称号及び氏名	博士（工学）　杉谷 栄規
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論　文　名	「Studies on Stability Analysis and Design of Amplitude Death in Delay-coupled Oscillators （遅延結合発振器群に誘発される振動停止現象の安定性解析と設計）」
論文審査委員	主査　小西 啓治 教授
	副査　石亀 篤司 教授
	副査　森澤 和子 教授

論文要旨

Oscillations are observed everywhere, in both artificial and natural systems. They can be classified into two categories: forced oscillations and self-excited oscillations. Self-excited oscillations are induced by constant external energy, such as a bridge oscillating due to a constant wind. Self-excited oscillations are sometimes undesirable, as they can adversely affect the stability and performance of various systems, such as oscillating bridges and galloping power transmission lines. Throughout this thesis, we will use the term "oscillators" to refer to self-excited oscillatory systems. The nonlinearity of oscillators generates robust stable oscillations against small perturbations. When oscillators interact with each other, various nonlinear phenomena can be observed, such as the synchronization of flashing fireflies and the synchronized firing of pacemaker cells in our hearts. In order to understand these nonlinear phenomena, coupled oscillators have been widely investigated in nonlinear science. By "coupled oscillators", we mean a system that consists of oscillators with simple dynamics, with the connections between the oscillators representing their interactions. Although these coupled oscillators have simpler dynamics than those of the interacting oscillators found in the real world, they provide a useful tool for understanding real-world phenomena. Due to the finite propagation speed of signals, there is a time delay in the interactions between oscillators. Thus, in recent years, researchers have been greatly interested in delay-coupled oscillators, in which the connections have delays. These connection delays make the analysis of coupled oscillators more difficult, since coupled oscillators have infinite dimensions.

Amplitude death, a phenomenon seen in coupled oscillators, is the stabilization of unstable fixed points by diffusive connections. Broadly speaking, all of the oscillations in coupled oscillators are quenched by their connections. It was previously thought that this phenomena could not be induced in coupled oscillators that all had the same frequency. However, in 1998, Reddy *et al.*, found that a connection delay can induce amplitude death even in a coupled system of identical oscillators. For engineering applications, amplitude death has been considered as a potential method for suppressing undesired oscillations in real systems, since the oscillations are quenched by the connections

themselves, and thus there is no need for controllers. In recent years, researchers have investigated this in such systems as coupled laser systems, DC microgrids, coupled thermoacoustic oscillators, and coupled permanent magnetic synchronous motors.

Most previous studies on amplitude death due to connection delays have focused on understanding the causes for this phenomenon, rather than ways of inducing it in real systems. Here we consider the following issues. First, most previous studies on amplitude death did not consider procedures for designing connections that will induce amplitude death in coupled oscillators. As a result, users who want to induce amplitude death in real systems must determine the connection parameters by trial and error. Second, we cannot use amplitude death in practical situations in which the connection delays are long compared with the period of the oscillators; this occurs when the distance between the oscillators is large, or the propagation speed of the connecting signal is slow. Third, most previous studies dealt with coupled oscillators with time-invariant network topologies. However, in the real world, topologies sometimes vary with time, such as those in the organs of the human body and in ad hoc networks. The main purpose of this thesis is to solve these three open problems. The contents of each chapter in this thesis are as follows.

Chapter 1 explains the background and purpose of this thesis, and briefly provies an overview of this thesis.

Chapter 2 presents a procedure for designing connection parameters to induce amplitude death in delay-coupled high-dimensional oscillators. Although in most previous studies, amplitude death was investigated only for low-dimensional oscillators, such oscillators cannot always be used to describe real engineering systems. Using the parametric approach of robust control theory, we provide a procedure that depends on neither the network topology nor the total number of oscillators. The effectiveness of this procedure is confirmed with numerical examples.

Chapter 3 investigates amplitude death induced by time-varying delay connections. We confirm that these connections can induce amplitude death in various network topologies with long connection delays, such as those with all-to-all, ring, small-world, and scale-free topologies. We then provide a procedure for designing the connection parameters that can induce amplitude death in situations where the connection delay, the number of oscillators, and the network topology are unknown. The effectiveness of our procedure is confirmed with numerical simulations. Furthermore, we propose partial time-varying delay connections, which consist of a time-varying delay connection and a time-invariant delay connection. Since our proposals require that only some of the connection delays are varied, the partial time-varying delay connections are easier to implement than the conventional time-varying delay connection. The effectiveness of these connections is confirmed analytically and numerically.

In Chapter 4, we present experimental results that confirm the effectiveness of the time-varying delay connection in an electronic circuit. Our system consists of two double-scroll chaotic circuits and a time-varying delay connection between them. The two double-scroll chaotic circuits use commercially available circuit devices, and the time-varying delay connection is implemented mainly by peripheral interface controllers (PICs) and digital-to-analog (DA) converters. We show analytically that, compared with a time-invariant delay connection, a time-varying delay connection enlarges the stable region in coupled double-scroll chaotic circuits. We also confirm that the analytic results are in good agreement with our experimental results.

Chapter 5 considers amplitude death in delay-coupled oscillators with fast time-varying topologies. The network topology periodically and randomly changes with a shorter period than that of the oscillators. In general, it is difficult to perform a stability analysis of time-varying network topologies, but for oscillators with rapidly varying periods, the local stability of the amplitude death is equivalent to that of a time-invariant system. Thus, we can easily analyze its stability. The analytical results are verified with numerical simulations, and the relationship between the stable region and the time-varying period is investigated numerically.

Chapter 6 summarizes our results and describes areas for future work.

審査結果の要旨

本論文は，相互作用の伝送路に遅延時間を伴う結合発振器群の安定化現象について，非線形数理・システム制御理論に基づいて安定性を解析し，安定化を誘発する設計も試み，さらに，電子回路による検証実験にも言及したものであり，以下の成果を得ている．

（１） 複数の高次元発振器が遅延時間を伴う相互作用で結合された発振器群について，その平衡点の安定化をシステム制御理論の視点で解析した．その解析結果に基づき，安定化を誘発する結合パラメータの設計問題に取り組んだ．特に，2 個の不安定根を有する高次元発振器の場合は，系統的な設計手順を与えている．数値例では，2 個の不安定な実根を有する高次元発振器を用いて，設計手法の有効性を示した．

（２） 相互作用の伝送路に伴う遅延時間が時間と共に変化する場合の結合発振器群の安定化現象を解析した．全ての伝送路が変動する遅延時間を伴い，かつ，その変動が発振器の固有周波数に対して十分高速であれば，安定化現象は解析的に扱うことができ，安定化を誘発する結合パラメータも設計できることを示した．さらに，一部の相互作用でのみ遅延時間が変動する場合の安定化現象についても調査を行った．

（３） 変動する時間遅延が相互作用に伴う 2 個の結合発振器に生じる安定化現象の実証実験を行った．発振器にはダブルスクロール回路を採用し，時変遅延相互作用は小型マイコンで実装した．安定化現象が生じるパラメータ集合が，解析的結果と実験結果で合致することを確認した．

（４） 遅延時間を伴う相互作用で結合された発振器群のネットワークトポロジーが，時間と共に変動する状況での安定化現象の解析を行った．トポロジーの時間変動が発振器の固有周波数に対して十分に高速であれば，解析的な推測結果と数値シミュレーションの結果がほぼ合致することを確認した．

以上の諸成果は，不安定化や振動を誘発する要因と見なされてきた遅延時間が，工学システムの不安定化や振動を安定化する要因として利用可能であることを示唆する知見を与えている．特に，ネットワークシステムを考慮した研究成果は，今後の複雑化した社会インフラの安定な運用に貢献できる可能性を秘めている．また，これらの成果は，申請者が自立的に研究活動を継続できる能力と学識を持ち合わせていることの証である．