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EUROPEAN MECHANICS SOCIETY

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EFMC11-EUROMECH Young Scientist Prize Paper

“Attenuation of gravity waves by vortices”

Pablo Gutiérrez won the EUROMECH Young Scientist Prize, awarded at the 11th EUROMECH FLUID Mechanics Conference held in Seville, September 2016

Pablo Gutiérrez[1], Alfredo García-Cid[1] and Claudio Falcón[1,2]

Abstract

Here we present an experimental set-up that allows the study of wave-vortex interaction. Low frequency gravity waves are generated by periodically moving a container in the horizontal direction. A vortex flow is generated with motors placed at the bottom of the container. We are interested in how fluid motion in the volume may reduce the amplitude of surface gravity waves, particularly because of its potential use as a control mechanism. Indeed, we observe that resonances in our container are reduced when vortical fluid motion is included. This dissipative effect is the result of a redistribution of wave energy into modes that neighbour the one at resonance.

1. Introduction

When a container with liquid moves horizontally, the liquid may attain very large amplitudes, even producing spilling or destabilization of the container. One deals with this sloshing problem, rather unconsciously, if one tries to walk with a cup of coffee [1]. Such an anecdotal problem, however, also has implications for the transport of large amounts of fuel. Consequently, it has deserved intense investigation [2, 3].

To avoid violent increases in the maximum height of the liquid, it is usually proposed to use particular container geometries [2] or to implement a feedback mechanism to control the motion of the container, as we naturaly do when carrying our coffee cup [1]. Here we explore how fluid motion itself may provide an alternative control mechanism. To go in this direction, we study the low-frequency resonances that appear on the free surface of a water volume, when its container is subjected to horizontal periodic forcing. Specifically, we study how vortical fluid motion attenuates these resonances.

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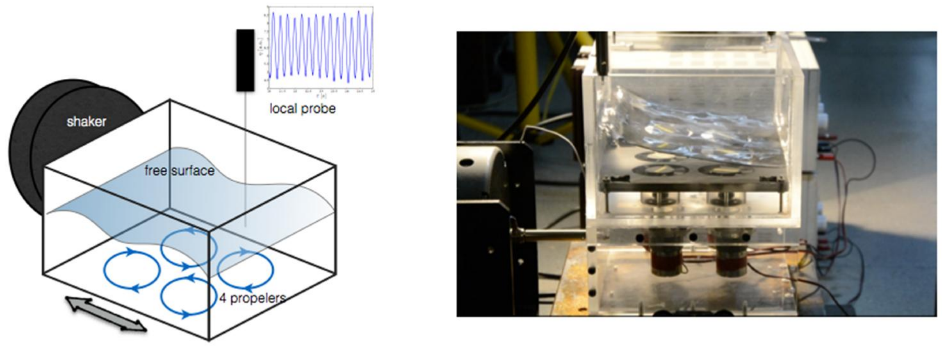

Fig. 1: Experimental set-up. A plexiglas container is filled with water up to a height h. Four DC motors with impellers introduce bulk fluid motion (motor sturnas indicated in the schema to the left). The whole container is on a carriage and is moved horizontally with an electromagnetic shaker. Local measurements of the water displacement η are obtained with a capacitive sensor. An example of a temporal signal is inset.

How vortices affect gravity waves is a question largely considered in oceanography [4-6] and physics [7-11]. For instance, deflections in the path of swell have been observed, as a consequence of surface currents acting during its travel across the ocean. Therefore, vorticity should be taken into account when inferring distant sources of ocean swell [6]. In laboratory experiments, wave deflection by vortices has also been observed [7]. However, more attention has to be paid to dissipation of wave energy by turbulence [8-11], as we do in the following analysis of sloshing gravity waves.

2. Sloshing motion experiments

Our experimental set-up is shown in Figure 1. It consists of a Plexiglas container with 20 x 20 cm^2 of available area, which is filled with distilled water up to a height h at rest. The available height of the container is 11.5 cm. To produce bulk turbulent fluid motion, we use four small DC motors placed under the bottom of the container (see Fig. 1- right hand side). The Motor shafts are in contact with water and have impellers at their ends. Each motor is powered by an independent source and can rotate at a maximum frequency of Ω = 3.5 Hz on the chosen direction. We kept the rotation direction of the motors fixed to get an hyperbolic flow (as it is represented in the schema), with negligible global circulation. We use the parameter Ω to control bulk fluid motion. If we consider the impeller radius R as the characteristic length scale, we can construct the Reynolds number as $Re = R^2\Omega/\nu$, with ν the water viscosity ($\nu = 10^{-6}\ m^2/s$). This Reynolds number of the imposed flow ranges between 720 and 3000.

The container including the four motors is mounted on a carriage allowing unidirectional motion of the whole setup. We impose a periodic oscillation of the container at frequency f, with the help of an electromagnetic shaker controlled by a personal computer. Thus, its position X is given by $A\ \cos(2\pi f t)$. First, we qualitatively show the observed phenomenology for a motion amplitude of $A = 3$ mm (Section 2.1). Then, we focus in a smaller amplitude motion, where the container amplitude is close to 0.5 mm (Section 2.2).

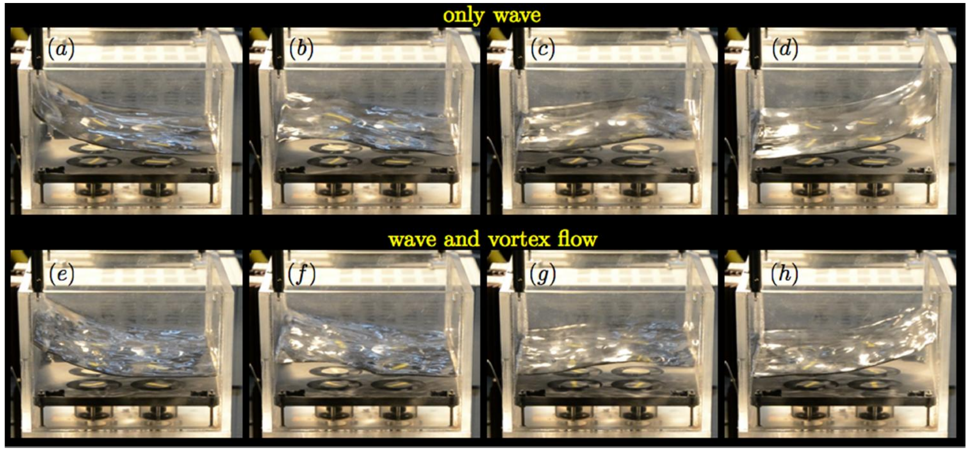

Fig. 2: Image sequences during sloshing motion forced at 1.45 Hz. In the upper images there is only the sloshing wave. In the lower images, motors are turning at 3.5 Hz. The upper and lower images correspond to the same phase in the container oscillation.

The water surface fluctuates in space and time as a consequence of the bulk fluid motion and by the oscillatory forcing of the container. First, we present a visualization using a high-resolution video camera acquiring images at 24 fps. To do a quantitative exploration, we measured the local displacement η from the water level at rest, using a capacitive sensor placed at a fixed position, near the centre of the cell (sampling at 1 kHz). A typical temporal trace of η is shown as an inset in Figure 1.

2.1 Phenomenology

In Figure 2, we show two sequences of images taken when the container is moved at 1.45 Hz, with a peak-to-peak amplitude of 6 mm. The water level at rest is 3 cm. One can see that the vertical fluctuations of the water level are much larger than the motion of the container. When we excite only the container, the water surface is very smooth, as can be seen particularly in Images (c) and (d). Also, in Image (d) one can see that the highest water level (happening when the container changes direction of motion) is at around 2/3 of the container height.
On the other hand, when one turn the motors on, the surface becomes deformed at scales smaller than the wavelength. More importantly, the maximum water level is smaller than in the former case.
In order to better quantify the effect of vortical flows in sloshing waves, we performed experiments with smaller amplitudes, also exploring a larger set of physical parameters.

2.2 Small amplitude motion

We perform a series of measurements, where we fix the shaker amplitude and frequency and measure the response of the surface. Typical temporal traces of η are presented in the insets 3(b)

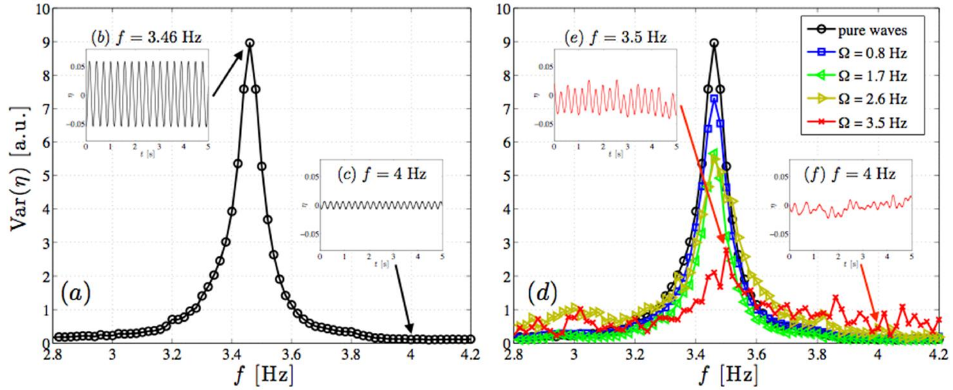

Fig. 3: Water response to a container motion of (small) constant amplitude. The rest water level $h = 6$ cm. Figure 3 (a) shows the variance of signals when there is only the sloshing wave; insets (b) and (c) are examples of temporal signals. Figure 3(d) shows the variance of signals for the combination of the sloshing wave and the vortical flow; insets (e) and (f) are examples of temporal signals for this case.

and 3(c) to Figure 3(a). We see here that the peak-to-peak amplitude is constant over the sample time, even though the amplitude depends strongly on the forcing frequency. We characterize the signal amplitude by its variance. We vary the shaker frequency to span a whole frequency range, as shown by the black dots in Figure 3(a). We observe that water surface has a natural resonance (here at $f_0 \sim 3.45$ Hz) where the wave amplitude is the largest. Resonances are determined by the container geometry and by the water level at rest. The example presented in Section 2.1 corresponds to the resonance frequency of a lower frequency normal mode.

Now the question is: what happens to the resonance when we add bulk fluid motion?. To answer this question, we turn the motors on at a fixed frequency Ω, and we perform the same series of measurements. Two examples of temporal traces are given in insets 3(e) and 3(f) to Figure 3(d). Both were obtained with motors turning at $\Omega = 3.5$ Hz. In both signals, the constant peak-to-peak amplitude in insets 3(b) and 3(c) is replaced by lower frequency fluctuations coming from the turbulent flow. When we impose bulk vortical fluid motion, the surface deformation η is always composed of the imposed sloshing motion and fluctuations produced by vortical fluid flow. For instance, near the resonance peak the wave-like motion is still very clear (inset 3(e) at 3.5Hz), but the origin of motion is less obvious away from the peak (inset 3(f) at 4 Hz).

In order to summarise the effect of vortical flow on the resonance, we compute the variance of all the signals, for the different imposed motor frequencies. This is shown using different colors in Figure 3(d). We see that the maximum amplitude of the peak (and therefore the maximum wave amplitude) decreases with increasing rotational frequency of the motors, and thus with increasing intensity of the vortical flow.

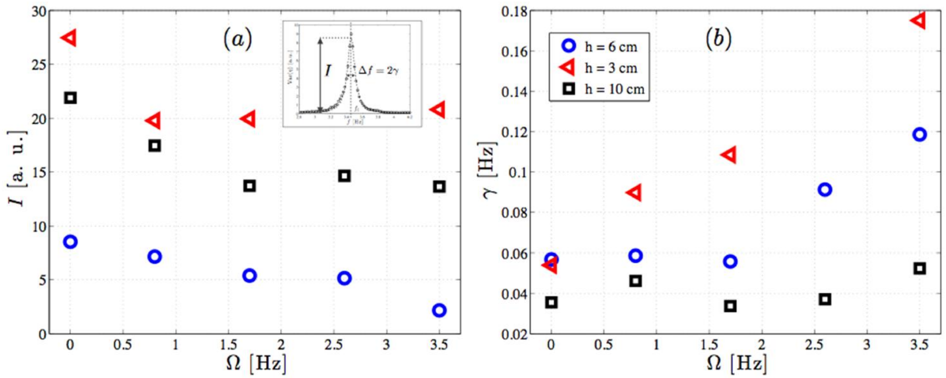

Fig. 4: Parameters of Lorentzian fits of resonance curves. As depicted in the inset to Figure 4(a), the parameter I corresponds to the maximum amplitude at the resonance. Figure 4(b) presents γ, which corresponds to half the peak width, and can also be interpreted as a dissipation coefficient.

To further quantify this wave attenuation, we can fit the resonance peaks as a Lorentzian (see the inset to Figure 4(a)). The variance is written as

$$\|\eta\|^2 = \frac{I\,\gamma^2}{(f - f_0)^2 + \gamma^2},$$

where I is the maximum amplitude, f_0 is the peak frequency and γ is the half the spacing of frequencies giving amplitude $I/2$. It may be noted that a Lorentzian function can be derived from a set of equations describing sloshing motion in an inviscid linear approximation [3] that can be further modified to include viscous dissipation [2]. Thus, one can introduce the effect of vorticity as a perturbation that enhances dissipation. This model, which should be valid for small amplitude waves and gentle vortical perturbations, will be described elsewhere [12].

The values of I and γ are shown in Figure 4 (f_0 does not show significant changes) for three depths of the fluid layer. As expected, when increasing the vortical flow, we observe a decrease in the maximum peak amplitude (Figure 4(a)) and a widening of the peak (Figure 4(b)). This data shows that the resonance loses coherence because of the vortical motion, suggesting a mechanism of control. The observation of a peak that decreases in amplitude and increases in width, was obtained previously in studies of wave-vortex interaction [10,11]. In those references, however, the peak appears directly at the excitation frequency where energy enters the system. The energy is then redistributed by turbulent fluctuations into neighbouring frequencies. In our case, we measured the response of the system to a whole range of frequencies. Therefore, here it is the system itself that changes by the effect of turbulence, becoming more dissipative.

3. Conclusions

In summary, we studied the effect of vorticity on gravity waves produced by the horizontal motion of a container. First, we observed qualitatively the attenuation of sloshing waves, and then

we quantified the effect. We performed a series of local measurements of the response of the water surface to horizontal oscillation in a chosen range of frequencies. By doing so, we obtained resonance curves, where the effect of vortical flow can be easily visualized. We performed Lorentzian fits to the resonance curves, showing a clear tendency: the amplitude of resonance peaks decreases with increasing intensity of the vortical flow, and the width of the peaks increases.

In the light of previous work [10,11], we can interpret our results in the following way: vortical motion reduces the ability of the container to develop resonances. Therefore, to include vortical motion in the bulk of the fluid may be considered as a mechanism to control spilling or destabilization of a container by large amplitude gravity waves.

4. Acknowledgements

We are grateful to Ricardo Silva for helping in the design and construction of the experimental setup, to Pablo Mardones for performing preliminary experiments, and to Sébastien Aumaître for helpful discussions. PG acknowledges CONICYT/FONDECYT postdoctorado No. 3140550.

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EUROMECH Young Scientist Prize Paper

"Depletion effects in repeated diffusive bubble growth"

ÁLVARO MORENO SOTO won the EUROMECH Young Scientist Prize, awarded at the 11th EUROMECH FLUID OR SOLID Mechanics Conference held in SEVILLA, SEPTEMBER 2016

Álvaro Moreno Soto[1], Andrea Prosperetti[2], Detlef Lohse[1] and Devaraj van der Meer[1]

Abstract

In weakly supersaturated mixtures, bubbles are known to grow quasi-statically as diffusion-driven mass transfer governs the process. Once the bubble detaches, it leaves behind a gas-depleted area. This gas depletion will delay the growth of bubbles that form later in the succession as compared to the first appearing ones. In this paper, we analyse this effect qualitatively.

1. Introduction

The evolution of bubbles is a question that scientists have been trying to solve for many years. There are numerous studies on how bubbles nucleate, grow and affect their environment, e.g. bubbles nucleating on top of needles [1], nanobubbles on surfaces [2] or bubble clouds generating chemical reactions by ultrasounds [3]. Recently, nucleation of bubbles has become extremely important, since the generation of energy in chemical reactions is highly influenced by the formation of gas. In this case, bubbles cover partially or completely the catalytic surface where the components react, decreasing the reaction rate or even impeding it. The goal of transporting this gas away from the active sites of the reaction must thus be regarded as a priority. The difficulties reside in the way bubbles are generated and interact with their surroundings.

In chemical reactions, there is a source generating the gas. The gas product of the reaction diffuses directly into the bubble. But, what happens if there is no mass source and the amount of dissolved gas is fixed? In those cases, depletion plays a major role in the diffusive growth of successive bubbles.

Our experiments consist of preparing a mixture of gas (in our case, CO_2) and liquid (water) in a deposit at a certain pressure and temperature. Thanks to Henry's law [4], the concentration of gas inside the liquid can be calculated as follows:

$$c(T,P) = k_H(T)P, \tag{1}$$

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where c is the calculated concentration, k_H is Henry's constant (which depends on temperature T) and P is the gas pressure. In a separated tank, we introduce a silicon substrate which contains a pit covered with black silicon, a superhydrophobic material. Afterwards, we fill this tank with the previously generated mixture, and proceed by decreasing the pressure in a controlled way, thereby lowering the equilibrium concentration, Eq. (1), and creating supersaturated conditions. Consequently, an excess of gas that needs to escape in the form of bubbles will be generated, which in turn will nucleate in the designed hydrophobic pit [5].

For low supersaturation levels, bubbles are known to grow quasi-statically. *Epstein and Plesset* [6] obtained a mathematical solution for bubbles growing in a regime only governed by diffusion in an infinite liquid. Given the non-dimensional variables,

$$\epsilon \equiv \frac{R}{R_0} \qquad x \equiv \sqrt{\frac{2D\beta}{R_0^2}t}, \tag{2a,b}$$

where R is the radius of the bubble at a certain time t, R_0 is a reference length scale radius, D is the diffusion coefficient and $\beta = (c_0 - c_s)/\rho_g$ (with c_0 and c_s the correspondent starting and saturation concentration levels of CO_2 in water and ρ_g the density of the gas), the evolution of the bubble growth can be simplified to the following approximate formula:

$$\epsilon \approx \left(\gamma + (1+\gamma^2)^{\frac{1}{2}}\right)x \equiv Sx, \tag{3}$$

where $\gamma = \sqrt{\beta/2\pi}$. However, in our experiments, we need to take into account the presence of the silicon substrate. This substrate locally inhibits the gas flow into the bubble, such that bubbles grow more slowly on the substrate than those in an infinite medium. *Enríquez et al.* [6] studied this substrate influence on the bubble growth, concluding that its presence could be modelled by modifying the original *Epstein-Plesset* solution, Eq. (3), which results in a slightly altered factor multiplying the dimensionless time x:

$$\epsilon \approx \left(\gamma + \left(\frac{1}{2}+\gamma^2\right)^{\frac{1}{2}}\right)x \equiv S^* x, \tag{4}$$

We choose the radius of the pit, R_p, as a reference for the non-dimensional radius ϵ.

2. Successive bubble growth

We want to study the effect that a series of bubbles growing on a determined spot has on the growth of future bubbles. The experimental results are shown in Fig. 1(a) and 1(b). For the first few bubbles, the evolution approaches very neatly the theoretical prediction given by Eq. (4) for the growth in the presence of the substrate, Fig. 1(a). In the final stages of growth, however, an enhancement of mass transfer can be appreciated, which can be attributed to a change from pure diffusion to density-driven convection. This is a result of the increase in the concentration gradient in areas close to the bubble, since it is extracting gas from its surroundings. The transition can be seen clearly in Fig. 1(b), where the corresponding derivative of the non-dimensional radius with respect to the non-dimensional time reaches a plateau in the diffusive regime, in agreement with Eq. (4), and then increases again in the convective regime [7].

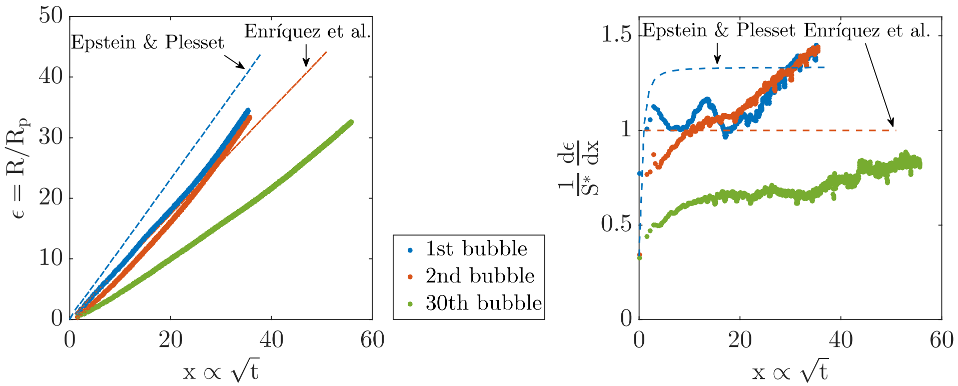

Fig. 1: a) On the left, evolution of the dimensionless bubble radius with respect to dimensionless time. As successive bubbles grow, a clear deviation from the theoretical curves is more noticeable. b) On the right, the derivative of the dimensionless radius vs. dimensionless time. Two main regimes can be observed: in the early and middle stages, a plateau is reached, corresponding to a diffusive evolution; in the final stages, the constant value turns into an increasing slope, which corresponds to a convective regime.

The most important effect that is observed in Figs. 1(a) and 1(b), is the clear deviation from the theoretical behaviour suffered by later bubbles in the succession. Although the detachment radius is more or less constant for all of them, the time they need to grow and detach is highly different, and so is the growth rate represented by its derivative. In Fig. 1(b), two main effects are apparent: for later bubbles, the plateau level of the derivative is smaller and the subsequent rate of change with time is weaker. There is therefore a strong influence on the mass transfer mechanism.

This influence is caused by a mechanism called 'gas depletion'. While a bubble grows, it extracts gas from its surroundings. Once the bubble detaches, it takes the extracted gas away with it. This gas cannot be compensated instantaneously with gas coming from regions far away from the bubble, since it has to obey the same diffusion laws that govern the growth of the bubble. Consequently, each successive bubble will grow in a region that has less available gas than before. This will lead to an influence on the mass transfer mechanism, thus decreasing the growth rate and increasing the time to reach the detachment radius.

3. Conclusions

We have argued that successive bubble growth causes a depletion area around the bubble nucleation spot, which will affect the growth of subsequent bubbles. Mass transfer is highly affected by this depletion, such that it becomes significantly smaller as more and more bubbles grow. The *Epstein-Plesset* equation, Eq. (3), and the modification correcting for the presence of the substrate, Eq. (4), are thus only valid for the first few bubbles, whereas for later bubbles the depletion needs to be taken into account. In a future article we will deal quantitatively with these depletion effects, introducing a new parameter which accounts for the lower apparent concentration that bubbles encounter while growing on a succession.

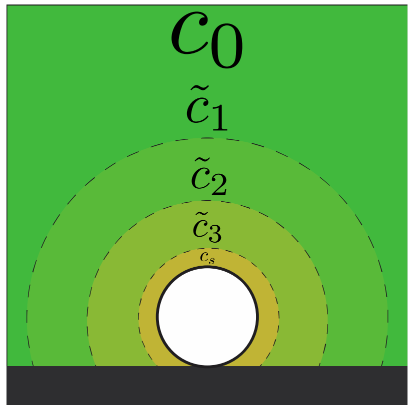

Fig. 2: Once a bubble detaches, it leaves behind a volume that is depleted of gas. The next bubble in the succession will encounter an apparent different local concentration of gas. Thus, its growth will be highly affected and the time it will take to detach will increase considerably.

4. Acknowledgements

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EUROPEAN MECHANICS SOCIETY

EUROMECH Conference Reports

EMMC15 – 15th European Mechanics of Materials Conference

The 15th European Mechanics of Materials Conference (EMMC15) was held in Brussels, Belgium from 7 to 9 September 2016. It gathered together researchers who have a common interest in the mechanics of materials but possibly have different backgrounds (mechanical or civil engineering, physics, chemistry etc.). Hence contributions included experimental investigations, theoretical models and advanced computational methods aiming at an improved understanding of materials mechanics at various length scales.

Symposia

Altogether 17 symposia were organized, with up to 7 parallel sessions. The EMMC scientific committee appointed the symposia organizers. The symposia titles, organisers and numbers of contributions are listed below:

1 Mechanics of polymers and metallic glasses - Experiments and models
Rafael Estevez (Grenoble INP, France) & H. van Dommelen (TU Eindhoven, NL)
27 contributions

2 Mechanics of composites - Experiments and models
Carlos Gonzalez (IMDEA Madrid, Spain) & Soraia Pimenta (Imperial College, UK)
39 contributions

3 Mechanics of metals - Experiments and models from nano to micro
William A. Curtin (EPFL, Switzerland) & Erica Lilleoden (HZ Geesthacht, Germany)
33 contributions

4 Ductile damage and fracture
Jonas Faleskog (KTH Stockholm, Sweden) & Thomas Pardoen (UCLouvain, Belgium)
21 contributions

5 Fatigue, reliability and lifetime predictions
S. Schmauder (IMWF Stuttgart, Germany) & N. Saintier (ENSAM Bordeaux, France)
20 contributions

6 Failure of quasi-brittle materials
Claudia Comi (Politcenico di Milano, Italy) & Bert Sluys (TU Delft, The Netherlands)
31 contributions

7 Functional and architectured materials (including additively manufactured materials)
Andreas Menzel (TU Dortmund, Germany) & Stephan Rudykh (Technion, Israel)
20 contributions

8 Coupled mechanics and biomaterials
Christian Hellmich (Vienna Univ., Austria) & Gerhard Holzapfel (Graz Univ., Austria)
23 contributions

9 Mechanics of interfaces and evolving microstructures (incl. phase transformation and recrystallization)
Roland Logé (EPFL, Switzerland) & Patrizia Trovalusci (Sapienza Univ. of Rome, Italy)
23 contributions

10 Contact, friction and mechanics of discrete systems (incl. tribology, scratch, indentation, adhesion and granular flows)
Stefan Luding (UT Twente, The Netherlands)
8 contributions

11 Experimental mechanics (incl. advanced full-field deformation measurements and parameter identification)
Magnus Ekh (Chalmers UT, Sweden) & Johan Hoefnagels (TU Eindhoven, NL)
18 contributions

12 The mechanics of highly porous materials: experiments and modelling
Eric Maire (INSA Lyon, France) & Patrick Onck (Rijksuniversiteit Groningen, NL)
15 contributions

13 Advanced modelling techniques: higher-order continua
S. Bargmann (HZ Geesthacht, Germany) & S. Forest (Mines ParisTech, France)
14 contributions

14 Advanced modelling techniques: multi-scale and scale bridging
V. Kouznetsova (TU Eindhoven, NL) & Bob Svendsen (MPIE Dusseldorf, Germany)
32 contributions

15 Advanced modelling techniques: Stochastics in materials mechanics
R. Cottereau (Ecole Centrale Paris, France) & F. Willot (Mines ParisTech, France)
12 contributions

16 Advanced modelling techniques: phase field approaches
Benoît Appolaire (ONERA, France) & Ralf Müller (TU Kaiserslautern, Germany)
22 contributions

17 Mechanics of Materials in Aeronautics (E-Caero 2)
Ugo Galvanetto (University of Padova, Italy) & Pedro Diez (UPC Barcelona, Spain)
6 contributions

Plenary Lecturers

The plenary lecturers were:

1. Prof. P. Gumbsch (KIT, Germany)
   "Evolution of microstructure underneath a sliding contact";
2. Dr. R. Peerlings (TU Eindhoven, Netherlands)
   "Micromechanics of fracture initiation in multiphase materials";
3. Pr. G. Dehm (MPIE Dusseldorf, Germany)
   "Mechanical Testing at Microscopic Length Scale".

EMMC Best Student Presentation Award

19 contributions were selected from the different symposia.
The prize was finally awarded to Laura Zorzetto for her oral presentation entitled "Auxetic inclusions in cellular solids allow tailoring Poisson's ratio and enhancing stiffness".

EFMC11 – 11th European Fluid Mechanics Conference

Organisation and Participation

The 11th European Fluid Mechanics Conference was held in Seville, Spain, from 12 to 16 September 2016. The scientific programme covered all aspects of Fluid Mechanics, from biological flows to aerodynamics and from microfluidics to environmental flows and combustion. It included eight plenary lectures, delivered consecutively in groups of two at the beginning of each day of the conference, six different minisymposia with 80 presentations in total, and over 430 regular presentations divided into eight parallel sessions. The social program included a cocktail reception on Monday 12th during a cruise along the Guadalquivir river and a gala dinner on Thursday 15th at a restaurant offering the best views of Seville.

EFMC11 brought together 580 scientists coming from all over the world to a place, Hotel Barceló Renacimiento, chosen for its fresh and singular architecture and for its rich gastonomy. It was our intention to create the conditions for Seville to become for a few days the scene of an intense exchange of knowledge and cutting edge ideas related to all aspects of fluid dynamics in a comfortable environment. The conference ran smoothly, and everyone was very pleased with the organization of the talks, with the venue, with the organization of the meals, with the gala dinner and also with the social programme. The EFMCC congratulated the Chair of the conference and his team for the good organization and for the beautiful venue. The minisymposia were very well attended.

Grants to Young Scientists

The participation of young students was encouraged, and support grants were given to 27 scientists aged below 35 (4,050 Euros in total) so that they could attend the conference. All the applicants who showed their motivation and willingness to participate by submitting a short CV, were given grants. Of the 580 participants, 272 were new members of EUROMECH. Retained Excel files include the list of registered participants as well the list of new members, whose affiliation can be deduced through their email addresses.

Prize Papers

After the conclusion of all contributed sessions, and before the beginning of the closing ceremony, the EFMCC evaluated the outstanding presentations by scientists aged below 35. The winners were agreed unanimously.

They were:

1 Alvaro Moreno Soto et al.
"Gas depletion through single gas bubble growth and its effect of subsequently growing bubbles" (0099 of the program)

2 Pablo Gutierrez et al.
"Attenuation of resonant gravity waves by vortices" (0411 of the program)

Conference Costs

The total budget for the conference was approximately 240,000 Euros. 8,200 Euros + taxes were transferred back to EUROMECH, including 1,000 Euros seed money. Therefore, the organization of the conference was at no cost to EUROMECH, notwithstanding grants to young scientists totalling 4,050 Euros.

ESMC9 – 9th European Solid Mechanics Conference

The 9th European Solid Mechanics Conference was held in Madrid, Spain from 6 to 10 July 2015. The Local Organizing Committee (LOC) was chaired by Prof. Javier Llorca, while the scientific organization of ESMC9 was the responsibility of the Euromech Solid Mechanics Conference Committee (ESMCC), chaired by Prof. Alberto Corigliano.

Organisation and Participation

The general organization of ESMC9 was managed jointly by the ESMCC and the LOC, with a series of teleconferences. Logistics and budget management were the responsibility of the LOC; a parallel report by Prof. Llorca contains the final figures concerning participation and budget.

During preliminary discussions about the framework of the ESMCC it was decided that a high scientific standard and the participation of young researchers would be principal objectives of ESMC9. The ESMCC invited a general lecturer and 5 plenary speakers, all having outstanding reputations in their subjects. It was decided to organize Mini Symposia (MS) using a top-down approach. 7 areas of interest were selected and well-known researchers were invited to collaborate in the organisation of various MS in specific areas; this process led to the organization of 44 MS in all, with limited overlap of scientific subjects. The conference was completed with 8 general sessions, selected and organized directly by the ESMCC members; the ESMCC also decided to avoid poster sessions.

Participation at ESMC9 was impressive, with almost 900 presented papers and a total of about 1,000 participating delegates (see final report by Prof. Llorca). During ESMC9, the Solid Mechanics Prize, new EUROMECH Fellowships and the Young Researcher Awards were presented. Finally, after preliminary proposals and discussions in the ESMCC, the responsibility of the organization of ESMC10, to be held during 2018 at Bologna. was given to Prof. Davide Bigoni of the University of Trento and Prof. Francesco Ubertini of the University of Bologna.

Concluding Remarks

The chairman congratulated the organisers on the overall succes of ESMC9, but noted some areas for improvement in the future:

1 The way in which the Young Researcher Awards are selected;

2 Choice of the day on which the Prizes, Fellowships and Awards are delivered;

3 The review process for the General Sessions.

ETC15 – 15th European Turbulence Conference

The 15th European Turbulence Conference was held in Delft, the Netherlands, from 25 to 28 August 2015. The first announcement of ETC15 was made in September 2014. The initial deadline for abstract submission was 5 January 2015. Eventually the deadline was extended for 1 week and a total of 522 abstracts were submitted by 12 January 2015.

Classification of Topics

As a starting point, the classification into topics was the same as that used by the previous ETC14 conference in Lyon. During the electronic submission stage of the abstracts the submitters were asked to give at least one but preferably two or three keywords for their submitted abstract. These keywords were used by the organising committee (Prof Lohse, Prof. Bodenschatz, Prof. B.J. Boersma Prof. C. Casciola, Prof. S. Fauve, Prof. D. Henningson, Prof. R. Kerswell, Prof. S. Malinowski & Prof. N. Sandham) in the reviewing process for the papers.

Due to very large numbers of papers which were classified as wall bounded flows, vortex dynamics and instability and transition, some of the papers had to be reclassified, for instance to sessions focusing on Large Eddy Simulations or transport and mixing. Inevitably, submitters were not always happy with this. The sessions on instability and transition, and wall-bounded flows, gained a lot of attention during the conference and stimulated lively discussion. Traditional engineering topics, like turbulent combustion and acoustics, were not as popular. Clearly, there was a shift from engineering-oriented papers to more fundamental papers. This could be a point of attention for subsequent conferences.

Organisation and Participation

The organising committee reviewed all the papers and 430 abstracts were selected for presentation during the conference. After acceptance, 19 submissions were withdrawn for various reasons. The conference was attended by 440 participants from more than 25 countries. The programme consisted of 8 parallel sessions spread over 3.5 days. The detailed programme for the conference will remain available online at http://www.etc15.nl/program.
The abstracts are available online on the conference website or via the library of Delft University of Technology.

Young Scientist Prizes

Young scientist prizes of 500 Euros each were awarded to:

1. Nicholas Ouellette for his presentation
   "Long-range ordering of turbulent stresses in 2D turbulence";
2. Iman Lashgari for his presentation
   "Flow regimes of inertial suspensions of finite size particles".

EUROPEAN MECHANICS SOCIETY

EUROMECH Colloquia Reports 2016

EUROMECH Colloquium 571
"Jet noise modelling and control"
28 – 30 September, 2016, Palaiseau, France
Chairperson: Lutz Lesshafft
Co-Chairpersons: Anurag Agarwal, Peter Jordan

Recent progress in jet-noise research has seen hydrodynamic stability theory occupy an increasingly central place. This is largely due to developments in modern numerical and experimental tools, and a closer association of these has clarified the extent to which linear theory can describe wavepackets in turbulent jets. EUROMECH Colloquium 571 succeeded in presenting a broad and rather complete overview of the state of the art, both from physical and technical viewpoints. Over the course of three days, a certain consensus became apparent regarding the appropriate theoretical framework for jet noise.

40 researchers participated in the colloquium, among them 18 PhD students, and a large number of leading experts in the field were present. Participants came from institutions in five different countries of the European Union (Belgium, France, Germany, Italy and The UK) as well as a number from Brazil, Russia and the USA. There were 32 oral presentations in total, spread out over the three days of the colloquium, plus three lively open-discussion sessions of about one hour each. The keynote lecture was given by Ulf Michel (CFD Berlin). All regular presentations were 20 minutes long.

EUROMECH Colloquium 571 was preceded by a two-day lecture series on "Measurement, simulation and control of subsonic and supersonic jet noise", organised by the Von Karman Institute. This event was held at a venue in the neighborhood of the Ecole Polytechnique campus.

The majority of the work presented involved association of data from either high-fidelity numerical simulation or experiments (or both) with kinematic or dynamic modelling approaches, the former being based on the acoustic analogy. With respect to the latter, traditional "local" stability analysis featured in a number of studies, where its capacity to provide physical insight regarding trends observed in data or "global" analyses was borne out. "Global" stability studies were almost exclusively performed in the resolvent (alternatively input-output or frequency response) framework, and this emerged as one of the focal points of Colloquium 571.

There was a consensus that the role of turbulence in wavepacket modelling goes beyond its role in producing the mean flow, and a recognition that it activates many acoustically important wavepacket traits via the non-normality of the linear operator. A small number of contributions from the colloquium will be selected for publication in a special issue of the "Comptes Rendus de l'Academie des Sciences" (C. R. Mecanique).

The feedback from participants was extremely positive. Despite a dense scientific programme, social interaction took place during coffee breaks, a dinner banquet and a cocktail reception. Financial support was provided by Euromech, IUTAM, Ercoftac, E-CAero2, LaSIPS and Ecole Polytechnique.

EUROMECH Colloquium 572
"Constitutive Modelling of Soil and Rock"
22 – 24 February, 2016, Innsbruck, Austria
Chairperson: Gunter Hofstetter
Co-Chairpersons: Alessandro Gajo, Dimitrios Kolymbas

Prediction of the mechanical behaviour of soil and rock is of great interest in geotechnical engineering. For modelling the complex behaviour of soil and rock a large number of advanced material models has been developed. They are based on different theories, like plasticity theory, damage mechanics and combinations of two additional theories: hypoplasticity and, recently, barodesy.

The aim of EUROMECH Colloquium 572 was to review the various existing constitutive models for soil and rock and to assess the potential and drawbacks of the different approaches in numerical simulations of geotechnical problems. Colloquium 572 was attended by 43 participants from 11 countries. A relatively broad spectrum of topics, related to numerical modelling of soil and rock, was covered in 24 presentations, which were organized in the following seven sessions:

1. Fundamental aspects of constitutive modelling (3 lectures);
2. Models of organic soils and clays (2 lectures);
3. Coupled and multiphase constitutive models (5 lectures);
4. Extensions of classical models (3 lectures);
5. Modelling of localisation (2 lectures);
6. Hypoplasticity and barodesy (4 lectures);
7. Modelling of rock, rock mass and rockfill (5 lectures).

The lectures led to lively and sometimes passionate discussions on the pros and cons of the approaches presented. The continuum models for soil and rock cover a large spectrum from very simple linear elastic and perfectly plastic models to sophisticated models with several yield surfaces, including complex hardening and softening laws. There is no consensus on the required complexity of the selected model. Ivo Herle demonstrated for an excavation process that model predictions can differ qualitatively for realistic stress paths. A further problem, addressed by several participants, is the large scatter of experimental data concerning the constitutive behaviour of soil and rock. In many cases this makes it very difficult to select a proper constitutive model. In addition, as pointed out by David Muir Wood, testing conditions may not be sufficiently severe to reach the limit state in all respects and this will influence the values of the mechanical properties reached at temporary critical states. An attractive alternative to classical continuum models for soil, the so-called multilaminate models, was presented by H. Schweiger. In two lectures by Aldo Madaschi and Christina Jommi, special aspects of modelling the behavior of peaty soils were addressed.

Coupled and multi-phase constitutive models were presented in different contexts, like unsaturated/saturated soil (P. Gamnitzer), chemo-mechanical interactions (A. Gajo), thermo-mechanical interactions (F. Cecinato), nonlocal integral-type models in combination with viscoplasticity for simulating strain softening (L. Sanavia) and the determination of transport properties of fractured rock (G. Meschke). Such models have great potential for enhancing the range of phenomena to be described, however, at the expense of a considerably higher degree of complexity for experimental investigations and far greater effort for developing efficient and robust numerical algorithms, both at the integration point level and the structural level.

Numerical models for shear localization and hydraulic fracturing were presented, based on the strong discontinuity approach. They were formulated within the framework of finite elements with embedded discontinuities (A. Alsahly) and the framework of the extended finite element method (J.M. Huyghe, G. Meschke). They still pose challenges, especially for three-dimensional applications. Extensions of classical models were presented for quite different applications, like artificial ground freezing (C. Vrettos), the fabric evolution of sands with anisotropic material behaviour (A. Papadimitriou) and for demonstrating similarities between the so-called hydrodynamic theory and hypoplasticity (M. Liu).

A special session on new approaches in hypoplasticity and barodesy was devoted to Dimitrios Kolymbas on the occasion of his retirement to emeritus status in 2017. In this session, D. Masin presented an approach for incorporating any predefined form of asymptotic states into the hypoplastic model structure, G. Medicus described the application of barodesy to model the mechanical behavior of clay and W. Fellin focused on adaptive time integration schemes of constitutive rate equations for efficient implementations of constitutive models into FE codes. The session was finished by the laudatio for Dimitris Kolymbas by G. Gudehus.

The lectures on modelling of rock, rock mass and rockfill comprised topics like models of coarse grained materials for rockfill dams (P.Y. Hicher), modelling approaches for weathered rockfill materials (E. Bauer) and calcarenite rocks subject to weathering (C. Tamagnini), and constitutive modelling of rock (D. Unteregger) and of the respective cyclic behaviour (B. Cerfontaine).

At the end of the colloquium, the excursion to the construction site "Wolf" of the Brenner Basetunnel, close to the Italian border, served as a case study for the big challenges related to both the execution of such large-scale geotechnical projects and realistic numerical predictions of the of the complex behaviour of the ground-support system in tunnelling.

Summarising, EUROMECH Colloquium 572 can be viewed as a further step in obtaining a valuable basis for selecting problem-specific material models for soil and rock and in intensifying the interaction between experts in the fields of continuum mechanics, numerical modelling and geotechnical engineering. The organisers received very positive feedback on the scientific programme, the excursion and the organisation of the colloquium. In particular, participants appreciated the format with comprehensive lectures and sufficient time for discussions immediately after the presentations and during breaks. Some participants encouraged the organisation of a further colloquium on this topic in the future.

EUROMECH Colloquium 576
"Wind Farms in Complex Terrains"
8 – 10 June, 2016, Stockholm, Sweden
Chairperson: Dan Henningson
Co-Chairperson: Henrik Alfredsson

The increasing need for renewable energy in Europe has led to the growth of wind farms both off-shore and over complex terrains. For the latter, hills, forestry and general surface inhomogeneities make the wind-resource assessment more challenging than in off-shore sites. There are several open issues that are now being investigated by the wind-energy community to improve the current evaluation methodologies and, simultaneously, to increase the physical understanding of such complex flow scenarios. EUROMECH Colloquium 576 was motivated by the need to bring together researchers actively working in the wind-energy field, to compare the available experimental, numerical and analytical techniques, and to propose new improvements. Wind energy is a relatively new field that combines both fundamental and applied fluid dynamics.

In total, 50 participants were present at Colloquium 576: 16 from Sweden, 9 from The USA, 8 from Germany, 5 from Denmark, 3 from The UK, 2 from Italy and Belgium, 1 from Canada, Israel, Netherlands, Norway and Portugal. Various fundamental and applied aspects of the site-assessment process were discussed, with a particular focus on the effects of complex terrains (forests, hills, inhomogeneous surface roughness, etc.) on the available wind resource and prediction using current evaluation methods. Recurring issues during discussion were:

1. **Wind turbine wakes**: several methods to simulate wind-turbine wakes and their dynamics were discussed. There is still a visible gap between what industry is currently using and the new research methods. Improved understanding of wake dynamics is leading to faster and more reliable methods and there is clear interest from the industrial world in new developments.
2. **Forestry and topography**: many talks reported experimental results and numerical predictions concerning the effects of forestry and/or terrain complexity. It is clear that more high-quality data are required to develop a better understanding of how flow features near the ground influence wind-turbine wake behaviour.
3. **Atmospheric stability**: the continuous growth of the wind-turbine hub height leads to increasing importance of stability effects, which influence the wake dynamics and the energy production from wind farms. At least 20% of the talks

discussed stratification effects, in contrast to just 5 years ago when stratification effects were seldom discussed.

4 **Wind farm control**: several methods are now adopted to control wind farms in order to alleviate fatigue loads or to produce more power. Several control approaches were discussed and compared mostly with numerical simulations, while experimental data from existing farms were reported.

5 **Synthetic turbulence**: with the growth of computational resources, large-eddy simulations have become the most reliable tool to simulate the wind flow over complex terrains with turbines. However, an initial velocity field must be prescribed, ensuring that some characteristic features of the wind field are kept. Several methods have been compared independently by many researchers but further work is needed.

6 **Atmospheric measurements**: measurements in the atmosphere have for a long time been made mostly with cup and sonic anemometers. LIDAR measurements now allow superior spatial coverage and provide information about turbulence characteristics as well as the mean flow. However, their precision is unclear and a comparison with mast data is still required to identify their reliability.

A 100-page book of abstracts was distributed amongst the participants. Many of them appreciated the meeting for its coverage of many interesting topics related to wind energy. The financial support of the Linné FLOW Centre, the Swedish Research Council (VR) and STandUP for Wind is gratefully acknowledged.

EUROMECH Colloquium 580
"Wind Farms in Complex Terrains"
11 – 13 July, 2016, Grenoble, France
Chairperson: Guillaume James
Co-Chairpersons: Chiara Daraio, Alexander Vakakis

EUROMECH Colloquium 580 focused on the nonlinear dynamics of granular media (disordered packings or ordered granular metamaterials) and mechanical metamaterials from a broad perspective. This covered experiments, physical modelling, numerical and analytical methods, applications and connection with industrial problems such as modelling of ballasted railway tracks, silo honking and vibration absorbers in vehicles. The colloquium brought together 54 participants from 11 countries, mixing researchers from the applied mathematics, engineering, nonlinear physics and mechanics communities. The programme comprised 38 talks and 11 poster presentations, leading to many stimulating discussions and exchanges of ideas among participants.

It was extremely useful for the metamaterials community to learn about continuum models and numerical methods developed in the context of disordered granular media or more general systems of interacting particles, and to be aware of up-to-date experimental approaches such as network-based characterisation of force chains. In addition, some nonlinear phenomena which have been discussed in the framework of disordered granular materials may lead to future design principles for metamaterials. Conversely, granular metamaterials provide a simplified framework for investigation of grain- or meso-scale processes in disordered granular media, with the goal of understanding larger-scale phenomena. In this way, some topics which have been discussed in the context of ordered metamaterials and nonlinear mechanical networks could provide interesting new theoretical approaches to achieve deeper insight into the physics of granular matter. For example, theoretical and numerical methods for prediction of nonlinear energy transfer between vibrational modes could find application in analysis of vibration in disordered granular media near the onset of jamming.

The interaction between groups working on mechanical metamaterials on the experimental side and nonlinear lattices on the theoretical side was also extremely fruitful. This connection arises naturally because different types of nonlinear lattices, such as the Fermi-Pasta-Ulam and discrete Klein-Gordon models or mass-in-mass chains, can be realised through various types of mechanical metamaterials reviewed during the conference: granular chains, woodpile phononic crystals, networks of snapping structures, magnets or Helmholtz resonators. As a consequence, different nonlinear wave phenomena investigated theoretically can now be realised experimentally. Colloquium 580 provided a forum to review useful theoretical concepts, suggest design principles inspired by theory and unveil interesting new theoretical problems. As described in several talks, the high tunability of certain metamaterials can lead to new dynamical effects and raise interesting theoretical questions.

Challenging new directions reviewed in the colloquium include the analysis of adhesion effects in microscale or magnetic granular crystals, nonlinear wave phenomena involving rotations of grains, two and three-dimensional wave propagation in granular crystals, interaction of continuous elastic media with nonlinear oscillators and breaking of time-reversal symmetry. Another important concept rewiewed during the colloquium is the notion of topologically protected modes, preserved under smooth deformations or imperfections of a metamaterial. Applications of concepts discussed during the colloquium concerned shock mitigation, vibration isolation, wave guiding, nonlinear diodes, mechanical logic gates and detection of cracks.

The colloquium organising committee received highly positive feedback from many participants. EUROMECH Colloquium 580 is expected to foster new collaborations between researchers with different areas of expertise and generate notable contributions to the field. The organisers are grateful to all contributors for the quality of their presentations and active participation, and to EUROMECH and INRIA for essential support.

EUROMECH Colloquium 581
"Dynamics of concentrated vortices"
30 May – 1 June 2016, Novosibirsk, Russia
Chairperson: Sergey Alekseenko
Co-Chairpersons: Jens N. Sørensen, Valery Okulov

Concentrated vortices of the vortex filament type are a key element in hydrodynamics. They play a fundamental role in the formation of the flow structure and the mechanisms of transport processes both at the micro- (quantum turbulence) and the meso- (coherent structures in turbulent flows; tornado) scales, and even in astrophysical systems.

The main focus of EUROMECH Colloquium 581 was on the specific features of vortex flows with vorticity concentration and the corresponding physical phenomena. The goal was to allow an effective exchange of ideas on recent developments in the field of concentrated vortex dynamics. Topics discussed included dynamics of vortex filaments, spiral vortices, the effects of instability and waves on vortices, vortex breakdown, vortex reconnection, swirling flames, vortices in two-phase flow, and quantum vortices. The latest methods of theoretical and numerical simulation of concentrated vortices, as well as experimental diagnostics and applications in the energy technologies and aerospace engineering, were presented.

There were 51 participants and about 52 presentations.
These included six keynote lectures, delivered by:

1. Thomas Leweke (Marseille, France);
2. Renzo Ricca, (Lombardy, Italy);
3. Natalia Berloff (Cambridge, United Kingdom);
4. William George (London, United Kingdom);
5. Yasuhide Fukumoto (Kyushu, Japan);
6. Vladimir Shtern (Houston, USA).

During the sessions there was time for discussions; most of them were continued during coffee-breaks as well as during a visit to scientific laboratories of the Kutateladze Institute of Thermophysics. The topics considered in the talks and discussed afterwards were:

1. **Theoretical and experimental methods for modelling swirl flows with concentrated vortices**

Results of experimental observation of the helix-like cavitating vortex were presented. The phenomenon of vortex reconnection between coils of the same helical vortex was experimentally registered for the first time. Two different scenarios of the vortex reconnection were found: reconnection with separation of an isolated vortex ring and formation of a system consisting of the vortex ring, geared with a helical tube. Much attention was paid to development of measurement techniques for swirl flows – PIV and LDA as well as to the methods of velocity field analysis such as Proper Orthogonal Decomposition, and vortex recognition methods.

2 **Concentrated vortices (dynamics, waves, helical vortices, vortex breakdown, PVC)**
The mechanisms of vortex breakdown (VB) have been discussed over more than a half-century with no consensus achieved. Participants at the colloquium argued that VB occurs via the swirl-decay mechanism. The known diagram by Escudier for VB in a cylindrical container with a rotating lid was essentially extended in terms of parameter ranges and types of VB. Data were presented on the transition from the circular geometry of a container to a polygonal shape, up to square cross-section. The VB existence versus 'Re – aspect ratio' curve shifts to the area of higher Reynolds numbers and lower aspect ratio as the number of polygon angles decreases. Participants also discussed some recent incorrect approaches for analysing helical vortex motion.

3 **Swirl flames. Heat transfer in swirl flows. Two-phase swirl flows**
The role of vortex structures in different physical processes such as combustion, transfer of light or heavy phases and heat transfer was discussed during the colloquium. Some new effects of non-uniform physical fields on the behaviour of vortices were revealed. The possibility of an analytical approach for adequate description for buoyancy vortex ring characterisation was demonstrated.

4 **Dynamics of quantized vortices in superfluids**
Among new findings in the area of superfluid vortices was the effect of mutual deformation of co-axial helical and rectilinear vortices. The effect is similar to the leapfrogging of vortex rings, but here the helical vortex transforms to rectilinear and back again, and the process repeats. Participants at the colloquium provided new knowledge about fundamental aspects, statistical data on superfluid turbulence and the possibility of modelling classical turbulence by quantized vortices in superfluids.

5 **Concentrated vortices in technical applications**
One of the sections of the colloquium that attracted particular interest was devoted to observation and description of concentrated vortices in real technical devices. A primary application is to vortex systems in wind turbines and hydroturbines. Recent achievements in this area became possible through fruitful cooperation of Danish, Russian, Canadian, Japan, French, Dutch, Swiss and Romanian researchers. At the same time, the vortex community recognised important historical studies on concentrated vortices (including Joukowski in Russia, Da Rios in Italy, Betz in Germany and Kawada in Japan).

During final discussion, participants agreed that in spite of considerable achievements in research on concentrated vortices there exist too many "white spots". In order to colour them in, it would be appropriate to organise a similar meeting at some time between 2019 and 2021. Many participants said how much they had enjoyed the colloquium. Some commented that they had not expected such high levels of experimental, numerical and analytical study in such a remote Siberian region. Some of them talked about their aim to visit Russia, Siberia and well known Academgorodok. The organisers thank EUROMECH for making Colloquium 581 possible, and for all the financial and organisational support. They are also grateful for financial support from the Russian Foundation for Basic Research.

EUROPEAN MECHANICS SOCIETY

EUROMECH Colloquium 583
"Scientific and technological challenges in offshore vertical axis wind turbines"
7 – 9 September 2016, Delft, The Netherlands
Chairperson: Carlos Simão Ferreira
Co-Chairperson: Uwe Schmidt Paulsen

After thirty years of successful implementation of Onshore Wind Farms based on Horizontal Axis Wind Turbine (HAWT) technology, the wind energy industry faces new challenges in developing offshore wind farms. Although most of the development is expected to be offshore, our current level of wind turbine technology, based on the HAWT concept, does not yet economically meet the requirements, driving the cost of offshore wind energy 70%-85% larger than onshore wind energy. For floating offshore wind energy, the challenge is even larger. The Vertical Axis Wind Turbine (VAWT) is a promising solution for floating offshore wind energy due to its scalability, robustness, reliability, simplicity of installation, low centre of mass and insensitivity to yaw.

The VAWT is, however. both a scientific and an engineering challenge. Its aerodynamics are defined by a 3D unsteady asymmetric actuator volume, where blade-vortex interaction and dynamic stall are predominant. Currently, validated models at airfoil, blade, rotor, and wake scale are unavailable. The lack of prototypes and test beds at full scale means that the few existing aero-elastic models are yet to be validated. Due to its 3D shape and asymmetric flow field, the design space is still mostly unexplored. This challenge is further increased by the application of a VAWT to a floating concept, where floater design and dynamics, including wave loading and mooring are key.

There is now an emerging community of researchers and industrial developers for floating VAWT, new developments in industrial prototypes, several national and EU funded projects on offshore VAWTs, and an increasing number of publications every year. These developments warranted a meeting of experts to identify key challenges and developments in design, models and scientific research. The colloquium brought together this community for the first time under a dedicated event to VAWT technology, science and research.

Participants travelled from all over Europe, Asia, and the Americas to participate in EUROMECH Colloquium 583. The colloquium was organized by D. Todd Griffith (Sandia National Laboratories), Michael Borg (Technical University of Denmark), and Bruce LeBlanc (Delft University of Technology). The main topics discussed were:

1. Aerodynamics and aeroacoustics, including wake modeling and analysis;
2. Structural design and aero-elasticity; Drivetrains and major components;
3. Offshore support structures;
4. Novel architectures and configurations;
5. System level design studies and optimization;
6. Cost analysis and making a business case for VAWTs;
7. Industry activities and technology demonstrations.

The event was unanimously considered a major success and agreements were made to reconvene in two years time to update research and highlight conclusions of current research and development activities.

EUROPEAN MECHANICS SOCIETY

EUROMECH Colloquium 584
"Multi-uncertainty and multi-scale methods and related applications"
14 – 16 September 2016, Porto, Portugal
Chairperson: Andrade Pires
Co-Chairperson: Chenfeng Li

The development of multi-uncertainty and multi-scale models has received significant attention over the last decade. New mathematical formulations and numerical solution strategies allied to the increase in computational power/cost ratio have fostered a dramatic growth in this rapidly expanding field. Research activity in this area has been devoted to the development and combination of different analytic tools and computational methods for application in fields as diverse as metal processing, composite materials, oil & gas development, fuel cell technology and biomedical tissue engineering. Such developments have played a central role in the understanding of the interaction among multi-physics and multi-uncertainty phenomena taking place at multiple scales in space and time. Nevertheless, new challenges continue to emerge, driven mainly by advanced industrial applications. These outstanding challenges continue to drive leading edge research in computational mechanics and computational engineering.

It is also true that in many scientific and engineering problems, the challenges associated with multi-scale and multi-uncertainty often occur together and may be coupled. Therefore, a synthesised solution approach is required. EUROMECH Colloquium 584 targeted the latest advances in the modelling of multi-uncertainty in multi-scale problems. The main aims of the colloquium were:

1. To present the state-of-the-art in this field by showing the most recent developments by leading experts;
2. To provide a forum for discussion of current research trends and future challenges in computational multi-uncertainty and multi-scale modelling.

Colloquium 584 had 38 presentations and about 50 participants. Key-note lectures from seven invited speakers must be highlighted, given their valuable contributions to the success of the colloquium:

1. Marc Geers, Eindhoven University of Technology: "Modelling of interfaces in engineering materials across the scales";
2. Javier Oliver, Technical University of Catalonia (UPC/Barcelona Tech) and International Centre for Numerical Methods in Engineering (CIMNE), Barcelona, Spain: "Hyper-reduced order modelling (HPROM) in multiscale fracture";
3. Michael Beer, Institute for Risk and Reliability, Leibniz University Hannover, Germany; Institute for Risk and Uncertainty, University of Liverpool, United Kingdom; Shanghai Institute of Disaster Prevention and Relief, Tongji University, China: "Coherent models for aleatory and epistemic uncertainties";
4. Wing K. Liu, Northwestern University: "Modelling and simulation challenges in materials design for additive manufacturing applications";
5. Ron Bates, Rolls Royce plc: "Multiscale robust design for product development";
6. Manolis Papadrakakis, Institute of Structural Analysis & Antiseismic Research - National Technical University Athens, Greece: "High performance methods for non-intrusive and intrusive multiscale stochastic simulations";
7. Eduardo de Souza Neto, College of Engineering, Swansea University, UK: "The method of multiscale virtual power: a variational recipe for derivation of RVE-based multiscale models".

From the above presentations and the interesting discussions they generated, along with other authors´ presentations, it was possible to develop stimulating ideas with the following highlights.

1. Multi-scale modelling, based on computational homogenisation, sets a very demanding challenge. The multiplicative (through-scales) computational cost might make the multi-scale analysis unaffordable for real problems involving a large number of RVE re-evaluations, as in non-linear models and time-advancing analysis. For the forseeable future, intensive computing techniques seem inadequate to address the computational costs involved in these type of problems. Therefore, algorithmic speed-up techniques that reduce the computational cost of the RVE model by means of specifically devised algorithms appear as a suitable remedy.
2. Uncertainties in structural and system parameters and in environmental conditions and loads are challenging phenomena in engineering analyses. They require appropriate mathematical modelling and quantification to obtain realistic results when predicting the behaviour and reliability of engineering structures and systems. The modelling and quantification are complicated by the characteristics of the available information, which involve, for example, sparse data, poor measurements and subjective information. This raises the question whether the available information is sufficient for probabilistic modelling. The framework of imprecise probabilities provides a mathematical basis to deal with these problems, which involve both probabilistic and non-probabilistic characteristics of information. A common feature

of the various concepts of imprecise probabilities is the consideration of an entire set of probabilistic models in one analysis.

3 The design and development of complex engineering products requires a structured Systems Engineering approach. This task can be broken down into the design of systems, sub-systems and components, all supported by detailed simulation models that validate the overall design against requirements. Evaluating these simulation models can be costly, and this cost can rise dramatically if the robustness of the system to uncertainty is to be assessed. There is great potential in reducing this cost by aligning these engineering models so that they are evaluated at an appropriate design scale and level of fidelity to address the question of component, sub-system and system validation as efficiently as possible.

4 One of the future trends identified is the development of new materials, which facilitate advancement of the world of design and manufacturing. Additive Manufacturing (AM) enables the printing of 3D complex geometries that are otherwise impossible to manufacture, such as a part within a part. AM comes in many different varieties for numerous material systems including polymeric, biological, cement-based, and metallic materials. These processes typically involve an accumulation of cyclic phase changes, such as melting and solidification of metallic particles, until the desired 3D geometry is achieved. This has major implications for concurrent material and product design, as it is possible using AM to adjust material composition for bulk property improvement or functional grading within the material. There is a strong need for robust and efficient modelling and computational approaches which improve predictive capabilities.

By providing a focused platform and a relaxing environment for face-to-face communications, the conference was well received by the participants and the wider research community. Valuable insights were developed through discussion panels and presentations. Participants with different backgrounds were keen to contribute their expertise. A special issue on "Multi-uncertainty and multi-scale methods and related applications", jointly edited by the conference chairmen, will be published by Engineering Computations. Plans have already been made to meet again in 2017, with a view to a biannual international event. We thank EUROMECH for all the support in making Colloquium 584 possible.