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EUROPEAN MECHANICS SOCIETY

President's Address

In 2008, the Council decided that non-EUROMECH members wishing to attend a colloquium or a conference were expected to become members of the society upon registration. This policy was meant to have a larger section of the research community become involved in EUROMECH activities. As a result of this initiative, the number of members of the Society has grown from 1253 in 2008 to 2223 in 2010. We view this significant increase as an encouragement to continue offering intellectually stimulating events to our members. In this context, I am also pleased to report that 11 colloquia will take place in 2011 on a wide variety of topics ranging from the Biomechanics of human motion to Ecohydraulics and from Cardiovascular fluid mechanics to Energy harvesting. The EUROMECH colloquium format originally proposed by George Batchelor remains very attractive: limited number of participants (40-50) who are all invited by the organizers for their expertise in a well-defined research area, simple meeting and accommodation facilities, plenty of opportunities for informal discussions and no required proceedings.

On the logistic side, the EUROMECH directory has gone electronic: it is now available online to members only. Other online services now include membership renewal and easy retrieval of ID number, as well as the possibility of updating personal data.

Thanks to the support of the European Commission, two meetings have been co-organized with other Aeronautics-related European societies: A EUCASS-EUROMECH Mini-Symposium on Flow control was held within the European Fluid Mechanics Conference last September in Bad Reichenhall; An ECCOMAS-EUROMECH colloquium on the fatigue of metals was sponsored in Palaiseau in July 2010.

Patrick Huerre
President, EUROMECH

Contents

Addresses for EUROMECH Officers

President: Professor Patrick Huerre
Laboratoire d'Hydrodynamique, Ecole Polytechnique
F - 91128 Palaiseau cedex, France
E-mail: huerre@ladhyx.polytechnique.fr
Tel.: +33(0)1 6933 5252
Fax: +33(0)1 6933 3030

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Müller-Breslau Strasse 8
D-10623 Berlin, Germany
E-mail: fernholz@pi.tu-berlin.de
Tel.: +49 30 314 23359
Fax: +49 30 314 21101

Secretary-General: Professor Bernhard Schrefler
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I-35131 Padova, Italy
E-mail: bas@dic.unipd.it
Tel.: +39(0)49 827 5611
Fax: +39(0)49 827 5604

Treasurer: Professor Wolfgang Schröder
Chair of Fluid Mechanics and Institute of Aerodynamics
RWTH Aachen, Wüllnerstr. 5a
D-52062 Aachen, Germany
E-mail: office@aia.rwth-aachen.de
Tel.: +49(0)241 809 5410
Fax: +49(0)241 809 2257

Newsletter editors: Dr Roger Kinns (E-mail: rogerkinns@aol.com)
Professor Bernhard Schrefler (E-mail: bas@dic.unipd.it)

Newsletter Assistant: Dr Sara Guttilla (E-mail: s.guttilla@cism.it)

Web page: http://www.euromech.org

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HANS H. FERNHOLZ, Herman - Föttinger - Institut für Strömungsmechanik, Technische Universität Berlin, Müll er-Breslau Strasse 8, 10623 Berlin, Germany ■ E-mail: fernholz@pi.tu-berlin.de

BERNHARD A. SCHREFLER, Dipartimento di Costruzioni e Trasporti, Università di Padova, Via Marzolo 9, I-35131 Padova, Italy ■ E-mail: bas@dic.unipd.it

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EUROPEAN MECHANICS SOCIETY

EUROMECH Young Scientist Prize Paper

"Development and Implementation of a Generic Methodology for Contact Dynamics of the Human Knee Joint"

Margarida Machado won the EUROMECH Young Scientist Prize, awarded at the 7th EUROMECH Solid Mechanics Conference held in Lisbon, September 2009

M. Machado[1], D. Lopes, J. Ambrósio, P. Flores, J. Pombo, M. Silva

Abstract

It is known that osteoarthritis, ligamentous rupture and meniscal tear are the most common knee diseases. These pathologies can cause anomalous contact loads, asymmetrical gait patterns and local pain, which ultimately can lead to a knee arthroplasty. Since there is no standard non-invasive approach to measure in vivo knee loads, knee contact patterns and pressures have to be predicted by computational methods. An efficient methodology to predict knee contact forces, under the framework of multibody (MBS) dynamics, is proposed here. This methodology covers four main modelling issues: (i) geometrical description of contact surfaces; (ii) contact-impact detection procedure; (iii) constitutive contact force laws; (iv) efficient MBS computational algorithm. The description of the contact bodies' geometry relies on parametric surface representations, which can be used to define simple shapes, as spheres, or freeform surfaces, via NURBS. Contact detection consists of evaluating the geometrical requirements that permit determination of the location of the potential contact points, and a penetration condition, that indicates whether the bodies are in contact or not. Subsequently, the contact forces are computed based on material and kinematic properties of the bodies. For this purpose, different constitutive contact laws are considered, namely the Hertz contact law, the Hunt and Crossley model and the Lankarani and Nikravesh model. The intra-joint contact forces are then added to the equations of motion. Since the description of the contact geometries and the contact-impact detection procedures are time-consuming tasks, some modifications have been implemented to a general MBS algorithm and a pre-processing unit was developed, in order to reduce the CPU times and ensure the computational efficiency. It can be said that the methodology proposed here is general and can be applied to other biomechanical systems that involve contact interactions, as well as the knee joint.

[1] Universidade do Minho, Campus Azurém 4800-058 Guimarães, Portugal.
E-mail: margarida@dem.uminho.pt

1. Introduction

The human knee is one of the most important and complex synovial joints, which allow the largest amplitude of relative motion and are therefore the potentially most painful joints of the human body. The most common knee diseases and injuries are osteoarthritis, ligamentous rupture and meniscal tear. These pathologies usually cause anomalous contact interactions and, consequently, non-physiologic gait patterns and local pain, that could lead to a knee arthroplasty, i.e., a joint replacement [1]. Therefore, contact-impact phenomena are of paramount importance in biomechanics. However, there is no standard non-invasive approach to measure in vivo knee loads, and so knee contact patterns and pressures have to be predicted by computational methods [1].

In Biomechanics, two computational approaches are commonly used to model the human body and its interactions, namely the finite element method (FEM) and the multibody systems formulation (MBS). The FEM method provides the system’s state of stress and deformation at any time, but tends to be very time consuming and requires a high level of information of the system. Thus, based on simplifying premises, several engineers and designers prefer to use simpler and still accurate methods such as those based on the MBS formulations [2].

Contact analysis based on MBS methodologies is not a trivial task. In fact, contact analysis focuses on four modelling issues: (i) geometrically accurate description of contact surfaces; (ii) contact detection approach; (iii) constitutive contact force laws; and (iv) efficient MBS computational algorithms [2-5]. A general methodology to deal with these issues is presented and discussed throughout this work.

2. Geometrical accurate description of contact surfaces

The knee joint presents a complex shape, with different curvatures and conformalities along the three orthogonal axes [1]. This geometrical feature is what makes the knee play its biomechanical roles [1]. In order to achieve a correct prediction of knee contact loads, the geometry of the articular surfaces well defined.

In recent decades, the geometry of knee contact surfaces has been taken into consideration in most knee contact studies and represented using different mathematical approaches. The first models were developed using regular shapes as planes and spheres. Recently, more advanced mathematical functions and fitting methods have been applied, as it is listed in Table 1 [6-11]. Also, advances in geometrical modelling and computer graphics have made it easier to get a geometrically accurate representation of a 3D surface from medical data [12-14].

A challenging task is to select the most suitable mathematical form to model the object, given the application. The most popular techniques used to represent the geometry of 3D

Table 1: Different mathematical approaches used to describe the knee articular geometries.

Authors Geometrical	Representation
Andriacchi et al. (1977)[6]	*Flat surfaces*
Wismans et al. (1980)[7]	*Polynomial surfaces*
Huiskes et al. (1985)[8]	*Coons’ bicubic patches*
Ateshian et al. (1993)[9]	*B-spline surfaces*
Delp and Loan (1995)[10]	*Polygonal Meshes*
Bei and Fregly (2004)[11]	*NURBS Surfaces*

Table 2: Properties of the most popular geometrical representations (adapted from [12]).

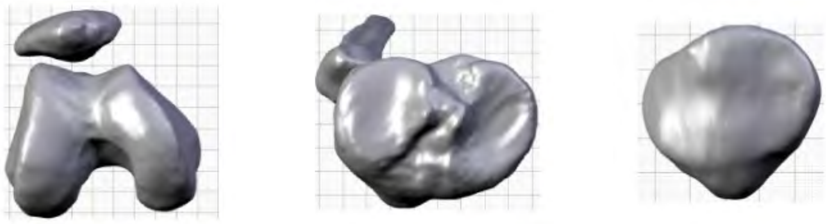
Geometrical Representation	Modelling Properties					
	Global	Compact	Local	Easily Control	Easily fit sampled	Example
Parametric	*Yes*	*Yes*	*Yes*	*Yes*	*No*	*NURBS*
Implicit	*Yes*	*Yes*	*No*	*No*	*Yes*	*RBF*
Superquadric	*Yes*	*Yes*	*No*	*Yes*	*Yes*	*Ellipsoid*
Polygonal Mesh	*No*	*No*	*Yes*	*Yes*	*Yes*	*Marching Cubes*

free-form surfaces are summarized in Table 2 [12]. Based on the modelling properties listed in Table 2 and previous contact studies (Table 1), the parametric representation was chosen to describe the contact surfaces. A standard parametric form for a 3D surface can be expressed by Equation (1), where (u,v) are the parametric spatial variables [12].

$$\mathbf{s}\,(u,v) = \begin{bmatrix} x = f\,(u,v) \\ y = g\,(u,v) \\ z = h\,(u,v) \end{bmatrix} \tag{1}$$

For the particular case of the knee joint, the parametric form selected was the non-uniform rational B-spline (NURBS) surfaces. This choice was made based on the attractive geometrical properties (local support, flexibility, differentiability, local approximation, partition of unity, among others) of NURBS [12-14] and also the availability of reverse engineering algorithms in some commercial modelling software, which fit a point-cloud sample data,

extracted from medical images, to a NURBS surface [13-14].
Thus, a 3D reconstruction procedure was used to generate the knee articular NURBS surface [13-14]. The first step was the acquisition of medical images that contain the relevant geometrical data. The geometric modelling was initiated with the identification of the tissues and their boundaries using a 3-D image dataset segmentation. To convert the segmented data into a surface, a mesh-based technique was used to extract a polygonal isosurface from the voxelized image dataset. Afterwards, the isosurface had to be smoothed and decimated in order to attenuate or eliminate the unwanted geometric features. Finally, the filtered isosurfaces were interpolated with freeform surface patches, i.e., NURBS Surfaces [13-14].
The generated NURBS surfaces for the knee are shown in Figure 1.



(a) (b) (c)

Fig.1: Generated NURBS surfaces for knee: (a) femoral condyles, (b) tibial plateaus and (c) patella.

3.Contact-Impact Detection Method

The second issue in a contact problem is to deal with the evaluation of the exact location of the contact points between two contacting bodies. Here, a contact detection methodology based on two steps is proposed. The first task consists of computing the accurate location of the potential contact points. Then, a penetration condition has to be evaluated in order to check whether the bodies are in contact or not [3-5].
Figure 2 shows a schematic representation of two bodies in contact, the femur *(i)* and the tibia *(j)*. The parametric surfaces S_i and S_j represent the contact geometries, being points P_i and P_j on surfaces S_i and S_j, which are potential contact points. To check whether a pair of points is a potential contact pair, firstly the global positions of both points have to be computed ($\mathbf{r}_i^{P_i}$ and $\mathbf{r}_j^{P_j}$), in order to be able to calculate the distance vector **d** given by

$$\mathbf{d} = \mathbf{r}_i^{P_i} - \mathbf{r}_j^{P_j} \qquad (2)$$

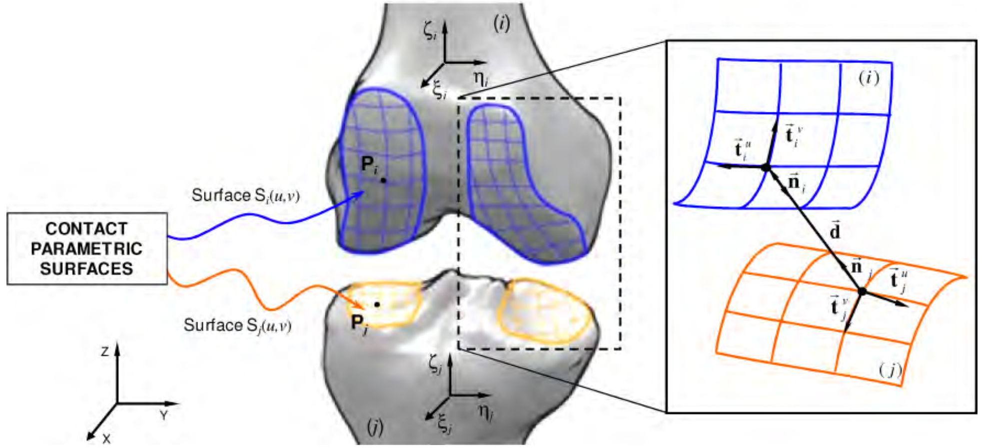
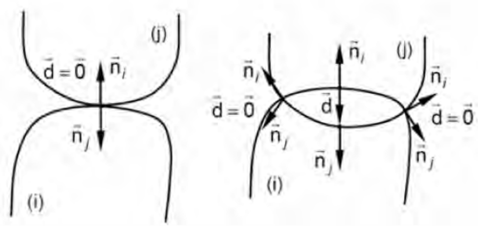


Fig.2: Schematic representation of two contacting bodies, *i* and *j*, its contact parametric surfaces S_i and S_j, a potential contact pair P_i and P_j, the distance vector **d** between these two points, and the normal $\mathbf{n}_{i,j}$ and tangential $\mathbf{t}_{i,j}^{u}$ and $\mathbf{t}_{i,j}^{v}$, vectors of each contact surface (adapted from [4]).

However, the minimum distance condition is not enough to ensure that the points are in contact, since there are still two possible contact scenarios: contact at a single point without penetration and contact at a multiple points with penetration, as illustrated in Figure 3 [3-5].



(a) (b)

Fig.3: Schematic representation of the two possible contact scenarios: (a) contact at single point without penetration and (b) contact at multiple points with penetration (adapted from [4]).

Thus, in order to ensure that a pair of points is a potential contact pair, the surface normal vectors $\mathbf{n}_i$ and $\mathbf{n}_j$ have to be collinear with each other and with the distance vector $\mathbf{d}$.
The collinearity condition between these vectors can be written as two cross product equations relating vectors $\mathbf{d}$ and $\mathbf{n}_i$, and vectors $\mathbf{n}_i$ and $\mathbf{n}_j$ [3-5], as expressed by the system of nonlinear equations presented in Equation (3).

$$\begin{cases} \mathbf{d} \times \mathbf{n}_i = 0 \\ \mathbf{n}_j \times \mathbf{n}_i = 0 \end{cases} \qquad (3)$$

Finally, the potential contact pair is in fact a contact pair if the penetration condition given by Equation (4) is also verified.

$$\mathbf{d}^T \mathbf{n}_j \leq 0 \qquad (4)$$

4. Constitutive Contact Laws

The elastic force developed in the contact between knee articular surfaces can be modeled by applying a Hertzian-type contact law (HM) [3,15], which can be expressed as,

$$\boldsymbol{F}_N = \boldsymbol{K}\delta^n \qquad (5)$$

where $\boldsymbol{F}_N$ is the normal contact force, $\boldsymbol{K}$ is a generalized stiffness parameter, and δ is the relative penetration depth, given by the magnitude of the distance vector $\mathbf{d}$, previously determined by Equation (2).
The HM is a purely elastic model and it does not include any energy dissipation [2-3].
Therefore, two other constitutive contact laws were considered here, namely the Hunt and Crossley model (HCM) [16] and the Lankarani and Nikravesh model (LNM) [17].
These authors extended the HM to include energy loss due to internal damping by

$$\boldsymbol{F}_N = \boldsymbol{K}\delta^n + \boldsymbol{D}\dot{\delta} \qquad (6)$$

where the first term corresponds to as the elastic force and the second term accounts for the energy dissipated during the impact [3]. In Equation (6), the quantity $\boldsymbol{D}$ is the hysteresis coefficient and $\dot{\delta}$ is the relative normal contact velocity. The hysteresis coefficient is written as a function of penetration by

$$\boldsymbol{D} = \chi\delta^n \qquad (7)$$

In turn, the hysteresis factor χ has different expressions for HCM and LNM, which can be written, respectively, as follows

$$\chi = \frac{3K\,(1 - c_r)}{2\dot{\delta}^{0}} \qquad (8)$$

$$\chi = \frac{3K\,(1 - c_r^2)}{2\dot{\delta}^{0}} \qquad (9)$$

c_r represents the classical restitution coefficient and $\dot{\delta}^{0}$ is the initial relative normal contact-impact velocity, with the remaining parameters having the same meaning as presented above. It is important to mention that these constitutive contact force models have been applied to the knee joint in previous studies [3, 18], as well as to other biomechanisms that involve contact interactions [19].

5. Efficient Multibody Computational Algorithm

The final step is to add the intra-joint contact forces to the equations of motion, which means that all the contact procedures described above have to be implemented in a MBS computational algorithm [3]. Although, some of these procedures, such as the contact geometry definition (Section 2) and the contactimpact detection approach (Section 3), require time-consuming tasks such as "load contact surface geometry" and "compute surface' tangent and normal vectors", respectively. In order to overcome this problem and achieve small CPU times, a computational pre-processing unit was developed. This pre-processing unit consists of a five-step procedure:

- *(i)* *Regular surface sampling* - a regular and representative set of points is selected from the parametric contact surface, as illustrated in Figure 4;
- *(ii)* *Tangent and normal vectors calculation* - the tangent vectors $\mathbf{t}^u_{P_k}$ and $\mathbf{t}^v_{P_k}$ the normal vector $\mathbf{n}_{P_k}$ of each point P_k of the regular sample of the surface S_k are calculated using Equations (9), (10) and (11), respectively [4].

$$\mathbf{t}^u_{P_k} \equiv \mathbf{t}^u_{P_k}(u,v) = \frac{\partial S_k(u,v)}{\partial u} \qquad (9)$$

$$\mathbf{t}^v_{P_k} \equiv \mathbf{t}^v_{P_k}(u,v) = \frac{S_k(u,v)}{u} \qquad (10)$$

$$\mathbf{n}_{P_k} \equiv \mathbf{n}_{P_k}(u,v) = \frac{\tilde{\mathbf{t}}^u_{P_k}\,\mathbf{t}^v_{P_k}}{\left\| \tilde{\mathbf{t}}^u_{P_k}\,\mathbf{t}^v_{P_k} \right\|} \qquad (11)$$

(iii) *Lookup table construction* - all the relevant geometric information of the regular surface sample, namely the parametric point coordinates (u , v), the Cartesian point coordinates (x , y , z), the Cartesian components of the tangent vectors ($\mathbf{t}^u_x$, $\mathbf{t}^u_y$, $\mathbf{t}^u_z$, $\mathbf{t}^v_x$, $\mathbf{t}^v_y$, $\mathbf{t}^v_z$) and the Cartesian components of the normal vector ($\mathbf{n}_x$, $\mathbf{n}_y$, $\mathbf{n}_z$), are organized in a lookup table with 14 columns and as many rows as the number of points at the surface sample;

(iv) *Lookup table reshuffle* - the lookup table is restructured in a matrix form, as illustrated in Figure 5;

(v) *Lookup table rewrite* - the lookup table file is divided into equal-sized record elements and saved as a direct access file.

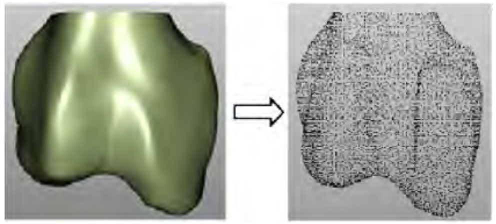


Fig.4: Illustration of first pre-processing step, i.e., regular surface sampling (adapted from [14]).

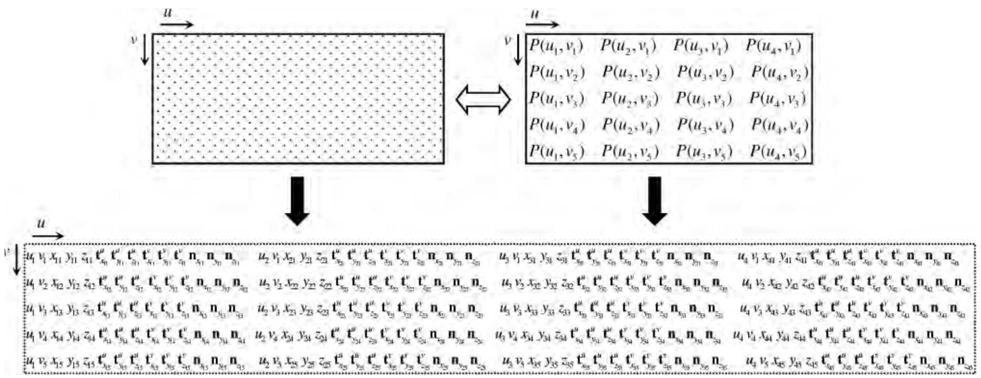


Fig.5: Schematic diagram that illustrates how the surface data is organized in the lookup table reshuffle pre-processing phase.

With this approach it is not mandatory to compute the tangent and normal vectors at each instant of simulation. Moreover, the way the surface data is organized during the pre-processing (matrix form and direct access file) requires only a portion of the surface data to be stored in memory, including the contact record where the potential contact point is located and a few neighbouring records. The portion of the surface data stored in memory is called "surface window", which has to be updated whenever the potential contact point turn out to be located at a border record. This storage practice decreases the memory consumption and consequently promotes computational efficiency. Actually, at the knee joint the contact point moves slightly and smoothly and, therefore, it still remains in the vicinity of previous contact points for a while. This means that the surface window does not need to be updated during some time steps. In cases where the contact point is not in the lookup table, i.e., the exact location of the contact point does not belong to the set of points selected during the regular surface sampling pre-processing phase, a bilinear interpolation between these points is performed in order to determine the relevant geometrical information of the contact point. Cartesian coordinates, surface tangent and normal vectors may be used. Since the bilinear interpolation is an extension of linear interpolation for interpolating functions of two variables on a regular grid and, due to the fact that linear interpolation is a very simple and basic mathematical method of curve fitting using linear polynomials [20], the eventual need to perform a bilinear interpolation in each instant of simulation does not compromise the efficiency of the computational algorithm. Figure 6 shows the flowchart for the computational algorithm proposed here, which has been developed using the MBS formulation framework.

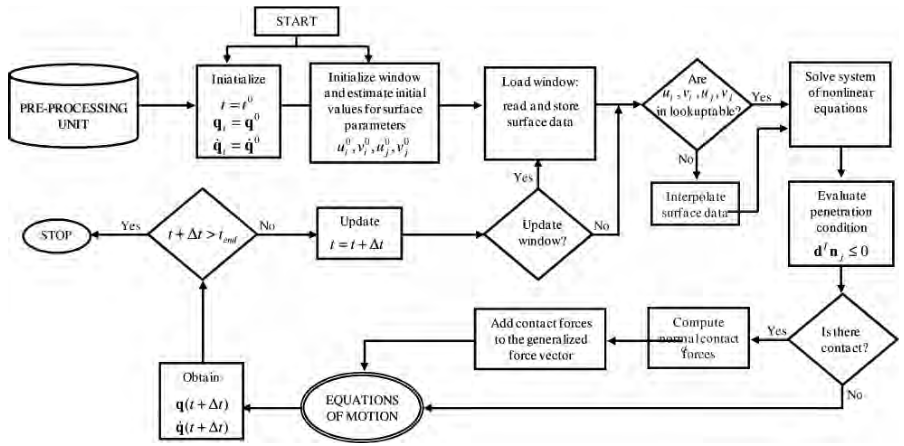


Fig.6: Flowchart of the proposed computational algorithm.

The computational algorithm (Figure 6) can be synthesized using the following steps:

(i) Run the pre-processing unit;

(ii) Set the system's initial conditions: initial time t_0 , initial positions $\mathbf{q}_0$, initial velocities $\dot{\mathbf{q}}_0$, surface window dimensions and initial guesses for surface contact point $\mathbf{u}_i^0$, $\mathbf{v}_i^0$, $\mathbf{u}_j^0$, $\mathbf{u}_j^0$;

(iii) Load window, read and store surface data;

(iv) Check if the surface point $\mathbf{u}_i^0$, $\mathbf{v}_i^0$, $\mathbf{u}_j^0$, $\mathbf{u}_j^0$ is reported at the lookup table; if it is not, perform a bilinear interpolation to determine its geometrical properties.

(v) Solve the system of nonlinear equations, which expresses the geometrical conditions that a point has to comply with to be considered a potential contact point;

(vi) Evaluate penetration condition and check for contact;

(vii) If there is contact, evaluate the contact forces with the contact model previously chosen;

(viii) Add the contact forces to the generalized force vector of the equations of motion;

(ix) Apply a multibody formulation in order to obtain the new generalized positions and velocities of the system for time step $t + \Delta t$;

(x) Update the system time variable;

(xi) Check if the surface window needs to be updated. If so, go to step *(iii)*;

(xii) Go to step *(iv)* and proceed with the whole process for the new time step, until the final time for the analysis is reached.

6. Concluding Remarks

A general methodology to perform contact dynamic analysis at the human knee joint was proposed in this work. To develop the presented methodology, four modelling features were taken into account, namely the geometrical description of contact surfaces, the contact-impact detection approach, the constitutive contact force laws and the efficiency of the MBS computational algorithm. The description of the contact surfaces is made using a parametric representation. The contactimpact detection approach adopted is a two-step procedure. The first one consists of verifying if the point is a potential contact point by checking two geometrical conditions. The second step involves the evaluation of a penetration condition that determines whether there is contact or not. Different constitutive contact laws were considered, for to the contact forces, on a purely elastic model (HM) and two with damping (HCM and LNM). Finally, a MBS computational algorithm that includes a pre-processing unit, which carries out all the geometrical manipulation and storage information, was proposed. The pre-processor avoids running some time-consuming tasks in each simulation cycle, which reduces CPU times during simulations of a real life activity such as walking.

7. Acknowledgments

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EUROMECH Fluid Mechanics Fellow 2008

"Input-Output analysis and control design of spatially developing shear flows"

D.S. Henningson*

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Abstract

A framework for the input-output analysis, model reduction and control design of spatially developing shear flows is presented using the Blasius boundary-layer flow as an example. An input-output formulation of the governing equations yields a flexible formulation for treating stability problems and for developing control strategies that optimize given objectives. Model reduction plays an important role in this process since the dynamical systems that describe most flows are discretized partial differential equations with a very large number of degrees of freedom.

1 Introduction

In this paper we present a framework for the input-output analysis, model reduction and control design for complex flows. As a prototype of spatially developing shear flows the Blasius boundary-layer flow is considered. The work is motivated by the need to provide efficient numerical tools to analyze complex flows and design efficient control strategies. Powerful tools from linear systems and control theory could not be used for fluid flows due to the complexity of the Navier-Stokes equations. However, the availability of increasingly powerful computer resources and recent advances of matrix-free methods now enables the application of analytical techniques that do not rely on physical insight into the specific flow configuration and can in principle be applied to any geometry. The methods presented here all rely on the availability of a numerical code for the solution of the Navier-Stokes equations and of the corresponding adjoint problem.

In the context of hydrodynamic stability, the input/output approach usually considers the flow subject to initial condition or forcing. The aim is to build a model of low dimension that captures the input-output behavior of the system and use this model for optimal feedback

*Linné Flow Centre, KTH Mechanics, SE-100 44, Stockholm, Sweden. E-mail: henning@mech.kth.se

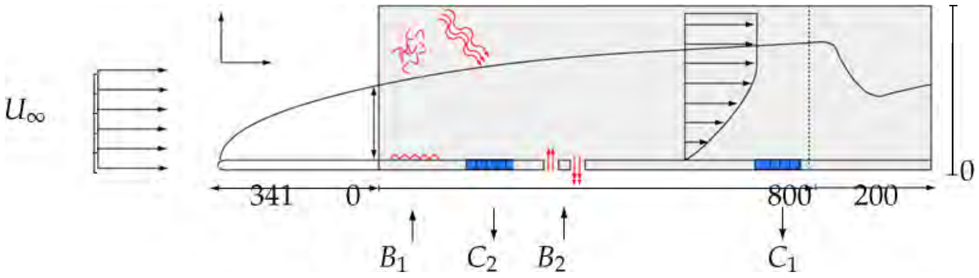

Fig.1: The input/output configuration used for the control of perturbations in a two-dimensional flat-plate geometry. The computational domain $\Omega = (0, L_x)\times(0, L_y)$, shown by the gray region, extends from $x = 0$ to $x = 1000$ with the fringe region starting at $x = 800$. The first input B_1, located at $(x_w, y_w) = (35, 1)$, models the initial receptivity phase, where disturbances are induced by free-stream turbulence, acoustic waves or wall roughness. The actuator, B_2, provides a mechanism to manipulate the flow, in this case by a localized volume forcing, and is centered at $(x_u, y_u) = (400, 1)$. Two sensors, C_1 and C_2, are located at $(x_v, y_v) = (300, 1)$ and $(x_z, y_z) = (750, 1)$ respectively. The upstream measurements are used to estimate the incoming perturbations, while the downstream sensor quantifies the effect of the control.

control design. With the help of the adjoint Navier-Stokes equations two fundamental dynamical structures can be identified; the flow structures most easily influenced by the actuators considered and the flow structures to which the outputs are most sensitive. These so-called controllable and observable structures determine the input-output behavior completely for linear systems. It is well-known that these two set of modes can be balanced [1], and represented by one set of nonorthogonal modes, called the balanced modes. These are used as a projection basis for model reduction. The approximated method employed to compute the balanced modes is the snapshot-based balanced truncation [2, 3]. This method has been recently applied to the channel flow [4] and the flow around a pitching airfoil [5].

Two aspects of the control problem have been identified as crucial in order to apply feedback control in more complex flows moving towards a possible implementation in wind-tunnel tests. They are i) model reduction to significantly decrease the cost of both constructing the controller and running it online, thus allowing fast computation of the control signal directly from the sensor output; ii) the need to naturally consider localized sensors and actuators. These are addressed in this work by using global modes, balanced modes in particular, to build an efficient low-order model to be used to compute the control signal.

2 Input-Output Formulation

We consider the two-dimensional incompressible flow over a flat plate with constant free-stream velocity U_∞ as shown in Figure 1. Starting from the leading edge a viscous boundary layer evolves downstream. The evolution of the streamwise velocity u, the wall-normal velocity v and the pressure p in time and space is governed by the incompressible non-linear Navier-Stokes equation [6]. Our analysis deals with the evolution of linear perturbations on the laminar boundary layer solution. The inflow boundary is set to the downstream position corresponding to a Reynolds number $Re_{\delta^*_0} = U_\infty \delta^*_0/\nu = 1000$, where δ^*_0 is the local displacement thickness of the boundary layer and ν is the kinematic viscosity. Throughout the paper all variables are nondimensionalized by U_∞ and δ^*_0. The length and height of the domain are $L_x = 1000$ and $L_y = 30$ in the streamwise direction x and wall-normal direction y, respectively. The equations are solved by a pseudo-spectral Direct Numerical Simulation (DNS) code described in Ref.7, where the spatial operators are approximated by Fourier expansion in the streamwise direction with $N_x = 768$ equally distributed points and Chebyshev expansion in the wall-normal direction on $N_y = 101$ collocation points. A fringe region enforces periodicity in the streamwise direction [7]. By marching the DNS in time we obtain a steady state, about which a linearization is performed. The linearized Navier-Stokes equations will in this paper be subjected to input-output analysis, model reduction by approximate balanced truncation and control in the H_2 framework. To this end we introduce the inputs $B = [B_1, B_2]$ and the ouputs $C = [C_1, C_2]$ as seen schematically in Figure 1. The first input B_1 models typical upstreamdisturbances entering the boundary layer through some receptivity mechanism such as freestream turbulence or acoustic waves interacting with roughness. The actuator B_2 provides a mechanism to manipulate the flow, in this case by a localized volume forcing. The upstream measurement C_1 is used to estimate the incoming perturbations, while the downstream sensor C_2 quantifies the effect of the control. Note that in this work all the inputs and outputs are Gaussian functions on both velocity components.

Once discretized and projected onto a divergence free subspace the linearized Navier-Stokes equations for the disturbances $q = [u, v]^T$ of dimension $n \times 1$, with $n = 2N_xN_y$, can be written as

$$\frac{dq}{dt} = Aq + Bf, \qquad (1)$$
$$y = Cq, \qquad (2)$$
$$q(0) = q_0. \qquad (3)$$

Here we have introduced the input operator B of dimension $n \times 2$ and the output operator C

of dimension $2\times n$. The formal solution to this system of equations is

$$y(t) = Ce^{At}q_0 + \int_0^t Ce^{A(t-\tau)}Bf(\tau)\, d\tau \;. \tag{4}$$

The first part of the above relation describes the output generated by the evolution of the initial condition q_0 while the second term describes the response to the forcing B with time dependent signals f. The evaluation of the matrix exponential $\mathcal{T}(t) = e^{At}$ in (4) is the key to both stability analysis, input-output analysis and control design. However, this operator also poses the greatest computational challenge due its dimension. The dimension, n, of the linearized operator depends on the number of non-homogeneous spatial directions of the base flow. Except for one-dimensional base flows the exponential matrix must be approximated. However, the action of $\mathcal{T}(t)$ on any flow field simply represents integrating the Navier-Stokes equations in time and therefore the exponential matrix can be approximated by numerical simulation of the governing equations, also referred to as a time-stepper. In what follows the reader should equate $\mathcal{T}(t+T)q(t)$ with a DNS simulation starting with an initial condition $q(t)$ and providing $q(t+T)$ at a later time. In this so called "timestepper approach", system matrices are never stored and storage demands in memory are of the same order as a small number of flow fields.

3 Input-Output Analysis

To apply modern control theory to design efficient flow manipulation it is important to construct a reduced order model of the system. The main feature of the flow behaviour which is relevant to maintain in the reduced order model is the input-output behaviour of the system, i.e. the relation between actuation and sensor output, since the disturbances are represented by an input and the objective consists of minimizing an output signal.

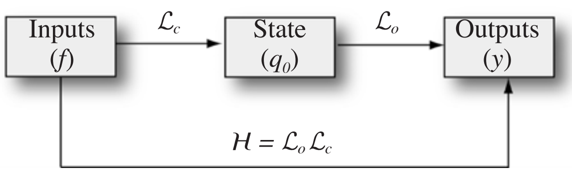

Fig.2: The operators used to examine the system input-output behavior. The controllability operator $\mathcal{L}_c$ relates past inputs to the present state, while the observabilitymapping $\mathcal{L}_0$ relates the present state to the future outputs. Their combined action is expressed by the Hankel operator $\mathcal{H}$.

As a consequence, we turn our attention to the particular solution with $q_0 = 0$ in the input-output (I/O) relation (4). Rather than investigating flow fields at different times, the I/O behavior considers the time signals $f(t)$ and $y(t)$. Fortunately, the I/O behavior has significantly simpler dynamics compared to stability analysis where the entire flow dynamics are under investigation.

The model reduction problem for the preservation of input-output dynamics can thus be posed as: Find the state-space system

$$\frac{d\kappa}{dt} = \hat{A}\kappa + \hat{B}f\,, \tag{5}$$

$$\hat{y} = \hat{C}\kappa. \tag{6}$$

so that for any input f, $\| y - \hat{y} \| \leq \epsilon$ where $\epsilon \ll 1$ and $\hat{y}$ the output of the model.
The reduced-order system (6) can be obtained by a Galerkin projection onto a small number of modes, typically less than $m < 100$.

3.1 Balanced modes

One way to compute the reduced-order model (6) with a nearly minimal model reduction error is called balanced truncation [1]. We outline the method by defining the mapping from past inputs to future outputs via the Hankel operator [8],

$$y(t) = \mathcal{H}f(t) = C\int_{-\infty}^{0} e^{A(t-\tau)}Bf(\tau)\, d\tau \;. \tag{7}$$

The difference of the above expression and the formal solution (4) is that the Hankel operator (7) characterizes the I/O behavior via a reference state q_0. As shown schematically in Figure 2, the Hankel operator can be decomposed into

$$\mathcal{H} = \mathcal{L}_o\mathcal{L}_c \tag{8}$$

where the controllability operator $\mathcal{L}_c$ is defined as

$$q_0 = \mathcal{L}_c f(t) = C\int_{-\infty}^{0} e^{-A\tau}Bf(\tau)\, d\tau, \tag{9}$$

and the observability operator $\mathcal{L}_o$ is defined as

$$y(t) = \mathcal{L}_o(t)q_0 = Ce^{A\tau}q_0. \tag{10}$$

The operator $\mathcal{L}_c$ describes the mapping of any input $f(t)$ with $t \in (-\infty, 0]$ onto the state vector

q_0 at the reference time $t = 0$. The action of $\mathcal{L}_c$ can be numerically computed by a time-stepper.

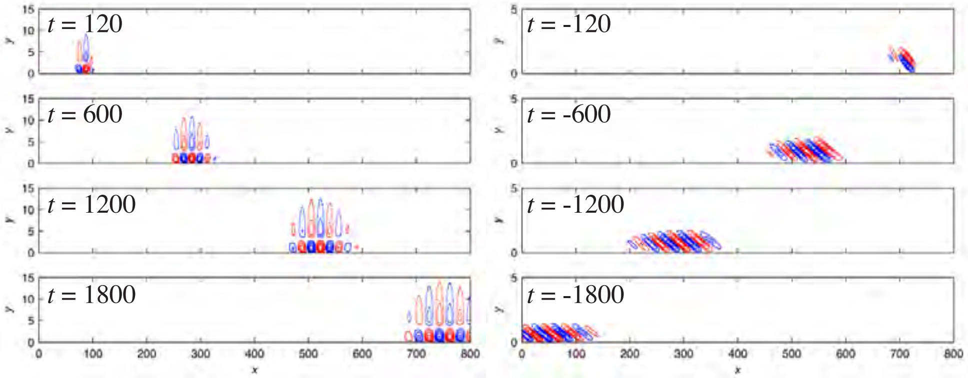

Fig.3: Instantaneous snapshots of the streamwise disturbance component of the forward (a) and adjoint (b) simulations.

It amounts to solving the linearized Navier-Stokes equations for the velocity field q with forcing term $f(t)$ and zero initial conditions. The operator $\mathcal{L}_o$ describes the mapping of any initial velocity field q_0 to the output signal $y(t)$. The action of $\mathcal{L}_o(t)$ can also be numerically computed and it amounts to extracting the output signal while solving the linearized Navier-Stokes equations with the initial condition q_0 at the reference time $t = 0$ and zero forcing.

The I/O analysis can be reduced to an eigenvalue problem. The amplification of the output signal at time t is given by

$$\|y(t)\| = (H(t)f, H(t)f) = (f, H^*(t)H(t)f). \tag{11}$$

Thus, the eigenmodes f_j of H^*H result in the largest output response, i.e.

$$H^*Hf_j = \sigma_j^2 f_j \tag{12}$$

where σ_j are called the Hankel singular values and inputs f_j have unit norm.

Using the mapping $\mathcal{L}_c$ we can now obtain a set of function $\{\phi j\}_{j=1}^{m}$ by mapping the eigenvectors of H^*H onto state-space, i.e.

$$\phi_j = \mathcal{L}_c f_j. \tag{13}$$

The balanced modes are non-orthogonal, and the set of modes that are bi-orthogonal to ϕ_i $((\phi_i, \psi_j) = \delta_{i,j})$ can be found from

$$\psi_j = \mathcal{L}_o^* g_j, \tag{14}$$

where g_j are the eigenvectors of HH^* and $\mathcal{L}_o^* = \int_0^\infty e^{A^H t} C^H \, dt$ the adjoint of $\mathcal{L}_o$.

Traditionally, the balanced modes are defined as the eigenvectors of the product of the controllability and observability Gramian. This formulation is easily obtained by noting that

$$\mathcal{L}_c H^* H f_j = \underbrace{\mathcal{L}_c\mathcal{L}_c^*}_{P}\,\underbrace{\mathcal{L}_o\mathcal{L}_o^*}_{Q}\,\underbrace{\mathcal{L}_c f_j}_{\phi_j} = = \sigma^2 \underbrace{\mathcal{L}_c f_i}_{\phi_j} \tag{15}$$

with the controllability Gramian

$$P = \mathcal{L}_c\mathcal{L}_c^* = \int_0^\infty e^{At} B B^H e^{A^H t} \mathrm{d}t, \tag{16}$$

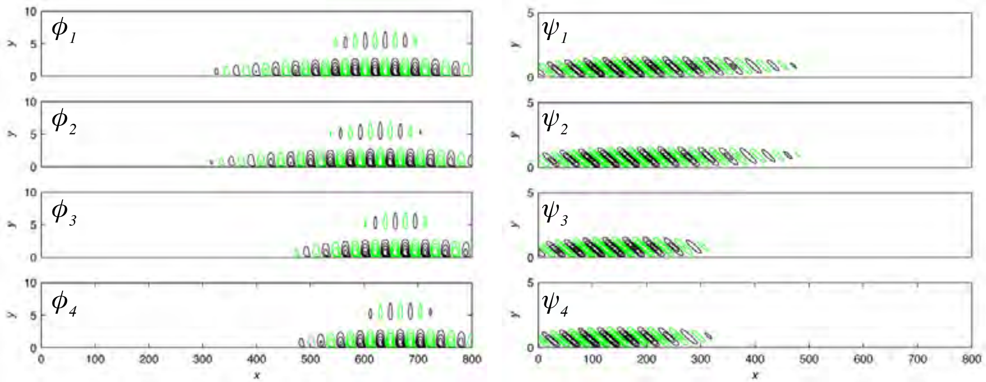

Fig.4: The streamwise velocity component of four first balanced modes ϕ_i (a) and adjoint modes ψ_i (b).

and observability Gramian

$$Q = \mathcal{L}_c^*\mathcal{L}_c = \int_0^\infty e^{A^H t} C^H C e^{At} \mathrm{d}t. \tag{17}$$

By recognizing that (16) and (17) are the state correlation matrices of the forward and adjoint state forced by impulses at the input and output respectively, the snapshot technique [9] can be employed to compute the balanced modes.

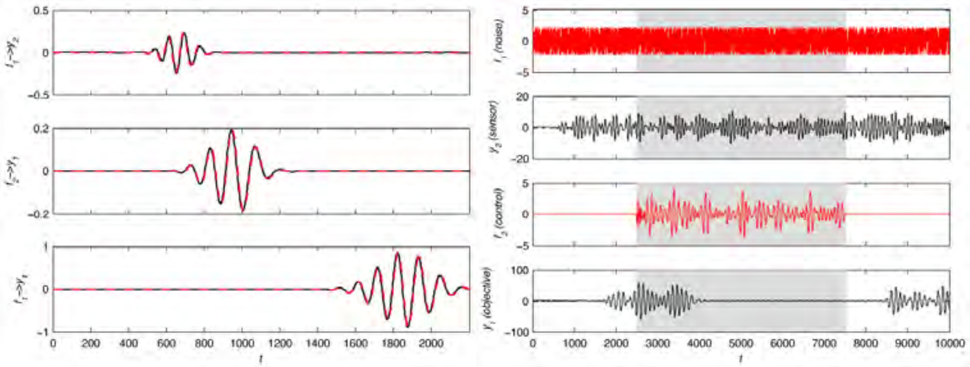

Fig.5: Left column: The impulse response from $B_1 \longrightarrow C_2$ (top), $B_2 \longrightarrow C_1$ (center) and $B_1 \longrightarrow C_1$ (bottom). The black solid line represents direct numerical simulations with 105 degrees of freedom and the red dashed line the balanced reduced-model with 50 degrees of freedom. Right column: Input and output signals of the closed-loop system. The random forcing f_1 (top), measurements signal y_2 (second from top), control signal f_2 (second from bottom) and the objective function y_1 (bottom) is shown. The cheap controller is active between $t \in [2500, 7500]$ marked with the gray area.

The method is described in detail in [2]: it amounts to collecting a set of snapshots from a forward simulation using the input B as initial condition

$$X = [u(t_1), \ldots, u(t_m)]\Delta, \tag{18}$$

and a set of snapshots from an adjoint simulation using the output C as initial condition,

$$Y = [p(t_1), \ldots, p(t_m)]\Delta. \tag{19}$$

In the above, Δ contains the square root of the quadrature weights of the time-integrals given in (16) and (17). Snapshots of the forward and adjoint simulation are displayed in Figure 3. The eigenvalue problem (15) can then be approximated as

$$PQ\phi_j \approx \underbrace{XX^H YY^H}_{n\times n} \phi_j = \sigma^2 \phi_j. \tag{20}$$

This eigenvalue problemis of size $n \times n$ and prohibitively expensive to solve for Navier-Stokes system. In the method of snapshots the balanced modes are expanded in snapshots, $u = Xa$, in order to obtain an eigenvalue problem of size $m \times m$,

$$X\,(\underbrace{XYY^H X}_{m\times m}\, a - \sigma^2 a) = 0. \tag{21}$$

The balanced modes and their associated adjoint modes computed in this manner are shown in to Figure 4.

3.2 Model Reduction

To obtain the balanced reduced-order model (6) we can project Navier-Stokes equations including inputs and outputs on the balanced modes

$$A_{i,j} = (\phi_i, A\phi_j) \tag{22}$$
$$B_{1'j} = (\phi_j, B_1) \tag{23}$$
$$C_{1'j} = C_1\phi_j \tag{24}$$

and similarly for B_2 and C_2.
The impulse response from all inputs to all outputs in the reduced-order model (6) and in the full Navier–Stokes system (1) is also compared. In figure (5) (left column) three signals $B_1 \longrightarrow C_1$, $B_1 \longrightarrow C_2$ and $B_2 \longrightarrow C_1$ are shown with black lines. The response of C_2 to forcing in B_2 is zero, since disturbances travelling upstream are quickly damped. These impulse responseswere obtained by using the time-stepperwith $\longrightarrow 10^5$ degrees of freedom.

The impulse responses of the reduced-order model (6) with $r = 50$ given by $y(t) = Ce^{At}B$ are shown with red dashed lines. We observe that the reduced-model registers the same signal as the full model from all inputs to all outputs. The wavepacket triggered by the impulse of B_1 reaches the first sensor C_2 after 600 time units and the second sensor C_1 after 1500 time units. The wavepacket triggered from the actuator B_2 reaches the second sensor after 600 time units.

4 Control Design

The final step after the analysis of the response of a linear system to initial conditions and external excitations is to manipulate the inherent dynamics of a system or to control it. To this end, a reduced-order feedback controller, which will have the same dimension as the reduced-order model of the previous section, is developed.

The reducer-order plant with three inputs $f = [f_1, g, f_2]^T$ and two outputs $y = [y_1, y_2]^T$ obtained from the model reduction procedure described in the previous section can be written,

$$\frac{d\hat{\kappa}}{dt} = Ak + B_1 f_1 + B_2 f_2 \tag{25}$$

$$y_1 = C_1 k + l f_2, \tag{26}$$

$$y_2 = C_2 k + \alpha g. \tag{27}$$

Note again that the above state-system is the reduced-order model, the hats on A, B and C being dropped for convenience. The input f_1 represents disturbances whereas f_2 is the control signal (see Figure 1). Note that additional forcing terms appear also in the definition of the output signal. The first output y_1 can be regarded as the objective function,

$$\|y_1\|^2 = \|C_1\kappa\|^2 + l^2\| f^2\|^2 = \int_{0\,-}^{T} (\kappa^H C_1^H C_1\kappa + l f_2^H f_2)\, dt, \tag{28}$$

where it is assumed that the cross weighting between the state and control signal is zero [10]. For large values of the scalar l the control effort is considered to be expensive, whereas small values indicate cheap control. The second output y_2 is forced with noise g to model the uncertainty that may exists in the measurements under realistic conditions. Large values of the scalar α indicate high level of noise corruption in the output signal, whereas for low values of α the measurement y_2 reflects information about the flow field with high fidelity.

For our purposes the so called H_2 control problem can be formulated as follows:
Find an optimal control signal $f_2(t)$ based on the measurements $y_2(t)$ such that the in the presence of external disturbances $f_1(t)$ and measurement noise $g(t)$ the output $y_1(t)$ is minimized.
The solution to this control problem is obtained by solving two quadratic matrix equations called Riccati equations[10]. These equations can be solved since the dimension of (25) is less than 100. The solution to the H_2 control problem in a stochastic framework is also known as Linear Quadratic Gaussian, where stochastic processes are introduced to describe the sensor noise $g(t)$ and the external disturbances $f_1(t)$.
We refer to [11-12-13] for further details on the H_2 control algorithm.

The closed-loop controller is obtained as

$$\frac{d\hat{\kappa}}{dt} = (A + B_2 K + LC_2)\,\hat{\kappa} - Ly_2, \tag{29}$$

$$f_2 = K\hat{\kappa}. \tag{30}$$

Given the measurements signal y_2 from the physical flow, the reduced-order controller provides an optimal control signal f_2 proportional to the estimated flow $\hat{\kappa}$.

We will now investigate the performance of the closed-loop system (30). In particular, the output y_1 of the closed-loop - with optimal control signal f_2 - and of the linearized Navier-Stokes equations without control are considered in the case of stochastic excitation from f_1.

The controller investigated is a cheap control/low noise contamination with $l = 0.1$ and $\alpha = 0.1$.

The performance of the control is examined in Figure 5 (right column), where the input and output signals are shown. The grey region indicates the time when the control is active. As disturbance signal $f_1(t)$ we choose white noise; the corresponding response of the sensor $y_2(t)$ in Figure 5 (second from top) confirms the amplification and filtering of the signal as it traverses the unstable domain. The disturbances reach the second sensor (Figure 5 (bottom plot)) after about 1500 time units where they have been amplified by one order of magnitude. The control is activated at time t = 2500, the actuator immediately begins to force the system with a control signal (Figure 5 (third from top)) based on the output y_1, and after a delay of another 1500 time units, the stabilizing effect of the control signal on the output f_1 is clear. When the control is deactivated (at t = 7500) the disturbances start to grow again.

5 Conclusion

A unified framework for the stability and input-output analysis, model reduction and control design of complex flows is presented. The two-dimensional Blasius boundary-layer flow is used here as example of a spatially inhomogeneous flow characterized by strong non-normality of the operator describing the linear evolution of velocity perturbations[14]. The approach followed here requires only the numerical solution of the Navier-Stokes equations and of the associated dual problem, the so-called timestepper approach[15]. It avoids therefore the manipulation of large matrices and can be extended to fully three-dimensional flows, complex geometries and physics.

To apply tools from modern control theory to fluid flow systems with many degrees of freedom model reduction becomes unavoidable. To build a low-order model of the problem the main features of the flow behaviour are investigated in an input-output framework. The quantity one wishes to optimize for is now defined by a sensor output, in our case the level of perturbations further downstream, while information to the controller is provided by a sensor located upstream. Perturbations are introduced by the inputs considered in the model: the input furthest upstream models incoming disturbances while a second actuator is used to manipulate the flow.

Model reduction is achieved by projecting the governing equations on the leading balanced modes of the system. We show that the input-output behavior of the flat-plate boundary layer can be captured accurately with a reduced-order model based on fifty balanced modes. These modes are shown to provide a good description of the flow [4, 13]. The spatial structure of these modes reflects the location of sensors/actuators and the dynamics of linear perturbation evolving in a boundary layer. The balanced modes are mainly located downstream, where the response to the forcing is largest. The adjoint balanced modes are instead located upstream, where the sensitivity to initial conditions is the largest.

Finally, the low-ordermodel is used to obtain the feedback gain relating directly the measurements from one upstream sensor to the actuator signal using the H_2 formulation. The control is then applied in the numerical simulation of the full system where we show that the perturbation growth could be reduced efficiently. The present formulation accounts naturally for localized sensors and actuators and therefore can be directly applied to different flow configurations. Further, the control law derived from the low-order system can be applied on-line in an experiment provided accurate modeling of the sensor and actuator is available for the I/O analysis.

Acknowledgments

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Solid Mechanics Prize

Regulations and Call for Nominations

The Fluid Mechanics Prize and the Solid Mechanics Prize of EUROMECH, the European Mechanics Society, shall be awarded on the occasions of Fluid and Solid conferences for outstanding and fundamental research accomplishments in Mechanics.
Each prize consists of 5000 Euros. The recipient is invited to give a Prize Lecture at one of the European Fluid or Solid Mechanics Conferences.

Nomination Guidelines

A nomination may be submitted by any member of the Mechanics community. Eligible candidates should have undertaken a significant proportion of their scientific career in Europe. Self-nominations cannot be accepted.
The nomination documents should include the following items:

- A presentation letter summarizing the contributions and achievements of the nominee in support of his/her nomination for the Prize;
- A curriculum vitae of the nominee;
- A list of the nominee's publications;
- At least two letters of recommendation.

Five copies of the complete nomination package should be sent to the Chair of the appropriate Prize Committee, as announced in the EUROMECH Newsletter and on the Society's Web site www.euromech.org Nominations will remain active for two selection campaigns.

Prize committees

For each prize, a Prize Committee, with a Chair and four additional members shall be appointed by the EUROMECH Council for a period of three years. The Chair and the four additional members may be re-appointed once. The committee shall select a recipient from the nominations. The final decision is made by the EUROMECH Council.

Fluid Mechanics Prize

The nomination deadline for the Solid Mechanics prize is **15 January in the year of the Solid Mechanics Conference**. The members of the *Solid Mechanics Prize and Fellowship Committee* are:

- A. Kluwick (Chair)
- O. E. Jensen
- D. Lohse
- P. Monkewitz
- W. Schröder

Chairman's address
Professor A. Kluwick
Institut für Strömungsmechanik und Wärmeübertragung
Technische Universität Wien
Resselgasse 3,
A -1040 Wien, Austria
Tel. : +43 1 58801 32220
Fax : +43 1 58801 32299
Email: akluwick@mail.tuwien.ac.at

Solid Mechanics Prize

The nomination deadline for the Solid Mechanics prize is **15 January in the year of the Solid Mechanics Conference**. The members of the *Solid Mechanics Prize and Fellowship Committee* are:

- W. Schiehlen (Chair)
- H. Myhre Jensen
- N.F. Morozov
- M. Raous
- B. A. Schrefler

Chairman's address
Professor W. Schiehlen
Institut für Technische und Numerische Mechanik
Universität Stuttgart
Pfaffenwaldring 9
D-70550 Stuttgart, Germany
Tel. : +49 711 685-66391
Fax : +49 711 685-66400
Email: schiehlen@itm.uni-stuttgart.de

EUROMECH Conferences in 2011

The general purpose of EUROMECH conferences is to provide opportunities for scientists and engineers from all over Europe to meet and to discuss current research.
Europe is a very compact region, well provided with conference facilities, and this makes it feasible to hold inexpensive meetings.
The fact that the EUROMECH Conferences are organized by Europeans primarily for the benefit of Europeans should be kept in mind. Qualified scientists from any country are of course welcome as participants, but the need to improve communications within Europe is relevant to the scientific programme and to the choice of leading speakers.
A EUROMECH Conference on a broad subject, such as the ESMC or the EFMC, is not a gathering of specialists all having the same research interests. Much of the communication which takes place is necessarily more in the nature of imparting information than exchange of the latest ideas. A participant should leave a Conference knowing more and understanding more than on arrival, and much of that gain may not be directly related to the scientist's current research. It is very important therefore that the speakers at a Conference should have the ability to explain ideas in a clear and interesting manner, and should select and prepare their material with this expository purpose in mind.

2011

ENOC7
7th European Nonlinear Oscillations Conference
DATE: 24 - 29 July 2011
LOCATION: Rome, Italy
CONTACT: Prof. Giuseppe Rega
E-MAIL: giuseppe.rega@uniroma1.it

ETC13
13th European Turbulence Conference
DATE: 5 - 8 September 2011
LOCATION: Warsaw, Poland
CONTACT: Prof. Konrad Bajer
E-MAIL: kbajer@fuw.edu.pl

EUROMECH Conferences Reports

"4th European Postgraduate Fluid Dynamics Conference"

The Fourth European Postgraduate Fluid Dynamics Conference was held between the 3rd and 7th of July 2010, at ESPCI-ParisTech in Paris. After three years of successful existence in the UK, the conference has moved to mainland Europe. This year's EPFDC meeting included 35 talks and 7 posters by postgraduate students, continuing previous practice with the widest possible variety of topics in fluid dynamics. The 45 delegates came from 9 European countries, with students from France and the UK being most numerous. Four respected academics from Europe and the US gave excellent lectures. Unfortunately their availability didn't allow them to stay longer at the conference, and to interact more with the students. This year's invited lecturers were:

- Prof. Elisabeth Guazzelli (Polytech Marseille, France)
  Some problems in particulate flows
- Prof. Howard Stone (Princeton University, USA)
  Surprises in multiphase flows
- Prof. Cord-Christian Rossow (German Aerospace Center, Germany)
  Research in Aerodynamics - Science and Applications
- Dr. François Forget (Université Paris 6, France)
  Atmospheric dynamics on Mars

The topics of student presentations were as diverse as the invited lectures, from the microscale to aeronautics research, and covering experimental, numerical and theoretical work. The lectures and presentations complemented each other very well, indicating the high quality of student research on a number of key topics in fluid dynamics. For more information, the Conference Programme and the Book of Abstracts can be found at:
http://epfdc10.ensta.fr/downloads/epfdc10_booklet.pdf
The prizes for the Best Talk and the Best Poster were awarded by a panel consisting of the members of the EPFCD2010 Local and European Organizing Committees and the Advisory Board. Members of the judging panel who participated actively in the program were excluded from the competition, in order to ensure a fair and impartial outcome. The Best Talk award was given to Nicolas Champagne (ESPCI PMMH) for his presentation entitled "Traffic jams and intermittent flows in micro fluidic networks". The Best Poster award was given to Iryna Kononenko (Kharkov National University) for her poster entitled "Integral equation method to study vibrations of partially filled shells of revolution".
This year's addition to the events program was the visits to the experimental laboratories

at ESPCI-PMMH, which was graded highly in the feedback from the delegates. Doctoral and post-doctoral students from the PMMH research group performed live experiments and presented their topics to small groups of participants, to enhance interaction with them.
The "Questions and Answers" session was not possible this time, due to time constraints and the availability of the lecturers, but the experimental demonstrations were an excellent addition to the conference. It is recommended that next year's event should last 5 days and encompass both features, plus an extended dedicated poster session.
We are grateful to EUROMECH, ESPCI-PMMH, ENSTA-UME and Springer for the financial support that made the event possible and to ESPCI for offering essential infrastructure and help. In particular, we would like to thank Prof. Patrick Huerre (École Polytechnique), Prof. Eduardo Wesfreid (ESPCI), Prof. Olivier Cadot (ENSTA-UME), Frederique Auger and Amina Mialet (ESPCIPMMH).

EUROMECH Colloquia in 2011-2012

EUROMECH Colloquia are informal meetings on specialized research topics. Participation is restricted to a small number of research workers actively engaged in the field of each Colloquium. The organization of each Colloquium, including the selection of participants for invitation, is entrusted to a Chairman. Proceedings are not normally published. Those who are interested in taking part in a Colloquium should write to the appropriate Chairman. Number, Title, Chairperson or Co-chairperson, Dates and Location for each Colloquium in 2010, and preliminary information for some Colloquia in 2011 and 2012, are given below.

EUROMECH Colloquia in 2011

511. Biomechanics of Human Motion. New Frontiers of Multibody Techniques for Clinical Applications
Chairperson : Prof. Jorge A.C. Ambrosio
IDMEC- Instituto Superior Tecnico
Av. Rovisco Pais 1
1049-001 Lisbon, Portugal
Phone: +351 2184 17680
Fax: +351 2184 17915
E-mail: Jorge@dem.ist.utl.pt
Co-Chairpersons: Prof. Frans van der Helm, Prof. Andrés Kecskemethy
Dates and location: 9-12 March 2011, Açores, Portugal

513. Dynamics of non-spherical particles in fluid turbulence
Chairperson: Prof. Helge I. Andersson
Department of Energy and Process Engineering
Norwegian University of Science and Technology
7491 Trondheim, Norway
Phone: +47 73 59 35 56
Fax: +47 73 59 34 91
Email: helge.i.andersson@ntnu.no
Co-chairpersons: Prof. Alfredo Soldati
Dates and location: 6-8 April 2011, Udine, Italy

516. Nonsmooth contact and impact laws in mechanics
Chairperson: Prof. Bernard Brogliato
INRIA Grenoble Rhone-Alpes
Inovallée
655 avenue de l'Europe
Montbonnot, 38 334 Saint Ismier Cedex France
Email: bernard.brogliato@inrialpes.fr
Co-chairpersons: Prof. Christoph Glocker, Prof. Caishan Liu
Dates and location: 6-8 July 2011, Grenoble, France

521. Biomedical Flows at Low Reynolds Numbers
Chairperson: Prof. Leonhard Kleiser
Institute of Fluid Dynamics
ETH Zurich, Switzerland
Email: kleiser@ifd.mavt.ethz.ch
Co-chairpersons: Prof. Thomas Rösgen, Prof. Timothy Pedley
Dates and location: 29-31 August 2011, ETH Zurich, Switzerland

522. Recent Trends in Optimisation for computational Solid Mechanics
Chairperson: Prof. Paul Steinmann
University Erlangen/Nuremberg
Erlangen, Germany
Email: paul.steinmann@ltm.uni-erlangen.de
Co-chairpersons: Prof. Kai-Uwe Bletzinger, Prof. Gunther Leugering
Dates and location: 10-13 October 2011, Erlangen/Nuremberg, Germany

523. Ecohydraulics: linkages between hydraulics and ecological processes in rivers
Chairperson: Prof. Wim S.J. Uijttewaal
Environmental Fluid Mechanics section
Faculty of Civil Engineering and Geosciences
Postbox 5048, 2600 GA Delft, The Netherlands
Email: w.s.j.uijttewaal@tudelft.nl
Co-chairpersons: Dr. Johannes Steiger
Dates and location: 15-17 June 2011, GEOLAB University Blaise Pascal Clermont- Ferrand, France

525. Instabilities and transition in three-dimensional flows with rotation
Chairperson: Prof. Benoît Pier and Prof. Fabien Godeferd
Laboratoire de mécanique des fluides et d'acoustique
CNRS-Université de Lyon
École Centrale de Lyon
36 avenue Guy-de-Collongue
F-69134 Lyon, France
Email: benoit.pier@ec-lyon.fr
Email: fabien.godeferd@ec-lyon.fr
Co-chairpersons: Prof. Nigel Peake
Dates and location: 21-23 June 2011, École Centrale de Lyon, France

526. Patterns in soft magnetic matter
Chairperson: Dr. habil. Adrian Lange
Chair Magnetofluiddynamik
Institute of Fluid Mechanics, TU Dresden
D-01062 Dresden, Germany
Email: adrian.lange@tu-dresden.de
Co-chairpersons: Dr. Sofia Kantorovich
Dates and location: 21-23 March 2011, Dresden, Germany

527. Shell-like Structures – Nonclassical Theories and Applications
Chairperson: Prof. Dr.-Ing. Holm Altenbach
Lehrstuhl Technische Mechanik
Zentrum für Ingenieurwissenschaften
Martin-Luther-Universität Halle-Wittenberg
Kurt-Mothes-Str. 1
06120 Halle (Saale), Germany
Email: holm.altenbach@iw.uni-halle.de
Co-chairpersons: Prof. Victor A. Eremeyev
Dates and location: 22-26 August 2011, Lutherstadt Wittemberg, Germany

529. Cardiovascular Fluid Mechanics
Chairperson: Prof. Giorgio Querzoli
Dipartimento di Ingegneria del Territorio,
Università di Cagliari
Via Marengo 3
09123 Cagliari, Italy
Email: querzoli@unica.it
Co-chairpersons: Prof. Gianni Pedrizzetti
Dates and location: 27-29 June 2011, Cagliari, Italy

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530. Structural Control and Energy Harvesting
Chairperson: Dr. Simon Neild
Department of Mechanical Engineering
University of Bristol
Queen's Building
University Walk
Bristol, BS8 1TR, UK
Email : Simon.Neild@bristol.ac.uk
Co-chairpersons: Prof. Dan Inman
Dates and location: 25-27 July 2011, University of Bristol, UK

531. Vortices and waves: identifications and mutual influences
Chairperson: Prof. Yuli D. Chashechkin
Institute for Problems in Mechanics of the Russian Academy of Sciences
101/1 prospect Vernadskogo
Moscow, 119526, Russia
Email: chakin@ipmnet.ru
Co-chairpersons: Prof. Xavier Carton
Dates and location: 21-24 June 2011, Moscow, Russia

EUROMECH Colloquia in 2012

514. New trends in Contact Mechanics
Chairperson: Dr. Michel Raous
Directeur de Recherche CNRS
Laboratoire de Mécanique et d'Acoustique
31, Chemin Joseph Aiguier
13402 Marseille Cedex 20, France
Email : raous@lma.cnrs-mrs.fr
Co-chairpersons: Prof. Peter Wriggers
Dates and location: May 2012, Marseille, France

524. Multibody system modelling, control and simulation for engineering design
Chairperson: Prof. Ben Jonker
University of Twente, Faculty CTW
Mechanical Automation
P.O. Box 217 – Building Horst
7500 AE Enschede, The Netherlands
Email : J.B.Jonker@utwente.nl
Co-chairpersons: Prof. Werner Schiehlen
Dates and location: 28 February - 2 March 2012, Ensched, The Netherlands

528. Wind Energy and the impact of turbulence on the conversion process
Chairperson: Dr. Joachim Peinke
Institute of Physics & ForWind
University of Oldenburg
D 26111 Oldenburg, Germany
Email: peinke@uni-oldenburg.de
Co-chairpersons: -
Dates and location: April 2012, Oldenburg, Germany

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EUROMECH Colloquia Reports

EUROMECH Colloquium 512
“Small Scale Turbulence and Related Gradient Statistics”
26-29 October 2009, Turin, Italy
Chairpersons: Daniela Tordella, Katepalli R.Sreenivasan

The results presented during EUROMECH Colloquium 512 from experiments and direct numerical simulations confirmed the evidence of high intermittency and anisotropy of the small turbulent scales which the literature has recently highlighted. This phenomenon can be explained through the long range interaction between the large and the small scales. The long range interaction can in fact transfer the information of the geometry of the system to the small eddies generated by the instability processes and the inertial stretching and tilting of the vortical structures. Participants in Colloquium 512 were not able to establish a clear consensus on a general interpretation to be used in the place of the Kolmogorov Theory. However, a general agreement has been obtained on the need to raise the level of knowledge in the basic non-homogeneous and/or anisotropic situations present in nature and in the technology to the level reached for the isotropic turbulence.
In addition to the isotropic case, the list of basic configurations should include three main cases:

- Homogenous anisotropy (homogeneous shear),
- Two homogeneous directions in the presence of full anisotropy (wall flows)
- inhomogeneity and anisotropy in flows with the same basic structure (shearfree mixing layer, plane mixing layer, jets, etc…).

The research work needed is not an impossible task. A significant update of the state of the art should be available in five years.
Proceedings have been published as: “Small Scale Turbulence and Related Gradient Statistics”, Proceedings of EUROMECH Colloquium 512, Torino, October 26-29, 2009. (Ed.s D. TORDELLA and K. R. SREENIVASAN), «Atti della Accademia delle Scienze di Torino.
Classe di Scienze Fisiche, Matematiche e Naturali», Supplement 2009 - Vol. 142, 2008. ISSN 0001-4419, ISBN 88-901608-4-
The proceedings as well as many presentations can be find on the web site, see:
http://www.euromech512.polito.it/proceedings_and_publications_latex_template
http://www.euromech512.polito.it/participants_abstracts_presentations
Participants all enjoyed the ambience and organization of Colloquium 512. The scientific program and complementary social and cultural programs were much appreciated.
The discussion is continuing in the Special Issue entitled “Smallscale Turbulence” in Physica D: Nonlinear Phenomena, to be published in 2011 (Guest Editors Daniela Tordella and Katepalli R. Sreenivasan).

EUROMECH Colloquium 515
“Advanced Applications and Perspectives of Multibody Sytem Dynamics”
12-17 July 2010, Blagoevgrad, Bulgaria
Chairpersons: D.Sc. Evtim Zahariev, Prof. Marco Ceccarelli

Colloquia in the field of Multibody System Dynamics have been promoted strongly by EUROMECH and have been held previously in: Lisbon, Portugal (1999); Paris, France (2001); Erlangen, Germany (2003); Halle, Germany (2004); Ferrol, Spain (2006); and Bryansk (2008). In 2010, EUROMECH Colloquium 515 was held in Blagoevgrad, Bulgaria, as planned several years ago and endorsed by many scientists from all around the world. The Co-chairs, Prof. Marco Ceccarelli and D.Sc. Evtim Zahariev, began its organization during January 2009. The initial Organizing Committee included: Prof. Dr.-Ing. Werner Schiehlen; Prof. Javier Cuadrado; Prof. Dmitry Pogorelov; Dr.-Ing. Andreas Mueller; Prof. Arend Schwab; Prof. Emil Manoach. Later, Prof. Dr.-Ing. Prof. E.h. Peter Eberhard and Prof. Jorge Ambrosio further strengthened the Committee.

The venue for Colloquium 515 was “Bachinovo”, the former residence of the municipality of Blagorvgrad at the foot of Rila Mountain, which is now part of the South-West University of Blagorvgrad. It is very convenient for scientific events, with six lecture rooms and accommodation for more than 70 participants.

Five leading experts in the field of Multibody System Dynamics were invited to present their recent achievements and developments. These were:

- Jan Mazuch, National Manager, MSC Software: “Products Portfolio - Multibody Dynamics and Finite Element Method”. MSC is a leading provider of commercial software for Multibody System Analysis and Syntheses;
- Prof. Marco Ceccarelli, University of Cassino: “Experimental Mechanics in the Laboratory of Robotics and Mechatronics”;
- Prof. Peter Eberhard, University of Stuttgart: “Visualization of applied developments at the Institute of Engineering and Computational Mechanics”;
- Prof. Jorge Ambrosio, IDMEC/IST, Portugal: “Problems of Multibody Dynamics;
- Prof. Dmitry Pogorelov, Bryansk State Technical University: “Application in Rail and Road Vehicles”.

Participants from 13 countries made significant contributions to the theme of the colloquium. Presentations covered a range of challenging problems and future applications of the methodology of Multibody System Dynamics. Significant topics were:

- Earthquake dynamic response of large flexible structures.
  This topic is especially important when the number of natural disasters is tending

to increase in a challenging economic environment. Possible development of projects supported by NATO Science for Peace program and EU funding is being considered;

- Development of new finite element approaches for application to multibody systems simulation. This includes development of new types of element and discretisation;
- Modelling nonlinear dynamic phenomena;
- Torque control of driving motors for manipulators, robots and walking devices. Effective driving of multibody systems is of major importance for practical application;
- Biomechanics, including modelling of the human skeleton. Presentations by representatives from countries including Japan, Canada, Portugal, Bulgaria and Germany showed the wide international interest in this area. A notable example of an application in medicine was presented by the representative from Iran: prediction of the impact response of the human chest during cardiopulmonary resuscitation;
- Active and passive control of multibody systems, motion control, suppression of deviations and vibration of flexible structures.

Colloquium 515 in Bulgaria demonstrated the level of interest in sharing experience within the multibody system community. The discussions and informal conversations during the colloquium were a promising start to future collaboration between teams from different countries. In their capacity as guest editors, the co-chairs of the colloquium organized a special issue of Mechanics Based Design of Structures and Machines, an international journal published by Francis and Taylor, Inc. The authors of eleven presentations were invited to submit extended papers to the journal for review and publication.

It was proposed that similar colloquia should take place every two years.

EUROMECH Colloquium 517
"Interfaces and inhomogeneous turbulence"

28-30 June 2010, London, UK
Chairperson: Prof. Ian Eames

The meeting concerned interfacial processes and inhomogeneous flows. There was considerable breadth to the meeting, with contributions from geophysics, engineers, mathematicians, computer scientists, plasma physicists. There were two invited speakers: Prof. Kaneda (Japan), Prof. Davidson (UK). There was also considerable input from Prof. Hunt, who gave an entertaining after dinner speech about the history of turbulence at UCL. The format gave opportunities for everyone to speak with plenty of spare time for discussion. The meeting concluded with a talk by Prof. Hunt and a round table discussion where everyone was given an opportunity to give their impression of the important questions for the future.

Key elements of the discussion at EUROMECH Colloquium 517 were:

- What is an interface, how to define it (there appears to be sensitivity to thresholding parameters), what is its geometry shape (fractal, smooth etc)?;
- The combustion community needed to be engaged more in this area because of the relevance to the energy sector;
- What is the link between the various scales? It became clear that the usual energy spectrum masks the inhomogeneity in the flow (both homogeneous/inhomogeneous and those flows where there is a interface between turbulent and non-turbulent regions). The experimental and computational work pointed out that dissipation was quite spotty in the flow and found at the edge of vortices (a result which Moffatt has shown for 2D turbulence);
- How does an interface related to the concept of a barrier to transport?;
- Methods for analysis of data have previously been in the area of either Eulerian or Lagrangian, while future methods that could resolve these sharp interfaces (important for the unsteady lift on wings) required methods which are intermediate between E and L. It was pointed out that such methods could make use to techniques drawn from dispersed multiphase flows;
- Davidson made the important point that to understand turbulence the community needs to go back to Prandtl's rather physical vorticity approach, but that there was also a need to engage more fully the statistical arm of the turbulence community.

The conclusion of the meeting was that this was a very stimulating discussion and many common elements were identified for future research. In terms of administration and follow up, the discussion concluded with a view that the meeting should be repeated again in two years time, possibly by joining up with a SIG of ERCOFTAC. Future funding opportunities were also identified and the UK attendees have discussed a possible framework to take forward some of the work packages identified in a manner that also brings in the EU expertise. Prof. Hunt volunteered to write a summary for the meeting, which he will submit to the Journal of Fluid Mechanics.

EUROMECH Colloquium 519
"Mixing and Dispersion in Flows Dominated by Rotation and Buoyancy"
20-23 June 2010, Kerkrade, The Netherlands
Chairperson: Prof. Herman Clercx

Rotation and buoyancy play an essential role in many geophysical, environmental and industrial flows. They strongly affect flow properties such as anisotropy and turbulence characteristics. This has an important impact on the dispersion of passive and active tracers and (inertial) particles in such flows, with direct relevance to heat and mass transfer in many natural and technological systems. The aim of EUROMECH Colloquium 519 was to bring together researchers with interests in theoretical descriptions and numerical studies of mixing and dispersion in flows that are influenced by rotation and buoyancy, and experimentalists involved in rotating, stably stratified and buoyancy-driven flows. Satellite and field observations play an essential role in mixing and dispersion studies of large-scale geophysical and environmental flows. Topics of interest range from the fundamentals of mixing and dispersion in canonical systems such as vortices in rotating or stratified fluids, through homogeneous rotating or stratified turbulence, to mixing from an Eulerian/Lagrangian point of view in geophysical, environmental and industrial flows. Special attention would be given to interdisciplinary topics where fluid mechanics and mixing are central themes. Some examples include the (large-scale) dispersion of marine species in oceans, estuaries and lakes, mixing in drinking-water supplies, transport in rivers and estuaries, and ventilation, comfort and safety aspects in buildings and public transportation systems.

Approximately 40 talks were presented during the colloquium, which were subdivided into six central themes:

- rotating flows;
- buoyancy dominated flows;
- transport in turbulence;
- flows with rotation and buoyancy;
- transport in geophysical flows;
- dispersion in flows dominated by rotation and buoyancy.

Each session started with an invited contribution that addressed important developments in one of the themes.

The session on rotating flows addressed the recent experimental developments which allow experimentalists to perform detailed measurements on the statistical properties of rotating turbulence. The new techniques like PIV, stereo-PIV and 3D-PTV have revived experimental research on rotating turbulence and flows in rotating shallow fluid layers. New well-resolved experimental data are becoming available which elucidate flow structuring in rotating turbulence and inertial wave turbulence, shed light on the mechanisms of return to isotropy in decaying rotating turbulence, and allow Lagrangian statistics of rotating turbulence to be retrieved. These tools also enable studies of the basic dynamics of vortices in shallow rotating flows.

Flows affected by buoyancy were the topic of two sessions. The first focused mostly on stably stratified flows while in the second Rayleigh-Bénard convection with rotation was the central theme. The current state of affairs on experiments and simulations of stably stratified turbulence was reviewed. The field is developing with the introduction of new flow measurement techniques. In recent years understanding of forced stably stratified turbulence and its dispersion properties has grown considerably due to increasing computing capabilities. These studies have also initiated new theoretical approaches towards transport in stratified turbulence. Developments in this field are of direct relevance to atmospheric scientists modelling flow and transport in the (stably stratified) atmospheric boundary layer. Rayleigh-Bénard convection with rotation is currently one of the focal areas in the field of thermal convection. Accurate heat transfer measurements are being combined with data from separate PIV and SPIV measurements to understand the flow structure under rotation. These studies are being complemented with extreme high-resolution DNS of this problem. Heat transfer enhancement due to rotation, flow structuring and Prandtl number effects was discussed. The role of rotation in thermal convection is being clarified. The dynamics and stability of vortices in stably stratified flows and in shallow two-layer fluids are also being explored. Understanding is being enhanced by application of (S)PIV and particle tracking.

The fundamentals of transport in turbulence and inertial particle dynamics in flows dominated by rotation and/or buoyancy were addressed in two sessions. The session on fundamentals focused on new developments in transport of finite-size particles in turbulence, dispersion in stratified systems, and transport in 2D turbulence and in Rayleigh-Taylor systems. These model systems are illustrative of the future directions of (computational) research in this field. Transport of inertial particles and droplets in turbulent flows affected by either rotation or buoyancy were addressed in the final session, when particle transport in rotating duct flows and thermal convection was discussed. The keynote lecture illustrated very nicely both the importance of understanding droplet dynamics in separation technologies and the key role played by rotation and phase transitions. These application-oriented research directions are illustrative examples where engineering science and fundamentals of particles in turbulence meet.

Finally, the session on transport in geophysical flows (and a few related talks in other sessions) provided an overview of the connections between physical oceanography, environmental and atmospheric sciences, and civil engineering applications on the one hand and the main topics of Colloquium 519 on the other. The topics presented in this session and the following discussions clearly showed that computational and experimental studies of transport in flows dominated by rotation or buoyancy can contribute to the applied sciences.

Two sessions during EUROMECH Colloquium 519 were organised in association with COST Action MP0806 (Particles in Turbulence). The working group on numerical modelling contributed to the colloquium with several presentations.

Rapid developments in experimental techniques that allow detailed measurements of turbulent flows affected by rotation and buoyancy, increasing use of high-performance computing, and promising developments in several areas (such as in rotating turbulence, Rayleigh-Bénard convection, high resolution DNS of stratified turbulence, geophysical flow experiments, etc.) will surely allow advances on several fronts. Combined with the growing interest in multiscale modelling of transport of particles and droplets in turbulence, it was recommended that another EUROMECH colloquium on this subject should be organised in three to four years time.

EUROPEAN MECHANICS SOCIETY

Objectives of EUROMECH, the European Mechanics Society

The Society is an international, non-governmental, non-profit, scientific organisation, founded in 1993. The objective of the Society is to engage in all activities intended to promote in Europe the development of mechanics as a branch of science and engineering. Mechanics deals with motion, flow and deformation of matter, be it fluid or solid, under the action of applied forces, and with any associated phenomena. The Society is governed by a Council composed of elected and co-opted members.

Activities within the field of mechanics range from fundamental research on the behaviour of fluids and solids to applied research in engineering. The approaches used comprise theoretical, analytical, computational and experimental methods.
The Society shall be guided by the tradition of free international scientific cooperation developed in EUROMECH Colloquia.
In particular, the Society will pursue this objective through:

- The organisation of European meetings on subjects within the entire field of mechanics;
- The establishment of links between persons and organisations including industry engaged in scientific work in mechanics and in related sciences;
- The gathering and dissemination of information on all matters related to mechanics;
- The development of standards for education in mechanics and in related sciences throughout Europe.

These activities, which transcend national boundaries, are to complement national activities.

The Society welcomes to membership all those who are interested in the advancement and diffusion of mechanics. It also bestows honorary membership, prizes and awards to recognise scientists who have made exceptionally important and distinguished contributions. Members may take advantage of benefits such as reduced registration fees to our meetings, reduced subscription to the European Journal of Mechanics, information on meetings, job vacancies and other matters in mechanics. Less tangibly but perhaps even more importantly, membership provides an opportunity for professional identification; it also helps to shape the future of our science in Europe and to make mechanics attractive to young people.

European Journal of Mechanics - A/Solids

ISSN: 0997-7538

The *European Journal of Mechanics A/Solids* continues to publish articles in English in all areas of Solid Mechanics from the physical and mathematical basis to materials engineering, technological applications and methods of modern computational mechanics, both pure and applied research.

The following topics are covered: Mechanics of materials; thermodynamics; elasticity; plasticity; creep damage; fracture; composites and multiphase materials; micromechanics; structural mechanics; stability vibrations; wave propagation; robotics; contact; friction and wear; optimization, identification; the mechanics of rigid bodies; biomechanics.

European Journal of Mechanics - B/Fluids

ISSN: 0997-7546

The *European Journal of Mechanics B/Fluids* publishes papers in all fields of fluid mechanics. Although investigations in well established areas are within the scope of the journal, recent developments and innovative ideas are particularly welcome. Theoretical, computational and experimental papers are equally welcome. Mathematical methods, be they deterministic or stochastic, analytical or numerical, will be accepted provided they serve to clarify some identifiable problems in fluid mechanics, and provided the significance of results is explained. Similarly, experimental papers must add physical insight in to the understanding of fluid mechanics. Published every two months, EJM B/Fluids contains:

- Original papers from countries world-wide
- Book reviews
- A calendar of scientific meetings