

EUROPEAN DOCTORAL TRAINING IN AEROACOUSTICS BY A MARIE CURIE INTEGRATED TRAINING NETWORK

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Training the next generation of aeroacoustic researchers is vital for addressing some difficult yet very important societal challenges, such as the provision of environmentally sustainable air transport operations, both for what concerns airport noise pollution and cabin noise. Sustained demand for more fuel efficient, environmentally friendly, and quieter aircraft power plants is promoting the development of ultra-high bypass engines for large transport aircraft. These turbofan engines require trained aero-acousticians and improved industrial design tools, to tackle some of the difficult design challenges posed by the larger diameter and by the larger fraction of the thrust delivered through the secondary (annular) nozzle. Whilst aeroacoustics is a well-established discipline in its own right, it tends not to be offered as an undergraduate course. This creates a recruitment challenge in doctoral training, with new post-graduate students being recruited across a range of qualifications, including Physics (physical acoustics), Mathematics, and Engineering (aerodynamics). A doctorate in aeroacoustics therefore poses the dual challenge of developing the underpinning basic knowledge in the researchers while pursuing advances in the state of the art. Seven European doctoral schools have teamed up in an Integrated Training Network of the 7th Framework Programme, AeroTraNet 2, in an effort to create an aeroacoustic doctoral training experience with greater critical mass, in which doctoral candidates could avail themselves of training facilities and courses across the network, to address their start-up knowledge gap. This

four-year experience generated a wealth of lessons learnt, from sharing doctoral training practices, as well as from bottom-up initiatives led by the Early Stage Researchers involved in the project.

Keywords: Marie Curie ITN, Integrated Training Network, Transnational mobility, Aeroacoustics, Jet noise.

1. Introduction

1.1 The scientific challenge

Advances in noise abatement technology for turbofan engines of wide-body civil aircraft have steadily reduced noise emissions by more than 20 EPNdB compared to their entry into service. Reductions in jet noise have mainly been achieved through the progressive increase of the turbofan bypass ratio. Current predictions of jet noise impinging on the fuselage skin of aircraft at cruise rely mostly on data from old flight tests or on mature and legacy empirical models, since accurate predictions using physics-based noise model are very challenging. Low-accuracy cabin noise prediction models drive conservative design choices for cabin acoustic liners, which increases the aircraft weight. This in turn increases the fuel consumption and the environmental impact of aircraft operations. Airframe manufacturers are introducing more carbon fibre composite fuselage skins that are stiffer and lighter compared to the aluminium modules used to generate past cruise jet noise correlation data. Integrating the sound transmission loss characteristics of these new airframes in the existing models is a further element of challenge for the prediction of cabin noise at cruise.

Current generation high bypass ratio turbofan engines discharge a dual-stream jet with a high-speed inner jet, from the engine core, and a lower speed coaxial jet, from the fan. Due to the high temperature of the combustion products, the Mach number of the inner jet is typically subsonic, whereas the coaxial jet that delivers most of the engine thrust typically expands from a choked nozzle. As the coaxial nozzle is convergent and of fixed geometry in current wide-body civil aircraft turbofan engines, shock-free fully expanded jet conditions are achieved only at given aircraft altitude and speed combinations. Air traffic route management constraints require operating the aircraft over a wider flight envelope, with the coaxial jet from the engines under-expanded. This generates shock-associated jet noise (shock-cell noise) radiating towards the cabin.

Shock-cell noise arises from the interaction of convected instabilities in an incorrectly expanded jet shear layer with the shock-cell train [1], resulting in a linear array of sound sources. The constructive interference of the linear array in the upstream direction results in jet screech, a loud form of shock-cell noise [2] that is usually absent in full-scale engine jets but it is often found in laboratory scale model tests. This simple well-established model is used in the current state of art aircraft noise models, such as SOPRANO, developed in FP6 SILENCE(R) and used in FP7 VITAL. A more advanced description of the noise production physics is by the interference of hydrodynamic (shear-layer) waves and upstream-propagating (pressure) waves [3], where the noise generation is by shock-cell leakage in the unsteady flow [4]. In experiment, the innovative use of wavelets [5] and linear stochastic estimation to pressure-decouple the aerodynamic and acoustic fields allows to identify the unsteady flow accelerations responsible for noise generation, therefore guiding noise control concepts by flow control.

Innovation in the methods for predicting aircraft jet noise is promoted by the ACARE targets on aircraft emissions and noise [6], which envisage a reduction of the perceived noise by 65% by 2050 compared to the turn of the century. Towards this target, engine and aircraft manufacturers have teamed up in research and technology consortia, with the aim of developing noise reduction concepts to higher level of maturity, promoting their progress through the Technology Readiness Level scale towards their use in new aircraft. Recent European projects include SILENCE(R), SYMPHONY, which

studies noise from mainly shock-free jets, OPENAIR, which studies airframe noise and jet-airframe interaction noise (aircraft engine installation effects), Clean Sky JU, and Clean Sky 2 JU, which works at a higher Technology Readiness Level (TRL), by developing and testing pre-production low-noise technology on commercial aircraft. One significant trend being pursued is the introduction of ultra-high bypass ratio engines, in which the larger mass flow through the fan enables the lowering of the nozzle pressure ratio of the fan stream, so that this convergent nozzle is operated either subsonic or choked, therefore preventing the onset of the flow conditions at which shock-associated jet noise is generated. Meanwhile, current generation airframes and high bypass engines are likely to remain in service over the next 40 years and represent a sizeable market for retro-fitting cruise shock-cell noise abatement technology.

Product development databases and shared Computer Aided Design (CAD) platforms are now commonplace in engineering manufacturing. The CAD information may well be integrated but there is no general framework to identify how the uncertainties in each design phase combine to determine the overall performance of the design, like an Airbus fuselage. It is left to the best judgement of the project engineer to identify and rank the key areas of improvement in the next iteration of the design process. From a financial viewpoint, given a limited budget for improving the design tools (Computational Fluid Dynamics, Finite Element Analysis and Computational Aeroacoustics), where should the money be best spent to yield the most significant design improvement? Providing an objective answer to this question requires developing a cross-disciplinary framework to estimate the uncertainties in the predictions (or performance parameter estimations) from different phases of the design workflow, find their cumulative output, and determine the output sensitivity to the individual contributions from each phase. This task requires a significant abstraction effort, to determine one methodology that is applicable across the broad range of disciplines that are used in the different stages of the design workflow. Furthermore, this methodology has to be affordable, deliver results within the time constraints of the industrial design cycle, and generate very limited additional work (work overhead) for the teams involved in delivering the individual stages of the design.

1.2 The training challenge

Aeroacoustics is not typically taught in the undergraduate curriculum. It requires a portfolio of skills spanning across mathematics, physical acoustics, and aeronautical engineering. It is a niche research subject, which is reflected by the presence of groups of a small number of individuals at individual universities or research institutes. Attracting researchers to this field is challenging, as aeroacoustic is not understood as a continuation of the undergraduate curriculum. The traditional doctoral training proposition in aeroacoustics is typically constrained to a one-to-one tuition by the supervisor, within a small research group that may feel small as a social environment and may feel as lacking critical mass to the prospective doctoral student. Within the European Union, the best aeroacoustic wind tunnels, computational aeroacoustic groups, and theoretical aeroacousticians are dispersed over a wide geographical area.

One additional element driven by the small critical mass of most of the aeroacoustic research groups is that higher education establishments struggle to generate opportunities for exposing early stage researchers to aeroacoustic technology across the full Technology Readiness Level (TRL) scale, from the proof of concept in a laboratory or in a computer simulation to the full-scale implementation. Yet understanding the gated process used in the acquisition of a new design tool in industry is critical for training the new generation of aeroacousticians in producing research output that can be turned in design methods of high added value and impact.

Between 2006 and 2010, innovation in aircraft propulsion technology focussed mainly on lowering emissions and on lowering aircraft specific fuel consumption, driven by the rising cost of fuel and by the environmental policies for the control of global warming. Aircraft noise abatement work was perceived as having shrunk, by comparison, leaving an increasing noise gap between the objectives

of Flightpath 2050 [6] and the projections from the noise technology that was being developed. There has been also a reduction of newly trained noise specialists, as more doctoral students have opted towards energy related research and other fields. There was a risk of producing an aircraft noise gap and an insufficient number of young noise specialist in Europe to address it.

2. Integrating the European training capacity in aeroacoustics

To address the scientific and training challenges, a group of four universities, two national research centres, one SME, and two industry sector leaders formed in 2012 a Marie Curie Integrated Training Network, supported by the European Commission 6th Framework Programme. Between 2012 and 2016, the AEROnautical TRaining NETwork in Aerodynamic Noise from Widebody Civil Aircraft - AeroTraNet 2 - offered a transnational training programme in methods for the characterization and prediction of wide-body civil aircraft jet noise at cruise.

Trainees could join as an Early Stage Researcher (ESR) or as an Established Researcher (ER), depending on their curriculum vitae. The position of ESR was open to researchers with no more than four years since gaining a degree that qualified them for undertaking doctoral studies in their home country. A researcher could join as ER provided they either held a doctoral degree or had completed four years of postgraduate training, and had no more than five years since gaining their degree that qualified them for doctoral studies in their home country. In addition, all trainees were asked to undertake a trans-national mobility, by moving to an AeroTraNet 2 partner located in a member state where they did not reside over the three years preceding their appointment as ESR or ER. Between 2012 and 2016, 11 Early Stage Researches and one Established Researcher were recruited, 10 of whom were from European countries.

In this network, the research output was made itself subject of research, specifically through a dedicated work package that systematically studied the different research methods and approaches, estimated the uncertainty in the predictions, and managed the compound uncertainty from using these methods in a prototype design workflow.

The consortium partnership was brought together drawing from research establishments with an international reputation and expertise in different aspects of jet noise knowledge and of knowledge management. The University of Leicester, in the UK, offered training in shock-tolerant finite-volume methods for developing time-resolved models of single and dual-flux jets operated highly under-expanded. The Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, CER-FACS, in France, made available a Large Eddy Simulation (LES) scheme with in-house algorithmic enhancements, featuring a high-order closure method and dedicated radiation or characteristic boundary conditions, which was well suited to modelling turbulent jets with weak shocks. The Università degli Studi Roma Tre, in Italy, provided doctoral training in advanced post-processing techniques, based on the wavelet transformation, applicable to both experimental and numerical data. These techniques enable the splitting of the jet pressure field between its radiating and non-radiating components, within limits. The Von Karman Institute, VKI, in Belgium, contributed with a rare opportunity to lead the design almost from a blank sheet of paper of a new dual-jet test rig, which represented a significant investment by this SME in jet noise research. The Institut National Polytechnique de Toulouse, INP, in France, offered training in the sensitivity analysis of flows by the implementation of adjoint techniques. The Istituto Nazionale per Studi ed Esperienze di Architettura Navale, CNR INSEAN, in Italy, offered both experiences in large-scale measurement campaigns related to its core business as well as an opportunity for applying optical techniques to a smaller jet noise test rig sited at Roma Tre. The University of Greenwich, in the UK, offered training in formal methods for evaluating the uncertainty in the predictions and measurements performed by the project participants.

On one hand, such spectrum of experimental, numerical, and analytical techniques was promising towards creating novel scientific insight through collaborative research. On the other hand, the research agendas at the institutional level as well as the research comfort zone of each group generated

natural tension with the pursuit of a common work programme. This tension was managed through two main actions. The first action was to recognise that, for the knowledge and flow and noise prediction/analysis methods to be available across the network, a formal process of knowledge management and capturing was required, which would enable consortium members to reproduce, interpret, or use results off-site and/or at a later date. This was implemented by a dedicated Early Stage Research post, sited at the industrial partner GE Power, who evaluated a range of off-the-shelf knowledge management methods for this purpose. The second action was to implement a top-level workflow for integrating the output from each consortium member (Fig. 1), towards producing a physics-based shock cell noise predictor for cruise that could be exploited by the industrial participating organization Airbus SAS, France.

3. Balancing network-wide training and individual research

Early Stage Researchers (ESR) and Experienced Researcher (ER) training at all partner institutes contributing to this programme is an established, high quality, individually driven, elective learning experience. The training hinges on the genuine interest of the trainee to read a subject and on the advice of a supervisor who gives him/her guidance. The onus rests on the ESR to produce a qualifying contribution to the advancement of the state of the art and progress, as recognised peer (PhD, Docteur or Dottore di Ricerca), among the community of experienced researchers. Experienced Researchers work as scholars and enjoy intellectual freedom supported by their supervisors. The training implemented in AeroTraNet 2 upheld these notions, by proposing learning and industrial training experiences appropriate to early stage and experienced researchers. These experiences provided both scientific training and transferable skills (complementary training), which were delivered both locally, through secondments, and by network-wide training events. The balance between local and network-wide training was tailored to each ESR and ER through the Career Development Plan. At the start of the training, each researcher, in collaboration with their main supervisor, drew up an individual Career Development Plan. This plan identified the scientific objectives and the individual research training needs of the trainee. The plan was then implemented by selecting appropriate learning experiences offered within the multi-host programme. The plan became an individually tailored training programme structure, which defined the mix of local versus network-wide activities for each researcher, tailored to his/her specific needs.

AeroTraNet 2 found good synergies with the European Commission Collaborative Action x-noise EV. Both consortia shared the objective of supporting the communication and exchange of ideas among the younger generation of aeroacoustic researchers. This was implemented by organising two ‘Aircraft Noise and Aeroacoustics in the UK’ and one ‘Aircraft Noise and Aeroacoustics in the UK/EU’ workshops, in collaboration with the UK x-noise National Focal Point and with the University of Lyon, France. The workshops provided a less formal environment than more established international aeroacoustic conferences, in which doctoral students and post-doctoral researchers were able to present to their peers more preliminary research, receive feed-back from their peers, and start building their own research network among the younger generation of aero-acousticians.

4. Evidence of effective collaborative research

4.1 Antares: an aeroacoustics post-processor for the wider community

A further area of successful international collaboration brought about by this network was the development of a community-based computational fluid dynamics post-processor. This activity used the software platform Antares, from CERFACS, which CERFACS made available as a royalty-free software subject to copyright. The development of a Ffowcs Williams and Hawkings (FWH) acoustic analogy post-processor for projecting noise from the vicinity of a sound source to further afield was coordinated between the Coordinator at the University of Leicester, UK, and CERFACS, in France,

as a development of Antares [7]. This activity benefited from the oversight of Airbus SAS. Joint code validation and testing has strengthened the confidence in this post-processor which, in the spirit of open research, CERFACS has made accessible to the wider research community. The testing included a sensitivity study on the proximity of the source to the FWH integration surface and on the topological sharpness of the surface edges. New insight has been generated in the application of numerical integration and differentiation procedures to this problem as well as more practical guidelines on how to use the software for producing predictions within engineering accuracy. A new module for the convective form of the FWH acoustic analogy was coded at Leicester and ported at CERFACS, specifically for studying jets from turbofan engines at cruise conditions.

4.2 Progress in European synergies on jet noise measurement and analysis

AeroTraNet 2 has fostered significant methodological, instrumentation, and technological development across Europe. Joint beneficiaries of this outcome have been VKI, in Belgium, and the Università degli Studi Roma Tre and INSEAN, in Italy. VKI and the Belgian government made significant capital investments in the experimental activity of AeroTraNet 2, which produced a dedicated new facility for testing dual-flux jets in the absence of co-flow. The design, commissioning, and testing of the facility was aided by mutual secondments at VKI, Roma Tre, and INSEAN. The exchanges promoted the transfer of knowledge among the experimentalists and the addition of new experimental techniques to the repertoire of VKI, specifically Background Oriented Schlieren photography. This non-invasive optical technique, combined with particle image velocimetry available at the VKI, enables complementary assessments of the oscillating shock train in the dual-flux jet when it is operated over-expanded. This is directly related to the broad-band shock-associated noise production. Pressure-density gradient correlations have shown the causality between jet shear-layer events and the pseudo-sound recorded outside the jet shear-layer. By a wavelet decomposition technique, the radiating component of the pressure fluctuation that contributes directly to the aircraft cabin noise was decoupled from the non-radiating pressure component.

4.3 Towards affordable cruise jet noise prediction by using Parabolized Stability Equations

A Reduced Order Model (ROM) of the noise emission was built based on the relationship between the noise emissions and the instability of large-scale coherent structures in the jet plume. Figure 1 shows a flow diagram of the model building blocks. The legend to the right of the flow diagram indicates the contribution to each task by each AeroTraNet 2 partner. A significant input from CERFACS was the RANS and LES simulations, using the *elsA* code of ONERA, and the tool for the far-field noise analysis, Antares. The ROM has three main constituents: the generation of an accurate mean flow profile, the solution of the linear Parabolized Stability Equation (PSE), and an efficient noise propagation methodology by the FWH acoustic analogy. An initial uncertainty quantification of the stability flow properties with respect to mean flow local variations was performed in partnership with the University of Greenwich. A further sensitivity analysis of the perturbation shape, growth rate, and wavenumber was proposed based on the adjoint equation of the PSE, in which the sensitivities are related to local source forcing. By including sensitivity analyses, this work demonstrated one approach for evaluating the dependence of the predictions on the uncertainty of the output from a chain of tasks. This builds a greater insight into where the largest uncertainties lie in a predictive tool chain.

Promising results were obtained in the prediction of the Sound Pressure Level (*SPL*) outside the jet plume, as shown in Fig. 2. The *SPL* predicted by the ROM of Fig. 1 and the unsteady pressure extracted directly from the LES from CERFACS exhibit the same trend over the Strouhal number range $0.4 \leq S_t \leq 1.2$. The sensitivity analysis highlighted the role of the two shear layers and their unstable modes in the mechanism of noise generation in the cold over-expanded dual stream jet. One of the lesson learnt is that the mean flow variation close to nozzle exit, due to the computational

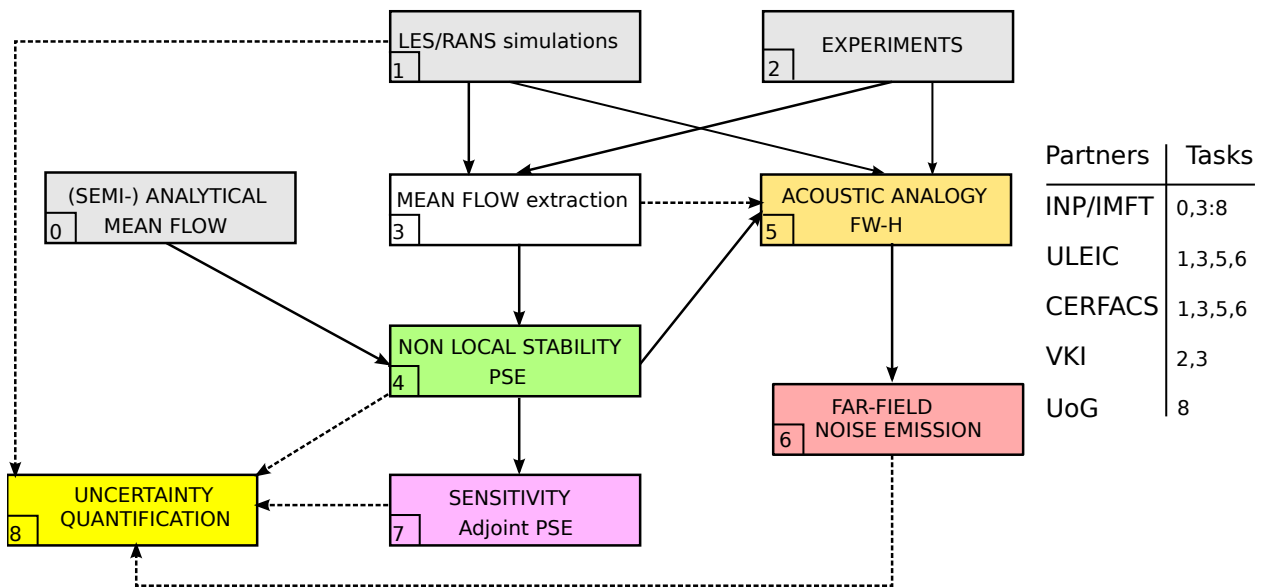


Figure 1: Jet noise Reduced Order Model flow diagram.

approach or the experimental measurement uncertainty, greatly influences the noise prediction.

5. Conclusions

Progress was made towards providing a more integrated, *a la carte*, trans-national doctoral training experience in aeroacoustics. Through the AeroTraNet 2 (2012 - 2016) programme, supported by the European Commission Marie Curie Actions of the 6th Framework Programme, doctoral schools in Belgium, France, Italy, and the UK were able to share their experimental, numerical, and analytical tools and resources, generating a doctoral training offer of greater appeal than their existing programmes. 11 Early Stage Researchers and one Established Researcher benefited from this training. The programme demonstrated the feasibility and the usefulness of systematically addressing the uncertainty in the noise prediction workflow, towards generating better design tools for industry.

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REFERENCES

1. Tam, C., Pastouchenko, N. and Viswanathan, K. Broadband shock-cell noise from dual stream jets, *Journal of Sound and Vibration*, **324**, 861–891, (2009).
2. Tam, C., Seiner, J. and Yu, J. On the relationship between broadband shock associated noise and screech tones, (1984).

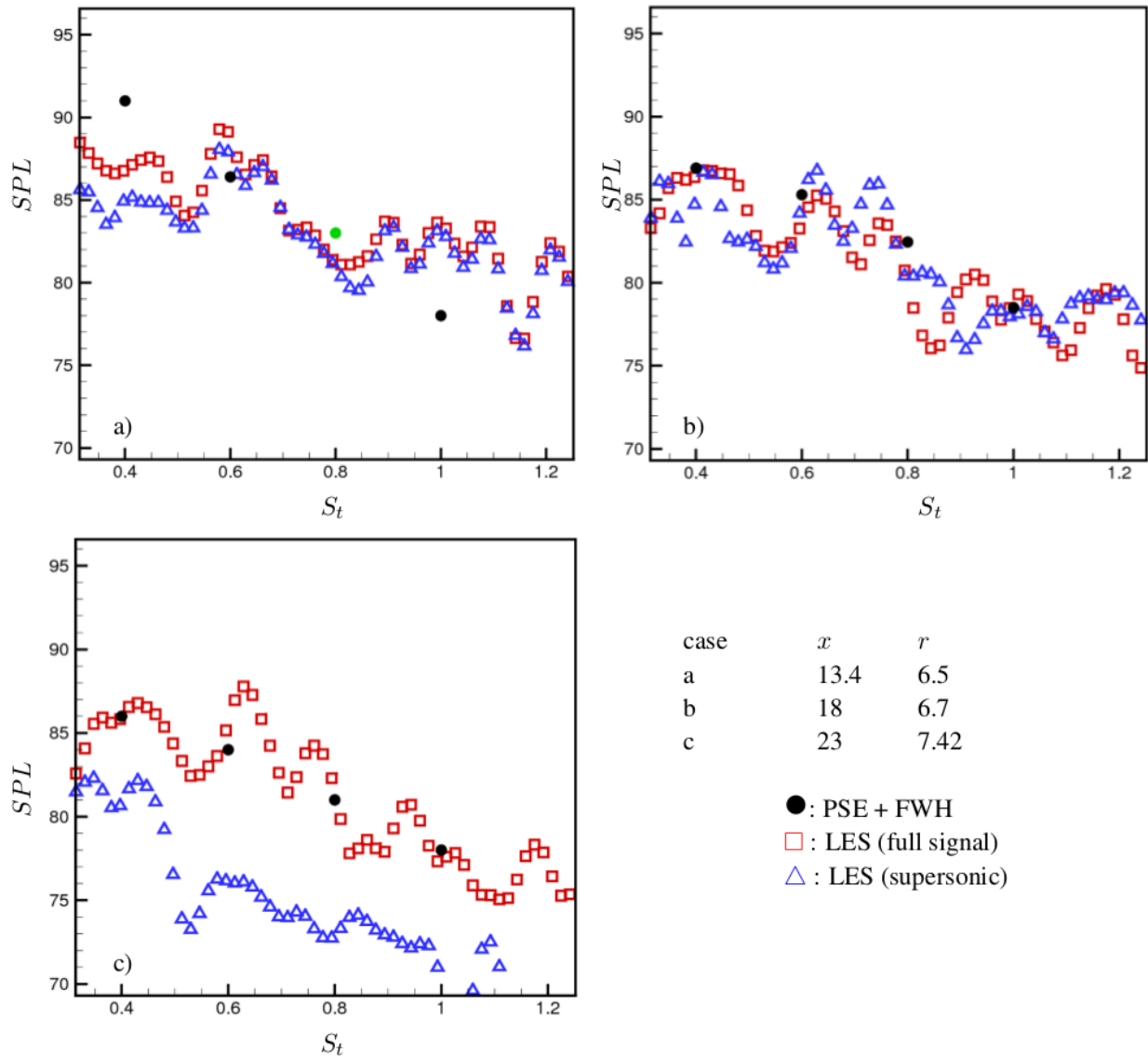


Figure 2: SPL in dB re $20\mu\text{Pa}$ outside the jet plume for three locations along a line inclined at 6° to the jet axis. The green filled points of Fig. 2 a) indicate the reference location for the perturbation amplitude with the PSE.

- Panda, J. Shock oscillation in underexpanded screeching jets, *Journal of Fluid Mechanics*, **963**, 173–198, (1998).
- Suzuki, T. and Lele, S. Shock leakage through an unsteady vortex-laden mixing layer: application to jet screech, *Journal of Fluid Mechanics*, **490**, 139–167, (2003).
- Camussi, R., Grilliat, J. and Caputi-Gennaro, G. Experimental study of a tip leakage flow: wavelet analysis of pressure fluctuations, *Journal of Fluid Mechanics*, **660**, 87–113, (2010).
- ACARE. <http://www.acare4europe.org/>, The Strategic Research Agenda SRA-1, SRA-2 and the 2008 Addendum to the Strategic Research Agenda, (2009).
- Di Stefano, D., Rona, A., Hall, E. and Puigt, G. Modelling directive sound radiation in antares by the fflowcs williams and hawkins analogy, *23rd International Congress on Sound and Vibration*, Athens, Greece, July, (10-14 July, 2016, Athens, Greece).