PIV MEASUREMENTS OF TURBULENT FLOWS ALONG THE RIBBED SQUARE DUCT UNDER ROTATIONAL CONDITION

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ABSTRACT
In this paper, the change rule of flow characteristics along the ribbed square duct was investigated experimentally by two-dimensional time-resolved particle image velocimetry (TR-PIV). The Reynolds number, defined by main flow velocity (1.82 m/s) and the hydraulic diameter (80 mm), is set to 10000, the rotation numbers are 0, 0.13, 0.26, 0.39, 0.52, respectively. The blockage ratio and aspect ratio of the ribbed square duct are 0.1, 1 respectively. As the rotation number increased, The vortices structure on the suction side became larger and the attachment point moved backward. The situation on the pressure side was just the opposite, and this trend would develop along the duct. Furthermore, the parameters of different ribs along the duct varied greatly under the same rotation number. In the downstream ribs, the mainstream velocity pattern was more inclined to the pressure side, where the vortex structure was larger.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>AR</td>
<td>aspect ratio (-)</td>
</tr>
<tr>
<td>D</td>
<td>Hydraulic diameter (mm)</td>
</tr>
<tr>
<td>M</td>
<td>Magnification factor (pixel/mm)</td>
</tr>
<tr>
<td>Ro</td>
<td>Rotation number (-)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number (-)</td>
</tr>
<tr>
<td>U</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>u'</td>
<td>Fluctuating velocity (X axis) (m/s)</td>
</tr>
<tr>
<td>v'</td>
<td>Fluctuating velocity (Y axis) (m/s)</td>
</tr>
<tr>
<td>X</td>
<td>Streamwise direction (m)</td>
</tr>
<tr>
<td>Y</td>
<td>Normal direction</td>
</tr>
<tr>
<td>Z</td>
<td>Spanwise direction</td>
</tr>
<tr>
<td>x</td>
<td>Streamwise along the test plane</td>
</tr>
<tr>
<td>PS</td>
<td>Pressure side</td>
</tr>
<tr>
<td>SS</td>
<td>Suction side</td>
</tr>
<tr>
<td>TR-PIV</td>
<td>time-resolved particle image velocimetry</td>
</tr>
<tr>
<td>U_0</td>
<td>relative velocity of the mainstream (m/s)</td>
</tr>
<tr>
<td>Ω</td>
<td>Rotating speed (rpm)</td>
</tr>
<tr>
<td>μ</td>
<td>Molecular dynamic viscosity (kg/(ms))</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (kg/m³)</td>
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1. INTRODUCTION

At present, the turbine inlet temperature of the pre-research fifth-generation engine (>2000K) has far exceeded the melting point of the turbine blade (about 1370K). Therefore, in order to ensure the long-term reliable operation of turbine blades at the high temperature (Sunden and Xie, 2010), high pressure and high speed, effective cooling measures must be taken for turbine blades. As a result, many investigations have been carried out in this field so as to offer valuable guidance advanced internal cooling techniques. Because the turbine blades work in high-speed rotating condition, which will lead to blade internal cooling law changes compared with the stationary case. Specifically, the internal cold air is deflected so that it does not cool the inner walls of the channels uniformly. At present, there is still the problem of local ablation of blades caused by uneven heat transfer, ribs can enhance heat transfer, but the more complex the cooling structure, the more complex the flow and heat transfer law near the wall. Therefore, the goal of this paper is to measure and analyze the complex flow structure along the ribbed channel under the influence of Coriolis force. However, most of them focus on the heat transfer and temperature distribution due to the relatively backward of measurement technology and difficulties of measuring flow field under rotational condition. Heat transfer is the embodiment of flow on the boundary, so flow characteristic in the rotating duct must be investigated detailedly. In order to make a clear difference in this paper, the aspect ratio (AR) of duct is finite and the AR of channel is infinite.

1.1 Mainstream in rotating smooth duct

Relevant research about rotating smooth duct can be dated back to 1960s, as one of the pioneers of rotating flow, Moore (Moore, 1967) studied the effect of transverse pressure gradient and Coriolis force on the velocity profile systematically by experiments and theoretical analysis, he found that these two effects have relative importance in rectangular ducts with different AR(0.5, 1, 4, 7.3), Reynolds number (Re) and rotation number (Ro). Therefore, a large number of studies have been conducted by subsequent researchers. Wagner and Velkoff (Wagner and Velkoff, 1972) measured the velocity and pressure distribution in the rotating duct with AR=1 by pilot tubes, they found that the mainstream velocity distribution is driven towards the pressure side (PS). At the same time, the velocity distribution presents two peaks in the normal direction. Keshgi and Scriven (Keshgi and Scriven, 1985) also found that the velocity distribution is driven towards the PS in the rotating duct with AR=1 by finite element method. Some researchers wanted to eliminate the impact of secondary flow generated by end-wall, so they increased the AR of rotating duct. Nakabayashi and Kitoh (Nakabayashi and Kitoh, 2005) experimentally investigated turbulence quantities on the mid-plane of rotating duct with AR=8 by hot wire. They found that the velocity distribution is driven towards suction side (SS), furthermore, Coriolis term makes significant contribution to Reynolds shear stress transport on the PS and SS. However, as single-point and contact measurements, pitot and hot wire can’t obtain detailed flow information. PIV (Particle Image Velocimetry) is an advanced technique, which can realize the visualization of flow field and the measurement of whole flow field. Di Sante et al. (Di Sante et al. 2008) used time-resolved PIV (TR-PIV) to measure a diverging duct under rotational condition, the experimental results show that TR-PIV has accuracy and high spatial and temporal resolution of the measurements than before (Bharadwaj et al. 2002, Iacovides et al. 2005). Visscher et al. (Visscher et al. 2011) used stereoscopic TR-PIV to measure all three components of the instantaneous velocity vector in the rotating duct with AR=5, and obtained the mean flow characteristics, the important turbulence statistics, such as all components of the Reynolds stress tensor. They reported that Coriolis force could stabilize and regularize the flow field along SS, the velocity profile become linear near PS when Ro ≥ 0.2, the location of peak velocity is driven towards SS. Results from DNS conducted by Kristoffersen et al. (Kristoffersen et al. 1993) show that the velocity profile in the rotating channel become increasingly asymmetric as the Ro increases, the profile in the centre region between PS and SS is approximately linear and the length of the linear region increases with Ro. Julien et al. (Julien et al. 2008) conducted a numerical study to better understand the effect of high AR on rotating duct flow. They found that secondary flow generated by the end-wall cannot be neglected even when AR=11, although being very weak. The results also show the AR of most ducts reported in former literature is small. They also found that when AR is relatively high, the location of peak velocity is driven towards SS, which is consistent with the results of previous researchers. Table 1 summarizes the parameters in the above literatures, in which Ro is unified according to \( \Omega D/U_0 \).

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>AR</th>
<th>Re</th>
<th>Max Ro</th>
<th>Measurement method</th>
<th>Mainstream Tendency (SS,PS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moore</td>
<td>1967</td>
<td>1</td>
<td>20000</td>
<td>0.08</td>
<td>Pitot</td>
<td>PS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.3</td>
<td>22400</td>
<td></td>
<td></td>
<td>SS</td>
</tr>
<tr>
<td>Nakabayashi and</td>
<td>2005</td>
<td>8</td>
<td>2500-5500</td>
<td>0.056</td>
<td>HWA-2C</td>
<td>SS</td>
</tr>
</tbody>
</table>

Table 1 Researches of the flow in different aspect-ratio rotating smooth ducts
1.2 Mainstream and secondary flow in the ribbed duct

In order to further enhance the heat transfer, artificial roughness such as period ribs are applied to turbine internal cooling duct. The flow characteristic is significantly impacted by ribs, which can induce flow separation, reattachment and recirculation. As one of the simplest reattaching flow, step flow has been extensively studied in the past decades (Brashaw and Wong, 1971; Kopera et al. 2011; Ta Ton and Johnston, 2012). Many heating experiments show that the heat transfer efficiency in the recirculation zone is very poor, and will often form local hotspots (Liou and Hwang, 1992; Lockett and Collins, 1990). That is because the fluid velocity in this region is very low compared with the mainstream, or even almost stagnant. Therefore, the main goal of studying the influence of rib is to shorten the length of the region and even completely disperse the region (Yavuzkurt et al. 2016), so there exist many literature concerning the flow in ribbed duct. Many studies have been conducted on ribbed channels under static conditions (Lockett and Collins, 1990; Han, 1988; Park et al., 1992), but due to the difficulty of rotational experiments, fewer experiments have been conducted on flow in rotating ribbed channels. In order to improve the flow mixing in the U-shaped duct and thus enhance heat transfer, Bharadwaj et al.[8] studied the effect of different Re, rib pitches and rib angles on the flow under rotating conditions and found that 45° ribs could increase in the number of vortices. Thereafter, Elfert et al. (Elfert et al. 2008) also used 2C-PIV to study detailly the complex flow in it, and they found that the flow was influenced by four main factors, namely Dean vortices induced by bending, separation along the dividing wall, vortices induced by rib and Coriolis vortices induced by rotation. Coletti et al. (Coletti et al. 2012) found that the reattachment distance, turbulence intensity and Reynolds shear stress would be determined by the Coriolis force, and turbulent activity is suppressed near SS, the opposite is true along PS. Furthermore, the effect of buoyancy force induced by the heating wall was also experimentally investigated by Coletti et al. (Coletti et al. 2012; Coletti et al. 2014). By comparing the heated and unheated cases, they found that the buoyancy force is strongly coupled to the Coriolis force, and that the effect of the two forces may be opposite at different senses of rotation.

2.EXPERIMENTAL APPARATUS AND MEASURING PROCEDURE

2.1 Rotating platform

The whole installation, i.e. the ribbed square duct, the high-speed camera and laser, the power supply and the data acquisition module, is located on the "rotating" platform, see Fig 1. With the rotation radius of 1 meter, it allows the TR-PIV system to be flexibly arranged to meet the needs of shooting. The rotation axis is vertical in order to eliminate the effect of gravity, it is driven by a DC motor, the rotation speed is regulated by the EUROTERM 590C controller up to 500 rpm with a control accuracy of ±0.1 rpm. The ribbed duct is placed on a horizontal rotation arm, as shown in Figure 1, such that the ribbed duct made by acrylic starts at about 0.2 m from the rotation axis, and the other arm will be added with the same weight to maintain balance.

The working process of the air supply system is as follows, first of all, the gas generated by the air source RHG-520 centrifugal fan through the temperature control system, to achieve the purpose of cooling and maintain a stable temperature, flow control valve and thermal flow meter to control the air flow into the experimental section to meet the experimental needs; through the rotary air inlet connector to achieve static and dynamic conversion, the entire air supply system can provide continuous air for the experimental system, its temperature can be kept stable and controlled up and down 0.5℃, and the flow rate can be continuously stabilized and controlled in the range of 0-180m³/h. The electric slip ring and the network slip ring are used for the dynamic and static transmission of power and photos respectively.
2.2 TR-PIV system and instrumentation

The TR-PIV system consists of highspeed camera and 532nm continuous laser(maximum power 10W). Its full resolution pixel is 1024*1024, the highest shooting frequency up to 6400 frames per second in this case, also has a super high sensitivity ISO40000 monochrome imaging. The thinnest sheet laser thickness of 1mm or less can be achieved by the sheet optical converter component, so that the 10W energy of the continuous laser can be fully focused. Compared to previous pulsed laser, this continuous laser is integrally air-cooled, smaller and lighter, and has adjustable output power.

Unlike our previous phase-locked trigger PIV(You et al. 2018), the current layout(see Fig 2) allows not only the camera but also the continuous laser to be placed on the rotating platform. This makes up for the lower resolution of the previous phase-locked PIV, thus achieving a temporal resolution, namely TR-PIV. The relative velocity of the fluid can be measured directly by the TR-PIV without subtracting the migration velocity, and after uncertainty analysis it is confirmed to be more accurate, so that it can be used to measure the velocity of the boundary layer.

One of the more important factors in the PIV measurement technique is the tracer particle, whose following performance will largely affect the response of the flow characteristics. In order to obtain better following, the diameter of the tracer particle needs to be smaller; however, too small a tracer particle may cause peak locking. Secondly, the concentration of particles in the fluid is also required, and the presence of 5-8 tracer particles in an interrogation domain is generally considered optimal. In this paper, diocyl sebacate(DEHS) is used as the particle source, and a home-made particle generator based on Laskin nozzle could produce particles with an average diameter of about 1 ~ 2 μm.

2.3 Experimental section and cases

The experimental section is a 0.7m long ribbed straight duct with a square cross-section, and height(H) and width(D) are 0.08m, i.e. AR=1. The rectifier device is used to eliminate the secondary flow generated by the airflow in the front zigzag duct, which covers three parts as shown in the following Fig 3: the expansion section, honeycomb section and screen section, so that the turbulent intensity of the airflow is less than 1%.

Fig 4 shows the geometry of the experimental section, the total length of the experimental section is 720 mm, the distance between the inlet and the rotation axis is 211 mm, the cross section of the experimental section is a square of 80 mm × 80 mm, X represents the flow direction, the height of the ribs is 8 mm, i.e. the obstruction ratio is 0.1, the first pair of ribs is arranged at 120 mm from the inlet, and the distance between each pair of ribs from then on is 80 mm, that is, the rib spacing P/e = 10, a total of seven pairs of ribs. In order to eliminate the influence of inlet and outlet effects, the test plane was photographed from the second to the sixth pair of ribs, and in addition the rotational coordinate system, the direction of rotation and the corresponding PS and SS are marked in the Fig 4.
The experimental parameters of the experiment are mentioned below, where \( Re = 10,000 \) and \( Ro \) varies in size from 0 to 0.52, both of which are defined as following Equ(1) and (2), where \( \Omega \) is the angular velocity of rotation, \( U_0 \) is the relative velocity of the mainstream, and \( D \) is the hydraulic diameter of the duct.

\[
Re = \frac{\rho U_0 D}{\mu}
\]

(1)

\[
Ro = \frac{\Omega D}{U_0}
\]

(2)

For the TR-PIV system, the magnification (\( M \)) is 12.8 pixels/mm, the exposure time is set to 100 \( \mu s \), the cross-frame time is 156 \( \mu s \), and the image resolution is 1024 pixels \( \times \) 1024 pixels. In order to ensure the convergence of the speed results, more than 10,000 images are taken each time under the current experimental working conditions to ensure convergence according to previous test results. Meanwhile, by comparing the velocity profile obtained by measuring with the TR-PIV at a position in the smooth channel and measured by the hot wire (Wei et al. 2015) under the same condition, it was found that the test results of the TR-PIV and those of the hot wire were consistent, as shown in the following Fig 5, which proved the accuracy of the experimental results in this paper.

2.4 Analysis of uncertainties

In the current work, velocity is the main characteristic that is measured and calculated. Some analysis of uncertainties will be presented below.

The velocity is measured by a TR-PIV system according to the calculation formula, Eq. (3).

\[
U = \frac{1}{M} \frac{\Delta s}{\Delta t}
\]

(3)

Here \( M \) is the magnification factor between the image pixels and test plane as mentioned above, which equals 12.8 pixel/mm. The time interval between two images is 0.15625 ms, regarded as \( \Delta t \). The displacement of a seeding particle during the time interval is \( \Delta s \), which is recognized by the TR-PIV system. For conventional PIV systems, the smallest unit of CCD images is 1 pixel, which is the minimum value of seeding particle displacement during the time interval. However, the accuracy is improved to 0.1 pixel by the method of subpixel fitting for the TR-PIV system. Eq. (4) gives the error transfer function of the current system. The accuracy of \( \Delta s \) is only determined by the camera due to the use of continuous laser. However, the current camera can control the \( \Delta t \) accurately. The accuracy of the ruler we use to calibrate size of the channel can reach 0.1 mm. The spanwise size of the channel is 80 mm. Therefore, compared with the error caused by \( \Delta s \), error of both \( M \) and \( \Delta t \) can be ignored in the calculation. The equation can be simplified as Eq. (5).
\[
\Delta U = \sqrt{\left( \frac{\partial U}{\partial M} \right)^2 (\Delta M)^2 + \left( \frac{\partial U}{\partial (\Delta s)} \right)^2 (\Delta (\Delta s))^2 + \left( \frac{\partial U}{\partial (\Delta t)} \right)^2 (\Delta (\Delta t))^2}
\]

3. Results and discussion

3.1 Velocity of mean flow along the duct

The duct between the 2nd and 6th rib pair is photographed by using TR-PIV at different Ro, and the velocity fields were obtained after software stitching as shown in Fig 6, where Y=0mm represents SS and Y=80mm represents PS. It can be seen that flow separation occurs at the back of the rib, separation vortex appear on the SS and PS respectively, and lower velocity region is formed. Due to the effect of rotation, the Coriolis force as an additional term of rotation must be considered, the Coriolis force affects the flow by modifying the mainstream velocity pattern as well as the structure of the vortex on the SS and PS in the flow field. The formula for calculating the Coriolis force is defined as follows:

\[
\bar{f}_{cor} = -2 \cdot \hat{\Omega} \times \bar{U}
\]

First of all, the velocity field between the same rib pairs under different Ro is observed. As Ro increases, the mainstream velocity pattern is driven towards the PS, the area of the vortex structure near SS becomes larger, and the length of vortex is elongated; while the area of the vortex near PS is compressed, and the length of it becomes shorter. At Ro=0.52, the flow length of the vortex near SS is even twice as long as that near PS. This is mainly because the direction of the Coriolis force caused by the mainstream is oriented to PS, the presence of the Coriolis force inhibits the vortex structure near the PS, resulting in the shortening of the flow separation length of the vortex structure at the PS, the opposite phenomenon occurs at the SS. As Ro increases, the magnitude of Coriolis force also increases, and the difference between the reattachment point of the SS and PS becomes more and more obvious. Then the velocity field at the same Ro is observed. Under the static conditions(Ro = 0), the velocity field of mean flow and vortex structure are symmetrically distributed, and repeat the process of flow separation and reattachment. When Ro is larger, the area of the vortex structure and the length of the flow along the SS and PS remains basically the same, which is mainly due to the fact that the Coriolis force is only related to the rotational angular velocity and the mainstream velocity, and both are constant along the duct, so the magnitude of the Coriolis force is the same at different downstream positions.
Figure 6 Velocity nephograms between the 2nd and 6th rib pair under different Ro (from top to bottom: Ro=0, 0.13, 0.26, 0.39, 0.52)

3.2 Reynolds shear stress along the duct

The rotation effect greatly changes the nature of turbulent flow. In the Reynolds time-averaged N-S equation, including the Reynolds shear stress u'v', and the Reynolds shear stress can be understood as the shear stress generated by the momentum transfer of fluid layers with different velocities due to pulsation, and the effect of the rotation-induced Coriolis force on the Reynolds shear stress will be discussed in this paper.

Fig 7 shows the spanwise Reynolds stress distribution 10 cm after the rib along the duct (between the 2nd and 6th rib pair) at different Ro. The extreme value and change rule of Reynolds shear stress along the duct have no significant difference. It also can be clearly seen that the Reynolds stress distribution is symmetrical at rest, while the ribs produce the opposite direction of vortex rotation, resulting in opposite signs. As Ro increases from 0 to 0.52, the Reynolds shear stress distribution changes significantly for the SS and PS, while the free shear layer generated by the obstruction of the ribs is the main source of Reynolds shear stress, and this high turbulence region spans almost the entire rib spacing near PS. For the SS, the strength of Reynolds shear stress gradually decreases with increasing Ro, and the extreme value of
Reynolds shear stress when $Ro=0.52$ is only 41% of that at rest, and this result is more consistent with the literature (Coletti et al. 2012). This is due to the fact that the vortex caused by the ribs and the Coriolis force caused by the main flow are all directed to the PS, which does not enhance the strength of shear stress in this region very well. Meanwhile, for the PS, the shear strength becomes stronger as the rotation number increases. The trend along the flow direction is as follows: the shear strength becomes stronger and stronger along the duct, and then reaches a localized strongest shear region, and then weakens as it approaches the next rib pair. This phenomenon occurs at PS because the main flow causes the Coriolis force to point to the PS, while the vortex induced by the blockage of the ribs points to SS. This causes a strong shear effect in this region, which elevates the shear stress near PS compared to the stationary condition.

![Figure 7](image1.png)

**Figure 7** Spanwise Reynolds shear stress 10 cm after the rib along the duct (from left to right, from top to bottom, 2nd-6th rib pair)

### 3.3 Reattachment point along the duct

The reattachment point is defined as the point where the wall shear stress is equal to 0, that is, the normal velocity gradient is 0. Fig 8 shows reattachment point along the duct of SS and PS under different $Ro$, and it can be seen that the reattachment point and the vortex structure have a great correlation, and the specific reasons have been explained above. The reattachment points on the SS and PS are basically the same at rest, but after rotation, the reattachment points on the SS and PS have opposite change rules: as $Ro$ increases, the reattachment point on SS keeps moving downstream, which indicates that the vortex structure near SS becomes larger; in contrast, the reattachment points on PS keep moving upstream, and the size of the vortex structure keeps decreasing. Under the same $Ro$, the length of reattachment point along the duct will also change. The length of reattachment point of SS will become larger along the duct, and the length of reattachment point of PS changes slightly.
CONCLUSIONS
In this paper, the TR-PIV technique is used to study the turbulent flow in a straight duct with ribs under rotation condition, and the experimental platform is modified to increase the shooting area, so as to study the change rule of the flow along the duct. The following conclusions are obtained:
(1) The Coriolis force generated by rotation has a significant effect on the flow in the ribbed channel. In the stationary case, the velocity nephogram is symmetrically distributed; with the increase of Ro, the mainstream velocity pattern is gradually driven towards PS, and the vortex structure near SS become larger, while the situation of PS is exactly the opposite, and this trend will continue to develop along the duct, and the length of the vortex structure near SS is even twice as long as that near PS.
(2) The distribution of Reynolds shear stress shows that rotation has an effect on it. The rotation effect causes the Reynolds shear stress to become weaker near SS, while the trend of PS is just the opposite. The extreme values and trends of Reynolds shear stresses between rib pairs along the duct remain basically the same.
(3) At rest, the reattachment points of SS and PS are basically the same. With the increase of Ro, the reattachment point of SS moves to the downstream, while the situation of PS is just the opposite. Under the same Ro, the length of reattachment point along the duct will also change. The length of reattachment point of SS will become larger along the duct, and the length of reattachment point of PS changes slightly.

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References
AIAA. (2002). PIV Measurements in Ribbed Ducts With and Without Rotation.


