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UFAST

Unsteady effects of shock wave induced separation

FINAL PUBLISHABLE REPORT

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Project summary

Aligned with the needs of the aeronautics industry, the general aim of the UFAST project was to foster experimental and theoretical work in the highly non-linear area of unsteady shock wave boundary layer interaction (SWBLI). Although previous EU projects concentrated on transonic/supersonic flows, they did not examine unsteady shock wave boundary layer interaction. Important developments in experimental and numerical methods in recent years have now made such research possible.

The main cases of study, shock waves on wings/profiles, nozzle flows and inlet flows, provide a sound basis for open questions posed by the aeronautics industry and can easily be exploited to enable more complex applications to be tackled. In addition to basic flow configurations, control methods (synthetic jets, electro-hydrodynamic actuators, stream-wise vortex generators and transpiration flow) have be investigated for controlling both interaction and inherent flow unsteadiness.

The interaction unsteadiness is initiated and/or generated by SWBLI itself but it is often destabilised by the outer/downstream flow field. Therefore, the response of shock wave and separation to periodic excitations is of utmost importance and has been included in the research program.

Thus emphasis is focused on closely linked experiments and numerical investigations to allow the application of numerical results in the experiments and vice versa for the sake of identifying and overcoming weaknesses in both approaches.

Using RANS/URANS and hybrid RANS-LES methods, UFAST has cast new light on turbulence modelling in unsteady, shock dominated flows. Moreover, LES methods were applied to resolve the large coherent structures that govern SWBLI. This way, UFAST provided the “range of applicability” between RANS/URANS and LES.

Project objectives

Before UFAST, not enough had been done to accurately predict and control flows dominated by unsteady shock wave boundary layer interaction. Even where advanced CFD techniques were applied to predict the flow around full aircraft configurations, they only dealt with the steady flow features and often only extrapolated from incompressible/subsonic domains to transonic/supersonic flow regimes. It is obvious that there was a lack of understanding of the flow-physics involved in unsteady SWBLI phenomena. There was also clearly a need for appropriate modelling and – even more importantly – for a control of the flows in order to minimalise the physical risks for aircraft. This is the clear objective of the UFAST project. The few attempts of applying compressibility flow corrections in turbulence modelling proved insufficient in respect to the predictive capabilities of unsteady transonic flows. Moreover, attempts of ‘transposing’ turbulence modelling from incompressible flows also proved insufficient for the accurate prediction of buffeting and dip-flutter (examples: research program ETMA, Vieweg, Vol. 65; European research program UNSI, final report published by Springer, Vol. 81) with regard to the simulation of buffeting phenomenon and shock unsteady motion. More recently a hybrid DES (Detached Eddy Simulation) approach, i.e. an inherently 3D approach, was applied to the transonic flows around airfoils, indicating the crucial need for improvement of our understanding of flow-physics in order to modify the turbulence scales caused by unsteadiness and compressibility. Another objective of the UFAST project is to increase the efficiency of prediction methods.

There was a pertinent need to improve the predictive capability of CFD methodologies, such as URANS, (Unsteady Reynolds Averages Navier-Stokes), LES, (Large-Eddy Simulation), and hybrid RANS-LES approaches. The present UFAST project has delivered a deeper insight into the physics governing the unsteadiness of the shock, the shock/boundary layer interaction, the development of buffeting, together with a study on efficient methods for controlling these phenomena.

As the mentioned physical phenomena occur in high speed, i.e. transonic and supersonic flows both in external and internal aerodynamics, these lead to boundary layer separation which can cause structural damage and in all cases downgrades the efficiency of the aircraft or propulsion system. SWBLI can occur in supersonic air intakes and reduce their efficiency because the induced separation becomes strongly unsteady and can induce serious damage in the engine.

The interaction of turbulent eddies with shock waves causes the formation of very large eddies which propagate downstream of the interaction and become yet another source of broadband frequency noise. The simulation of such off-similarity and off-equilibrium phenomena delivers new information, particularly in cases where the scales of unsteadiness and/or of large coherent eddies play a dominant role. Furthermore, the modification of the turbulent scales in respect of the unsteadiness and compressibility effects within strongly separated regions is now better understood. UFAST has delivered an in-depth analysis of the aforementioned compressible flow phenomena using a triple approach (theoretical, experimental and numerical) helping to supply efficient, robust and easy-to-implement methods, for available prediction tools.

For these reasons, the UFAST project has delivered set of well focused experiments, relevant to the above mentioned flow-physics phenomena and the Data Bank of both experimental and numerical results. This provides a sound basis for work to be carried out in the future. It is accessible to other interested groups in Europe, but primarily of course to the aeronautics industry.

To summarise, the treatment of shock wave/boundary layer interaction involves joining together a number of different physical aspects:

i) High frequency unsteadiness occurring in the incoming boundary layer which is not clearly related to shock unsteadiness.
ii) Unsteadiness of the whole flow field induced by a forced shock oscillation.
iii) Unsteadiness of the separation bubble, which may be due to a flow field forced pulsation or may result from vortex shedding. In the latter case, the vortices produced in the separated zone are convected downstream often over large distances.
iv) Turbulence production (including strong compressibility effects) caused by the shock wave itself.
v) Formation of a new boundary layer downstream of the separation, more precisely downstream of re-attachment which is characterized by vortex interactions, but also by low-frequency unsteadiness that might be induced by the shock motion.
vi) Strong coupling through acoustic waves between the different phenomena.

This UFAST project has improved knowledge and expertise by delivering:

- Reference experiments focused on unsteady effects
- Improvement of existing numerical modelling methods
- Enhanced understanding of complicated physical phenomena.

To arrive at general conclusions regarding these complex and challenging issues most of the flow configurations in which shocks play a key role have been addressed. These could only be met by a sufficiently large consortium of organisations with appropriate skills and expertise in both experimental and theoretical research. And this was achieved in the UFAST project, where experimentalists and theoreticians collaborated closely to improve our understanding of SWBLI. This pooling of resources allowed us to achieve the upstream goals of the UFAST project. In the work there was a small degree of overlapping, which allowed for cross validation. The simultaneous gathering and categorising new results produced a reliable knowledge base.

The first objective of the UFAST project was to provide a comprehensive experimental Data Bank documenting both low frequency events and the properties of the large scale coherent structures in the context of SWBLI. It should again be stressed that before the project almost no experimental information had been available, especially in industrially relevant flow cases. Therefore flows in the important Mach number range going from transonic conditions to Mach number 2.25 were investigated. The measured flow configurations correspond to generic geometries that can be easily exploited in more complex geometries, such as airfoils/wings, nozzles, curved ducts/inlets, in other words, all important flow cases governed by normal and oblique shocks. This wide shock configuration platform was necessary to identify general interaction unsteady features. And it should be repeated that the realisation of this objective in a short space of time could only be achieved by involving a sufficiently large number of laboratories sharing an enormous amount of crucial experimental work.

The work was split into so-called "basic" (WP-2) and "control" (WP-3) cases, the latter carried out to provide a means for industry to reduce the risk of damage caused by flow dynamics, in particular by reducing flow unsteadiness, noise and even material fatigue. Control devices were used to control large eddies and included: perforated walls, a number of stream-wise vortex generators, synthetic jets and electro-hydrodynamic actuators EHD/MHD.

As mentioned above, in the UFAST project great emphasis was placed on the close connection between experimental and theoretical work. The experiments were modified according to the geometry or flow parameters whenever numerical results indicated a need for it. The UFAST structure involved CFD groups in the design of experiments.

The second objective concerned the application of theoretical methods to improve the understanding of unsteady SWBLI as well as the modelling of such flows. The methods used were, RANS/URANS (WP-4), hybrid RANS-LES and LES (WP-5). This investigation included advanced numerics, as well as advanced modelling strategies and investigations on the "range of applicability" for the different methods involved. The outcome of UFAST in this respect provides "best-practice guidelines" for the simulation of SWBLI problems.

From the application of CFD to SWBLI it becomes evident that there is a strong need for high accuracy schemes, applied to the main three categories of numerical tools. This requirement stems from the necessity to accurately capture and resolve spontaneous unsteadiness, such as shear layer instabilities generated by shock interactions. With the numerical work carried out before the project it was obvious that shock wave/boundary layer modelling had to be improved.

The third objective of the UFAST project was to improve our understanding of all physical phenomena governing shock wave/boundary layer interaction. New knowledge has been acquired concerning unsteady interaction phenomena, such as coupling between low frequency vortex shedding and shock movement and turbulence amplification/decay at the shock wave. This raised a number of important questions which the UFAST project could not answer with a sufficient degree of generality. They included:

- what is the nature of the perturbations?
- what are the links and the possible couplings between them?

- what is the role of compressible and subsonic turbulence in the evolution of relevant mechanisms?
- is it certain that the very low frequencies found close to the foot of the mean shock are produced by the oscillation of the shock wave?

The project has improved our understanding of the investigated phenomena in specific cases but has not allowed us to produce general conclusions that would concern all the considered Flow Cases.

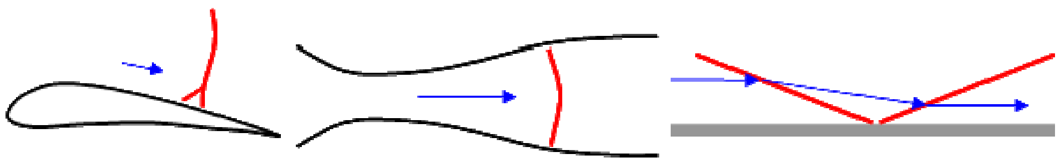
To conclude, it is evident that by working together, all the UFAST project partners, with their excellent expertise in the field of interest, have contributed to closing the knowledge gap on unsteady shock wave/boundary layer interaction. In other words, a high interactivity between experimental and theoretical work, resulted in a transparent set of deliverables summarized in two books:

1. *"UFAST Experiments – Data Bank"*, IMP PAN Publishers, ISBN978-83-88237-51-5, 2009
2. *"Unsteady effects in shock wave induced separation"*, Springer series - Notes on Numerical Fluid Mechanics and Multidisciplinary Design (NNFM), ISBN 978-3-642-03003-1, 2009.

Project structure

The UFAST project divided its funds and research work into two main areas. The one concerned experiments which delivered the Data Bank on SWBLI and its control. The other area concerned numerical simulations, including the modelling of SWBLI, using URANS, hybrid RANS/LES and LES methods, and delivered an assessment of their applicability to the problem.

To consider the general features of unsteady SWBLI, most of the typical flow configurations with shock waves had to be included in the investigation. Three flow configurations were selected, as shown in Fig. 1.



Transonic interaction *Nozzle flow* *Oblique shock reflection*

Fig.1. *UFAST configurations of flow with shock waves*

The selection of three configurations implied a high number of flow cases. Three different experiments were designed for each configuration. In order to manage this in a three-year project, a number of experimental facilities were engaged and various theoretical methods, e.g. CFD codes, were used. That was the main reason why as many as 18 partners participated in the realisation of the ambitious goals of the UFAST project.

The structure of the research part of the project including the work program details is presented in Fig.2. The Work Packages are presented horizontally. The left column shows the WP number, the WP topic and the WP leader's name. The physical phenomena groups are presented in the remaining three columns, numbered and using different colours for greater clarity. In each WP row this division into three physical phenomena columns defines three different Tasks.

In each Task of WP-2 different flow cases are labelled by a letter, whereas in each Task of WP-3 each flow control method is labelled by a number. Thus in each Flow Case a label consisting of a letter and a number allows to identify the flow case together with the flow control device.

In WP-4 and WP-5 these labels are used to indicate the flow cases simulated numerically by each CFD partner. It is important to note that this labelling is only relevant to its given physical phenomena column.

Experiments in WP2 are presented separately, depending on where they were carried out, even if the nature of the experiments was similar. Thanks to this valuable information is provided on the dependence of interaction unsteadiness on flow constraints.

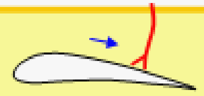
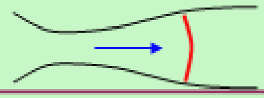
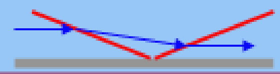
UFAST	Transonic interaction	Channel flow	Shock reflection
			
WP -2 Basic experiments ***Jean-Paul Dussauge***	**1** A) **QUB** – wall bump B) **INCAS** – biconvex aerofoil C) **ILOT** – NACA0012 with aileron	**2** A) **ONERA** (DAFE) –nozzle, forced shock oscillation B) **CUED** - nozzle, forced shock oscillation C) **IMP** - nozzle - curved channel	**3** A) **TUD** - M=1.6 B) **ITAM** - M=2.0 C) **IUSTI** - M=2.25
WP – 3 Interaction control experiments ***Holger Babinsky***	**1** 1) **QUB** - SJ 2) **QUB** - EHD 3) **INCAS** - SJ 4) **ILOT** - pitching aerofoil and aileron	**2** 1) **ONERA** – VG, AJVG 2) **CUED** - SVG 3) **IMP** - active suction, 4) **IMP** - AJVG	**3** 1) **ITAM** - EHD 2) **IUSTI** - AJVG
WP -4 RANS, URANS ***Charles Hirsch***	**1** **LIV** – A-1 **INCAS** – B-3 **IMFT** – A-1, B-3, C-4	**2** **LIV** - A-1, C-4 **FORTH** - A-1, B **IMP** - C-3, C-4 **NUMECA** – B **LMFA** – C3	**3** **URLMS** – A **NUMECA** – C **IMFT** - C **LMFA** – A, B **UAN** – B, C2
WP -5 Hybrid, RANS/LES, LES ***George Barakos***	**1** **LIV** - A-1, C-4 **INCAS** – B-3 **IMFT** – A-1, B-3, C-4 **EADS-M** - B	**2** **LIV** - A-1, C-4 **FORTH** – A-1, B **IMP** – C-4 **NUMECA** – B, C-4	**3** **SOTON** – A, B, C **NUMECA**- C **IMFT** - C **URLMS** – A **ONERA** (DAAP) – C-2

Fig.2. Graphical presentation of work program