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(回転円板流れの安定性と遷移に関する研究)
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論 文 内 容 要 旨

The spiral vortex structures which appear in the transition process of rotating-disk flow are investigated by numerical simulations. Especially, the nature of the instabilities which cause the spiral vortices to appear in the three-dimensional boundary layer are closely examined. The 3-D boundary layer transition over a rotating disk is studied because it resembles boundary layer over a swept wing. The boundary layer over a rotating disk becomes three dimensional because of the centrifugal force. The transition process on a rotating disk is basically the same as the one on a swept wing flow. Instabilities on a rotating disk flow can be classified into three distinct groups. Convective instability in which the amplitude of disturbances increase as they move downstream is the instability most commonly found in the experiments. The source of the vibration is the unavoidable minute roughness on a real disk. The roughness continuously provides disturbances into the boundary layer. In case of the convective instability, if a disturbance is not provided ceaselessly, the disturbed flow should return to the laminar state. However, for other instabilities, namely the absolute instability and global instability, the flow becomes unstable even if the supply of disturbance is stopped. Usually, when the absolute instability is discussed, the flow field is assumed not to be growing in space, on the other hand, the global instability does not assume such a restriction.

The laminar-turbulent transition over the rotating disk has also been studied intensely because the research setup for the rotating disk flow is more easier compared to a swept wing and various instabilities can be studied in the rotating disk flow. Since a rotating disk flow can reduce flow parameters such as wall curvature and pressure

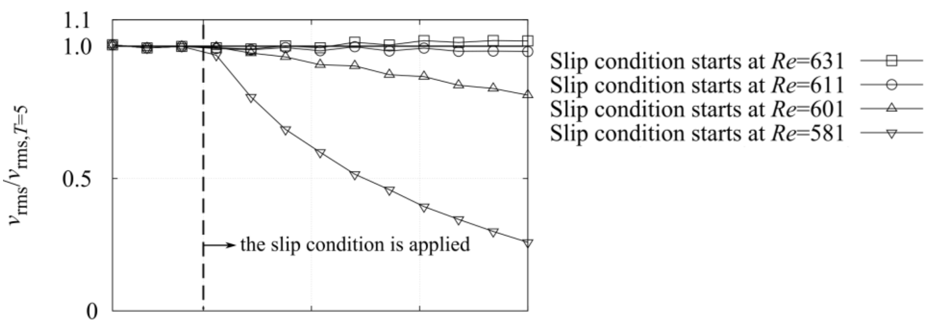

Figure 1. Temporal development of v_{rms} for each slip condition case at *Re* = 560.

gradient compared to the swept wing flows and the steady and laminar flow on a rotating disk has an exact numerical solution for Navier-Stokes equations, many experimental and theoretical researches have been carried out as well as numerical researches.

First, direct numerical simulations solving the full Navier-Stokes equations are carried out to investigate the role of the downstream turbulent region in a self-sustaining system with spiral vortices. The results show that the upstream spiral vortex structure is unaffected by the removal of the turbulent region downstream by applying sponge regions or slip conditions. Figure 1 shows the temporal development of vrms at *Re* = 560 with the slip condition applied at the wall starting from different locations, namely *Re* = 630, 610, 600 and 580. The RMS values at *T* = 5.0 are used to normalize the profiles. The slip conditions are applied after *T* = 5.5. When the slip condition starts at *Re* = 631, the RMS value does not change with time. However, when the slip condition starts at *Re* = 611, 601 or 581, the RMS values decrease with time, clearly revealing that the fluctuation cannot be maintained under these conditions. This result suggests that the downstream turbulent region is not related to the velocity fluctuations which grew by the global instability, and there is a wavemaker at a location between *Re* = 611 and *Re* = 630.

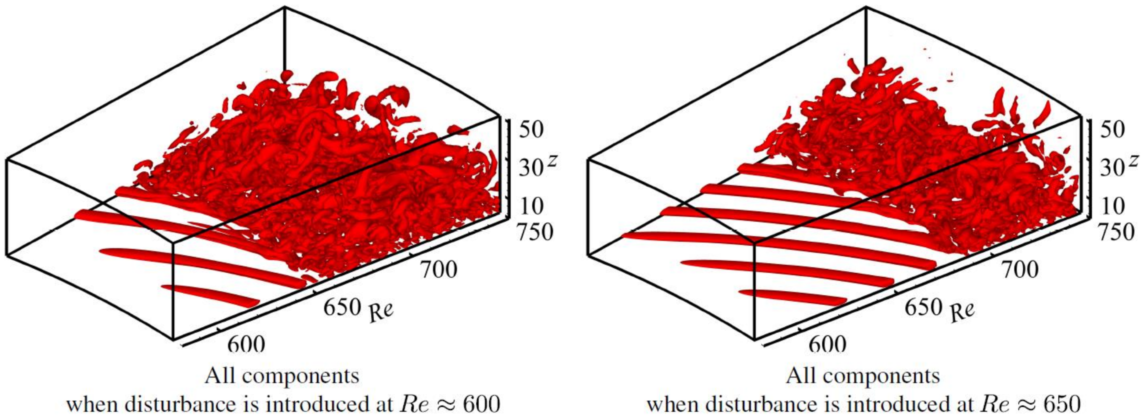

Figure 2. Iso-surfaces of $Q = 50$.

Next, the location to excite the velocity fluctuations which grow by the global instability is changed, and the relation between the exciting location and the feature of the spiral vortices is investigated solving the full Navier-Stokes equations. The flow field is of 2π/32 domain and is disturbed only for a short period in the beginning of the computation in two ways. The vortical structures inside the boundary layer are shown in Figure 2 using the iso-surfaces of the second invariant of velocity gradient tensor, *Q*. In the first case, a disturbance is introduced at *Re* ~ 600, while in the second case, a disturbance is introduced at *Re* ~ 650. The wavenumber 64 component becomes dominant in the first case, while the wavenumber 96 component becomes dominant in the second case. The results show that the flow field converges to two different states depending on the location of exciting the flow. Even the transition points are different between the two cases. In both cases, the distances between two neighboring spiral vortices are around the nondimensional distance of 15 when measured at the locations where the turbulence begin.

Then, the azimuthal size of the computational domain is changed to investigate whether spiral vortex structures with different wavenumber components could coexist in a globally unstable region of a rotating disk. Four domains with different azimuthal sizes of $2\pi/10$, $2\pi/70$, $2\pi/80$ and $2\pi/90$ are computed and compared. In the $2\pi/10$ domain computation, the wavenumber components of 70, 80 and 90 are all found to co-exist in the flow field. Among the three, the wavenumber 80 component is much stronger than the other two components. Comparing the same wavenumber components between the $2\pi/10$ domain computation and others, it is found that only amplitudes of the wavenumber component 80 are equal. On the other hand, for the other wavenumber components, the fluctuations in $2\pi/10$ domain are much weaker. The results imply that the amplitude saturation levels of wavenumber components 70 and 90 are suppressed by the dominating wavenumber 80 component through the non-linear effect.

As for the geometric configuration of the spiral vortices or their relative velocities against the disk surface, there are no difference found between the results of the wider domain computation and the narrower domain computations. The outcome indicates that each wavenumber component independently grows by the global instability and the effect of non-linearity appears only in their saturating amplitude.

Next, the relation between convective instability and global instability is studied by solving the full Navier-Stokes equations. Taking the advantage that the surface roughness can be freely controlled in numerical simulations, the stationary velocity fluctuations deriving from convective instability is set much weaker than existing experiments, and whether the traveling velocity fluctuations deriving from global instability can grow under the condition is investigated. When the artificial disturbance is continuously introduced upstream to stimulate the convective and stationary mode, the stationary wavenumber 32 component dominantly grows by the convective instability. However, the wavenumber 64 component of traveling mode is also present in the flow field. When the short-duration artificial disturbance is introduced downstream to trigger the globally unstable mode, the wavenumber 64 component of traveling mode grows dominantly, owing to the global instability. Though there is a large difference in their amplitudes, the relative velocities of wavenumber 64 component vortices against the disk surface are the same. The result suggests that, when the flow field is stimulated upstream, the traveling mode wavenumber 64

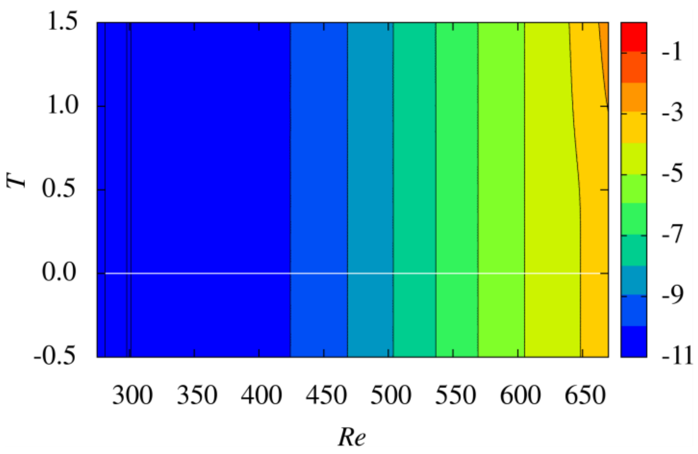

Figure 3. Spatio-temporal development of $\log(v_{rms})$ in the z = 1.3 plane

component, deriving from global instability, is suppressed by the dominant wavenumber 32 component, which is stationary and convective. Figure 3 shows the spatio-temporal development of the RMS value log(v_{rms}) at z = 1.3 for two disturbance cases mentioned above. For T = -0.5 ~ 0.0, the flow field is identical to the T = 2.5 ~ 3.0 flow field disturbed by convectively instability when the weaker continous disturbance was introduced upstream. The results show that even in a flow field dominated by the convective and stationary spiral vortices, the vortical structures deriving from global instability can be excited by introducing a short-duration artificial disturbance, although their amplitudes are considerably smaller.

Last, the characteristics for the linear global instability is studied by solving the linearized Navier-Stokes equations by direct numerical simulations. The results show that the linear global instability is not related to the edge location of the disk, as is widely believed in the past, and that the linearly globally unstable mode can be exited even when the radius of the disk is infinite.

As results of the investigation using numerical simulations, many new aspects and the roles of the global instability are revealed. Some hints for the unanswered questions regarding the transition of three-dimensional boundary layer over a rotating disk are provided.

論文審査結果の要旨

回転円板上の流れは，航空機の後退翼面上の流れと類似した遷移形態を取る。いずれも壁面からの距離に応じて流れの方向が異なる３次元境界層を有し，平均流れの方向に軸を持つ縦渦が形成された後に乱流化する。この縦渦は境界層内の微小な速度変動が平均流の不安定性により増幅された結果であり，円板上では周方向に規則的に並んだらせん状の配置をとって現れる。移流不安定が支配的となる実験では 30 本前後の縦渦が観測されることが多いが，全体不安定が支配的となる環境下ではその本数も大幅に増加し，実験とは異なるルートで乱流に遷移する可能性があることが近年の理論解析や数値計算により示唆されている。本研究の目的は，様々な数値実験を通して乱流遷移に至る過程を詳細に調べ，回転円板流れにおける不安定性と乱流遷移の関係を明らかにすることにある。本論文はこれらの研究成果をまとめたものであり，全７章からなる。

第１章は緒言であり，本研究の背景，目的および構成を述べている。

第２章では，円板表面の速度の境界条件を操作することで部分的に乱流を抑える数値実験を行い，らせん渦の外側，レイノルズ数 Re ≈ 650 よりも下流に存在する乱流領域がらせん渦に及ぼす影響について調べている。その結果，らせん渦は下流の乱流領域の有無に関わらず存在し続けること，また，Re = 611 ~ 630 の範囲にらせん渦の構造を維持させる加振源が存在することを明らかにしている。これは，全体不安定なモードは乱流によって自己維持しているわけではないことを指摘する重要な成果である。

第３章では，撹乱を導入する位置が乱流遷移に及ぼす影響を調べ，らせん渦の本数は撹乱の導入位置によって異なること，また乱流の開始位置も影響を受けることを明らかにしている。さらに乱流開始位置はらせん渦間の距離で決まることを見出しており，工学的に有用な知見である。

第４章では，計算領域を広げた計算を行い，回転方向の波数が異なる複数のらせん渦が共存できる環境で生じる現象と回転方向波数が限定される計算領域の結果とを比較している。その結果，ある波数成分だけが卓越すると他の成分の成長が非線形干渉により抑制されることを明らかにしており，工学的に重要な知見である。

第５章では，移流不安定による速度変動の成長が卓越した場で全体不安定を刺激するとどうなるのかについて調べており，たとえ移流不安定が支配的な環境であっても全体不安定性によって速度変動が成長しうることを示している。これは，実験であっても円板表面を十分滑らかに研磨することができれば全体不安定性が観察可能であることを意味しており，回転円板流れを理解するうえで重要な成果である。

第６章では，線形計算により全体不安定性に対する円板の端部の影響について調べている。本章の結果は，無限大の大きさの円板は線形全体安定であると考えられてきた現在主流の説が誤りであることを明らかにしており，工学的に有用な知見である。

第７章は結論である。

以上要するに本論文は，様々な新しい発想に基づいた数値実験を通して，回転円板上の３次元境界層が示す不安定性と乱流遷移の関係について調べたものである。本研究によって得られた知見は，回転円板流れにおける乱流遷移現象に関する理解に資するもので，機械システムデザイン工学および流体工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。