Fluid Dynamics, Focusing on Vortex Motion and its Applications

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From a mathematical point of view, fluid motion consists of vortices and waves. Commonplace examples of vortical structures include the vapor trails created by aircraft wings and the columns of air bubbles that form above bathtub drains as water flows out. Systems exhibiting vortex motion can be described as dynamical systems with infinitely many degrees of freedom, in which various modes of different sizes form a hierarchical structure and interact nonlinearly with one another. Such interacting modes may evolve to form coherent structures or eventually produce chaotic and turbulent states. Once formed, a vortex possesses the ability to 'transport' and 'mix' matter. It is well known that an air gun can cause a specific volume of air to be transported to a distant place. As exemplified by cardiac pumps that drive blood flow, living organisms exploit vortex rings in various forms. The formation and stability (or instability, depending on the case) of vortices created by objects moving through fluid are vital to safe aviation, efficiency in wind power generation, and the operation of flying robots. These examples illustrate how the nonlinear dynamics of vortices play important roles in present-day technology in a variety of contexts, ranging from energy and global environmental problems to advanced technologies in the manufacturing industry.

Figure 1. Curvature instability of a vortex ring

My current research interest is in mathematical analyses of vortex motion. Some of the results I have obtained in the theory of three-dimensional vortex motion precede those of any other groups in the world. In 1994, I became the first recipient of the Ryuumon Award, which is given to a young researcher by the Japan Society of Fluid Mechanics, for my work on the three-dimensional motion of vortex filaments. My collaborators and I recently succeeded in deriving a formula for the traveling velocity of a vortex ring that is consistent with experimental results. This formula is applicable not only to high but also to low Reynolds number regions. Moreover, we discovered an unstable mechanism of vortex rings (Figure 1), and my coauthor received a Ryuumon Award for this work (2006). Our group is currently developing a new Lagrangian approach that can treat both continuous and point spectra of vortex motion and the nonlinear dynamics of vortices.

Euler developed the first approach to analyzing fluid motion using partial differential equations in the 18th century. An entire century then passed before Helmholtz published his seminal paper (1858), which led the way to the investigation of vortex motion. Helmholtz demonstrated that "in the absence of viscosity, vortex lines are frozen into the fluid." This implies that link-type and knot-type vortex lines do not change with time. One major thrust of research in fluid dynamics in the latter half of the 20th century was to understand the topological meaning of Helmholtz's laws and to find applications thereof. This research was initiated by Arnol'd (1966). However, the results obtained in such investigations are yet limited to two-dimensional flows. The Lagrangian approach, which employs the displacement field of fluid particles as the fundamental variables, can be used to investigate vortex motion with rigorously time-independent topological invariants. For this reason, it provides a universal framework for investigating the motion of molecules, solid (elastic) bodies, fluids, and even plasmas. Currently, I am attempting to construct (by exploiting the high degree of extensibility of the Lagrangian description) a new mathematical framework in which three-dimensional interactions between waves and mean flows can be calculated.

I am the subleader of the Global COE Program "Education and Research Hub for Mathematics-for-Industry," supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan. In cooperation with other program members, I organize the Math for Industry forums and other activities. I am also engaged in organization of the Study Groups that started in Japan in 2010.

Substantial effort is made in our research group to train graduate students, including those in the Ph.D. program. We have also made the hosting of students from abroad a priority and are active in international exchanges for the promotion of advanced research. I won the Visiting Professorship (Long Term) of the Japan Society for the Promotion of Science (JSPS), and visited the University of Cambridge for ten months in 1996, were I carried out a collaboration with Professor H.K. Moffatt on the motion of viscous vortex rings. Since my return to Japan, prominent, world-renowned researchers have frequently visited our group to exchange information on research frontiers. Since 2001, I have hosted eight researchers under the Invitation Fellowships Program (Short Term) of the JSPS. These activities have helped us develop an international network of world-class researchers in the field of topological fluid mechanics, including Professor H.K. Moffatt, the pioneer, and Professors. R.L. Ricca (University of Milan), D.D. Holm (Imperial College London), and B.A. Khesin (University of Toronto). I intend to continue using this network to train young researchers. Since 2012, my Ph.D. students have made long-term and short-term visits to universities around the world for study and collaborative research in mathematics.