Title	Dynamical Systems Approach to Subcritical Transition to Turbulence in Wall-Bounded Shear Flows
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Abstract of Thesis

Name	(Julius Rhoan T. Lustro)
Title	Dynamical Systems Approach to Subcritical Transition to Turbulence in Wall-Bounded Shear Flows (壁面剪断流における亜臨界乱流遷移現象への 力学系アプローチ)

Abstract of Thesis

The phenomenon of subcritical transition to turbulence in wall-bounded shear flows is one of the outstanding problems in fluid mechanics ever since the seminal work by Reynolds Osborne in 1883 [1]. A theoretical description of the spatiotemporal events that are observed during the transition has remained the principal challenge for researchers taking on this topic. In the last two decades, a significant success in characterizing the transition has been achieved by applying concepts and ideas derived from dynamical systems theory. Dynamical systems approach pictures the transitional flows as invariant sets in phase space. For the transition in wall-bounded shear flows this translates to the coexistence of two invariant sets that represent the laminar flow and chaotic motion. The discovery of invariant saddle sets known as 'edge states' in midst of these two invariant sets shows that the basins of attraction of the laminar and chaotic sets can be separated by the edge state itself and its stable manifold. The investigation of the long-time behavior of these edge states along its unstable manifold provides nontrivial results as to which state the system will achieve. It is then important to examine such long-time behavior to understand the role of edge state in the determination of the onset of transient turbulence occurring in wall-bounded shear flows.

We first describe the rich bifurcation scenario in a plane Couette flow with slightly longer streamwise period. We identify for the first time the presence of homclinic bifurcation in a system governed by the full Navier-Stokes equation. Three homoclinic bifurcations are found correspond to the creation or destruction of periodic orbits at $Re \approx 163.58$, $Re \approx 198.50$, and $Re \approx 238.30$ ($Re \equiv Uh/\nu$, where U, h, and ν being half the difference of the two wall velocities, half the wall separation, and the kinematic viscosity of fluid, respectively). At the Reynolds number where the homoclinic bifurcations occur, the periodic orbit functions as homoclinic orbit to the fixed point. In between $198.50 < Re < 238.26$, the edge state is observed to shift from the fixed point to the periodic orbit at the homcolinic bifurcation at $Re \approx 238.30$. The periodic orbit which originates from homoclinic bifurcation at $Re \approx 198.50$ undergoes period-doubling cascade which leads to a chaotic attractor. This chaotic attractor collides with the periodic edge state on the boundary of the laminar basin at $Re \approx 238.26$. After the crisis on the boundary of the laminar basin, for $Re > 238.26$, transient turbulence that eventually relaminarizes is observed.

The onset of transient turbulence in minimal plane Couette flow has been described theoretically as the first homoclinic tangency with respect to the periodic edge state, which is the gentle periodic orbit by Kawahara and Kida [2]. A Smale horseshoe appears on the Poincaré section through transversal homoclinic points to generate a transient chaos that eventually relaminarizes at the onset Reynolds number $Re_T \approx 240.88$. In numerical experiments a sustaining chaos, which is a consequence of period-doubling cascade stemming from the upper branch of periodic edge state, is observed in a narrow range of the Reynolds number, $Re = 240.40$–240.46. At the upper edge of this Re range it is found that the chaotic set touches the lower branch of this pair, i.e., another edge state. The corresponding chaotic attractor is replaced by a chaotic saddle at $Re \approx 240.46$, and subsequently this saddle touches the periodic edge state on the boundary of the laminar basin at the tangency Reynolds number $Re = Re_T$. After the boundary crisis, for $Re > Re_T$, chaotic transients that eventually relaminarize can be observed.

It is seen from both works that when the chaotic set touches a periodic edge state during boundary crisis, a leak is opened up for the laminar basin. Transient chaotic behavior that relaminarizes after some time becomes a possible state of the system. In wall-bounded shear flows a wide variety of onset of chaos is observed but this leaky boundary after the setting of the boundary crisis is a common theme. Therefore, the determination of first homoclinic tangency with respect to the periodic edge state in this study as the mechanism for onset of transient turbulence that eventually relaminarizes provides us a blueprint for the theoretical estimation of the subcritical transition to turbulence in wall-bounded shear flows.

様式７

論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

亜臨界乱流遷移問題とは，基本流である層流が微小振幅撹乱に対して（線形）安定であるにも拘らず，乱流状態への遷移が認められるものである．この問題の解決には本質的に非線形な理論が必要となるため，O. Reynolds教授の先駆的研究以来130年以上の長年にわたる研究がなされて来たが，依然として未解明である．亜臨界問題として著名な平面Couette流では，層流状態は任意のReynolds数で線形安定であり，層流解の線形不安定と解の分岐は生じない．本論文では，この未解決問題に対して，最新の力学系理論に基づくアプローチを試みている．具体的には，ミニマル流と呼ばれる，乱流が持続する最小の周期箱における流れの乱流遷移での（有限寿命を有する）過渡乱流の発生をホモクリニック・タンジェンシーとして捉えたものである．まず，エッジ状態と呼ばれる特別な不変解に注目する．エッジ状態は，その安定多様体と解自身が，位相空間において乱流と層流との吸引領域境界を形成する．すなわち，位相空間におけるエッジ状態の不安定方向は１つである．特に周期的エッジ状態に対してホモクリニック軌道が存在すれば，力学系に馬蹄写像が存在することになることから，過渡的なカオス動力学が力学系に見出される．本研究ではこの点に着目し，ミニマル平面クエット流における周期的エッジ状態に関するホモクリニック軌道を求めた．流体に代表される大自由度力学系においてホモクリニック軌道を求めることは，数値的にも極めて困難であるが，本研究ではエッジ状態の不安定方向が１つであることを活かして，Poincare断面における周期的エッジ状態の不安定多様体の接方向（固有ベクトル）に沿って二分法を適用することによって，大自由度力学系に対するホモクリニック軌道を数値的に求めることに成功した．さらに，Reynolds数を下げながら１対の互いに異なるホモクリニック軌道を追跡し，有限Reynolds数で２つのホモクリニック軌道が一致すること（ホモクリニック・タンジェンシー）を示し，過渡的乱流が発生するReynolds数を理論的に決定できることを示した．この研究成果は，亜臨界乱流遷移問題への全く新しい理論的アプローチを提示した点で極めて重要な意義を有し，博士（工学）の学位論文として価値のあるものと認める．