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Trends in Research on Turbulence Control Aiming at Reducing Friction Drag

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1 Introduction

When a gas such as air or a fluid such as water flows along a surface of an object, a well-ordered laminar flow takes place at low velocity. However, when the volume or velocity of the flow exceeds a certain limit, minute eddy motion develops and grows into diversified shapes of large vortices, one after another, which are collectively referred to as turbulent flow. Turbulent flows have common characteristics such as irregular motion, three-dimensional eddy movement, and dissipation. It is said that a turbulent flow occurs at a Reynolds number*1 of around 2000, but it depends on the state and conditions of the flow. Figure 1 shows the state at the moment when the flow changes from a laminar to a turbulent flow.

While a turbulent flow has adverse effects on the progress of aircraft and ships by generating friction drag due to air or water and increasing fluid noise, it also brings about beneficial effects by accelerating mixing, heat transfer, and combustion. Turbulence control is a technology used to suppress the adverse effects and promote beneficial effects by adequately controlling the flow. Turbulence control not only contributes to energy saving, high-quality products, and prevention of environmental deterioration, but also be capable of bringing about breakthroughs in the transportation field.

Although research on turbulence has long been conducted, it remains both an old and new theme, due to the relatively slow progress made. Recently, however, basic data on turbulent structures are being accumulated thanks to the increased capability of supercomputers and the development of direct numerical simulation (DNS)*2. In addition, microelectricalmechanical systems (MEMS) *3 technology to realize turbulent control is being rapidly developed. Studies attempting to actively control turbulent flows are also being conducted extensively because turbulence control is expected to contribute significantly to energy saving and measures resolve environmental problems.

This report describes the trends in research on turbulent flows, especially those concerning studies attempting to reduce the friction drag of wall turbulence by constructing a control system and applying MEMS technology, consisting of sensors used to detect microstructures of turbulence and actuators for controlling the fine structure.

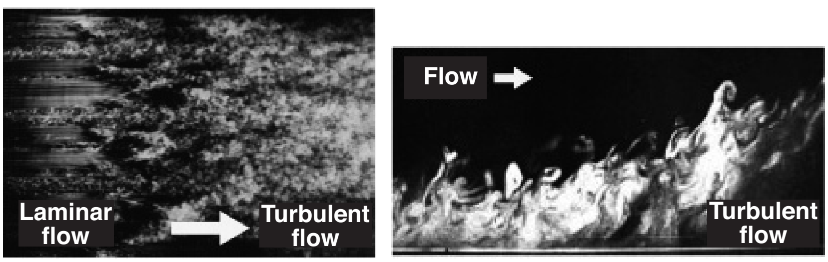

Figure 1 : Change from a laminar flow to a turbulent flow

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2 Trends in research on turbulent flow

2-1 Trends in research on elemental technologies

Studies on turbulent flows in the modern age were started by Osborne Reynolds (1842-1912), who discovered the transition from a laminar flow to a turbulent flow by observing the phenomenon whereby the trajectories of dye in a pipe suddenly becomes irregular at a certain velocity; over 110 years have since passed.

In the United States, the living organism of a shark, which could swim very fast, was studied in the 1970's. The surface conditions of sharks' scales differ depending on the type of shark, and those that can swim fast have fine longitudinal grooves (riblets) on the surface of each scale. The intervals between the grooves are very short, within the range 35 and 100μm, depending on the position of the body. Experiments confirmed that these riblets reduced the turbulence friction drag by up to 8%[1]. In 1983, 3M Company developed a riblet film (Figure 2), which had fine longitudinal grooves on the surface of a vinyl sheet and used it in the Olympic Games and America's Cup (yacht racing).

The National Aeronautics and Space Administration (NASA), military organizations and aeronautics industry in the United States are also widely conducting research targeted at the practical use of devices applying riblets using the control theory and numerical simulation, and a demonstration test conducted by the airline industry proved that 2% of the total resistance could be reduced. If the surface of the fuselage were covered with riblet films that could reduce resistance by 2%, the fuel cost of Airbus A320 could be saved by 50 thousand l/year with a standard flight frequency[3], which would lead to estimated savings of $200 million in the airline industry of the United States[4]. However, the results of this research were not practically implemented, because the economic effect is reduced when the maintenance cost is considered.

Presently in the United States, research on the elucidation of the basic mechanism of turbulent flows and the active control of turbulence is mainly carried out at universities. For example, research attempting to reduce the friction resistance of ships using polymers and micro bubbles has been carried out since 2000 as part of a project of the Defense Advanced Research Projects Agency (DARPA(1)) of the U.S. Department of Defense.

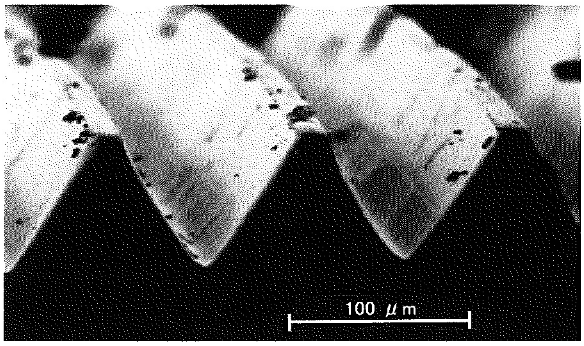

Figure 2 : Photo showing the surface of riblet films made by the 3M Company

Reprinted from Reference[2]

More practical studies are also underway in Europe at present. Holland, a maritime nation, has a history of research on reducing the friction drag of ships. Also, research on turbulence control is being extensively conducted by a Special Interest Group from the European Research Community On Flow, Turbulence And Combustion (ERCOFTAC(2)), which is an organization made up of research institutes studying turbulent combustion in the European Union (EU) and neighboring countries.

"Study on Rapidly-developing Research Area"[5], conducted by the National Institute of Science and Technology Policy in FY 2004, points out that "Smart Control of Turbulence" is one of the rapidly developing global fields in recent years. The analysis showed that this field includes wall turbulence, turbulent combustion, and numerical simulation. Unfortunately, Japan is not playing an important role in this field. Although basic studies on turbulence have been conducted in Japanese universities since the latter half of the 1950's, one of the reasons for the negative impression is that papers written in Japanese are not globally recognized.

The Japanese level of individual elemental technologies, such as MEMS technology including sensors and actuators, DNS technology necessary to elucidate and predict phenomena, and turbulence monitoring technology using optical sensors, that are required for turbulence control is quite high. However, since cooperation of diversified fields is required to conduct research on turbulence control, it is difficult for a single organization to implement. Therefore, the Center for Smart Control of Turbulence was established in the National Maritime Research Institute based on the Organized Research Combination Systems sponsored by the Ministry of Education, Culture, Sports, Science and Technology. At this center, the “Smart Control of Turbulence: A Millennium Challenge for Innovative Thermal and Fluid Systems” project was carried out for five years from FY 2000, to collectively harness the capabilities of independent administrative agencies and universities (Table 1).

In this project, the mechanisms for the development of turbulence and control theory were studied utilizing various sensors and actuators as the control measures, and a prototype control system was built up. In the study on “active turbulence control” of “Smart Control of Turbulence: A Millennium Challenge for Innovative Thermal and Fluid Systems” project for FY 2005[7], for example, the friction drag of turbulence was found to be reduced by about 6±3% in laboratory tests. In the study on “wall turbulence control” using micro bubbles, the mechanism via which turbulence is suppressed by the existence of bubbles larger than the vortex scale was elucidated, and it was demonstrated that local friction drag could be reduced by up to 60% in experiments using actual ships. In the study on “turbulent combustion control,” combustion behavior in the gas turbine combustor was analyzed using LES*5 and flamelet model*6, and combustion control experiments were conducted using a small combustor, which resulted in the elucidation of oscillating combustion using secondary fuel injection. Now the research is in the practical application stage.

2-2 Progress of supercomputers and simulation

The turbulent flow includes characteristics of irregular motion, three-dimensional eddy movement, and irregularity which cause chaotic fluid phenomena*7 accompanied by extremely nonlinear behavior, meaning it has been difficult to control turbulent flows to date. In the latter half of the 1980’s, however, it became practicable to implement DNS due to the improvement of computing capability of supercomputers, which made it possible to visualize the entire three-dimensional picture by simulating turbulence on computers.

In the 1990’s, studies on constructing turbulence models and predicting thermal hydraulic phenomena were conducted utilizing many empirical data and numerical simulations

Table 1 : Status of research related to “Smart Control of Turbulence: A Millennium Challenge for Innovative Thermal and Fluid Systems”

Sub theme	Objectives of research	Description	Responsible organizations
Research on active turbulence control	(1) Development of fundamental technologies, such as micro machine technology consisting of sensors and actuators (2) Constructing a system that controls friction resistance, exfoliation, and heat transfer by active turbulence control	Development of devices for active turbulence control	AIST, JAXA, NMRI, universities
		Construction of active turbulence control theory	AIST, JAXA, universities
		Numerical simulation of turbulence control	JAXA, AIST, NMRI, universities
		Demonstration by model systems	AIST, JAXA, NMRI, universities
Research on turbulent combustion control	(1) Elucidation of turbulent combustion phenomena and the development of sensing technology (2) To promote the control of diffusion and mixing of combustion gas and air in turbulent jets to expand the application of lean premixed combustion*4 by stabilizing it to improve combustion efficiency and reduce hazardous gas	Development of turbulent jet control	JAXA, AIST, NMRI, universities
		Development of measuring technologies for turbulent combustion	JAXA, AIST
		Elucidation of the micro mechanism of turbulent combustion	JAXA, universities
		Assessment by model systems	JAXA, AIST, NMRI, universities

* AIST : National Institute of Advanced Industrial Science and Technology; JAXA: Japan Aerospace Exploration Agency; NMRI: National Maritime Research Institute

Prepared by the STFC based on Reference[6] using supercomputers (CFD: Computational Fluid Dynamics[3]). In the early 1990's, modern control theory for fluid dynamics was mathematically established, and algorithms for turbulence control were extensively developed and verified. Since the latter half of the 1990's, active control of turbulent flows has also been attempted for artifacts based on these data. Table 2 shows the correlation between theory and empirical data in relation to the increased capability of supercomputers.

Table 2 : Correlation between theory and empirical data in relation to the capability of supercomputers

Age	Typical supercomputer	Correlation between theory and empirical data	Implementing institute
Latter half of 1980's	• CrayXMP/2 (U.S.A.) • SX2/SX3 (Japan)	• The results of detailed calculation of turbulent flows between parallel plates using DNS were reported for the first time. Reynolds number Re_{τ} =180 (close to the minimum value which exhibits characteristics of a turbulent flow along wall surface). Approximately consistent with statistical values obtained by experiments.	Kim et al.,1987, NASA Ames Research Center /Stanford University (U.S.A.)
	• Capacity of DNS memory : 10MB	• The particle tracking velocimeter was developed, and the results of detailed experiments, including data in areas close to the wall surface, agreed quantitatively with the DNS results.	Kasagi, Nishino, 1991, University of Tokyo.
1990's	• CrayYMP/C90 (U.S.A.)	• DNS for turbulent channel flows with Reynolds numbers up to about Re_{τ} =600 was attempted to discover which of the logarithm and power laws were followed for the velocity distribution. However, no conclusion was obtained because the Reynolds numbers were too low.	Moser et al., 1999, NASA Ames Research Center /Stanford University (U.S.A.)
	• IBMSP1/SP2 (U.S.A.) • SX-4/SX-5 (Japan) • SR-22000 (Japan) • VPP-500/NWT (Japan)	• Application of the modern control theory to flow control problems was formulated. - Numerical experiments on the reduction of friction resistance of turbulent flows using DNS have since been boosted. • A reduction of friction resistance by about 20% was achieved both by suboptimal control*8 that requires a relatively low calculation load and by more intuitive control based on the quasi-ordered structure of turbulent flows.	Abergel & Temam, 1990, University of Paris 11 Choi et al., 1993; Lee et al., 1998, Stanford University (U.S.A.), Choi et al., 1994, Stanford University (U.S.A.)
	• Capacity of DNS memory : 10MB-10GB	• Numerical experiments using DNS under conditions with more consideration given to hardware systems, considering the physical values measured at the wall surface and the deformation of actuators, confirmed that certain resistance reduction effects could be obtained, even when the sensors and actuators are located discretely.	Endo et al., 2000, University of Tokyo
First half of 2000's	• SX-6/SX-7/ Earth Simulator (Japan)	• DNS for turbulent channel flows with Reynolds numbers of Re_{τ} =1000 – 2000 was carried out.	Del Alamo et al., 2004, Polytechnic University of Madrid (Spain), Iwamoto et al., 2005, University of Tokyo
	• SR8000/11000 (Japan) • ASCIWhite (U.S.A.)	• Reduction of friction resistance by 6% was demonstrated by a wind tunnel experiment using a feedback control system (Yoshino et al., 2005, University of Tokyo)	
	• Linux cluster grid based on Intel architecture (worldwide)	• Although corroborative evidence for the reduction of friction resistance by the mechanism based on the suboptimal control theory (Fukagata, Kasagi, 2004, University of Tokyo) has been obtained (Yoshino, et al., 2006, University of Tokyo), it has not been sufficiently verified.	
	• Capacity of DNS memory : 10GB-1TB	• DNS for controlling turbulent flows between parallel plates with a low Reynolds number of Re_{τ} =100 using an optimal control theory, which requires laborious calculation load, was reported. It was shown that the feedback control could change a turbulent flow into a laminar flow (Bewley et al., 2001, UC San Diego (U.S.A.)).	

Prepared by the STFC based onRreference[8]

3 Recent research results in Japan

3-1 Development of wall turbulence and control mechanism

The limitless number of longitudinal vortices that occur in the direction of flow generate Reynolds shear stress causing turbulent friction drag. Figure 3 shows a near-wall longitudinal vortex in the cross section perpendicular to the flow direction and the relationship of spatial positions of the instantaneous production, destruction, and diffusion processes of Reynolds shear stress[9].

At the center of the longitudinal vortex is a core portion (L) where the pressure is locally low, and in the right side region (sweep side) is a portion where the pressure is locally high because the fluid impinges upon the wall surface. On the left side (injection side), the fluid of low pressure is elevated and forms a high-pressure stagnant region (high-pressure potato) bumping against the high-speed fluid supplied from upstream due to convection. The Reynolds shear stress is actively generated on both sides of the vortex and the generated shear stress is subsequently transferred to neighboring regions via turbulent diffusion and pressure diffusion, which disappears in the low and high pressure regions with strong correlation between the pressure and strain. The turbulent flow is maintained by such a ceaseless process of production , diffusion, and dissipation.

As mentioned above, factors that generate friction drag fluctuate intermittently in space and time, and the temporal and spatial scales of the actual object govern the dimension and response time[10] required for the sensors and actuators used. As shown in Figure 4, the required dimension is within the range 0.001mm and 10mm, and the response time is approximately between 0.01ms and 100ms. This indicates that the temporal and spatial scales handled in wall turbulence are small compared with those handled in conventional mechanical systems. The MEMS technology that has been rapidly developing in recent years has the potential to reduce friction drag at the wall surface by effectively suppressing the generation of Reynolds shear stress and turbulent kinetic energy, by selectively controlling the vortices.

3-2 Wall turbulence control using sensors and actuators

The motion of longitudinal vortices is suppressed by external force to annihilate the revolving movement exerted by actuators in response to the positional information on the longitudinal vortices on the wall surface detected by sensors. This results in the reduction of friction drag and noise. Figure 5 shows a

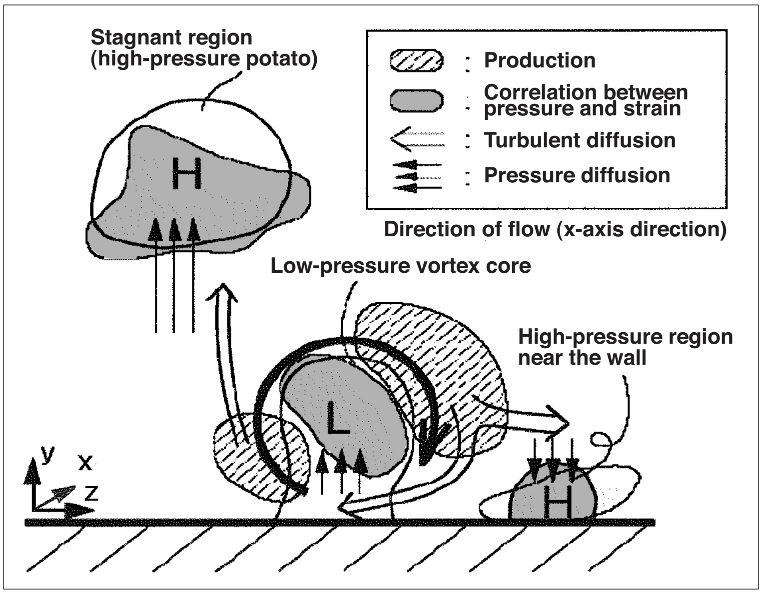

Figure 3 : Near-wall longitudinal vortex and the relationship of spatial positions of the instantaneous production, destruction, and diffusion processes of Reynolds shear stress

Prepared by the STFC based on Reference[9] with partial modification

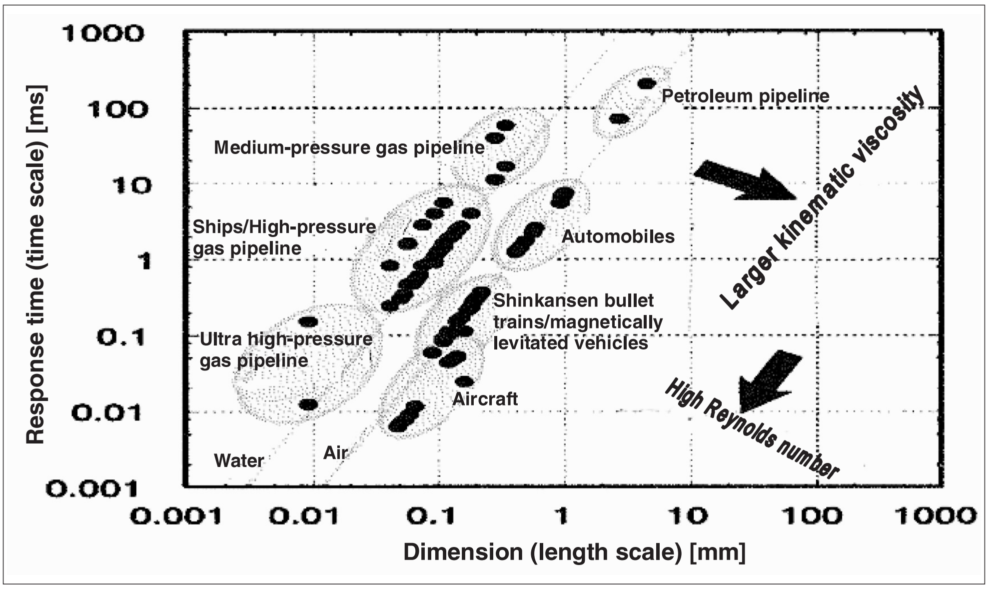

Figure 4 : Specifications for sensors and actuators used for longitudinal vortex control

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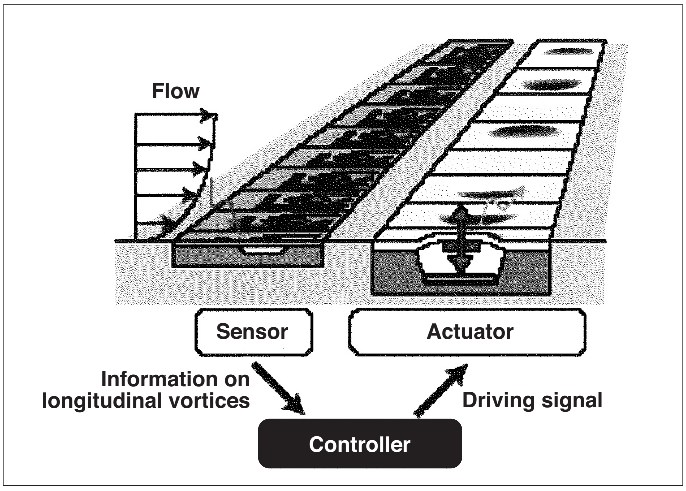

Figure 5 : Schematic diagram of a feedback control system for wall turbulence

Prepared by the STFC based on Reference[2] with partial modification

schematic diagram of a feedback control system combined with a controller.

Although many studies have been made on elemental technologies such as the algorithm, sensors, and actuator used for turbulence control, those aiming at constructing a total system are few. A group from Brown University (U.S.A.) constructed a system combining three sets of hot-film shear stress sensors, a cantilever actuator using piezoelectric elements, and a controller[11]. Meanwhile, Tsao et al. of the United States attempted to reduce friction drag by producing a prototype of a sophisticated control chip consisting of hot-film shear stress sensors, flap type electromagnetic actuators and a drive circuit[12]. However, these endeavors did not come into practical use.

Professor Nobuhide Kasagi et al. of the University of Tokyo developed a prototype of a turbulence control system, as shown in Figure 6, consisting of 192 micro shear stress sensors, 48 electromagnetic actuators, and a controller. Sensors are arrayed in four rows, each containing 48 sensors at 1 mm intervals, and actuators are arrayed in three rows, each containing 16 actuators at 3 mm intervals. The sizes of sensors and actuators are as small as 1 mm and 2.4 mm respectively; and the response time is about 0.1ms for both sensors and actuators. The displacement of the actuator film is about 50μm.

The DNS of this system applying turbulen t-structure-based control*10 that controls the low-velocity streak fluctuation*9 showed that a reduction of about 12% was possible due to the stabilization of streak[13]. In the wind tunnel experiments to verify the drag reduction effect using the optimal control by Genetic Algorithm (GA)*11, drag was reduced by up to 11%. Taking the uncertainty of the shear stress measurement into consideration, this value corresponds to a drag reduction of 6%[14]. It was the first time in the world that the effects of friction drag reduction had been confirmed using such a large-scale feedback control system, which is considered to be a significant step toward the practical application.

Comparing the dimensions of the sensors and actuators with those shown in Figure 4, it is clear that the above-mentioned system can be applied to the control of longitudinal vortices in petroleum pipelines. To control the vortices of bullet trains, aircraft, and high-pressure gas pipelines, however, further miniaturization and sophistication of the system are necessary because dimensions within the range 0.001 to 0.1 mm and a response time of about 0.01 ms are required.

Turbulence control remains in the basic research stage in the laboratories, and to migrate to the stage of practical use, sensors and actuators must be miniaturized from the viewpoint of hardware so that they match the length scale of longitudinal vortices to be controlled. In addition, high accuracy, energy saving, low cost, durability, and long-term stability against staining are also required. It is also necessary to improve the micro fabrication technology and establish a mass production technology such as printing and embossing, based on a low cost production process. From the viewpoint of software, a highly efficient control algorithm that significantly reduces the volume of data processing must be developed. Such technical development is highly dependent upon the progress of technology in the industrial sector. To promote the application to practical use, therefore, information must be actively transmitted to the industrial sector so that combined research and development are accelerated among industrial fields that possess individual technologies.

By solving problems of both hardware and software and developing necessary technologies, turbulence control is expected to play an important role, particularly in fields where high speed is pursued, such as magnetically levitated vehicles, bullet trains, and aircraft. Since studies similar to those conducted in Japan are underway in the United States and Europe, Japan must take measures to keep ahead of foreign countries in applications for practical use.

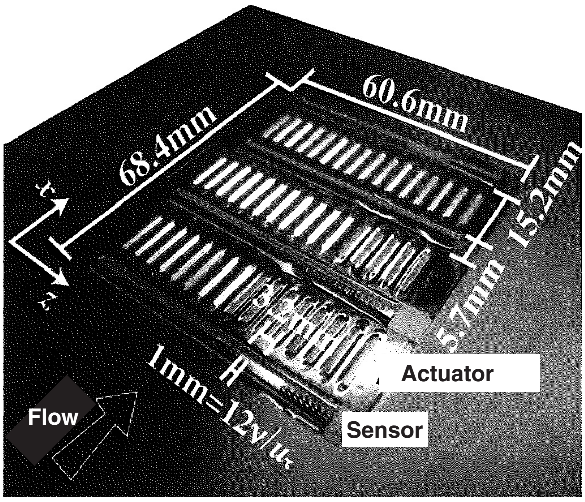

Figure 6 : Feedback control system for wall turbulence

Prepared by the STFC based on Reference[14] with partial modification

4 Conclusion

Turbulence control is one of the key points to reduce the resistance of fluids, improve combustion and heat and mass transfer, and to solve energy and environmental problems. It also has the potential to bring about breakthroughs in the transportation and other fields.

At present, as a result of the development of supercomputers, modern control theory, hardware for control, and CFD, research on the feedback control of turbulence phenomenon in response to momentary changes of flow conditions is being extensively carried out. Although turbulence control had previously been considered impossible due to the lack of analytical solutions, it is now one of the highly promising emerging technologies. In this field, Japan has produced appreciable results in the miniaturization of sensors and actuators that compose the control systems for wall turbulence. These subjects further require systematic studies on higher accuracy, energy saving, lower cost, and the establishment of long-term stability, as well as MEMS technology and micro fabrication technology to back up the research and development of control algorithms that elicit significant effects.

Since the research on turbulence control includes diversified fields of technologies, it is difficult for a single organization to solve all the problems. Therefore, top-class researchers in Japan must cooperate from a long-term standpoint. It is also necessary to cooperate with the industrial sector that has mass production technologies. To this end, information on turbulence control must be actively transmitted to the industrial sector.

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Glossary

*1 Reynolds number
A dimensionless number that characterizes a flow; defined as LU/v where L is a length scale, U is velocity, and v is the coefficient of kinematic viscosity. The value expresses the ratio of inertia force to viscous force.

*2 Direct numerical simulation (DNS)
a numerical simulation using a computer to solve a primitive equation without using additional mathematical models. When solving a turbulent field by DNS, tremendous computing power is required because the computational grids must be divided so finely that the minimum unit of eddies is distinguished.

*3 Microelectricalmechanical systems (MEMS)
A generic term for small machines that perform functions in the order of several μm to several mm.

*4 Lean premixed combustion
a combustion system in which a lean fuel gas-air mixture is combusted.

*5 LES (Large Eddy Simulation)
A simulation method in which larger eddies are solved similarly to DNS whilst smaller eddies are modeled.

*6 Flamelet model
a model that postulates that a laminar flame is deformed wrinkly in a turbulent flow when the value of the Reynolds number is large.

*7 Chaotic fluid phenomenon
a nonlinear that is too complex and irregular to predict.

*8 Suboptimal control
a control method in which the optimal control distribution is theoretically calculated by momentarily minimizing the evaluation function defined by the sum of friction drag and control energy.

*9 Low-velocity streak fluctuation
in turbulent flows along a wall, low-velocity portions (low-velocity streaks) appear in streaks near the wall. These streaks are destabilized due to the interaction with vortices and shear stress and fluctuate.

*10 Turbulent-structure-based control
a control method based on knowledge concerning the mechanism of turbulence generation.

*11 Genetic Algorithm (GA)
an optimum solution search algorithm using an evolutionary method.

Abbreviations

(1) DARPA	Defense Advanced Research Projects Agency
(2)ERCOFTAC	European Research Community On Flow, Turbulence And Combustion
(3) CFD	Computational Fluid Dynamics

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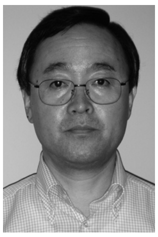

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