

span membrane wings; this is not mere fail safe structures. Recent experiments show the doubly folded vortex wake of bats; digits afford complex camber control during flapping.

IL-3. SMALL-SCALE STATISTICS IN HIGH REYNOLDS NUMBER TURBULENCE – A STUDY BY DIRECT NUMERICAL SIMULATION

Y. KANEDA, *Department of Computational Science and Engineering, Nagoya University, Japan*, In 1941, Kolmogorov proposed an idea of universality in turbulence [1]. According to this idea, there is a certain kind of universality in small scale statistics of turbulence far from flow boundaries, provided that the Reynolds number (Re) is high enough and the scale is small enough. The universality is insensitive to the details of the large scale flow conditions. This idea has been generally supported by experiments and direct numerical simulations (DNSs), and it is at the heart of modern theories of turbulence. However, little seems known quantitatively about the meaning of “ Re is high enough and the scale is small enough”. What is needed here is the understanding on the dependence of the statistics on the finite Re and the scale. The talk presents a review of results of the analysis of high resolution DNS data of incompressible turbulence, with an emphasis on the dependence of the small scale statistics on Re and the scale. The DNSs consist of two series of simulations of forced turbulence obeying the Navier-Stokes equation in a periodic box with the number of the grid points up to 4096^3 ; one is with $k_{max} \eta \sim 1$ (Series 1) and the other is with $k_{max} \eta \sim 2$ (Series 2), where k_{max} is the highest wavenumber in each simulation, and η is the Kolmogorov length scale [2, 3]. The DNS is based on a spectral method free from alias error. In the 4096^3 DNSs, which were performed on the Earth Simulator, the Taylor-scale Reynolds number $R_\lambda \sim 1130$ (675) and the ratio L/η of the integral length scale L to η is approximately 2130 (1040), in Series 1 (Series 2). The data analysis has shown new aspects of the Re or scale dependence of the statistics including (i) the energy spectrum in the inertial subrange and the near dissipation range, (ii) the third order velocity structure functions, (iii) the normalized mean energy dissipation rate, (iv) moments of the velocity gradients, (v) intermittency of energy dissipation, and (vi) the energy cascade from large to small scales. The visualization of intense vorticity regions at high Re shows a clear difference between the structures of small eddies in the dissipation length scale and those of clusters of eddies in the inertial subrange scale. The talk also presents a review on a study of the anisotropy in small scale statistics in turbulent shear flow, stably stratified turbulence and magneto-hydrodynamic turbulence under a strong uniform magnetic field. A simple analysis suggests that one may regard the effect at small scale of mean shear, buoyancy, and external magnetic field as disturbances applied to the locally homogeneous and isotropic universal equilibrium state determined by the inherent Navier-Stokes dynamics. The theoretical predictions are in good agreement with experiments and DNSs.

IL-4. SUPERSONIC FLOW OVER CAVITIES : A FEW THERMO FLUID DYNAMIC ASPECTS

Job KURIAN, *Indian Institute of Technology, India*, Self sustained oscillations generated by wall mounted cavities were studied earlier as a source of flow noise and undesirable structural loading. In recent times, studies are conducted to investigate their utility to aid applications such as fuel air mixing in high speed streams and in the generation of stable regions of vortex dominated flows for flame holding. The present paper consolidates a part of the work on cavities carried out in the Gas Dynamics Laboratory of Indian Institute of Technology, Madras, India and gives details of the results of studies on the scaling effect of cavities, effect of aft-wall modifications and on the active control of the oscillations generated by the cavity. The experiments are done on the supersonic free jet facility. Rectangular cavities of lengths, $L = 50, 70$ and 90 mm and of $L/D = 1.8, 3,$ and 6 are tested in a confined supersonic flow of Mach number 1.76. Mean static pressure and acoustic pressure measurements are done with in and in the vicinity of the cavities. The results presented demonstrate that the flow and acoustic behavior are considerably affected by changing cavity dimensions for a given L/D ratio. Amplitude of acoustic pressure which is a measure of oscillatory behavior of the flow field is found to increase with cavity size for open shallow cavities. The increased mean static pressure level inside the cavity and more recompression of the flow towards its trailing edge are observed with increase in cavity size. This could give rise to more cavity drag. Aft ramp cavities could be effectively used for suppression of oscillations and for passive entrainment control. The low aspect ratio cavity is more stable for lower ramp angle than that for high aspect ratio. Cavity based injection strategies are suggested for the active

control of cavity performance for applications such as in flame holding. The technique is suitable for controlling the entrainment in to the flame holding region. Further, it suppresses the cavity oscillations and improves the cavity residence time.

11:00 ~ 12:20 (Room101)

Acoustics / Waves

Session Chair : Prof. D. J. Lee, KAIST/Korea

M-1A-1. VORTEX SHEDDING FROM A LEADING-EDGE SLAT AND NOISE GENERATION AT LOW REYNOLDS NUMBERS

Saneshiro MAKIYA, Masahito ASAI and Ayumu. INASAWA, *Department of Aerospace Engineering, Tokyo Metropolitan University, Japan*, In order to clarify the mechanism of noise generation around a slat, vortex shedding from the slat trailing edge and the associated noise generation are investigated experimentally at low Reynolds numbers. When the slat operates to suppress the leading-edge stall, periodic vortex shedding occurs due to the global (absolute) instability of slat wake for the slat Reynolds numbers $Re_s < 2.3 \times 10^4$. For such low Reynolds numbers, acoustic noise is not found in spite of the occurrence of strong vortex shedding. For $Re_s \geq 2.6 \times 10^4$, on the other hand, discrete spectra appear both in the velocity and sound-pressure fluctuations. The frequencies of the dominant discrete tones which coincide with those of vortex shedding exhibit ladder-type variations with each rung proportional to $U_\infty^{0.85}$. These frequency variations are similar to those observed in the past experiment on the discrete tone generation in a single-element airfoil at small angles of attack, strongly suggesting the onset of feedback mechanism between the boundary-layer instability on the slat surface and the vortex shedding from the trailing edge through radiation of acoustic waves generated by the shedded vortices. That is, instability waves are excited in the slat boundary-layer by acoustic waves generated by the periodic vortex shedding, sufficiently amplified up to the trailing edge under adverse pressure gradient and force the wake instability to be locked on. The resulting wake vortices are so strong in the vicinity of the trailing edge and radiate acoustic waves, which trigger a feedback loop. Indeed, a frequency lock-on phenomenon that the absolute instability mode is suppressed as the discrete tone increases in magnitude is observed in the transient Reynolds numbers $Re_s = 2.3 \times 10^4 \sim 2.6 \times 10^4$. Thus, the transition from the global instability of the absolutely unstable wake to the onset of feedback loop mechanism occurs in the vortex shedding from the slat trailing edge.

M-1A-2. THE FREQUENCY SPECTRUM OF SOUND RADIATED FROM ISOTROPIC TURBULENCE

H. D. YAO, *LNM, Institute of Mechanics, Chinese Academy of Sciences, China*, Since Lighthill proposed the acoustic analogy (1952), many works have been carried out to study the frequency spectrum of sound radiated by isotropic turbulence. Proudman derived an $\omega^{-7/2}$ scaling law by considering decaying isotropic turbulence. Lilley suggested that the spectrum scales as $\omega^p (1+2\omega^p)^{-3}$ (1994). Rubinstein and Zhou (2000) deduced an $\omega^{-4/3}$ scaling law at high frequencies if the random sweeping hypothesis is used. And it is found that Lilley's model follows the sweeping model. Recently, Yao et al (2008) have extended the sweeping model to pressure without invoking the quasi-normal assumption. Besides, the hybrid method of direct numerical simulation (DNS) and the Lighthill analogy were used to compute the frequency spectrum by Sarkar et al (1993) and Seror et al (1999, 2001). In the hybrid method, the turbulence velocity is computed by DNS to get Lighthill's tensors and, then, the turbulence noise is computed by Lighthill's analogy. In this paper, it is theoretically deduced that the time correlations of Lighthill's tensors are dominated by the sweeping effect in isotropic turbulence without using the quasi-normal assumption. Then, the hybrid approach of DNS and Lighthill's analogy is used to prove the theory. The numerical results from the hybrid method show that Proudman's $-7/2$ law does not exist in isotropic turbulence. The results obtained support Rubinstein and Zhou's model where the frequency spectra scale as $-4/3$ in the initial range. The Lilley's model is more appropriate for finite Reynolds numbers. And both of the models are based on the random sweeping model after using the quasi-normal assumption. It suggests that the sound spectra are dominated by the sweeping effect and thus determined by the sweeping hypothesis in isotropic turbulence.

M-1A-3. NUMERICAL SIMULATION OF UNDERWATER LANDSLIDE INDUCED TSUNAMI WITH SPH METHOD

H. LIU, *SJTU, China*, X. T. DU, *SJTU, China*, K. GONG, *SJTU, China*, W. WU, *SJTU, China*, Landslide-generated water waves have always been of great interest to hydraulic and coastal engineers because the large deformation and breaking of the free surface bring great challenges for theoretical and numerical studies. Smoothed particle hydrodynamics (SPH) is a mesh-free method that offers substantial potential in many classes of problems especially those characterized by large deformations. The two-dimensional underwater landslide is studied numerically by using the Smoothed Particle Hydrodynamics (SPH) method. The experimental data of two dimensional tsunami waves induced by landslides in a flume is used to validate the numerical model. It demonstrated that SPH method can deal with the hydrodynamic flows generated by landslides in reservoir or coastal waters, and the SPH method has the superiority in simulating the phenomena of large deformation of the free surface. The two-dimensional underwater landslide is studied numerically by using the Smoothed Particle Hydrodynamics (SPH) method. Numerical examples show the computed results are very close agreement with the experimental ones. The second plunging appears during the sliding of the box. Two vortexes with different directions were observed above the box after it slide on the bottom of the numerical flume, and the vortex will maintain for a long time even when the water surface become still. In order to study the effects of the sliding speed of the block on the hydrodynamic characteristics, three cases of sliding speed at three values are computed numerically using the SPH model. It turns out that the patterns of the free surface and vortex are different, particularly at the phenomena of reversed plunging.

M-1A-4. THE INFLUENCE OF THE ORIENTATION STRESS TENSOR ON THE BLOOD FLOW IN A VESSEL

G. ZAMAN, *Department of Mathematics, Pusan National University, Korea*, Y. H. KANG, *Department of Mathematics, University of Ulsan, Korea*, I. H. JUNG, *Department of Mathematics, Pusan National University, Korea*, The objective of this paper is to present a short overview of some macroscopic constitutive models that can mathematically characterize the rheology of blood and describe its properties. The three-dimensional Oldroyd-B model coupled with the momentum equation and with the total stress tensor which consists of the isotropic pressure stress tensor, the shear stress tensor and the orientation stress tensor will be presented. Some numerical simulations obtained in geometrically reconstructed vessel will be also presented to illustrate the hemodynamic behavior using non-Newtonian inelastic models under a given set of physiological flow conditions.

11:00 ~ 12:20 (Room102)

Microfluidics (I)

Session Chair : Prof. S. Song, Hanyang Univ/Korea

M-1B-1. A HYBRID MULTISCALE SIMULATION OF MICRO AND NANO-FLUIDICS WITH SURFACE ROUGHNESS

Ping ZHANG, *Laboratory for Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, China*, A modified Usher algorithm is developed for hybrid multi-scale simulation of micro- and nano-fluidics with surface roughness. In the hybrid simulation, molecular dynamics (MD) is used in one region where the continuum assumption breaks down, and the Navier-Stokes (NS) equations are used in another region where the continuum assumption holds. A constrained particle dynamics with the dynamic coupling model is introduced to couple the MD and NS equations in the overlap part of those two regions for the mass and momentum continuum. In dynamic coupling model, coupling parameter is flexible and positive as it is dynamically determined by the current states and self-adjusted as computation progresses. When the mass flux obtained from the NS equations is negative, particles nearest to the top boundary should be removed from MD area, when mass flux is positive, additional particles have to be introduced into the MD region to maintain the mass continuum. The critical issue is how to find the locations for the additional particles. In the past, new particles are often placed randomly on the MD region boundary, which causes program stoppage, because some particles are expelled far from the computational region because new particles are too close to the old particles. And solutions to this problem such as long time relaxation are always time-consuming or will cause unsteady temperature fluctuation. The Usher algorithm was developed to search the locations of the additional particles in order to avoid energy to blow up. However, the algorithm is slowly convergent in hybrid method because of the relatively smaller area. In this study, we modify the Usher algorithm to improve its search process. The modified Usher algorithm is used to simulate the Couette flows with surface roughness. The results obtained are found to be

in good agreements with the ones obtained from the full MD simulations.

M-1B-2. DROP OSCILLATIONS EXCITED BY POINT FORCE IN AC EWOD

J. M. OH, S. H. KO, K. H. KANG, *Pohang University of Science and Technology, Korea*, The wetting tension is changed by the Maxwell stress concentrated at the three-phase contact line in EWOD (Electrowetting on dielectrics). AC EWOD is preferable in various applications such as LOC (Lab-on-a-chip), liquid lens, and reflective display because it has some advantages such as the delay of the saturation and the decrease of the hysteresis of the contact angle. When the contact angle is changed periodically in AC field, the drop oscillation can be induced. Recently, a few researchers have reported the oscillation of a sessile drop in AC EWOD, and some of its consequences. However, no theoretical analysis of the problem has been attempted yet. In the present paper, we observe the frequency and amplitude dependences of drop oscillations in experiments and propose a theoretical model to analyze the oscillation by applying the conventional method to analyze the drop oscillation. A conventional experimental setup is prepared for observing EWOD. In experiments, the high speed camera is used to observe the instantaneous images of the drop oscillation. It is observed that the drop oscillation becomes resonant at specific frequency and that the dominant shape mode is different at each resonant frequency. It is also observed that the maximum amplitude of the oscillation at resonance decreases with respect to frequency. In theoretical analysis, the conventional domain perturbation method is used to derive the shape mode equations under the assumptions of weak viscous flow and small deformation. The Maxwell stress is exerted on the three-phase contact line of the droplet like a point force. The electrical force is simplified by using a delta function, and is decomposed into the driving forces of each shape mode. In the theoretical analysis, it is observed that the amplitude of each shape mode is maximized at the resonance frequency and that the maximum amplitude decreases with the mode number. The theoretical results on the shape and the frequency responses are compared with experiments, which show a qualitative agreement.

M-1B-3. ELECTROHYDRODYNAMIC FLOWS IN A DIELECTRIC LIQUID

H. J. PARK, J. M. OH, K. H. KANG, *POSTECH, Korea*, It is of great interest to understand the characteristics of colloidal particles under electric field in the dynamics of electrorheological fluid, electrophoretic deposition, and electrophoretic display. The analysis for the dynamics of colloidal particles has been mainly performed in the case of aqueous electrolyte solution. However, if dielectric liquids (DLs) are considered, there is an advantage of little electrolysis. This means that electric field strength can be raised much highly ($\sim 10^6$ V/m) to enhance a dynamic response of colloidal particles. Until now, the dynamics of colloidal particles is poorly understood, in a DL under electric field. In this work, we found a new EHD phenomenon occurring around the colloidal particles. We carried out experiments for a circular-cylindrical rod located in the middle of the electrodes and analyzed the EHD flow around the rod theoretically and numerically. We observed a symmetric flow pattern together with four vortices around the rod. We suggest that the EHD flow will be generated by the gradient of electrical conductivity which is induced by the field-dependent dissociation of impurities in the DL. Experimental result shows good agreement with our numerical results. The numerical solution is verified with analytical solution which is obtained by a perturbation analysis. According to our analytical result, the sign of induced free charges due to the conductivity gradient are negative at the top region and positive at the bottom region of the rod. The corresponding fluid pattern is found to be driven from the 'equator' of the rod towards the 'poles'. The greatest magnitude of velocity is located in the vicinity of the 'poles' of the rod where the Coulombic body force is the greatest. The EHD flow is distinct from the conventional electrokinetic flow such as the induced-charge electroosmosis (ICEO), judging from its flow direction and locations of center of vortices.

M-1B-4. NUMERICAL STUDY OF ELECTROOSMOSIS IN A MICRO-CAVITY USING IMMERSED BOUNDARY METHOD

D. V. FERNANDES, *Dong-A University, Korea*, S. KANG, *Dong-A University, Korea*, Y. K. SUH, *Dong-A University, Korea*, The bulk motion of an aqueous solution induced by the application of electric field is studied numerically. The physical model consists of a micro-cavity with two completely polarizable cylindrical electrodes. The electric double layer (EDL) model coupled with Stokes equations governing the electroosmotic flow has been described. The ionic species distribution is predicted by solving the Poisson-Nernst-Planck equations. All the spatial derivatives are