IUTAM Symposium on Transition and Turbulence in Flow through Deformable Tubes and Channels

Bangalore, India
January 20-23, 2014

Organised by,

Jawaharlal Nehru Centre for Advanced Scientific Research
and
Indian Institute of Science.

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Organising committee

- Prof. V. Kumaran, *Indian Institute of Science Bangalore, India.*
- Prof. V. Shankar, *Indian Institute of Technology Kanpur, India.*
- Prof. S. Ansumali, *Jawaharlal Nehru Centre for Advanced Scientific Research Bangalore, India.*

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- Prof. G. Holzapfel, *Institute for Biomechanics, Graz, Austria.*
- Prof. O. Jensen, *University of Nottingham, Nottingham, United Kingdom.*
- Prof. S. Kumar, *University of Minnesota, Minneapolis, United States of America.*
- Prof. G. Fuller, *Stanford University, Stanford, United States of America.*
- Prof. V. Kumaran, *Indian Institute of Science Bangalore, India.*
- Prof. V. Shankar, *Indian Institute of Technology Kanpur, India.*

Welcome message

The flow past deformable surfaces, and surface deformation to generate flow, is a highly inter-disciplinary field at the intersection of fluid mechanics, engineering, applied mathematics and biology. These flows are ubiquitous in biological systems, and are increasingly of importance in microfluidic technologies. An IUTAM symposium on this subject was held in Warwick, UK in 2001. Since then, there have been numerous advances, theoretical and experimental, in the field, and there has been a sharpening of focus in different areas of fluid-structure interactions. The objective of the symposium is to bring together experts in the field, with emphasis on latest advances and challenges in the following areas:

1. Effect of a dynamical coupling between fluid flow and soft surfaces on flow instability and the transition to turbulence.

2. Tissue mechanics, and the rheology of soft solids.

3. Flow-structure interactions in the cardio-vascular system.

4. Respiratory flows, and collapsible-tube models of the respiratory system.

5. Use of soft and active materials for mixing and pumping in microfluidics.

Though considerable progress has been made in each of these areas, significant challenges remain. We are confident that an exchange of ideas between experts in different areas will prove to be fruitful and stimulating, will engender new collaboration and will facilitate further advances in all areas.

V. Kumaran

General information

- **Venue**
  Conference Hall, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur, Bangalore-560 064, India.

- **Registration**
  Please register on January 20, 2014 between 09:30 am and 09:45 am at the symposium venue and collect the conference kit.

- **Name badges**
  Name badges will be issued at the registration desk. Please display your badge when requested. Entry to auditorium, food areas, etc. requires display of badge.

- **Accommodation**
  Accommodation has been arranged at I-house, JNCASR for invited participants and Jawahar Guest House, IISc for student participants.

- **Speaker check-in information**
  Participants are requested to load their presentation file well ahead of the start of the session. Student volunteers will help you in the process. Kindly preview your slides before the presentation.

- **Mobile phone policy**
  Kindly switch your mobile phone off during the talk.

Technical programme

Monday, 20 January 2014		
09:30-09:45	Registration	
	Session chair: V. Shankar	
09:45-11:00	T.J. Pedley	Flow and oscillations in collapsible tubes: physiological applications and low-dimensional models
11:00-11:15	Tea	
11:15-12:15	N.M. Bujurke	Stability of high Reynolds-number flow through collapsible channels
12:15-13:00	G.G. Fuller	Rheotaxis: the sensing and migratory response of microvascular endothelial cells to wall shear stress profiles
13:00-14:00	Lunch	
	Session chair: N.M. Bujurke	
14:00-14:45	A. Ghatak	Application of microfluidic channels in designing solid-liquid composite materials
14:45-15:30	N. Gundiah	The advancing edge: role of geometric constraints in cell migrations
15:30-16:15	L. Yeo	Spreading films, fingering instabilities and soliton-like wave propagation triggered by high frequency surface vibration
16:15-16:30	Tea	
	Session chair: L. Yeo	
16:30-17:15	N. Tiwari	Contact line instability in a thermocapillary-driven thin film and the effect of gravitational couterflow
17:15-18:00	A. Samanta	Falling film over a slippery inclined plane

Tuesday, 21 January 2014

Session chair: G.G. Fuller

09:30-10:30	S. Sane	How flexible wings influence flows over flapping wings
10:30-11:15	K.R. Sreenivas	Experimental and numerical simulation of flapping flight
11:15-11:30	Tea	
11:30-12:15	D. Das	Role of passive flexibility of wing in flapping flight
12:15-13:00	S. Ansumali	Lattice Boltzmann method for solid-fluid interactions
13:00-14:00	Lunch	
14:00-15:30	Poster session	
16:00	G.G. Fuller	Academy lecture
	Venue: Faculty Hall, IISc.	
18:00	Cultural programme	
	Venue: CSIC Auditorium, IISc.	
19:30	Banquet	
	Venue: JNC Guest House, IISc.	

Poster presentations

S.K. Das	Deformation and breakup of a perfectly conducting charged liquid drop in a quadrupole electric field
D. Giribabu	Stability of plane Couette flow past a deformable bilayer
R. Neelamegam	Stability of pressure-driven flow through a deformable tube

Wednesday, 22 January 2014

Session chair: T.J. Pedley

09:30-10:30	V. Shankar	Stability of fluid flow through deformable channels and tubes: an overview
10:30-11:15	J. Gajjar	High Reynolds number liquid layer flow with flexible walls
11:15-11:30	Tea	
11:30-12:15	A. Lucey	Local, global and transient analysis of disturbances in Blasius boundary layer flow over a compliant panel
12:15-13:00	R. Thaokar	Stability of oscillatory and electrohydrodynamic flows over flexible surfaces
13:00-14:00	Lunch	

Session chair: J.S.B. Gajjar

14:00-14:45	P. Chokshi	Role of viscoelasticity in wall mode instability in plane shear flow over deformable solid
14:45-15:30	Gaurav	Manipulation of interfacial instabilities by using a soft, deformable solid layer
15:30-16:15	P.K. Sen	Stability of disturbance waves in developing shear flows, with application to boundary-layer flow over a flat-plate, and other examples
16:15-16:30	Tea	

Session chair: A. Lucey

16:30-17:15	M.K.S. Verma	Transition and ultra-fast mixing in micro-channel due to a dynamical instability induced by a soft wall
17:15-18:00	V. Kumaran	A dynamical instability due to fluid-wall coupling lowers the transition Reynolds number in the flow through a flexible tube

Thursday, 23 January 2014

Sightseeing Sravanabelagola, Belur Halebid.

Contents

Flow and oscillations in collapsible tubes: physiological applications and low-dimensional models.

T.J. Pedley[1*] and Draga Pihler-Puzovic[2]

[1] *DAMTP, University of Cambridge, U.K.*
[2] *Department of Mathematics, University of Manchester, U.K.*

This lecture is an overview of its subject. The motivation comes from physiology: Air-flow in the lungs, where the phenomenon of flow limitation during forced expiration is a consequence of large-airway collapse, and wheezing is a manifestation of self-excited mechanical oscillations; Blood flow in veins, such as those of giraffes, in which the return of blood to the heart from the head must be accompanied by partial venous collapse, and in arteries, which exhibit self-excited oscillations (Korotkov sounds) when compressed by a blood-pressure cuff. Laboratory experiments are frequently conducted in a *Starling resistor*, a finite length of flexible tube, mounted between two rigid tubes and contained in a pressurised chamber. Steady conditions upstream and downstream give rise not only to steady flows, but also to a rich variety of self-excited oscillations [1], which theoreticians have been seeking to understand for at least four decades. Some of the observations have been reproduced in full Navier-Stokes computations for a two-dimensional model [2], but these do not provide physical understanding of the mechanisms that give rise to the oscillations.

In order to gain such understanding we seek a self-consistent mathematical model. We concentrate principally on 1D models, in which the key dependent variables are the cross-sectional area A and the cross-sectionally averaged velocity u and pressure p, all taken to be functions of longitudinal coordinate x and time t. The governing equations are those of conservation of mass and momentum and a tube law representing the elastic properties of the vessel. In the momentum equation, the viscous resistance term depends on the fluid velocity profile, which itself depends on both the geometry and time; this is conventionally modelled either as a linear function of fluid velocity, accurate at low Reynolds number, or with an ad hoc representation of the energy loss at flow separation. Even with such crude approximations, the 1D models agree quite well both with observations in the giraffe [3] and with some of the 2D computations and 3D experiments [4].

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Nevertheless, it is desirable to make the model completely rational, at least for the 2D model problem, in which part of one wall of a parallel sided channel is replaced by a membrane under tension. One approach, for large Reynolds-number flow, and a long membrane, is to consider small deflections of the membrane and use interactive boundary-layer theory [5]. This leads to interesting predictions, such as the impossibility of simultaneously prescribing the flow rate and the upstream pressure, but not to oscillations, except in cases where wall inertia is important (flutter). Another approach is to assume a parabolic velocity profile everywhere, leading to a rational choice for the inertia and viscous terms in the 1D momentum equation [6]. If, further, the undisturbed membrane is taken to be flat, by a suitable choice of external pressure distribution, the system leads to an oscillatory instability even without wall inertia [7]. Whether these oscillations have the same physics as those computed numerically at lower Reynolds number remains to be seen.

References

[1] Bertram, C.D., et al, J Fluids Struct., **4**, 125-154 (1990).

[2] Luo,X.Y. & Pedley,T.J., J Fluid Mech., **314**,191-225 (1996).

[3] Brook,B.S. & Pedley,T.J., J Biomech., **35**, 95-107 (2002).

[4] Jensen,O.E., J Biomech. Eng., **114** 55-59 (1992).

[5] Pihler-Puzovic,D. & Pedley,T.J., J Fluid Mech., **714** 536-561 (2013).

[6] Stewart,P.S. et al, Eur J Mech B/Fluids, **28**, 541-557 (2009).

[7] Xu,F., et al. J Fluid Mech. **723**, 706-733 (2013).

Stability of high Reynolds-number flow through collapsible channels

Ramesh B. Kudenatti[1], N.M. Bujurke[2*] and T.J. Pedley[3]

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We investigate the linear stability of the asymptotically high Reynolds number flow in a planar collapsible channel of which a part of the lower wall has been replaced by a flexible membrane under longitudinal tension with and without wall inertia. Deformation of the membrane is assumed to have small amplitude and long wavelength. Far upstream the flow is Poiseuille flow at high Reynolds number. The flow consists of the inviscid core and the viscous boundary layers on both walls coupled to each other and to the membrane deformation. In the study, we use unsteady interactive boundary layer theory to investigate the stability of the flow for zero external pressure. We observe that in the absence of wall inertia, the problem is ill-posed when the pressure is fixed upstream ($x = 0$). However, when it is fixed downstream end of the membrane ($x = 1$), the problem is well-posed and all observed solutions are stable. Also, multiple solutions are possible, if the pressure is specified further downstream ($x \geq 1.0$). When the pressure is fixed (at $x = 1.0$ and 1.1), multiple solutions exist and are all always unstable. Nevertheless, when $x \geq 1.5$, one of the solutions is predicted to be stable for some range of the tension T. Now, with the addition of wall inertia to the membrane, we expect the system to generate flutter-type oscillations which play an important role in destabilizing the system. The physical mechanisms underlying these phenomena will be explored and studied in detail.

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Rheotaxis: the sensing and migratory response of microvascular endothelial cells to wall shear stress profiles

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Endothelial cells (ECs) line the inner diameter of our blood vessels and control the dilation of those vessels to ensure that wall shear stresses remain in within desirable ranges. However, the manner in which these cells sense wall shear stress is not known. Existing observations have long been available, however, that establish that healthy ECs elongate and orient in the direction of wall shear stress for uniform fields. However, it has been observed that disruption in wall shear stress can misalign these cells. This lecture presents data where live cell imaging has been used to follow the migratory response of microvascular ECs exposed to well defined, stagnation point flows. These flows are generated by aiming jets of fluids at monolayers of ECs at modest Reynolds numbers. Impinging jet flows generate wall shear stress profiles that are zero at the stagnation point and that rise to a maximum in the vicinity of the jet diameter before dissipating to zero far from the jet. It is found that the ECs migrate upstream, against the wall shear stress and realign to an orthogonal orientation at the location of maximum stress. This distinctive migratory pattern is shown to be exquisitely sensitive to mechanotransduction pathways within the cells and this is confirmed by introducing chemical inhibitors that block proteins thought to be involved with signaling pathways.

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Application of microfluidic channels in designing solid-liquid composite materials

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Microfluidics has been driving many discoveries in biology, chemistry, material science and engineering e.g. synthesis of biomolecules and nano-particles, development of microassays and sensors, novel optofluidic and drug delivery devices, computation of complex mathematical problems, even generation of 3D-solid microstructures. A largely unexplored area is the development of solid-liquid composite materials using embedded network of liquid filled micro-channels. Recent experiments show that physical properties of the liquid, e.g. surface tension, pressure, refractive index, colour, when combined with similar properties of the solid can give rise to many novel phenomena which brings in new functionality to the material. Importantly, deformability of the solid can lead to dynamically but reversibly altering effective property, not achievable by either the homogenous solid or the liquid. In this talk we will present the design of a novel material which incorporates the effect of solid-liquid interfacial tension leading to for novel applications.

In brief, we will elaborate on the method of preparation and characterization of elastomeric layers embedded with network of three dimensionally oriented microchannels. We will show that with intelligent use of this microstructure and filling them with liquid of suitable characteristics, one can design smart material with enhanced characteristics, e.g. microfluidic mixer, aspherical optical lenses, compact-lens filter system, material with controlled shape. One can design adhesive the adhesive strength of which varies over a large range, from almost negligible to almost 60 times that of a homogeneous adhesive layer, and all these performed without changing the intrinsic rheological property of the adhesive. Besides, it is possible to achieve directional adhesion, load dependent adhesion and adhesion with shock absorption by suitably filling the channels with liquid. Finally, we will show how interaction of solid and liquid can be used to generate limbless locomotion in soft-bodied object.

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The advancing edge: role of geometric constraints in cell migrations

Namrata Gundiah*

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Cell motility is fundamental to many mechanisms including those guiding embryogenesis, in wound closure associated with epithelial cell movements, immune response by white blood cells, and in uncontrolled movement of metastatic cells in cancers. Chemotactic stimuli or morphogens are an integral component of these responses but are alone insufficient to explain cell migrations, formation of tissues through morphogenesis, and the measured forces underlying these processes. Mechanical stimuli, such as interfacial tension between cells, are known to be a fundamental determinant underlying the vast repertoire of shapes and patterns observed in life. An understanding of the generic principles underlying self-assembly of individual cells leading to coordinated and collective cellular movements is challenging because it requires an integrated approach to assess how local perturbations in cells and shapes lead to collective migrations. In this talk, I will discuss recent investigations in my lab studying migratory behavior of breast cancer cells following constraining them in specific geometric shapes using a microstencil. Through such studies we show the importance of geometric curvatures that affect overall coordinated migratory behaviors of cancer cells.

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Spreading films, fingering instabilities and soliton-like wave propagation triggered by high frequency surface vibration

Leslie Y Yeo*, Amgad R Rezk, Ofer Manor, James R Friend

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We unravel the mechanisms underpinning a collection of wetting phenomena recently observed in which a thin viscous film, with thickness on the order of 10 microns, is drawn out from a sessile drop by Rayleigh waves propagating on a piezoelectric substrate in the form of 10 MHz order surface acoustic waves. Quite peculiarly, the thin film advances in a direction opposing that of the surface wave propagation. The film subsequently suffers from a transverse instability to form fingering patterns above which soliton-like wave pulses are observed to grow and translate in the opposing direction. In addition to deriving a dynamic spreading model, we show the competing influence of the various acoustic streaming mechanisms at different length scales that are responsible for the flow reversal observed by the advancing film front and the solitary wave pulses.

References

[1] AR Rezk, O Manor, JR Friend, LY Yeo, Nature Communications, **3**, 1167 (2012).

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Contact line instability in a thermocapillary-driven thin film and the effect of gravitational couterflow

Naveen Tiwari*

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For a micro-scale liquid film interfacial forces may play important role in the dynamics due to high surface area-to-volume ratio. Thermocapillary stress due to an applied temperature gradient can force a thin liquid film to rise-up on a vertical solid substrate against gravity. Generally a capillary ridge forms at the three phase contact-line for such a flow that is susceptible to a rivulet or fingering instability at the advancing front. Larger ridges have been observed to be more unstable. The application of a sufficiently strong gravitational counterflow has been shown to drain fluid from the ridge and stabilize the film against rivulet formation as well as lead to interesting spreading dynamics. In this presentation, mathematical model of such a film dynamics is presented. Through proper scaling gravitational drainage parameter is introduced in the model which is a ratio of force due to gravity to the applied thermocapillary stress. The dynamics and stability of thermocapillary driven films are analyzed for the entire range of gravitational drainage parameter. At the three phase boundary slip is allowed. Conventional slip-model is employed to alleviate the stress singularity at the contact-line. The slip model introduces the static contact angle and slip coefficient as parameters in the model that can typically be specified independently. The contact angle of the spreading film is allowed to depend on the velocity of the contact line, and the effects of this dependence on the film profile, linear stability, and transient response of perturbations are examined. Increasing gravitational drainage from zero has a stabilizing influence on the traveling wave solutions but is accompanied by an increase in the amplitude of the capillary ridge, which is contrary to stability results for spreading films with only one driving force. This behavior is explained through an energy analysis of the disturbance operator. Above a threshold value of the drainage parameter the film becomes stable to rivulet formation, and the film shape evolves continuously in time. For even larger amounts of drainage, traveling wave solutions can again be found, but only for particular combinations of the slip coefficient and contact slope. While results for the different spreading regimes are generally consistent with predictions based on the more extensively used

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precursor film model of the contact line, there are deviations in the spreading predictions for a substantial range of gravitational drainage, which suggests potential differences in the spreading behavior of completely and partially wetting films.

Falling film over a slippery inclined plane

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A gravity-driven film flow on a slippery inclined plane is considered within the framework of long-wave and boundary layer approximations. Two coupled depth- averaged equations are derived in terms of the local flow rate $q(x,\ t)$ and the film thickness $h(x,\ t)$. Linear stability analysis of the averaged equations shows good agreement with the OrrSommerfeld analysis. The effect of a slip at the wall on the primary instability has been found to be non-trivial. Close to the instability onset, the effect is destabilising whereas it becomes stabilising at larger values of the Reynolds number. Nonlinear travelling waves are amplified by the presence of the slip. Comparisons to direct numerical simulations show a remarkable agreement for all tested values of parameters. The averaged equations capture satisfactorily the speed, shape and velocity distribution in the waves. The Navier slip condition is observed to significantly enhance the back flow phenomenon in the capillary region of the solitary waves with a possible effect on heat and mass transfer.

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How flexible wings influence flows over flapping wings

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In recent years, it has become possible to study the flows over flapping wings using mechanical flappers that are scaled to model insects of various sizes. These models enable us to directly measure the forces on the flapping wings as well as visualize the flows using Digital Particle Image Velocimetry (DPIV). These studies have led to the fundamental understanding of how insects and birds generate the aerodynamic forces and flows required for flight. Such research requires both a careful measurement of wing kinematics of insects using high-speed videography, as well as their recreation in a flapper. In previous years, we focused on the basic questions regarding aerodynamic force generation by flapping rigid wings. These data are particularly relevant to smaller flies in which wings are more or less rigid except during pronation and supination. However, the wings of larger animals such as butterflies and moths show considerably more flexion which is likely to influence aerodynamic force generation. To understand how wing flexion influences flight forces, we have recently begun a series of investigations in which we measure the forces and flows around flapping flexible wings. In my talk, I will describe the results of these studies and also their biological implications of our findings.

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Experimental and numerical simulation of flapping flight

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Unlike a fixed-wing aircrafts, birds and insects reciprocate their wings changing the wing direction and the pitch twice in each stroke. They operate at relatively low Reynolds numbers and generate their lift and thrust by unsteady aerodynamics. Many insects use "eight-shape" wing beat pattern which involves both back-and-forth reciprocating motion (feathering) combined with up-and-down (flapping) motion. However, insects like butterflies, have predominantly flapping motion, which is more simpler wing-kinematics and hence suitable for adopting into Micro Air Vehicle (MAV) applications. In this study using 3-D, Lattice Boltzmann Method (LBM) based numerical simulations and experiments, we present results on flow fields and lift force generated in flapping flight as a function of flapping frequency, asymmetry-ratio ($AR = t_D/t_U$; where t_U and t_D are time required for up and down strokes respectively).

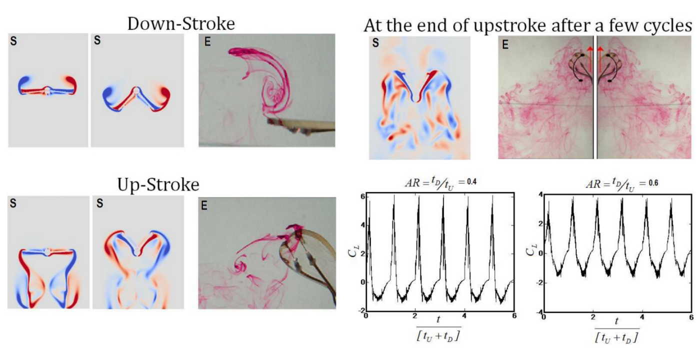

Figure 1: Montage of flow-fields observed in 3-D simulations (marked S) and in experiments (marked E) along with estimated lift force obtained in numerical simulations for AR = 0.4 and $AR = 0.6$.

In Fig. 1, a qualitative comparison of flow-fields at various stages of flapping cycle observed in simulation and experiments are made. A critical observation in the asymmetric flapping ($AR < 1$) is that the wing-tip vortex observed in the down-stroke is absent while wing is moving in the upward direction. The non-dimensional lift force (C_L) shows dependence on AR. Detailed analysis will be presented in the full-length paper.

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Role of passive flexibility of wing in flapping flight

Debopam Das*, Saurav K Ghosh†, Joydeep Bhowmik‡

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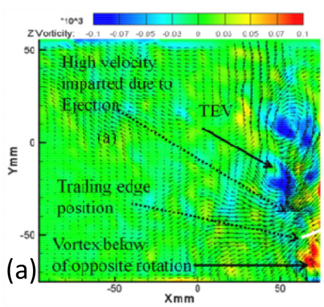
Role of the wing flexibility and deformation in flapping wing aerodynamics under zero and non-zero advance ratio are investigated The study can be divided into insects flight regime [1] and birds flight regime [2] as the wing flexibility plays a vital role in both unsteady and quasi-steady regimes respectively. The insect models are investigated for the Re range of 2000-10000 and the wing aspect ratio 1.5 to 3 with different flexural rigidity. The role of flexibility in the retention duration of the leading edge vortex (LEV) and the resulting flow field and force field is investigated in details in these parameters ranges. The flow field is measured using PIV at zero forward velocity [3] and force field is measured using unsteady force transducer. PIV measurements conducted in the wake profile of the insect model enhance the understanding of the vortex interactions and other flow features that take place in flapping. The butterfly shaped wing shows better lift and thrust generation than a rectangular wing of the same span and same aspect ratio. Among the rectangular wings, the one with aspect ratio 2 gives optimum lift and thrust characteristics.



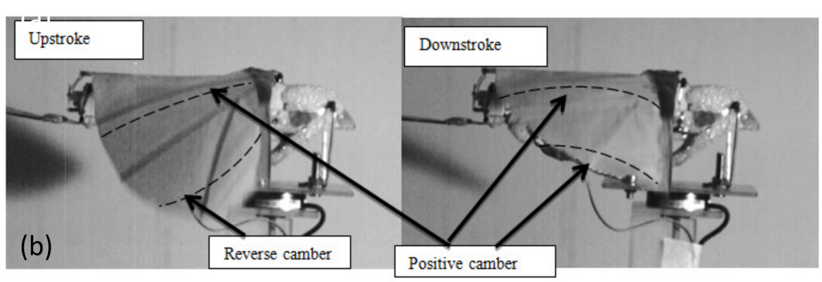


Figure 1: (a) PIV velocity field of the butterfly wing flapping at 5Hz, at t/T = 0.5Hz (b) Passive wing deformation in the bird model showing the change in the camber of the wing in both the strokes.

In the birds flight regime flow visualization and force measurements are carried out for different wing flexibility in the Re range of 4000 to 21000. A theoretical model has been developed based on quasi-steady lifting line theory. The experimental observations predict close match with the analytical estimations at lower J (advance ratio) values (as at lower

Electronic addresses: * das@iitk.ac.in † skghosh@iitk.ac.in ‡ joydeepb@iitk.ac.in frequencies the inertial and added mass effect are low which is neglected in the theory). Increase in rigidity favors the lift and thrust upto a certain point and then it falls, thus there is only a range of flight parameters where flexibility and deformation is useful. The stiffness of the wing also changes on the flight parameters like the effective angle of attack at various wing sections, including the change of camber along the wing span helping in sustaining an overall positive lift or thrust depending upon the case.

Acknowledgements

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References

[1] Abhijit Banerjee, Saurav K. Ghosh, and Debopam Das, ISRN Mechanical Engineering, **2011**, 162687 (2011).

[2] Bhowmik, J.,Das, D., and Ghosh, S. K., International Journal of Intelligent Unmanned Systems, **1**, 36-61 (2013).

[3] Ghosh, S.K., Dora, C., and Das, D., J. Aerosp. Eng. **25**, 547558 (2012).

Lattice Boltzmann method for solid-fluid interactions

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Lattice Boltzmann method has become popular in the recent past for simulating fluid-structure interaction as the cost of modeling and the complexity are simplified. A highly efficient and simple grid generation mechanism, the complete absence of pressure Poisson solver, the hyperbolic nature of the underlying partial differential equation and an almost local algorithm helps in dealing with complex scenarios of fluid-structure interactions with efficient parallelization and reduces the time in implementation of a fairly realistic practical application. However, the standard solid-fluid boundary conditions used in LB literature results in error in force calculation. We proposed a boundary condition which retains the simplicity of bounce-back condition and similar to diffuse boundary condition leads to positive definite populations. The fluid nodes which are newly formed because of the movement of the solid boundary are proposed to be initialized with Grad's distribution. Fig. 1 shows a plot of the percentage standard deviation in the calculation of C_D for a translating cylinder at Re = 40 in the present scheme and that proposed by Aidun et. al [1]. It can be observed that the error in the present scheme has reduced. The performance of the code was improved with vector-friendly blocked computing strategy, along with a recently developed hybdrid data structure SoAoS for such models [2]. A fast, accurate and simple three dimensional scheme which is capable of dealing with moving boundaries using Lattice Boltzmann method has been developed to be used as a model. We utilize this code to perform 3-dimensional numerical simulations of asymmetrical flapping flight which involves complex fluid-structure interaction. Our computational study, along with experimental flow visualization would explain how asymmetric-flapping leads to a flow-field that produces net upward lift-force which would be presented at the conference. Fig. 2 shows the vorticity contours in a forward flapping flight at Re = 1000.

References

[1] C. K. Aidun, Y. Lu and E.-J. Ding, J. Fluid Mech. **373**, 287 (1998).

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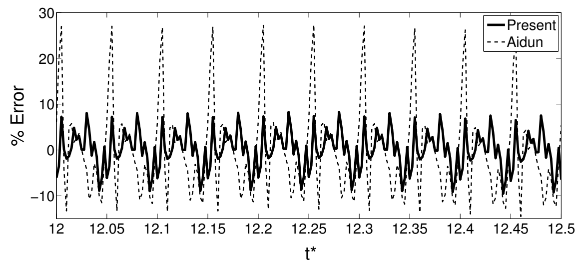

Figure 1: Percentage standard deviation about the steady state C_D for present implementation compared to Aidun's implementation at Re = 40, Ma = 0.087.

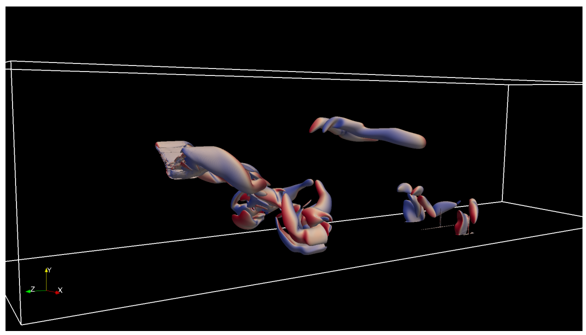

Figure 2: Vorticity contours in a forward flapping flight at Re = 1000.

[2] Aniruddha G. Shet, Shahajhan H. Sorathiya, Siddharth Krithivasan, Anand M. Deshpande, Bharat Kaul, Sunil D. Sherlekar and Santosh Ansumali, Phys. Rev. E **88**, 013314 (2013).

Stability of fluid flow through deformable channels and tubes: an overview

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This presentation will provide a systematic overview of the study of instabilities in flow past deformable solid surfaces, with particular emphasis on internal flows through tubes and channels. The subject is certainly more than five decades old, and arguably began with Kramer's pioneering experiments on drag reduction by compliant surfaces. This was immediately followed by the theoretical studies of Benjamin and Landhal in the early 1960s. Most earlier theoretical studies were focused on boundary layer stability, and had used simplistic wall models comprised of spring-backed plates. There was a resurgence in the field since the mid-1980s, and more attention was focused on internal flows through deformable tubes and channels. The wall deformation was described by both phenomenological spring-backed plate models as well as by continuum linear viscoelastic solid models. All these studies predict several types of instabilities in flow past deformable surfaces. This presentation will attempt to place all the theoretical results in perspective, and try to classify the instabilities predicted by various studies. Recent studies have also emphasized the importance of using a frame-invariant constitutive model, such as the neo-Hookean model, for the solid deformation. Until recently, however, the field has been dominated by theoretical and numerical studies, with very little experimental observations to corroborate the theoretical predictions. Recent experiments in flow through deformable tubes and channels indeed show instability at Reynolds number much lower than their rigid counterparts, and the experimental observations are in qualitative agreement with some of the theoretical predictions. There have also been a few studies on the non-linear aspects of the instability using the weakly non-linear formulation to determine the nature of the bifurcation at the linear instability, and this presentation will briefly touch upon these as well.

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High Reynolds number liquid layer flow with flexible walls.

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We consider the liquid layer flow over an inclined flexible wall, see figure 1, using asymptotic methods based on the assumption that the Reynolds number is large. The flexible wall behaviour is described by a spring-plate model, and parameters chosen so that the wall flexibilty affects the governing boundary layer problem. For the case of a rigid wall, the problem reverts to one studied by [1]. Asymptotic analysis of the governing equations leads to the following reduced triple-deck equations governing the interaction between the wall layer and the free-surface. Here $H(X,T)$ describes the scaled flexible wall, $P(X,T)$ is the scaled pressure, $-A(X,T)$ is the scaled free-surface displacement, $U(X,Y,T)$, $V(X,Y,T)$ are the scaled fluid velocities in the boundary layer. We will discuss the linearised and other solution properties of these set of equations.

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0,$$

$$\frac{\partial U}{\partial T}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\partial^2 U}{\partial Y^2},$$

$$P=-sA-\frac{\partial^2 A}{\partial X^2},$$

$$U=0,\ V=\frac{\partial H}{\partial T},\ \text{on } Y=H(X,T),$$

$$U\to Y+A(X,T)\ \text{as } Y\to\infty,$$

$$C_M\frac{\partial^2 H}{\partial T^2}+B\frac{\partial^4 H}{\partial T^4}-\bar{T}\frac{\partial^2 H}{\partial X^2}+k_E H=-P.$$

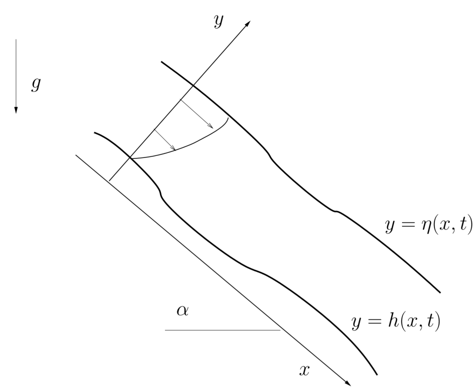

Figure 1: Schematic diagram showing the liquid layer flow over an inclined flexible surface $y=h(x,t)$ with a free-surface $y=\eta(x,t)$.

References

[1] Gajjar, J.S.B., Computers & Fluids, **15**, 337-360 (1987).

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Local, global and transient analysis of disturbances in Blasius boundary layer flow over a compliant panel

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Theoretical and experimental studies have shown that compliant walls are able to reduce the growth rates of unstable Tollmien-Schlichting waves (TSWs) that are the conventional route to boundary-layer transition in low-disturbance environments; e.g. see [1]. Transition can therefore be postponed by an appropriately designed compliant coating adhered to an otherwise rigid surface, leading to reductions of skin-friction drag in marine applications. The more compliant the wall, the greater is the suppression of TSWs.

However, a compliant also supports wall-based waves that can become unstable - such as the hydro-elastic instabilities of divergence and travelling-wave flutter (TWF) - when the wall is too compliant thereby undermining the overall flow-stabilization strategy. Accordingly, when designing useful complaint coatings, it is necessary to take into account all of the possible instabilities of the fluid-structure interaction (FSI) system [2]. Short compliant sections, or panels, offer a promising way to control hydro-elastic instabilities in a design strategy [1, 3, 4] and thus the effect of finite stream-wise extent is the focus of the present study.

Many studies of the system utilize local analyses based upon the assumptions of an infinitely long compliant wall and parallel-flow to identify and characterise the instabilities while numerical simulation has been used for walls of finite extent [3]. In contrast, we carry out a bi-global linear stability analysis of the FSI system by combining features of the modeling strategies developed in [4, 5]. Thus, we model the flow using a combination of vortex and source boundary-element sheets on a computational grid while the dynamics of a plate-spring, Kramer-type, compliant wall are represented in finite-difference form. The assembled FSI system is then couched as an eigenvalue problem and the eigenvalues of the various flow- and wall-based instabilities analyzed for a range of system parameters. To validate our modeling we conduct local analyses for comparison with the results of previous studies. We also use our system model to conduct a non-modal analysis of transient growth in the FSI system.

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The key new findings of the study are that coalescence - or resonance - of one of the structural eigenmodes with either the least stable TSW or a travelling-wave flutter (TWF) mode can occur. This renders the convective nature of these instabilities to become global for a finite compliant wall. A local analysis of the temporally unstable modes shows that besides the TSW and TWF modes, a divergence-type mode associated with the structural behaviour can additionally yield global instability. Finally, a non-modal analysis reveals that the transient behaviour of flow-based instabilities over a compliant wall in response to an initial disturbance have lower amplification rates that those over a rigid wall.

References

[1] Carpenter, P.W., Davies, C. and Lucey, A.D., Current Science, **79**, 758-765 (2000).

[2] Dixon, A.E., Lucey, A.D. and Carpenter, P.W., AIAA Journal, **32**, 256-267 (1994).

[3] Davies, C. and Carpenter, P.W., Journal of Fluid Mechanics, **335**, 361-392 (1997).

[4] Davies, C. and Carpenter, P.W., Journal of Computational Physics, **172**, 119-165 (2001).

[5] Pitman, M. W. and Lucey, A. D., Proceedings of the Royal Society A, **465**, 257281 (2009).

Stability of oscillatory and electrohydrodynamic flows over flexible surfaces

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The stability of oscillatory flows over compliant surfaces is investigated using analytical and numerical methods. Two models are used for describing the compliance, the spring backed wall model and the viscoelastic gel model and both are found to exhibit an instability in the limit of zero Reynolds number. The amplitude of the oscillatory velocity for transition to instability increases with the frequency of oscillations. The transition amplitude has a minimum at zero wavenumber for the spring backed plate model, whereas the minimum occurs at finite wavenumber for the viscoelastic gel model. Experimental studies on the stability of an oscillatory flow past a viscoelastic gel confirm the theoretical predictions [1].

The second part of my talk deals with an electrohydrodynamic instability at the interface between a gel and a fluid. A sensitive dependence of the electrohydrodynamic instability on the thickness of the gel was observed. The analysis indicates that a single interfacial mode undergoes an electrohydrodynamic as well as the shear instability mode and the effect is additive in the linear limit.

The electrohydrodynamics of an infinitesimally thin elastic capsule, obeying the Mooney-Rivlin constitutive equation, is presented next. The effect of electric capillary number Ca, a ratio of electric and elastic stress on the unstressed geometry and the type of membrane material on the deformation of a capsule is presented using analytical theory and boundary element calculations. The small Ca analysis is verified with experiments conducted on polysiloxane microcapsules with oil and water as the fluid outside and inside the capsule. The comparison of experimental results with analytical theory and BEM simulations suggests that the capsule deformation is highly non-linear and possibly plastic even at moderate values of Ca.

References

[1] Rochish Thaokar and V Kumaran, EPJB, **41(1)**, 135-145 (2004).

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Role of viscoelasticity in wall mode instability in plane shear flow over deformable solid

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With the objective to investigate the role of polymer addition in otherwise Newtonian fluid flowing past a flexible solid medium, the linear stability analysis has been carried out for the plane Couette flow geometry. The polymeric solution is modeled as an Oldroyd-B fluid. The system consists of a viscoelastic fluid layer of thickness R, density ρ, viscosity η, relaxation time λ and retardation time $\beta\lambda$ flowing past a linear elastic solid wall of thickness HR, density ρ, and shear modulus G. The emphasis is on the high Reynolds number *wall mode* instability, which has recently been shown in experiments to destabilise the laminar flow of Newtonian fluids in soft-walled tubes and channels at a significantly lower Reynolds number than that for flows in rigid condiuts [1, 2]. For Newtonian fluids, the wall modes are known to become unstable when flow Reynolds number exceeds a certain critical value Re_c which scales as $\Sigma^{3/4}$, where the where the Reynolds number $Re = \rho VR/\eta$m V is the top plate velocity, and the dimensionless parameter $\Sigma = \rho GR^2/\eta^2$, characterizing the fluid-solid system. For very high Reynolds number, the addition of polymer tends to decrease the critical Reynolds number from its value for the Newtonian fluid, indicating destabilizing role of fluid viscoelasticity. The analysis suggest that the transition Reynolds number could be decerased by upto a factor of 10 by the addition of small amounts of polymer. The critical Reynolds number follows the scaling $Re_c \sim \Sigma^{3/4}$ in the limit $Re \gg 1$, the characteristic scaling of the Newtonian wall modes. However, for moderate Reynolds number, there exists a narrow region in β-H parametric space, corresponding to very dilute polymer solution ($0.9 < \beta < 1$) and thin solids ($H < 1.1$), in which the addition of polymer tends to increase the critical Reynolds number for instability beyond its value for the Newtonian fluid. Hence, the addition of a small amount of polymer tends to delay the flow transition in this regime.

References

[1] Verma, M. K. S. and Kumaran, V., J. Fluid Mech, **705**, 322 (2012)

[2] Verma, M. K. S. and Kumaran, V., J. Fluid Mech, **727**, 407 (2013)

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Manipulation of interfacial instabilities by using a soft, deformable solid layer

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Flow configurations with presence of one or more fluid-fluid (gas-liquid and/or liquid-liquid) interfaces occur in wide variety of technological applications such as coating processes, polymer co-extrusion, falling film reactors and lubricated pipeline transportation. Such flow configurations are susceptible to several qualitatively different interfacial instabilities depending upon the discontinuity of different properties like viscosity, elasticity, density, etc across the interface. It is frequently required to control and manipulate these interfacial instabilities in various applications. We demonstrate here the possibility of using a deformable solid coating to control such interfacial instabilities for various flow configurations and for different fluid rheologial behaviors. In particular, we show complete suppression of interfacial flow instabilities by making the wall sufficiently deformable when the configuration was otherwise unstable for the case of flow past a rigid surface. While these interfacial instabilities could be suppressed in certain parameter regimes, it is also possible to enhance the flow instabilities by tuning the shear modulus of the deformable solid coating for other ranges of process parameters. Thus, we illustrate that the coupling between the fluid and deformable solid can be exploited to either inhibit interfacial instabilities, induce new instabilities which remain absent for flow past rigid surfaces or enhance interfacial instabilities already present for flow past rigid surfaces.

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Stability of disturbance waves in developing shear flows, with application to boundary-layer flow over a flat-plate, and other examples

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This paper attempts to induce some formalism in the study of stability of developing shear flows, by use of so called ad-hoc methods wherein all terms upto and inclusive of a particular order are lumped together in the same equation. However, whether the ordering is perturbation or asympotic is somewhat vague. The classical example of stability of a developing shear flow is the stability problem of boundary-layer flow over a flat-plate including the non-parallel effects. Other examples are free shear flows; also, problems involving flow over alternate rigid and porous panels with suction, or suction from one plate and injection from the opposite plate. The quick method for stability analysis is to use the local Orr-Sommerfeld solution, using the quasi-parallel approximation. This is sometimes augmented by inclusion of some non-parallel terms, perhaps in an ad-hoc manner, and so called improved solutions are obtained. The present paper attempts to establish a formal framework for these methods so that these methods are no more termed 'ad-hoc'.

Illustration and numerical corroboration are sought from the stability of boundary-layer flow over a flat-plate, inclusive of non-parallel effects and two other allied problems.

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Transition and ultra-fast mixing in micro-channel due to a dynamical instability induced by a soft wall

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Achieving efficient mixing in microfluidics devices poses a great challenge because the Reynolds number is small in channels of submillimetre dimensions. Here, we demonstrate an experimental realization of ultra-fast mixing in a micro-channel due to dynamical instability induced by a soft wall [1]. This dynamical instability is observed in experimental studies on micro-channels of rectangular cross-section with smallest dimension 100 μm and 160 μm in which one of the walls is made of soft gel. A spontaneous transition from an ordered, laminar flow to a chaotic and highly mixed flow state is observed in the channel when the Reynolds number increases beyond a critical value as shown in figure 1. This critical Reynolds number decreases as the elasticity modulus of the soft wall is reduced. The instability onset is detected using dye-stream experiments where the break-up of a dye-stream in the channel is observed and detection of wall oscillations by embedding fluorescent micro beads in the soft wall. The mixing efficiency is determined by image processing and conductance measurements at the outlet.

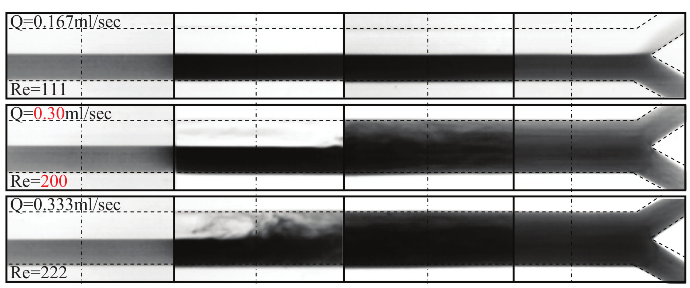

Figure 1: Images showing the dynamical instability in a Y micro-channel with dye-stream injected in one inlet and clear water in the other inlet at different Reynolds numbers.

References

[1] M.K.S. Verma and V. Kumaran, J. Fluid Mech., **727**, 407-455 (2013).

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A dynamical instability due to fluid-wall coupling lowers the transition Reynolds number in the flow through a flexible tube.

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The instability in the flow through soft tubes is studied experimentally, in order to examine whether the interaction between the flow and the soft wall could reduce the transition Reynolds number. In the experiments, tubular bores of diameter about 1 mm are cast in polymer gels made of polydimethylsiloxane (PDMS), and shear modulus of these gels is varied in the range $10 - 500$kPa by varying the catalyst concentration. The flow is driven by a pressure difference across the tube, and the friction factor f is measured as a function of the Reynolds number Re. Experiments show that the laminar flow becomes unstable, and there is a transition to a more complicated flow profile, for Reynolds numbers as low as 500 for the softest gels used here. The nature of the $f - Re$ curves is also qualitatively different from that in the flow past rigid tubes; in contrast to the discontinuous increase in the friction factor at transition in a rigid tube, it is found that there is a continuous increase in the friction factor from the laminar value of $(16/Re)$ in a flexible tube. The onset of transition is also detected by a dye-stream method, where a stream of dye is injected into the center of the tube. The transition Reynolds number is significantly lower than that predicted theoretically for the parabolic flow in a cylindrical tube. In order to resolve the discrepancy, the flow modification due to the channel deformation is determined, and the transition Reynolds number for the non-parabolic flow is determined using the locally parallel approximation. For the deformed tube, transition is first predicted in the downstream converging section, and the transition Reynolds number is in agreement with experiments.

References

[1] M.K.S. Verma and V. Kumaran, J. Fluid Mech., **705**, 322-347 (2012).

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Deformation and breakup of a perfectly conducting charged liquid drop in a quadrupole electric field

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A neutral or a charged spherical liquid drop when placed in an electric field, deforms into a prolate or oblate spheroid depending upon the the external electrical forces. The technological relevance made this electro-hydrodynamic phenomena an important area of study. Through analytical (asymptotic) and numerical (boundary element) methods we investigate the deformation and breakup of a perfectly conducting neutral and charged liquid drop suspended in a dielectric medium in a quadrupole electric field. On account of net charge a positively dielectrophoretic conducting drop can be stabilized at the low electric field region at the centre of a quadrupole field, thereby facilitating a systematic study of the deformation. Unlike, uniform electric field, a charged drop placed at the centre in a quadrupole field does not show electrophoresis.

Depending upon the polarity, the non dimensional strength of the electric force ($Ca_Q = \epsilon_e \epsilon_0 \Lambda_0^2 a^3/\gamma$) type (positive and negative) and nondimensional amount of charge (γ/Λ_0) a drop can attain a prolate or an oblate shape. At hight negative value of charge and low Ca_Q, a drop attains an oblate spheroid shape and a prolate shape is observed otherwise. The ultimate stable shape of the drop does not depend upon the viscosity ratio of the external and the internal fluid, whereas the dynamics of deformation and the breakup is strongly dependent on the viscosity ratio.

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Stability of plane Couette flow past a deformable bilayer

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An elastohydrodynamic stability of plane Couette flow past a deformable bilayer in the creeping flow limit is studied. The solid layers of equal thickness and different elastic moduli are placed one on the other, and modelled as Neo-Hookean solids. The stability of fluid flow past bilayer depends on nondimensional parameters Γ_c (critical strain rate), H (solid thickness), η_{r1} (ratio of solid1 to fluid viscosity), η_{r2} (ratio of solid2 to fluid viscosity) and γ (interfacial tension). For a bilayer, two possible cases are considered in this study: (i) $G_r = \frac{G_1}{G_2} < 1$ where G_2 and G_1 are bottom (softer gel) layer and top (Harder gel) layer respectively, and the other case (ii) $G_r = \frac{G_1}{G_2} > 1$ (soft gel on top). A bilayer with $G_r < 1$ (Hard gel on top), the predicted Γ_c is high compared with a single layer ($G_r = 1$) results for all H, because of no effect of short wave instability. If the viscous dissipation of both the layers are considered, the result shows low $_c$ (destabilizes). A bilayer with $G_r > 1$ (soft gel on top), the predicted Γ_c is low compared with a single layer results for $H < 2$, because short waves detabilizes the flow in this limit and when $H > 2$ the Γ_c is same when compared with a single layer. If viscous dissipation of both layers are considered, the results show high Γ_c (stabilizes) for all thickness. Analysis shows that flow past bilayer is advantageous than single layer because we can tune the stability for a given elastic moduli.

References

[1] V. Kumaran, G. H. Fredrickson, and P. Pincus, J. Phys. II 4, 893 (1994).

[2] V. Gkanis and S. Kumar, Phys. Fluids 15, 10 (2003).

[3] V. Gkanis and S. Kumar, Phys. Rev E 73, 026307 (2006).

[4] P. Chokshi and V. Kumaran, Phys. Rev E 77, 056303 (2008).

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Stability of pressure-driven flow through a deformable tube

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An experimental work is carried out to understand the different modes (Viscous, wall and inviscid) of instability for flow through a soft polydimethylsiloxane (PDMS) tube. The experimental system consists of a feed and the disturbance suppression tank connected through a flow sensor. The disturbance suppression tank is connected to a tube made up of two (development and test) sections. Keeping a flow rate is constant, the pressure is measured along a soft tube and the friction factor is calculated from pressure drop between the ends of a test section. The friction factor is plotted as a function of Reynolds number (Re) and a deflection point from 64/Re line is considered as transition Reynolds number for instability. The experiment is bench marked using a tube (1.65 mm diameter) prepared with PDMS material (9.09 % crosslinker) and found that the rigid tube transition Reynolds number is 2000. The tubes are made with development (9.09 % crosslinker) and test section with crosslinker concentrations 3, 2.25, 2.1, 2 and 1.9 %, and the observed transition Reynolds numbers were 2000, 1993, 1441, 1061 and 500 respectively. The transition Reynolds number versus Σ (gel softness parameter) curve is plotted. The experiments are carried out with extreme care using disturbance suppression tank, good resolution microscope and constant temperature fluid, the result shows that the instability is wall mode instability observed by Verma and Kumaran (JFM, 2012). However, no evidence of inviscid instability modes were found in our experiments, the observed transition Reynolds number is very much lesser than the predicted values will open up the question for theoretical understanding of the flow (non parabolic) in a converging tubes.

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Notes

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Images courtesy of Siddharth Krithivasan, JNCASR, India. Image on front page shows vorticity contours in a forward flapping flight at obtained from LBM simulations at Re = 1000. Image on this page is obtained using streak photography (1 sec exposure) after 4 cycles indicating the 2 jet configuration in asymmetric flapping at Re = 2000.