14 by plotting the values of aerodynamic damping in respect with each IBPA positions. It shows that from the IBPA positions evaluated, aerodynamic damping values are positive. This indicates a low to none potential of flutter occurrence, with the least stable position at around -70° IBPA. It should be noted that this outcome is the result of using harmonic deformation model at 150 Hz frequency after steady state CFD pressure, as explained before. Some other studies, including the Fourier Transformation method referenced before [11], use mode shapes from modal analysis. This study did not use mode
shapes deformation from modal analysis, in order to closely capture the deformation magnitude from
the pressure loading when the blade is under steady operation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{aerodynamic_damping_curve.png}
\caption{Aeroelastic stability curve, plots aerodynamic damping in respect with IBPA.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{wall_power_density.png}
\caption{Samples of wall power density results at IBPA (a) 77° and (b) 0°.}
\end{figure}

Lastly, wall power density parameter can be utilized to determine areas on the blade surfaces that have potential for large deformation during if flutter does occur. A more positive wall power density indicates such potential. Figure 15(a) and (b) shows samples of wall power density at IBPA (a) 77° and (b) 0°. Other IBPA positions exhibit the same trends with slight difference on the maximum and/or minimum values. The most positive wall power density values coincide with the position of lace wire. This confirms the design of the last blade, especially the lace wire placement. Due to the characteristic of the slender last stage rotor blade, largest deformation will occur at the location without support and extends more outward radially, hence the placement of the lace wire. Despite of these areas where wall power density is positive, the aerodynamic damping of the rotor blade from IBPA -180° to 180° have positive values that suggest unlikelihood of flutter occurrence.

6. Conclusion
Based on the results from transient blade row CFD analysis on last stage steam turbine blade of unit 2 at Tanjung Awar-Awar 350 MW coal-fired power plant, inter blade phase angle (IBPA) position of -180°, -70°, 0°, 77° and 180° have positive value of aerodynamic damping. The potential of vibration from flutter to occurs is low to none. Furthermore, all of mentioned IBPA position shows that the area with the most positive wall power density value is around lacing wire location at the pressure side of
blade surface. The wall power density trends confirm the design of lace wire placement to minimize the high risk of deformation due to the structural characteristic of the slender last blade profile.

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