F. G. Zhuang
J. C. Li

New Trends in Fluid Mechanics Research

Proceedings of the Fifth International Conference on Fluid Mechanics (Shanghai, 2007)

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PREFACE

On the occasion of the 20th anniversary of initiation of this series meeting, the Fifth International Conference on Fluid Mechanics (ICFM-V) is to be held from August 15 to 19, 2007 in the coastal metropolitan, Shanghai. Its purpose is to provide a forum for researchers to exchange original ideas and recent progresses in their respective field and enhance mutual understanding between scientists and engineers. We have regarded the organization of ICFM as a part of the long-term mission in promoting international academic exchange for CSTAM since it became one of the adhering organizations of IUTAM.

Well-known 8 leading scientists in the world are invited to present frontier topics in concerned field and branches. More than 247 contributed papers are read in 47 sessions, respectively. The participants of 6 continents come from 26 countries and regions such as: Algeria, Australia, Canada, Czech, France, Germany, Japan, Korea, Hong Kong(China), India, Iran, Italy, New Zealand, Pakistan, Russia, Saudi Arabia, Serbia, Singapore, Spain, Sudan, Sweden, Taiwan(China), UK, USA, Venezuela as well as China including both developed and developing countries. We are extremely pleased to see through 20 years' common efforts that this series of meeting have attracted ever growing numbers of researchers to join in the events.

Both traditional and newly emerging areas are general concern of the Congress. It means that researchers are endeavoring to study classic topics by novel approaches and advanced apparatus to tackle the tough problems in manned flight, moon landing and civil aircraft design. At the same time, they are also exploring microscopic territories of the field to meet nowadays' need in understanding behaviors of complicated media and applications in material preparation, micro-fluidics and biomechanics. The scope of the present conference therefore covers Flow transition and instability; Turbulence; Aerodynamics and gas dynamics; Hydrodynamics; Geophysical and environmental fluid mechanics; Industrial fluid mechanics; Multiphase flows, Non-Newtonian flows and flows in porous media; Bio-fluid mechanics; Micro-scale flows; Plasma and magnetic-hydrodynamics. If the 20th century witnessed the achievements of fluid dynamics in aeronautical and astronautical engineering; energy resources, environment improvement and human's health become the most challenging issues to us at present days. Therefore, fluid dynamics remains an active branch with wider applications in the 21th century.

On behalf of the Scientific and Academic committee, we appreciate the presence and collaboration of all the participants with enthusiasm, in particular, all invited speakers for their informative talks. Many thanks are also due to GAMM, BED/ASME, FED/ASME, EMD/ASCE, JSFM, HKSTAM, HKIS and SHSTAM for their sponsorship. The financial support from K. C. Wong Education Foundation of China, NSFC, Institute of Mechanics, CAS and Shanghai Jiaotong University should be acknowledged. We highly evaluate the excellent work and arrangement of the local organizing committee to render the meeting in good order. At this moment, we should remember the contribution and efforts of late professor Allen T. Chwang, who unfortunately past away not long ago, during the organization of ICFMs. Finally, we are also grateful to the staff of the CSTAM office for their efficient work in the preparation of this volume.

Funggan Zhuang
Chairman of Scientific Committee, ICFM V

Jiachun Li
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CONTENTS

Plenary Lectures

Flow Transition and Instability

Turbulence

Aerodynamics and Gas Dynamics

Hydrodynamics

Geophysical and Environmental Fluid Mechanics

Industrial Fluid Mechanics

Multiphase Flows, Non-Newtonian Flows and Flows in Porous Media

Bio-fluid Mechanics

Micro-scale Flows

Plasma and Magneto-Hydrodynamics

Supplement

NEW TRENDS IN FLUID MECHANICS RESEARCH
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Biomechanics of Aquatic Micro-Organisms

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Abstract Aquatic micro-organisms play a major role in ocean ecology, the global carbon cycle and bioreactor engineering. The complex foodweb of an oceanic ecosystem may be modelled in terms of a few species of different types whose population densities obey coupled differential equations. However the functions and constants that appear in those equations depend in a complex way on the details of the dynamics of individual organisms and how they interact in larger scale phenomena. This talk will survey some of the following topics: (1) the fluid dynamics of micro-organism swimming, (2) the effect on nutrient uptake of an organism's swimming motions, (3) chemotaxis in bacteria, (4) capture rate of phytoplankton by zooplankton when they all swim in a turbulent environment, (5) pattern-formation (e.g. bioconvection) in suspensions of upswimming micro-organisms (algae and bacteria), (6) the hydrodynamic interactions between swimming model micro-organisms and (7) their effect on the rheology and transport properties of the suspension as a whole. The long-term goal is to formulate a continuum model for concentrated suspensions of swimmers; this is not yet realised and may be impossible!

INTRODUCTION

Aquatic micro-organisms, many of which are active swimmers, play a vital role in life on earth. Phytoplankton are the bottom link of the food chain in oceans and lakes, absorbing energy from sunlight and elementary nutrients from the water. They contain and are surrounded by even smaller bacteria (2~10 μm) and are themselves the prey for zooplankton which in turn are eaten by copepods which are eaten by fish and so on. The phytoplankton absorb CO_2 from the water, most of which comes from the atmosphere via complex mixing processes, and thus they play an important role in the global carbon cycle and hence in global warming. Every spring, in every ocean, there are massive phytoplankton blooms (population explosions) which underlie the ecology of all aquatic species and need to be understood for fisheries prediction, for example. Harmful algal blooms also occur in coastal waters ('red tides') and can lead to economic damage to coastal communities that rely on shellfish. Some micro-organisms are used in bioreactors. Thus the study of micro-organism behaviour is a proper subject for scientific investigation.

The complex food web of an oceanic ecosystem is hard to simulate: the number of species is far too large, as is the number of ways in which they can interact. Some progress can be made with idealised models such as that outlined in Figure 1 [1]. Organisms are arranged in two rows of three categories each. Members of the lower row consume nutrients and are themselves consumed by members of the top row which are also linked by predator-prey interactions. A model of the interactions consists of a set of nonlinear ordinary differential equations. For example, the population density of ciliates (C) is governed by an equation of the form

$$\frac{\mathrm{d}C}{\mathrm{d}t} = Y_c(g_{CA} + g_{CH})C - g_{ZC}Z \tag{1}$$

where Y_C is the ciliate yield and the g's are functions in which g_{PQ} means the rate at which species P grazes on species Q (the symbols A, H, Z are defined in Figure 1). Examples of the sort of functions involved are

$$g_{CA} = \frac{\lambda_c A^2}{\mu_c(A+H) + A^2 + H^2}, \; g_{BN} = \frac{\lambda_B N}{\mu_B + N} \qquad (2)$$

where the λs and μs are constants.

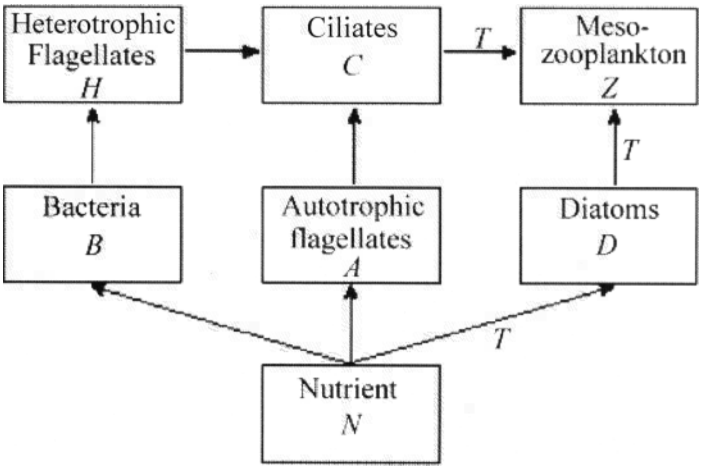

Figure 1: A "minimum model" for plankton population dynamics. Arrows between boxes represent predator-prey interactions; the letter T by an arrow means that turbulence may have an influence [1,2]

These are standard models, but where do the functional forms and constants come from? In other words, how should the population-level model be derived from individual behaviour? This talk will outline briefly some of the fluid mechanical aspects which have been or are being investigated to shed light on both the individual and the collective behaviour of swimming micro-organisms.

INDIVIDUAL BEHAVIOUR

The question of how micro-organisms swim has attracted fluid dynamicists for over 50 years, the pioneers being G. I. Taylor [3] and James Lighthill [4]. The Reynolds numbers of the cells in question, and of their moving appendages, are very small so inertia is negligible. It follows that the appendages cannot execute purely reversible motions if the cells are to make progress. Biflagellate algae such as Chlamydomonas spp execute a sort of low-Reynolds-number breaststroke; monoflagellates and sperm send unidirectional waves along their flagella; bacteria generate thrust from a bundle of rotating, fairly rigid flagella; ciliates beat large numbers of cilia in the form of co-ordinated waves. The hydrodynamics of such propulsive devices was first investigated using the rather crude (but extremely useful) resistive force theory [5,6], according to which the normal and tangential components of the force exerted on the fluid by one short segment of a beating flagellum are directly proportional to the normal and tangential components of the velocity of that segment relative to the fluid far away, but with different, constant, coefficients of proportionality K_N and K_T(K_N is nearly twice as large as K_T for a segment of a circular cylinder). The next level of sophistication is to use slender body theory [4,7~9], and these days it is feasible to do complete simulations using the boundary element method [10].

If an organism is neutrally buoyant then the net force acting on the whole organism is zero, an important constraint in the theory. If it is homogeneous, then the net torque on the organism must also be zero. However, most micro-organisms are denser than water and tend to sediment, though at a speed that is much smaller than their swimming speed. For example, dead Chlamydomanas nivalis sediment at about 3μm s^{-1} while live ones swim at over 50μm s^{-1}. In addition, C. nivalis naturally tend to swim upwards, on average, against gravity (though individual trajectories are very erratic). This is because they are bottom-heavy, so a deviation from the vertical generates a gravitational torque that rotates them back towards the vertical again (albeit slowly, against the viscous torque set up by such rotation) [11, 12]. It follows that the swimming direction, relative to the fluid, will change when the cell is put into a shear flow which exerts a viscous torque on the cell.

As stated above, bacteria generate thrust and thereby swim in a roughly straight line, by rotating a bundle of individual flagella behind them. The flagella come together when the rotation is counter clockwise. From time to time (stochastically) the flagellar motors turn clockwise. Then the flagella fly apart and the cell tumbles, before setting off on a run in a new direction [14]. The details of this process have been thoroughly investigated only for Escherichia coli (a gut bacterium) but it is presumed that other bacteria behave similarly. How the rotating flagella come together in a bundle when rotating counter clockwise is itself a fluid mechanical problem. Recent studies suggest that bundling could occur passively if the flagella were slightly flexible [15,16], but there is more detailed work to be done.

It is known that bacteria exhibit chemotaxis - a tendency to swim up gradients of chemoattractant (food). However, they are too small to be able to measure concentration gradients directly [17], so how do they know to swim up the gradient? The mechanism (in E. coli at least) requires that (a) they can measure concentration, (b) they can remember it for a short time, so that they can tell whether the concentration is rising or falling with time, and (c) they can then alter the probability of tumbling according to the answer to (b). This is what they do: the tumbling rate falls when they are swimming up a gradient [18]. How the chemotaxis process is affected when the bacteria are in a shear flow, which will rotate them, has not been investigated experimentally, but has been analysed theoretically [19,20]. It is predicted that they sometimes swim the wrong way!

The functions of equation (2) require that we know the rate at which organisms take up nutrient from the water. Even for individual cells, this problem exhibits interesting features which have not all been resolved. If the organism is small enough then adequate nutrient uptake can be achieved, in still water, by pure diffusion. However, larger organisms need to enhance this rate, and can do so by moving through or stirring the fluid around them [21].

A precise analysis of how low-Reynolds-number stirring motions can enhance nutrient uptake has been undertaken for a very simple model of a micro-organism: a spherical 'squirmer', which propels itself through the fluid by driving a tangential motion along its surface [22,23]. This model was chosen for its simplicity, not because it was meant to represent a real organism (though it is a good representation of the envelope of cilia tips in certain ciliates, or algal colonies like Volvox, or cyanobacteria such as the Oscillatoriaceae). The velocity field of a 'steady squirmer' is represented by a two-term series of axisymmetric solutions to the Stokes equations, in which the coefficient of the first term, B_1, is proportional to the speed at which the squirmer swims, U, and that of the second, B_2, is proportional to the force-dipole, or stresslet, that it exerts on the fluid.

In [22] the advection-diffusion equation for solute concentration C, in the velocity field of the squirmer, was solved numerically subject to the boundary conditions $C \to 1$ as $r \to \infty$, $C = 0$ on $r = a$. After non-dimensionalisation the results could be expressed as a plot of the Sherwood number Sh as a function of the Péclet number Pe for different values of the 'squirming parameter', $\beta = B_2/B_1$. Here Sh is the ratio of the actual nutrient uptake to the value it would have through pure diffusion in a still fluid ($4\pi aD$, where D is the solute diffusivity); $Pe = Ua/D$ is the ratio of advection to diffusion. The results are compared with those for a rigid sphere driven through the water at the same speed, U, by an external force. They confirm that squirming has negligible effect on the mass transport unless $Pe > 0.2$, but as Pe rises the effect of squirming becomes more and more important, as the concentration boundary layer on the body surface becomes thinner. Indeed, for large Pe it is shown that $Sh \propto Pe^{1/2}$, not $Pe^{1/3}$ as for a rigid sphere.

The value of Pe for an algal cell of radius 10μm, swimming at $50\mu \mathrm{ms}^{-1}$, with a small solute of diffusivity $10^{-9}\mathrm{m}^2\mathrm{s}^{-1}$, is only 0.5, so the effect of swimming or stirring is small. However, spherical colonies of Volvox can be as big as 150μm in radius, and generate fluid motions of $100\mu \mathrm{ms}^{-1}$, so for them the Péclet number is quite large and the fluid flow driven by their flagella is very important for nutrient uptake[24].

Another aspect of nutrient uptake by small organisms is that of predator-prey dynamics. At what rate do microzooplankton encounter and consume their phytoplankton prey? And how is this affected by turbulence in the ambient fluid? Models of these processes were developed by Gerritsen & Strickler [25] and by Rothschild & Osborn [26] and extended by Lewis & Pedley [27,29] who also tested the modified model against a numerical simulation. The simulation consisted in placing a number of predator and prey individuals randomly in a periodic box and allowing them to swim with random speeds and orientations (according to specified probability distributions), recording an encounter when they came within a distance R of each other. The fluid was also moving randomly, with a turbulent-like incompressible velocity field specified by a random Fourier series with the same energy spectrum as for isotropic, homogeneous turbulence. Simulating real turbulence would have required enormous computer resources, for reasonable Reynolds numbers, as can be seen from the corresponding work of Yamazaki [28]. The main result was that the modified model agreed rather well with the full simulations in predicting encounter rates; the value of the model is that it is analytical and can be used to specify the functional forms required in equation (1).

COLLECTIVE BEHAVIOUR

We turn now to the fluid dynamic behaviour of populations of swimming micro-organisms, in particular the phenomenon of bioconvection. Bioconvection patterns are observed in shallow suspensions of randomly, but on average upwardly, swimming micro-organisms which are a little denser than water. Images of typical bioconvection patterns formed by suspensions of single-celled algae and bacteria can be found in [12]. The basic mechanism is analogous to that of Rayleigh-Bénard convection, in which an overturning instability develops when the upper regions of fluid become denser than the lower regions. The reason for the upswimming however depends on the species of micro-organism: some algae are bottom-heavy, (see above) while certain oxytactic bacteria, such as Bacillus subtilis, swim on average up oxygen gradients that they generate by their consumption of oxygen.

The rational continuum modelling of bioconvection in dilute suspensions (volume fraction of cells < 0.001) has been fully described in many original papers and, in particular, in two review articles [30,31]. Here we concentrate on aspects of the phenomena or the modelling that are not completely understood.

In a continuum model it is assumed that every volume element, small compared with the scale of the bulk flow, contains very many cells, so that variables such as the cell number density n or the bulk velocity $\boldsymbol{u}$ can be represented by their averages over the volume element. They can thus be taken to be smooth functions of position and time t. Averaging has to be done with care, because the cells swim randomly. Data on the trajectories of *C.* nivalis in still fluid are given in [32], and the bias to upswimming is confirmed.

Perhaps the most important equation in the continuum model is the cell conservation equation:

$$\frac{\partial_n}{\partial t} = -\nabla \cdot [n(\boldsymbol{u} + \boldsymbol{V}_c) - \boldsymbol{D} \cdot \nabla n] \tag{3}$$

where $\boldsymbol{V}_c$ is the average cell swimming speed, representing directed cell swimming, and the last term represents the flux due to random cell swimming, here modelled as a diffusive process. Both $\boldsymbol{V}_c$ and $\boldsymbol{D}$ can be calculated if we know the probability distribution for cell swimming velocity, incorporating both magnitude and direction. The data in [32] provide information on this distribution, in one case. However, assuming that the cell swimming speed was constant, Pedley & Kessler [33] proposed that the p.d.f. $f(\boldsymbol{p})$ for swimming direction $\boldsymbol{p}$ (a unit vector) should satisfy a quasi steady Fokker-Planck equation. The solution of that equation for bottom-heavy algae in a still fluid is

$$f(\boldsymbol{p}) = \mu e^{\lambda \boldsymbol{k} \cdot \boldsymbol{p}} \tag{4}$$

where the unit vector $\boldsymbol{k}$ is vertically upwards, and λ, μ are constants, which is reasonably consistent with the data.

When the fluid is moving, the Fokker-Planck equation can still be used to find $f(\boldsymbol{p})$ if it is possible to write down an equation for $\dot{\boldsymbol{p}}$, the rate of change of $\boldsymbol{p}$, in the absence of the random reorientations. This is straightforward for the bottom heavy algae, because $\dot{\boldsymbol{p}}$ is determined by the balance between gravitational and viscous torques and the latter can be evaluated for any ambient shear flow. However, we do not have an equation for $\dot{\boldsymbol{p}}$ in the case of chemotactic bacteria, because the chemotaxis process cannot be expressed in terms of a torque balance. In addition, there is no general guarantee that random swimming can be represented as a diffusion process.

In the standard model of chemotaxis in a still fluid, first proposed by Keller & Segel [34], the cell swimming term in (3) is given by $V_c = \chi \nabla C$, where C is the chemoattractant distribution (for which, in general, another conservation equation is required) and χ is a scalar chemotaxis parameter. The main objective of the thesis work of Bearon [19,35] was to see under what circumstances equation (3) can still be used for run-and-tumble chemotaxis in a shear flow, with some rational choice for V_c. The investigation was highly probabilistic. The findings of [35], briefly, were that the Keller-Segel model could be used in a general shear flow, only if the perturbation to isotropic tumbling were small enough and if the vorticity in the flow were much less than the tumble rate. What to do in a general flow is still very unclear.

All the research referred to above has been restricted to dilute suspensions, in which cell-cell interactions are neglected. However, there is an increasing body of experimental evidence that some very interesting hydrodynamic phenomena arise in concentrated suspensions, mainly of swimming bacteria (B. subtilis). Mendelson et al [36] observed a population of B. subtilis swimming in a thin liquid layer on top of an agar gel, and reported a rich structure of meso-scale motions (by which is meant motions on length-scales intermediate between the population as a whole and the size or spacing of individual cells)which they called "whorls and jets". Dombrowski et al [37] also observed meso-scale motions in three-dimensional concentrated suspensions of B. subtilis. These are not yet understood.

Our approach to modelling suspensions in which hydrodynamic cell-cell interactions are important involves simulations in which each cell is followed as it moves and in which the interaction with other cells is analysed in a pairwise manner. Real micro-organisms are too complicated for their geometry and kinematics to be represented accurately in a simulation of many cells. Instead we have gone back to the "steady squirmer" introduced above. Each 'cell' is an identical spherical squirmer, of radius a, swimming with a given swimming speed U and squirming parameter β. An additional possibility is to allow the cells to be bottom-heavy, in gravity $\boldsymbol{g}$. The only distinction between different individuals is their orientation, or swimming direction, $\boldsymbol{p}$. The first step in the simulation is to calculate the trajectories of pairs of interacting squirmers in the absence of others. This is done by computing the virtual or effective force applied to one squirmer by the presence of another, for arbitrary initial orientations and relative positions. In the far field the effective force can be calculated analytically, as it can in the very near field, when the squirmers are nearly touching and lubrication theory can be used. In between the calculation is performed numerically, using the boundary element method. A database of the results, covering the space of orientations and relative positions more-or-less uniformly, has been compiled and is used to speed up the simulations of larger numbers of spheres[38]. The macroscopic simulations are performed for random conditions in a triply-periodic cubic domain. They have been used to compute (a) the effect of squirming on the rheology of a suspension of neutrally buoyant spheres in a simple shear flow and (b) the mean square displacement of individual spheres: is the spreading diffusive or not [39]? In both cases a volume fraction of 0.1 is taken as typical. The answer in (a) is that squirming has a negligible effect on Batchelor's [40] results for the viscosity of a suspension of rigid spheres up to $O(C^2)$, when the squirmers are not bottom-heavy, but a significant effect when they are bottom-heavy, depending on the orientation of the shear flow relative to $\boldsymbol{g}$. In that case there can also be significant non-Newtonian normal stresses. In (b), the answer is that the spreading apart of non-bottom-heavy squirmers in three dimensions is correctly described as a diffusive process (i.e. their mean square displacement increases linearly with time t at large times), despite the fact that all the squirmers' motions are calculated deterministically. However, this is valid only for time-scales greater than about 30 a/U. Moreover, when their trajectories are confined to two dimensions, squirmers tend to aggregate, not disperse!

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NEW TRENDS IN FLUID MECHANICS RESEARCH
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An Investigation of Scalar Dispersion in Grid Turbulence

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Abstract
The structure of scalar dispersion from a continuous release point was investigated for moderate Reynolds number flow in grid turbulence. Using laser-induced fluorescence techniques, laser-volume scanning, a custom-designed fast-readout CCD focal plane array, and high-speed digital-imaging/-acquisition/-storage techniques, the instantaneous three-dimensional structure of a passive scalar was investigated in flow in water (high Schmidt number). Laser Doppler and scalar-correlation velocimetry were employed to measure th flow speed entering the test section and in the interrogated volume. Such scalar-dispersion structure away from the release point is typically modeled assuming a Gaussian profile. This provides a good description for the mean scalar profile as a function of the transverse distance from a line parallel with the flow and downstream of the release point, as also confirmed by experiment (Yamamoto & Sato 1979, Gad-el-Hak & Morton 1979, Nakamura et al. 1987, Sawford 2001). The instantaneous three-dimensional structure, however, reveals a rich topology of scalar structures that was found to persist in the volume interrogated, spanning a distance from the grid and release point between 22 and 30 grid mesh lengths, which is in the self-similar grid-turbulence regime where the present three-dimensional scalar-field measurements were conducted.

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NEW TRENDS IN FLUID MECHANICS RESEARCH
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Flow Control and Hydrodynamic Instability

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Abstract Scientific problems related to modern aeronautical engineering and dealing with basic properties of shear flows and the associated fluid mechanics phenomena are emphasized. In this context some recent experimental results on subsonic aerodynamics are considered.

Key words: flow control, subsonic aerodynamics, flow instability, boundary layer, MEMS-technology.

INTRODUCTION

Optimization of aerodynamics of modern and perspective air vehicles needs the solution of several fluid mechanics problems. They are related to studying the flow phenomena occurring close to a body surface with further elaboration of new methods to control local and global flow characteristics. As a result, it becomes possible to increase lift of wings, reduce drag of the vehicles and their acoustic radiation. As a whole, flow control is aimed at improvement of economy and operational functionality of air vehicles of different destination.

A phenomenon which is crucial for the near-wall flow pattern is hydrodynamic instability one can observe in two- and three-dimensional attached and separated boundary layers. Amplification of the laminar flow disturbances results, finally, in transition to turbulence, generation of vortex structures close to the body surface, and has a strong effect on formation of separated flow regions.

Thus, solution of the aerodynamic problems is integrated to studying various aspects of flow instability. In what follows, exploration results obtained recently on this topic are discussed from the standpoint of the main, by the author sight, problems of fluid mechanics involved in progress of commercial aviation.

1. Flow laminarization on lifting surfaces

Flow laminarization on lifting surfaces In laminar boundary layers the skin friction is much smaller than that in turbulent layers which is the reason for flow laminarization. Maintenance of the laminar flow over an extended part of the wing is obviously appropriate for fuel savings and increasing efficiency of the aircraft.

Basically, the problem is approached through current knowledge on transition to turbulence in boundary layers at a low level of the external flow perturbations. Normally, the process of laminar-turbulent transition is subdivided into several main stages including generation of the boundary layer disturbances, their subsequent amplification at small amplitudes of the exited oscillations, and nonlinear interactions of the perturbations prior to onset of the turbulent motion, Figure 1. Accordingly, the methods of transition delay utilize reduction of the initial amplitudes of the laminar boundary layer disturbances and modification of its stability characteristics, see [1~3]. To date, the linear theory of hydrodynamic stability, dealing with exponentially growing (damping) wavy disturbances in two- and three-dimensional boundary layers, has been verified in a large number of experiments. The methods of laminarization employing stability solutions are well substantiated so that some of them are in use in engineering applications.

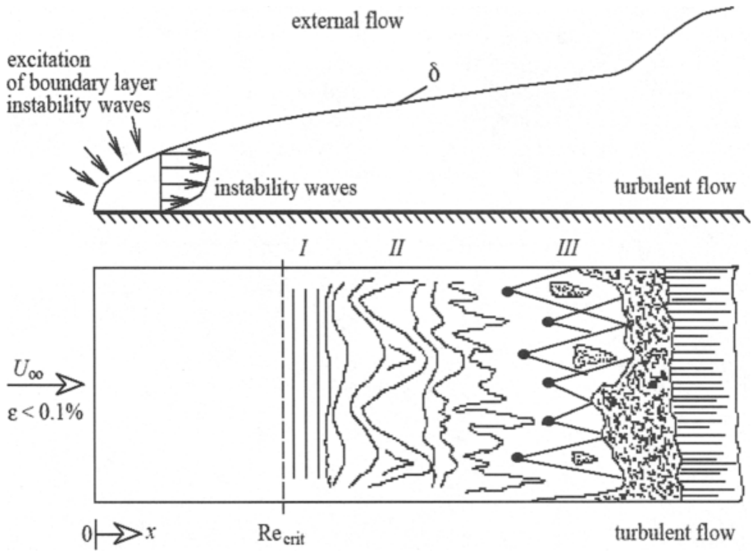

Figure 1. Main stages of laminar-turbulent transition in a boundary layer at a low level of the external flow turbulence: *I* – amplification of small-amplitude perturbations (Tollmien-Schlichting waves), *II* – evolution of three-dimensional non-linear disturbances (Λ-structures), *III* – origination and interaction of turbulent spots [4]

Beyond the scope of the classic stability theory are specific localized disturbances of the boundary layer, the so called "streaky (streamwise) structures" or "streaks", nowadays calling much interest during the research of laminar-turbulent transition, see [3∼5]. Under appropriate conditions, such structures may grow in the streamwise direction initiating secondary disturbances andg lambda-shaped vortices found at late stages of the transition to turbulence in boundary layers, Figure 2. In this case, the effect of laminarization can be obtained through application of control techniques for modification of the origination and dynamics of the localized perturbations which are to be investigated in more details.

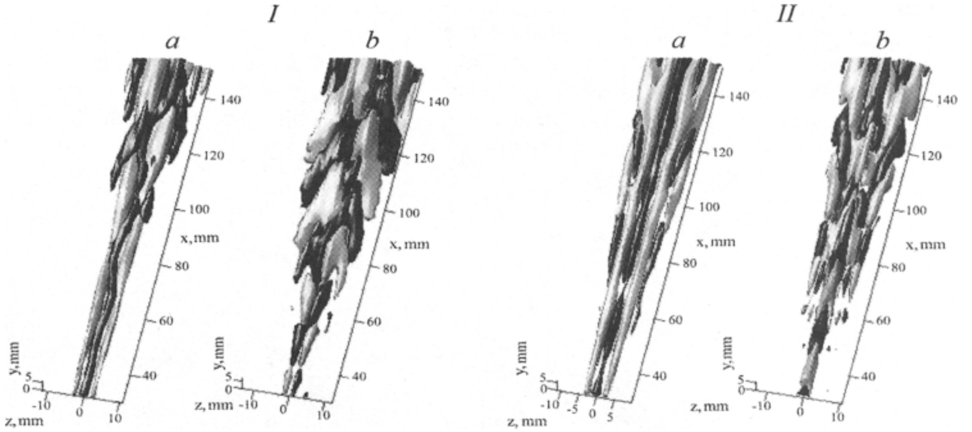

Figure 2. Streaky structures of a laminar boundary layer with amplifying antisymmetric (I) and symmetric (II) secondary oscillations: the streamwise evolution of the secondary disturbances combined with their effect on the mean flow (*a*) and without it (*b*) (dark and light halftones indicate the regions of increased and reduced flow velocity comparing to its unperturbed values) [6]

The streaky structures developing in Blasius boundary layer, on straight and swept wings were examined under controlled experimental conditions in a series of recent studies [7~9]. Along with determination of main characteristics of the localized laminar flow disturbances, some approaches to their control were tested. One of them is application of the surface grooves, or riblets, used for drag reduction in a turbulent boundary layer. As a result of Ref. [7], a beneficial effect of streamwise riblets on the transitional flow was observed, that is, diminution of the streaky structures magnitude, suppression of their secondary oscillations and glambda-shaped vortices, Figure 3.

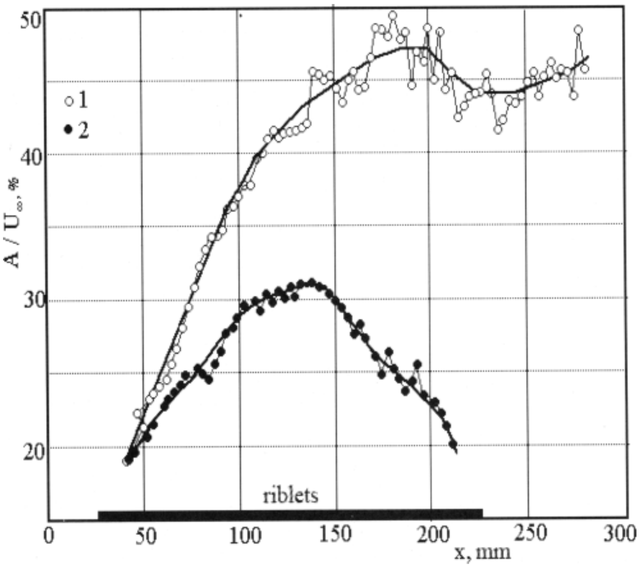

Figure 3. Streamwise amplitude variations of gΛ-shaped vortices on the smooth (1) and grooved (2) flat plates [7]

Another possibility to delay the transition to turbulence caused by evolution of the streaky structures was examined in [8] where the boundary layer was controlled by flow suction through tiny holes in the surface of experimental models. This technique, similarly to the surface ribbing, was found as an effective one for damping of the streaks and their secondary instabilities. Interaction of the streaky structures generated by roughness elements on a swept wing was investigated in Ref.[9]. The experiments have shown that isolated stationary disturbances of the boundary layer are more prone to high-frequency secondary instabilities and the following turbulization, than the interacting perturbations evolving close to each other, Figure 4.

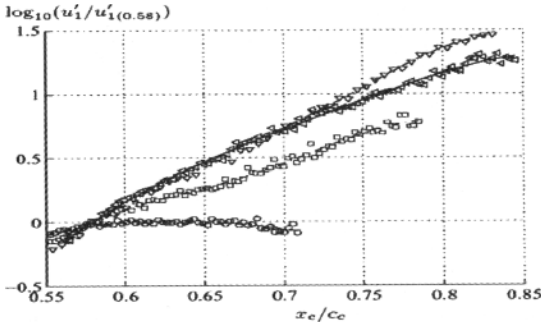

Figure 4. Streamwise amplitude variations of the secondary perturbations evolving on the isolated (□, Δ) and interacting (○) streaky structures [9]

Thus, one expects the transition to turbulence induced by the streaky structures generated at the roughness elements can be controlled by optimization of their shape, size and the spatial arrangement.

As a whole, the results of the above studies substantiate new approaches to laminarization of the lifting surfaces in addition to the control methods inferred from the classic stability theory.

2. Control of flow separation on small-scale air vehicles

Small-scale air vehicles such as paragliders, gliding parachutes and unmanned remote-controlled devices are exploited at rather low Reynolds numbers. Under such conditions, the aerodynamic characteristics of the vehicles are much influenced by the laminar flow separation. In the main, this phenomenon affects negatively drag and lift of the wings, constraining their operation over the angles of attack. Moreover, at a low speed of the flight vehicle in a disturbed atmosphere, sudden flow variations on the wing may happen up to leading-edge stall. A number of passive and active methods to control flow separation are known today. Employing different principles, they are implemented in practice and examined in laboratory experiments, see [2, 10]. Search for new possibilities of separation control is still an important subject of aerodynamics.

One of them was in focus of Refs. [11, 12] where flow separation on a low-aspect-ratio wing with a surface modification was investigated. A prototype of the experimental model was a wavy wing of paraglider, Figure 5.

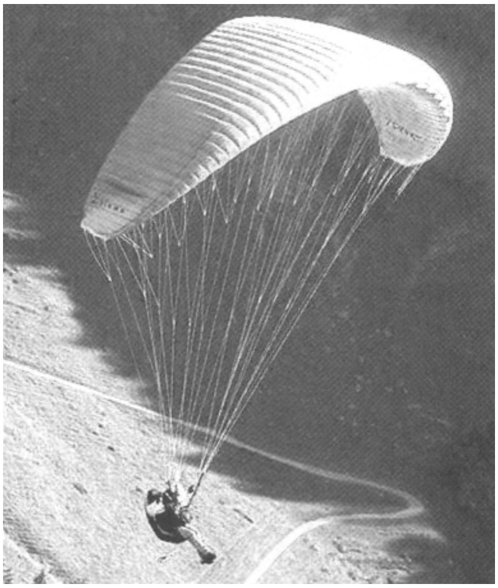

Figure 5. A paraglider in flight

The wind-tunnel tests indicated a strong effect of the transverse waviness of the lifting surface upon laminar flow separation. One can observe in Figure 6 that the separated flow covering the entire span of the smooth wing splits into

local regions of boundary layer separation spaced between the surface waves in the spatially periodic configuration.

A result of such a flow transformation is an increase of the wing critical angle of attack, which turned one and a half time higher under the experimental conditions of Ref. [11]. Moreover, at moderate (subcritical) angles of attack the wavy wing has a larger lift-to-drag ratio than the smooth one. Also, an advantage of the modified lifting surface is the flow symmetry even at the leading-edge stall, Figure 7.