European research on unsteady effects of shock wave induced separation UFAST - project

Piotr DOERFFER

IMP PAN, Fiszera 14, 80-231 Gdansk, Poland, doerffer@imp.gda.pl

Abstract. Research carried out in the project is aimed at the improvement of our physical understanding of the shock wave boundary layer interaction by focusing attention on unsteady phenomena such as fluctuations occurring in shock induced separation and large amplitude oscillation involving the whole flow. To deal with the topic a consortium has been formed within a project financed by the European Commission. The project is in the initial stage and the first results just appear. Therefore only goals and methods of the project realisation are presented in this paper.

Keywords: shock waves, separation, unsteady flows

1. Introduction

In respect to the needs of the aeronautics industry the general aim of the UFAST project is to foster experimental and theoretical work in the highly non-linear area of unsteady shock wave boundary layer interaction (SWBLI). Although in the past several EU projects were aiming at transonic/supersonic flows, the area of unsteady shock wave boundary layer interaction has not yet been treated. Moreover, during last years experimental methods as well as numerical approaches have been improved considerably.

The main considered cases: shock waves on wings/profiles, nozzle flows and inlet flows as well as oblique shock reflection will serve as 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 the basic flow analysis control methods (vane type vortex generators, jet driven vortex generators, synthetic jets, electro-hydrodynamic actuators and transpiration flow) will 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 flow field. Therefore, the response of shock wave and separation to periodic excitations is of utmost importance and is included in the research program.

Thus emphasis is placed on closely coupled experiments and numerical investigations to allow for feeding back numerical results to 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 will assess new methods for turbulence modelling in particular for unsteady, shock dominated flow. Moreover, LES methods will be applied to resolve the large coherent structures that govern SWBLI. This way, UFAST will investigate the “range of applicability” between RANS/URANS and LES.

The first objective of the UFAST project is to provide a comprehensive experimental data base, which will document both the low frequency events and the properties of the large scale coherent structures in the context of SWBLI. It must be mentioned: almost no experimental information is available, in particular for industrially relevant flow cases. Therefore flows in the important Mach number range going from transonic conditions to Mach numbers about 2 will be investigated. The flow configurations going to be measured will correspond to generic geometries that can be easily exploited when more complex geometries need to be treated, as there are airfoils/wings, nozzles, curved ducts/inlets, i.e. all important flow cases governed by normal and oblique shocks. This wide shock configuration platform is necessary when attempting to identify general interaction unsteady features. And also it should be said: realisation of this objective in a short project time can be achieved only by the involvement of a sufficiently large number of laboratories which will share the huge amount of necessary experimental work. Following partners are taking part in UFAST:

Experiment:

QUB	Queens University Belfast, School of Aero. Eng.
IoA	Institute of Aviation, Warsaw
INCAS	Romanian Institute for Aeronautics
UCAM	University of Cambridge, Dept. of Engineering
ONERA	DAFE
IMP	Institute of Fluid Flow Machinery, Gdansk
IUSTI	CNRS Lab., UMR 6595, Marseille
TUD	Delft Univeristy of Technology, Aerodyn. Lab.
ITAM	Russian Academy of Science, Novosibirsk, Inst. of Theor. App. Mech.

CFD:

SOTON	University of Southampton, (SES)
URLMS	University of Rome "La Sapienza"
ONERA	DAAP
LIV	University of Liverpool, Dept. of Aero. Engin.
NUMECA	Belgium, SME
INCAS	Romanian Institute for Aeronautics
IMFT	Institute Mécanique des Fluides de Toulouse
FORTH	FORTH/IACM, Found. for Res. And Techn.-Hellas
LMFA	Ecole Centrale de Lyon
EADS	EADS-M, Deutschland GmbH

To conclude, it is evident that the UFAST project is extremely innovative and is clearly dominated by upstream research. However, innovation is accompanied by risks. But it is foreseen that risks can be handled and converted into success due to all the selected partners with their excellent expertise in the field of interest, working jointly and bringing in their skills for closing the knowledge gap on unsteady shock wave/boundary layer interaction. In other words, a high interactivity between experimental and theoretical work, led by a strict management, is going to be achieved and will result in a transparent set of deliverables and milestones describing and assessing properly all achievements.

Moreover, the UFAST is not solely aiming at an advanced understanding of flow-physics in general, it is targeting the support of industrial needs and requirements in a field which is of utmost importance for current and future aircraft – but has never been investigated thoroughly in the past.

2. Flow Cases

The nature of unsteadiness depends on Mach number. In the transonic range, strong acoustic coupling may occur through the large subsonic zones which exist downstream of the interaction, and this may be one of the causes of shock motion and buffeting. On the other hand, for supersonic cases it is the separated zone which mainly drives unsteadiness. Accounting for such situations, UFAST will cover Mach numbers ranging from the transonic to the supersonic regime. Moreover, as the causes of unsteadiness depend on flow geometry, many configurations of interaction have to be studied. ***Three Flow Cases have been identified.*** They include respectively, transonic interactions on a profile, channel flows and oblique shock reflections. These are typical shock interaction cases which can be encountered in many industrial applications. Our belief is that this wide scope of interaction flow fields will make it possible to extract the main physical phenomena independent of a particular flow configuration.

Transonic interaction

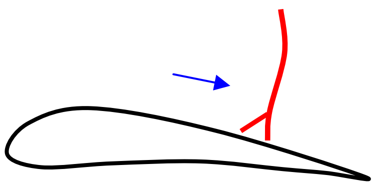

Figure 1. Transonic interaction

Three partners will be involved in this Task dealing with aerofoil flow. INCAS is using a biconvex profile and QUB a corresponding wall mounted bump. IoA uses a NACA0012 profile with aileron. This range of transonic profiles will provide an exceptional opportunity to reveal the influence of the geometrical configuration on the interaction flow structure and the unsteady shock behaviour. The IoA model will also allow the study of the effect of aileron deflection angle on the unsteady behaviour of the shock and the separation.

Measurements in this Task will concentrate on the determination of the main characteristics of unsteady flow and will map out the buffeting boundary. The three selected test configurations will provide an opportunity to directly compare the unsteady characteristics of each flow. Comparison between INCAS and QUB experiments should show significant differences in unsteady flow behaviour. It may be expected that lack of trailing edge coupling in QUB may eliminate a buffeting type of unsteadiness. A valuable additional contribution is offered by IoA who will investigate the flow unsteadiness for different aileron deflections. This will provide a different coupling between the shock and the trailing edge, which may lead to global changes of unsteady flow features.

Shock in a nozzle

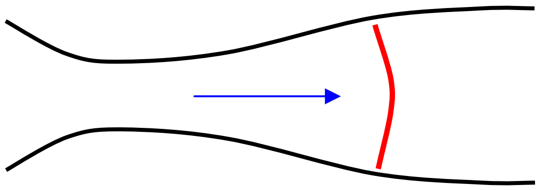

Figure 2. Shock in a nozzle

Research in this Task is focused on the shock wave interaction in internal flows. Despite the large number of previous studies on similar configurations, there remains a strong need to perform basic investigations of shock wave/boundary layer interactions to cover aspects which have not been sufficiently addressed before. Three partners will be involved: ONERA, UCAM and IMP. Measurements will concern shocks in straight nozzles / channels for two Mach numbers, one just before separation and another with developed separation. In the case of a normal shock interaction in a channel any severe separations modify the flow properties downstream which in turn may have important consequences for the unsteady behaviour overall. For these flow cases a detailed comparison between three test sections will be performed, covering flow unsteadiness, separation flow structure and mean flow parameter distribution.

Experiments on quasi normal shock wave/boundary layer interactions occurring at moderate Mach number (below 2, typically M=1.3-1.6) will be performed. This regime is of crucial interest in the present context, both for external and internal aerodynamics, because it allows the characterization of the leading mechanisms of unsteadiness on a simple, well-defined, geometry at flow conditions relevant to all applications covered by UFAST. The goal is to provide a set of reference flow cases which will be compared to the flow control experiments and CFD results on the same geometries.

Internal flows are often subject to forced excitations. Therefore ONERA and UCAM will incorporate a rotating cam into their nozzle outlets which will periodically destabilise the outflow. The frequency of excitation will be varied and the unsteady shock response will be measured. This process provides a strong, nonlinear, coupling between the shock and the outflow. The physical mechanisms studied here are similar to those encountered in the oscillating aileron investigated.

It is known that shock induced instabilities also depend on the wind tunnel geometry but this problem has not yet been investigated systematically. In order to study this effect the experiments in this task will concentrate on two different shock formation geometries. One is in a straight channel, where the shock is normal and of uniform strength throughout. The second configuration is a curved duct with a local supersonic area. Here, the shock is strongest at the convex wall where its interaction with the boundary layer is studied. But at the opposite, concave wall the shock intensity approaches zero. Such flow topology affects also the unsteady effects of SWBLI.

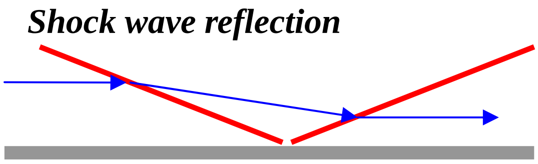

Figure 3. Shock wave reflection

The goal of this task is to study an oblique shock reflection from a planar surface. At the same Mach numbers oblique shock reflections introduce much smaller disturbances into the boundary layer than a normal shock. In order to provide a comparable interaction the Mach numbers in the oblique shock studies have been increased accordingly. Three laboratories participate in this task covering a range of Mach numbers ranging from M=1.6 (TUD), via M=2.0 (ITAM) to M=2.25 (IUSTI).

In this task a detailed experimental description of the unsteadiness in the SWBLI will be provided. This unsteadiness can be provoked by large-scale structures in connection with shock motion. The results will highlight possible physical mechanisms present in such interactions, and further insight will be gained from a comparison with simulations. Moreover, as the SWBLI produces large scale structures, they are also at the origin of pressure fluctuations in the external flow (aerodynamic noise), which will be measured in the experiments at IUSTI. Of course, this aspect of measurements is not a consistent investigation of aeroacoustics; it is mainly an opening on such questions, to check the ability of making first measurements for comparisons. In particular, pressure fluctuations in the outer flow will be also measured in the case with control by AJVG and this will serve as an indication of the effect of the interaction control on the radiated noise. These results will further contribute to the experimental data base.

The objective of the experiment developed at ITAM is to provide data and understanding on the control of large scale eddies and shock unsteadiness in an oblique impinging shock with separation, at a Mach number of 2. ITAM has developed skills to make detailed experimental investigations of the reflecting shock wave on a flat plate. Its tunnel is ideally suited to this study due to its very low level of free-stream turbulence. This makes it especially useful for the detection of coherent structures.

The general objective of the experiment performed in Delft is to provide shock reflection data at Mach numbers similar to those of the normal shock studies. The originality of the contribution of TUD comes from the extensive use of 3-D PIV to measure flow statistics, with a particular care to 3-D structure of this nominally 2-D flow.

3. Basic experiments (WP-2)

Although SWBLI has been investigated for several decades, the unsteady behaviour of the interaction remains a challenging problem. This is related to the complexity of the interaction flow fields and the shortcomings of traditional measurement techniques. Nowadays, new experimental tools are available and traditional methods have considerably improved. UFAST therefore will deliver important and valuable experimental data.

Such investigations require dedicated experiments, designed to reproduce such phenomena, with measurements characterizing the unsteady properties of the flows, and to provide high quality test cases necessary for the development of more reliable and accurate predictive methods and their validation. Numerical simulations commonly have difficulties to predict such severe interactions, including both their steady and unsteady properties. This may be due to purely computational aspects, but it may also be suspected that compressibility effects may affect turbulence, along with the unsteady characteristics of the large scales. Consequently, it is necessary to provide some insight into the physical mechanisms which are involved, and into the necessary improvement of turbulence closures.

Therefore, the overall objective of WP-2 is to provide experiments, which can serve as reference test cases capturing the unsteady nature of shock/boundary layer interactions (SWBLI), to contribute to their understanding, and to collect the measurements in a data bank.

4. Flow control experiments (WP-3)

The goal of WP-3 is to determine the potential of several novel concepts for the control of shock wave / boundary layer interactions. In particular the ability of control methods to suppress / delay shock induced separations and the effect of control on SWBLI unsteadiness will be examined. Apart from novel control methods several older techniques will also be investigated to enable a comparison with previous research. The investigation of SWBLI control for separated unsteady flows is not only important because flow control is a crucial technology for next generations of aircraft, but also because it increases our knowledge of the interaction phenomenon. Apart from the natural unsteadiness of SWBLIs this work package also investigates the effect of control under forced unsteady shock conditions. Such forced excitations cannot be ignored because they may dominate the characteristics of the interaction behaviour.

The experimental configurations in this WP are the same as in WP-2 but here a number of flow control techniques will be applied. The results of WP-2 will form the baseline for an evaluation of the effectiveness and physical influence of each control technique. In particular, the following methods will be investigated:

- periodic profile pitch and/or oscillating aileron
- electro-hydrodynamic actuators (EHD)

- synthetic jets (SJ)
- traditional vortex generators (VG)
- sub-boundary-layer vortex generators (SBVG)
- air jet vortex generators (AJVG)
- perforated wall suction

A complete review and critical assessment of all control methods will be undertaken, resulting in recommendations for their application to various interaction situations. Following a comparison with numerical simulations, an assessment will also be made about the level of confidence in the use of CFD for practical investigations. The final report will contain all key results as well as recommendations concerning the potential integration of control devices into future aircraft.

5. Numerical simulations – RANS/URANS (WP-4)

One of the main outcomes expected from UFAST is the improvement of simulation techniques which should increase the confidence in predicting these complicated flows using traditional numerical approaches, based on RANS and URANS approximations associated with various turbulence models. To support this evaluation of (U)RANS based CFD methods, it is essential to validate the simulations against the new experimental measurements obtained in WP-2 and WP-3. The resulting improved understanding of the involved phenomena may help to reconsider current turbulence modelling issues. Successful improvement of the CFD modelling carried out in this WP will constitute the main achievement of the project.

The most challenging part in WP-4 is to reconsider turbulence modelling in the (U)RANS approach in order to take into account compressibility effects and the rapid changes introduced by the shock wave. In particular, the impact of unsteadiness on the current turbulence models will be given particular attention. This will be the essence of this WP.

The results will be presented as a data bank similar to experimental bank worked out in WP-2 and WP-3. However, provided information should contain "guidelines" for numerical approach to investigated flow case.

The work in WP-4 will be realised in three Tasks corresponding to the interaction type. Intensive interactions between the experimental and CFD groups are necessary. These should result in a joint decision concerning test cases definition, as well as providing guidelines to the experimental teams, such as location of instrumentation, expected order of magnitude of flow quantities. It will also inspire mutually agreed flow conditions which will be selected, following lines indicated by CFD.

The simulations to be performed under WP-4 concern the basic experiments and different flow control methods. The UFAST project partnership will allow an exceptional number of flow control simulations and this provides a unique opportunity to combine knowledge that will lead to better physical modelling of flow control methods. Many important questions of turbulence treatment in such models will be addressed and hopefully answered, providing an improved quality of control methods modelling.

6. Hybrid RANS/LES and LES simulations (WP-5)

Nowadays, in industrial CFD practice statistical turbulence modelling is used almost exclusively, via the Reynolds-averaged Navier-Stokes equations (RANS). RANS modelling has reached a state where for physically moderately complex and statistically stationary flows reliable predictions are possible if an appropriate model for the considered flow configuration is chosen. With increasing readiness of RANS computations the deficiencies of the available models for the prediction of large-scale instationary flows became evident and lead to the concept of unsteady RANS (URANS) which is subject of Work Package 4.

Yet, URANS is not suitable for flows which are instationary over a wider range of scales. Also URANS cannot predict critical flow phenomena which appear only in a statistically insignificant number of realizations. These problems can be addressed, however, by Large-Eddy simulation (LES). LES does not represent a statistical flow description but a single flow realization. Computational savings are achieved by reducing the range of resolved spatial scales, at the expense of a subgrid-scale model.

The objective of WP 5 is to bridge the gap between the current RANS and URANS modelling strategies for turbulent flows in industrial CFD applications and future LES for physically complex supersonic flows. For many practical situations it is unnecessary to apply LES over the entire flow domain. In particular for external flows physical complexity is confined to regions near a body surface and in its wake, whereas the remainder of the flow domain can be well treated by RANS approaches. Also, RANS approaches are considered for the near-wall region in high-Reynolds-number turbulent boundary layers in order to reduce the computational cost of wall-resolving LES. These latter approaches are so-called hybrid-RANS-LES models which are also considered in this Work Package. Hybridization can be done by interfacing RANS and LES regions, where RANS and LES models can be of entirely different type, or by using modifications of RANS models which assume the character of an LES model for sufficiently fine grids. The latter is frequently called Detached-Eddy simulation (DES). DES has been developed to handle massively separated flows where separation is most frequently fixed by the geometry (e.g. base flow). Up to now, a very limited amount of numerical studies were attributed to address the predictive capabilities of DES for thin-layer shock-induced separation, although some problematic issues, such as grid-induced-separation, are commonly observed. This knowledge is of significant importance in applied aerodynamics where full LES computations of complex configurations will be out of reach for the available computational power in the near future. One objective of the current Work Package is to evaluate and to improve the capabilities of DES to handle shock-induced boundary layer separation.

Current RANS and URANS models fail to deliver correct predictions of averaged skin friction and wall heat transfer for **s**hock **b**oundary **l**ayer **i**nteraction (SWBLI) configurations. Despite considerable effort and sophisticated modelling closures this deficiency has not been remedied so far. This fact suggests that our current understanding of prevailing physical mechanisms in SWBLI is insufficient. Prime suspect for the reason of the failure of RANS methods is the presence of large-scale three-dimensional unsteady flow structures which by principle cannot be captured by RANS or URANS without additional a priori assumptions. These a priori assumptions lead to the so-called engineered RANS models which cannot be transferred to other flow configurations. They remain restricted to the specific configurations which they were tuned for. Recent well-resolved LES reproduce large-scale structures in the interaction region, in agreement with experimental data, and also show indications for large-scale unsteadiness of the interaction system. Yet, the origin of these large-scale unsteady structures is unknown. It is possible that they arise from perturbations present in the incoming boundary layer. In a quiescent environment such as in free flight, it is more likely that they develop from an inherent instability mechanism. In experiments both effects can be present, however, due to inevitable disturbances in the outer flow and in the incoming boundary layer, or caused by model surface roughness. These could even overwhelm an inherent instability mechanism. Numerical simulation is the only tool to clarify this issue, where a full control on exterior and inflow data is possible. Also, in order to assess the effect of experimental uncertainty, artificial disturbances can be introduced in a controlled manner.

The main objective of the current Work Package is the assessment of LES for simulating shock-induced separation for generic flow geometries. Due to its physical complexity the joint numerical-experimental analysis of SWBLI provides an ideal ground for further model improvement. The work will assess the current ability of LES to properly simulate physical phenomena, specifically time averaged flow features, and unsteadiness. A major challenge is associated with the increase in Reynolds number from most of current LES calculations to the proposed experiments. Close cooperation between numerical-modelling groups and experimental groups allows the inclusion of physical mechanisms identified from the experimental data into the LES model modifications at early stages and their immediate verification based on the experimental data.

The industrial requirement of rapid turnaround of qualitatively correct CFD data cannot be matched currently by LES. A remedy is offered by the aforementioned hybrid RANS-LES methods which are an area of active research. This is indicated by the strong industrial participation in the DESider (Detached eddy simulation for industrial aerodynamics) project. We also address this approach applied to SWBLI in UFAST.

A number of participants of WP-5 are also contributing to WP-4 making simulations of the same flow cases. This provides a unique opportunity for comparison between RANS and LES results. The results of the LES simulations would be used to evaluate the different source terms in the various turbulence models. In particular, the LES output contains all the information in order to calculate and evaluate the production, dissipation, diffusion and other nonlinear terms in the r.m.s. quantities of the turbulence models used by the partners in WP-4. This will be an original contribution of great interest and could provide a basis for further improvements of the RANS type turbulence models. These comparisons will be presented in the final reports.

7. Conclusions

Data to be obtained will be split into so-called “basic” (WP-2) and “controlled” (WP-3) cases, the latter carried out to provide the means to industry for reducing risks in the domain of flow-physics, in particular by reducing unsteadiness of flow, i.e. stabilising flow, reducing noise and even fatigue. Moreover, the data base will include some measurements of radiated noise, but it is not intended to aim at aero-acoustics investigations – only as a measure of improvement for environmental aspects (Vision-2020). Control devices will be used to control large eddies and include e.g. perforated walls, stream-wise vortex generators, synthetic jets, electro-hydrodynamic actuators EHD/MHD.

As already mentioned the UFAST project will put a great deal of emphasis on the fact that experiments will be accompanied by theoretical methods that have been enhanced according to the needs for SWBLI.

UFAST is concerned with the application of theoretical methods to improve the understanding of unsteady SWBLI as well as the modelling of such flows. The methods used are, RANS/URANS (WP-4), hybrid RANS-LES and LES (WP-5). This investigation also includes 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 will be in the form of “best-practice guidelines” for the simulation of SWBLI problems.

Acknowledgement

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Contract n^{o}: AST4 – CT – 2005 – 012226 UFAST

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1. Project description UFAST, European Commission, Contract No. AST4-CT-2005-012226 UFAST