UNSTEADY AERODYNAMICS AND FORCES CHARACTERISTICS OF DUAL ROW CONTROL STAGE WITH PARTIAL ADMISSION CONDITION

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ABSTRACT

Unsteady aerodynamic performance and forces on the rotor blades of dual row control stage with partial admission condition were numerically investigated using three-dimensional unsteady Reynolds-Averaged Navier-Stokes (URANS) and $\varepsilon - k$ turbulent model. The numerical steady aerodynamic performance of the partial admission dual row control stage is well in agreement with the experimental data. The obtained unsteady results show that the periodic variations of mass flow rate and output power were correlated with the relative position between two admitted arcs of the nozzle box and guide vane group. The unsteady aerodynamic performance of nozzle cascades was influenced by the downstream rotor blade. The rotor blades were subject to large unsteady and periodic forces while traveling along the circumferential direction. The magnitude and direction of the unsteady forces on the rotor blades were significantly influenced by the rotor blades entering or leaving the admission arcs. The spectrum analysis of the excitation forces on the rotor blades show that the high amplitudes caused by partial admission were at low multiples of rotational frequency.

KEYWORDS: DUAL ROW CONTROL STAGE, PARTIAL ADMISSION, UNSTEADY AERODYNAMICS, FLUID EXCITATION, NUMERICAL SIMULATION

INTRODUCTION

Dual row control stage is widely applied in the industrial steam turbines because it has large enthalpy drop and flexible control power function for the full and part load conditions. Partial admission is sometimes used in the dual row control stage to avoid short nozzle blade in order to reduce the leakage loss and secondary flow loss (Singh et al. 2011). Specific aerodynamic loss including pumping loss, emptying and filling loss due to the partial admission deteriorate the energy transfer efficiency of the turbine stage. Furthermore, unsteady fluid force on the rotor blade with consideration of the circumferential non-periodic load changes due to the partial admission significantly influences the operational safety (Hushmandi, 2010; Fridh, 2012).

The complex internal flow and unsteady fluid force in the partial admission turbine stage has been conducted using experimental measurements and numerical simulation to increase its aerodynamic efficiency and operational safety. Denton (1993) described the physical interpretation of the unsteady losses induced by partial admission in turbomachinery environment. The non-uniform and unsteady flow behavior is occurred in the subsequent stator and rotor blade rows after the partial admission stator row in his conclusions. The rotor passages entering and leaving the jets, originate from flow through certain segments of the first stator rows, would induce additional entropy increases. Fridh et al. (2004) experimentally measured the aerodynamic and efficiency of the two stage axial turbine with low reaction steam turbine blades at different partial admission degrees, as well as 2D numerical simulations. The total-to-static turbine efficiency drops and the efficiency peak appears at lower velocity ratios for lower partial admission degrees mostly due to the pumping losses increase with the increased velocity ratios according to their experimental data. Hushmandi and Fransson (2011) conducted numerical studies on the effects of the axial first gap
distance between the first stage stator and rotor blades and multiblocking on aerodynamic performance of the partial admission turbines with low reaction degree blades. The numerical results showed that the two stage partial admission turbine with smaller axial gap has higher efficiency of the first stage. Survilo et al. (2015) conducted the aerodynamic performance of the multi-stage axial partial admission ORC turbine.

Partial admission creates the circumferentially unsteady and non-periodic flow with dynamic pressure amplitude at the inlet of the rotor blade downstream of the partial admission nozzle cascades. This flow behavior results in specific unsteady fluid force on the rotor blade with the stator/rotor interaction and stator cascade partial admission degree. He (1997) used unsteady flow calculation to analyze the aerodynamic performance and force on rotor blade based on two-dimensional flow model. He pointed out that a cyclic pumping and sucking flow behavior occurs in the rotor blade row and results in large unsteady loading. Lampart et al (2004) numerically investigated the unsteady force of the rotor blade of the partial admission control stage using a 2D flow model at the mid-span section of the stator and rotor. The circumferential non-uniformities of the flow fields and unsteady forces on the rotor blade were captured. Three-dimensional unsteady numerical analysis was conducted to obtain the flow behavior of partial admission two axial steam turbine stages by Hushmandi et al. (2008). Their results showed that the first stage rotor blade appears large variations of unsteady forces while passing the blocked channel. The partial admission flow behavior results in the large entropy generation at the pressure side of the blockage because of the strong mixing occur. Cho et al. (2010) experimentally measured the operating force and surface pressure on a blade with three different solidities at partial admission condition. The experimental data showed that the maximum rotational force increased and the maximum axial force decreased with the decrease of the cascade solidity. Hushmandi et al (2011) conducted the numerical and experimental study on the unsteady flow field and forces of rotor blade of low reaction two-stage axial air turbine with partial admission condition. They concluded that the largest amplitudes caused by the partial admission were at first and second multiples of rotational frequency due to the existence of single blockage and change in the force direction. Fridh et al (2013) experimentally investigated the forced response in the two axial turbine stages at partial admission degree ranged from 28.6% to 100%. The results showed that the blockage, pumping, loading and unloading process results in the large number of low-eigen-order forced response. Altering the stator and rotor pitches can be able to change the excitation pattern in their studied partial admission turbine stage.

Unsteady flow fluid force significantly impacts on the operational safety of the partial admission dual row control stage. Low partial admission degree would create the strong unsteady fluid force on the rotor blade with the effects of interaction between the partial admission nozzle cascades and the downstream rotor blade row. Up to now, few research works on the unsteady fluid force of the dual row control stage with partial admission condition was conducted. In this paper, the unsteady flow fields and fluid force of the dual row control stage with partial admission degree was numerically investigated using Unsteady Reynolds-Averaged Navier-Stokes (URANS) and $k-\varepsilon$ turbulent model based on the CFD software ANSYS-CFX. The detailed unsteady aerodynamic parameters variations were analyzed. The unsteady fluid force on the first and second rotor blade due to the partial admission and stator/rotor interactions were obtained and discussed.

COMPUTATIONAL MODEL AND NUMERICAL METHOD

Figure 1 shows the computational domain and grid of the dual row control stage with partial admission degree. Tab. 1 gives the geometrical parameters of the dual row control stage. The tip seal and diaphragm seal are considered in the computational domain. Four nozzle boxes are located non-uniformly along the circumferential direction. The first and third nozzle box has two stator cascade passages. The second and fourth nozzle box connects together and has four stator cascade passages. Two guided vane groups horizontal symmetrical locates along the circumferential direction downstream of the first rotor blade row. The partial admission degree of the nozzle is
0.339 and guided vane is 0.440 in respective. The multi-block structural grid is generated for the computational domain using the software NUMECA. The HOH type grid is used to generate the mesh for the cascade passages. The total grid number of the present computational domain equals 10.15 million.

![Figure 1: Computational domain and grid of the dual row control stage](image)

**Table 1: Blade geometrical parameters of the dual row control stage**

<table>
<thead>
<tr>
<th></th>
<th>Nozzle</th>
<th>Rotor 1(R1)</th>
<th>Guided vane</th>
<th>Rotor 2(R2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>full annulus blade number</td>
<td>24</td>
<td>68</td>
<td>77</td>
<td>51</td>
</tr>
<tr>
<td>averaged diameter/mm</td>
<td>440</td>
<td>440</td>
<td>440</td>
<td>440</td>
</tr>
<tr>
<td>Root diameter/mm</td>
<td>417</td>
<td>414.5</td>
<td>409.5</td>
<td>406</td>
</tr>
<tr>
<td>pitch/mm</td>
<td>58.6</td>
<td>20.3</td>
<td>17.9</td>
<td>27.1</td>
</tr>
<tr>
<td>blade width/mm</td>
<td>40</td>
<td>34</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>blade height/mm</td>
<td>23</td>
<td>25.5</td>
<td>30.5</td>
<td>34</td>
</tr>
<tr>
<td>aspect ratio</td>
<td>0.33</td>
<td>0.75</td>
<td>1.22</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The physical time of the single passage of the first rotor blade is 12. The unsteady period of the first rotor blade has 816 physical times due to 68 blade passages. The physical time of the single passage of the second rotor blade is 16. The unsteady period of the second rotor blade has 816 physical times due to 51 blade passages. The time of the rotor blade take a turn round equals to the unsteady period. Thus the physical time step is $1.31303 \times 10^{-5}$ s. The steady computation is needed in each time step. The dual time marching methods is used to solve the URANS. The steady solutions were obtained by solving the steady compressible RANS equations in which a finite control volume method was used to discretize these equations based on CFD software ANSYS-CFX. The overall accuracy is of the second order. The standard $k-\varepsilon$ turbulent model with the wall function method was used to describe the turbulent effect. The inlet boundary condition imposed at the entrance sector of nozzle boxes. The outlet boundary condition was placed at 3.0 times of the axial chords downstream from the trailing edge of the second rotor blade to avoid backflow. The absolute total pressure and temperature were specified at the inlet boundary condition. The averaged static pressure was set at the outlet boundary. The adiabatic wall condition was used. The rotor blade rotational speed is 5600rpm. Detailed computational boundary conditions for the partial admission dual row control stage are listed in Tab. 2. As to the steady computation of each time step, the convergence criteria of the present calculation is based on the reduction of RMS residuals for momentum and mass with associated volume fractions and energy less than $1.0 \times 10^{-5}$. In addition, the equilibrium steam model based on the IAPWS-IF97 steam properties database is used. The unsteady computation convergent until the periodic variations of the monitored aerodynamic
performance including the pressure and temperature in the nozzle passage of the dual row control stage is obtained.

Table 2: Computational Boundary condition of the dual row control stage

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet total pressure/MPa</td>
<td>8.83</td>
</tr>
<tr>
<td>Inlet total temperature/°C</td>
<td>530</td>
</tr>
<tr>
<td>Inflow angle/°</td>
<td>0</td>
</tr>
<tr>
<td>Outlet static pressure/MPa</td>
<td>4</td>
</tr>
<tr>
<td>Rotational speed/r.min⁻¹</td>
<td>5600</td>
</tr>
<tr>
<td>Working fluid</td>
<td>Water steam IF97 (Steam5v)</td>
</tr>
</tbody>
</table>

Table 3 gives the comparison of the aerodynamic performance including the mass flow rate, power output and total-static efficiency of the partial admission dual row control stage between the numerical results and experimental data. The power output is calculated as equation (1).

\[ P = m \cdot (h_{t,01} - h_{t,02}) \]  \hspace{1cm} (1)

where \( m \) is mass flow rate of the dual row control stage, \( h_{t,01} \) and \( h_{t,02} \) is the inlet and outlet total enthalpy respectively.

The total-static efficiency of the dual row control stage is obtained as (2).

\[ \eta = \left( h_{t,01} - h_{t,02} \right) / \left( h_{t,01}^{u} - h_{t,02}^{u} \right) \]  \hspace{1cm} (2)

where \( h_{t,02}^{u} \) is outlet static enthalpy.

Table 3: Comparison of aerodynamic performance of the numerical and experimental data

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass flow rate/t.h⁻¹</th>
<th>Power/MW</th>
<th>Total-static efficiency/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical data</td>
<td>72.3</td>
<td>2.46</td>
<td>48.3</td>
</tr>
<tr>
<td>Experimental data</td>
<td>72.0</td>
<td>2.50</td>
<td>49.3</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

The unsteady flow in the partial admission dual row control stage was conducted. The unsteady fluid force on the first and second rotor blade was calculated based on the obtained the unsteady pressure fields.

Unsteady Aerodynamics

Figure 2 shows the periodic variation of the static pressure and temperature in the nozzle cascade. The synchronous changes of the pressure and temperature in the nozzle cascade are observed. The variation period equals 12 physical times and corresponding to the time of the first rotor blade pass through one pitch. This means that the thermal parameters of the nozzle cascade is mostly influenced by the downstream rotor blade. Figs. 4 and 5 show the variation of the mass flow rate and power output of the dual row control stage along the physical time. The periodic fluctuation of the mass flow rate and power output is appeared due to two rotor blade rows rotate. The synchronous fluctuation of the mass flow rate and power output are captured. In addition, the time-averaged of the mass flow rate and power output are well in agreement with the steady computations as given in Tab. 3.

As shown in Figs. 3 and 4, the variation period of the aerodynamic performance of the dual row control stage is about 81 physical times. In each variation period, the first rotor blade passes through 7 pitches and the second rotor blade passes through 5 pitches. The rotor blade passes through about 1/10 ring. The nozzle and guided vane has 5 groups and 10 arc ends. The rotor blade enters the arc end of admission of the nozzle or guided vane, the aerodynamic performance of dual row control stage changes. It is noted that the 1/10 ring is not strictly period time due to the arc length between
the adjacent admission nozzle and guide vane is not same. Strictly speaking that the period time of
the dual row control stage is the time of the rotor blade turns one ring.

![Figure 2: Periodic variation of the static pressure and temperature in the nozzle cascade](image)

![Figure 3: Mass flow rate variation along physical times](image)

![Figure 4: Output power variation along physical times](image)

Figure 5 illustrates the relative position between the first row rotor blade and the first nozzle
cascade. The T1 time indicates that the leading edge of the first row rotor blade aims at the inlet
side of the admission for the nozzle cascade. Fig. 6 shows the entropy contours distribution at the
mid-span of the first rotor blade downstream of the first nozzle box at different physical times. The
suction side of the first rotor blade is subject to be influenced when it enters into the admission arc
from the non-admission arc of the first nozzle box. The flow separation at the suction side of the
first row rotor blade is observed according to the larger positive incidence. The separation region
decreases gradually when the first row rotor blade turns. The large entropy generation region
located at the leading edge of the first row rotor blade is captured when it leaves the admission arc
of the nozzle cascade. The reason is that the inflow decreases abruptly when the first row rotor
blade enters into non-admission arcs. The flow velocity in the rotor blade cascade is still high and
steam is pulled out. This flow behavior is called as the emptying phenomenon and results in the
emptying loss due to the partial admission.

Figure 7 shows the entropy contours distribution at the mid-span of the rotor blade downstream
of the third nozzle box at different physical times. The steam in the rotor blade cascade is
accelerated due to the high velocity steam enters into it from the admission arc when the rotor blade
enters into the admission arc from the non-admission arc. This flow behavior is called filling
phenomenon and leads to the larger mixing loss named as the filling loss. The entropy distribution
at the mid-span rotor blade cascade downstream of the first nozzle box is very different with the
third nozzle box. The first row rotor blade cascade locates at the region where the non-admission
between the nozzle and guided vane. The large entropy is generated due to the vortex filled in these regions.

**Figure 5:** Rotor blade relative position to the first nozzle box at different physical times

**Figure 6:** Entropy contours distribution at the mid-span of the first rotor blade downstream the first nozzle box at different physical times

**Figure 7:** Entropy contours distribution at the mid-span of the rotor blade downstream the third nozzle box at different physical times

**Unsteady Blade Load**

Figure 8 illustrates the relative position of the first row rotor blade related to the second and fourth nozzle and guided vane at different physical times. Fig. 9 shows the static pressure
distribution at mid-span of the first row rotor blade at different physical times. The $T'$ stands for the first row rotor blade pass through four rotor pitches.

![Image](image.png)

(a) three-dimensional space
(b) two-dimensional space

**Figure 8: Relative position of the first rotor blade comparison to the second and fourth nozzle and guided vane at different physical times**

![Graphs](graphs.png)

(a) $t$ time  (b) $t + T'$ time  (c) $t + 2T'$ time
(d) $t + 3T'$ time  (e) $t + 4T'$ time  (f) $t + 5T'$ time

**Figure 9: Static pressure distribution at mid-span of the first row rotor blade at different physical times**

At the $t$ time, the steam in the rotor blade cascade is stagnation because it locates downstream of the non-admission arc of the nozzle cascades. The static pressure at the pressure and suction surface overlaps. No pressure difference from the leading edge to the trailing edge of the rotor blade is observed as shown in Fig. 9(a). The rotor blade is not subject to the axial and tangential force at this time and the load of the rotor blade is zero. At the $t + T'$ time, the rotor blade enters the inlet side of the admission arc of the nozzle cascade. The steam near the suction surface of the rotor blade is accelerated by the high speed flow from the upstream admission nozzle cascade. At the same time, the flow near the pressure surface of the rotor blade remains the non-admission condition. As shown in Fig. 9(b), the static pressure at the pressure surface remains unchanged. The static pressure at the suction surface increases obviously. The rotor blade is subject to the tangential force which direction is from the suction surface to the pressure surface. The direction of the
tangential force of the rotor blade is opposite to the rotational direction. This load behavior is not beneficial to the output power and decreases the aerodynamic efficiency of the partial admission dual row control stage. At the $t + 27\tau'$ time, the rotor blade enters into the region between the admission arc of the nozzle and guided vane cascades. The axial force, tangential force and load of the rotor blade return to normal. The largest load locates at the 75% axial chord position of the rotor blade as shown in Fig. 9(c).

At the $t + 37\tau'$ time, the suction surface cascade of the rotor blade locates at the region where the upstream and downstream is the non-admission arc. At the same time, the upstream region of the pressure surface cascade is the admission arc of the nozzle cascade and the downstream region is the non-admission arc of the guided vane. The pressure at the trailing edge is higher than that of the leading edge due to the non-admission arc exists upstream and downstream of the rotor blade cascade. The downstream of the suction surface passage of the rotor blade is impeded by the non-admission arc of the guided vane. Thus, the static pressure at the suction surface of the rotor blade is higher than that of the pressure surface as shown in Fig. 9(d). At the $t + 47\tau'$ time as shown in Fig. 9(e), the rotor blade leaves the admission arc of the upstream nozzle cascade. The static pressure at the pressure surface of the rotor blade remains unchanged. The static pressure at the suction surface tends to placid. Compared to the $t + 37\tau'$ time, the direction of the tangential force acts on the rotor blade changed again. The direction of the tangential force is from the pressure surface directed to the suction surface at the $t + 47\tau'$ time. At the $t + 57\tau'$ time, the rotor blade enters into the non-admission arc region and the static pressure distribution is the same as the $t$ time as shown in Fig. 9(a) and (f). The direction of the tangential fluid force on the rotor blade changes once time when it passes through the admission arc and non-admission arc. The variation of the tangential force direction would significantly influences the safety of the rotor blade.

**Unsteady Fluid Force**

Figure 10 shows the variation of the tangential and axial force on the first row rotor blade in one period. When the rotor blade enters into the admission arc side of the third nozzle box, the steam with high speed and pressure fills the blade passage of the suction surface. The static pressure of the suction surface is higher than that of the pressure surface. This leads to the direction of the tangential force of the rotor blade is opposite to the rotational direction. When the rotor blade leaves the non-admission arc side, the steam in the blade passage of the suction surface was carried away. The steam with high speed and pressure fills the pressure surface passage. The rotor blade is subject to the tangential force with the same direction of the rotational direction. When the rotor blade locates at the region of the non-admission arc between the first and third nozzle box, the rotor blade is subject to the tangential force with the opposite direction of the rotational direction. The first negative peak value of the axial force on the rotor blade is captured when the rotor blade locates at the admission arc side of the first nozzle box as shown in Fig. 10. This means that the static pressure at the trailing edge is higher than that of the leading edge. The direction of the axial force on the rotor blade directs upstream. The second and third negative peak value of the axial force on the rotor blade is captured when the rotor blade locates at the non-admission arc side of the first and fourth nozzle box. At this position, the rotor blade leaves the admission arc and enters into the non-admission arc. The leading edge of the rotor blade lies in the low pressure regions. The kinetic energy transfer into the pressure energy of the trailing edge of the rotor blade due to this region flow is prevented by the guider vane. Thus, the rotor blade is subject to the negative axial force.

Figure 11 shows the frequency domain of the axial and tangential force on the first row rotor blade by means of fast Fourier transform (FFT). The axial force mainly includes the frequencies lower than the 63 times of the rotating frequency of the axial force components. The tangential force mainly includes the frequencies lower than the 54 times of the rotating frequency of the tangential force components. Larger amplitude frequency of the axial and tangential force concentrates within the 10 times of the rotating frequency. The largest amplitude frequency of the axial force is the 2 times of the rotating frequency. The combined action of the non-admission arc
side of the first and fourth nozzle box and non-admission arc of the guided vane results in the larger negative axial force of the rotor blade. The largest amplitude frequency of the tangential force is the 8 times of the rotating frequency.

![Figure 10: Tangential and axial force of the single blade of the first row rotor blade](image1)

![Figure 11: Frequency domain of the first row rotor blade](image2)

![Figure 12: Tangential and axial force of the single blade of the second row rotor blade](image3)

![Figure 13: Frequency domain of the second row rotor blade](image4)

Figure 12 gives the variation of the tangential and axial force on the second row rotor blade in one period. The larger negative axial force on the second rotor blade is observed when the rotor blade leaves the admission arc side of the first guided vane group. The smaller negative axial force on the second row rotor blade is captured when it leaves the non-admission arc side of the second guided vane group. Two minimal values of the tangential force on the second row rotor blade are observe due to the wake function of the admission arc of the first guided vane group and admission arc side of the second and fourth nozzle box.

Figure 13 shows the frequency domain of the axial and tangential force on the second row rotor blade using fast Fourier transform. The frequency of the axial and tangential force on the second row rotor blade mainly includes 2,4,6,8 times of the rotating frequency. The largest amplitude frequency of the axial and tangential force on the second row rotor blade is the 2 times of the rotating frequency. The frequency component of the fluid excitation force on the second row rotor blade is lower than that of the first row. The fluid excitation force on the second row rotor blade is mainly related to the partial admission of the guided vane. However, the fluid excitation force on the first row rotor blade is mainly related to the partial admission of the nozzle box and guided vane.

**CONCLUSIONS**

The unsteady flow field and fluid excitation force of the partial admission dual row control stage was numerically investigated in this work. The unsteady aerodynamic performance of the first row nozzle is mostly influenced by the first rotor blade row. The influence period is the turned time of
the first row rotor blade pitch. The unsteady variation of the mass flow rate, output power and aerodynamic efficiency of the partial admission dual row control stage is related to the position of the nozzle vane and guider vane.

The rotor blade is subject to the tangential force with the opposite rotational direction when it enters the admission arc side of the nozzle box. The rotor blade is subject to the tangential force with the same rotational direction and negative axial force when it leaves the admission arc side of the nozzle box. The rotor blades are subject to large unsteady and periodic forces while traveling along the circumference. These forces would experience great changes in magnitude and direction while rotor blades enter and leave the admission arcs. The spectrum analysis of the excitation forces on the rotor blades show that the high amplitudes caused by partial admission are at low multiples of rotational frequency.

The frequency of the fluid excitation force of the second row rotor blade is much smaller than that of the first row rotor blade. The fluid excitation force of the second row rotor blade is mostly influenced by the guider vane partial admission. The fluid excitation force of the first row rotor blade is not only influenced by the nozzle vane partial admission, but also the guider vane partial admission.

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REFERENCES


