PROJECT FINAL REPORT

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Project acronym: ORINOCO

Project title: cOoperation with Russia in the field of advanced engIne NOise Control based on plasma actuators

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1 Final publishable summary report

1.1 Executive summary

After several years of efforts on jet noise reduction, acoustic benefits have been obtained thanks to the increase of the Bypass Ratio of the double stream nozzle engine (even if this choice was not motivated by aeroacoustics considerations) and thanks to passive devices such as chevrons. To go ahead, technology breakthrough is now necessary especially with active devices that could be switched off after take-off.

ORINOCO is the cooperation between Europe and Russia for advanced engine noise control based on plasma actuators. It is one of the first projects co-funded by the European Commission and the Ministry of Industry and Trade of Russian Federation. To cope with this new funding scheme, a joint coordination was organized between Onera and TsAGI. ORINOCO started in August 2010 and was completed in January 2014, with respect to the initial schedule. An external feedback on the results was provided by an Industrial Expert Panel, composed of 6 members from Europe and Russian Federation: Airbus, Alenia-Aermacchi, Beriev, Snecma, Sukhoi and Tupolev.

Plasma technologies have initially been developed for flow control and their first applications for jet noise reduction were confronted with technical aspects far from acoustics. This use of plasma actuators is a novel concept that required fundamental approaches to understand the interaction mechanisms with the main jet shear layer and the resulting radiated sound. During the project, three main points were investigated: the development of plasma actuators, the evidence about the existence of instability wave (also known as wave packets) and the evaluation of the capability of plasma actuators to reduce this instability wave.

Several plasma techniques were improved and developed: the Dielectric Barrier Discharge, the Barrier Corona Discharge, the Magnetically Driven Arc Discharge, the Gliding Surface Discharge and the Plasma Synthetic Jets. Their actions on the main jet are the generation of ionic wind parallel or normal to the jet axis or micro-jet impinging on the main jet. All these techniques have proved their efficiency to generate coherent structures connected to instability waves.

Theoretical investigation of the instability wave concept physics was carried out for determining instability wave parameters and for formulating of active control strategy. Experimentally, an Artificial Instability Wave (AIW) was generated on a single stream jet thanks acoustic excitation coming from a loudspeaker. After having showed the feasibility of Suppression of AIW with external acoustic excitations, the same results were obtained with plasma actuators: the suppression of the AIW was proved thanks to PIV measurement.

Coupling mechanisms between the azimuthal modes of the jet were also investigated thanks to theoretical analysis and experiments based on a corrugated nozzle. The same effect was then obtained with High Frequency Dielectric Barrier Discharge actuators succeeding in reducing the noise in the far field.

Finally, ORINOCO demonstrated the existence of the instability waves as a mechanism of noise generation in the jet, thanks the analysis of near field pressure measurements and PIV measurements. Deeper investigations pointed out that linear stability analysis is not able to explain the noise radiated in the far field. What is at stake is the Jittering behavior of the instability waves which involves non-linear dynamics.

Altogether, the results obtained by ORINOCO have reached the objectives fixed at the beginning of the project. New plasma actuators were developed, when others were improved. They have been implemented on single stream nozzle and succeeded in generating strong coherent structure convected by the jet. In some cases, noise reduction was obtained on the far field. On the subject of jet noise mechanisms based on instability wave concepts, great progresses were achieved: experimentally, the existence of instability waves was demonstrated and the possibility to suppress them too. Fundamentally, it was found that instability wave mechanisms are strongly connected with the noise radiated in the far field, and non linear behaviours were highlighted. Thereby, ORINOCO project has increased knowledge on jet noise and plasma actuators mechanisms, and draw recommendations on the future research to be performed in the field of jet noise by aeronautical industries to reduce external noise and conform to ACARE agenda. Thus, The ORINOCO project will support European competitiveness in aeronautical domain as well as benefiting to citizens by promoting noise reduction.

1.2 Summary description of project context and objectives

In the domain of civilian aeronautics, the increasing noise restrictions around airports are a challenging problem for aircraft and engine manufacturers. By 2020, the ACARE agenda has stated a reduction of the external noise by 10 EPNdB per operation of fixed-wing aircraft. The efforts in research and development for many years have resulted in significant reduction in the sound pressure level radiated by aircrafts engines currently in service, especially for jet noise which remains the main source of noise at take-off.

After the introduction of the high by-pass ratio engine, which contributed to both an improved aerodynamic efficiency and a substantial noise reduction, jet noise reduction has been treated by the implementation of passive devices such as chevrons or mixers, which enhance the mixing in the shear layers to reduce jet noise, but unfortunately decrease the engine performance during cruise. Therefore, to reach ambitious noise reduction goals without thrust penalty, it is necessary to implement new ideas, based on active devices that can be switched off during cruise. Micro-jet actuator was one of the first implemented solutions, with reduction comparable with chevrons. However, air supply for these devices has to be taken from the engine, at the moment when the maximum thrust is needed. Another solution is to use plasma actuators system that can be easily configured in any spatial form near nozzle orifice.

ORINOCO is the cooperation between Europe and Russia for advanced engine noise control based on plasma actuators. Plasma technologies have initially been developed for flow control and their first applications for jet noise reduction were confronted with technical aspects far from acoustics. This use of plasma actuators is a novel concept that requires fundamental approaches to understand the interaction mechanisms with the main jet and the resulting radiated sound.

Toward the final goal of the evaluation of plasma actuators concepts for jet noise reduction, several points have been identified, including theoretical, numerical and experimental investigations:

- **To develop and enhance plasma actuators technologies dedicated to jet noise reduction**

At the beginning of the project, the only experiences of jet noise control with plasma actuators come from OPENAIR project, but no fundamental investigations were performed to optimize their behaviours for jet noise reduction. ORINOCO has the objective to focus on fundamental mechanisms between the actuators and the jet in order to design plasma actuators specifically for jet noise reduction. This high level of understanding requires accurate numerical simulations supported by experimental tests. Moreover, new plasma techniques coming from other domains will be adapted to the specific mechanisms of jet noise.

- **To investigate instability waves concepts for jet noise**

It is known that instability waves are specific solutions of governing Equations in the region far downstream from the nozzle exit where they dominate the other disturbances due to Kelvin-Helmholtz instability. However it is difficult to organize the control strategy based on the instability wave signature far downstream using the actuators located on the nozzle (or near the nozzle). Therefore for development of control strategy the principle objective consists in the description of the perturbation field near the nozzle exit and relation of these field characteristics with amplitude and phase of the developed instability wave. The best solution is to measure the near field on the nozzle surface where the mean flow is absent. It gives the direct measurements of initial wave characteristics which are necessary for control. In ORINOCO project, the objective is to develop the theory for instability wave description in the field near the nozzle, obtain the robust formula for relation of near field signature with characteristics of instability wave, experimental diagnostics of the instability wave in the near field and far downstream where it dominates.

- **To formulate noise control strategy**

What is the most efficient action on the jet to reduce the radiated noise is a fundamental issue that is still under investigation. Knowing actuators mechanisms is not sufficient to obtain successful acoustic reduction. Complementary studies are necessary to optimize their global effect on the jet noise (number, location, magnitude, phase…). Thanks to previous European projects (JEAN, CoJEN), Computational Fluid Dynamics (CFD) and Computational AeroAcoustics (CAA) simulations has been improved to develop methodologies adapted to jet noise. ORINOCO uses the resulting numerical tools to define the best control strategy. For instability wave concept, theoretical and experimental considerations focus on a strategy to generate instability wave in anti-phase with the jet one.

- **To implement jet noise control based on plasma actuators.**

Jet noise reduction is a major goal for aeronautical industry, and plasma technology presents a promising solution. However, the concept needs to prove its potential. Thanks to the fundamental works performed during the first stages of the project, aeroacoustics tests will be carried out in wind tunnel facilities. The experimental results will be analysed to evaluate the potential of plasma actuators concepts for jet noise reduction.

In order to address these themes and succeed in reaching its goal, ORINOCO is organised in five Work Packages:

WP1 – Plasma actuators concepts for jet noise reduction

The plasma actuators is developed and improved in this Work Package with the support of theoretical considerations, numerical simulations and experimental tests in laboratory. At the beginning of the project, a scientific workshop is organised in order to enhance discussions on the specificities of plasma actuators for jet noise reduction. Control strategies are investigated to define the best mean of acting on the flow in order to reduce the jet noise. Finally, linear and non-linear feedback control laws are developed in preparation of the assessment performed in WP3.

More accurately, the objectives of the WP1:

- to organise scientific workshop on the state of the art in the field of available plasma actuator technologies and instability wave concept development,

- to develop, optimise and manufacture plasmas innovative actuators (surface and arc plasmas types) dedicated to jet exhaust noise reduction,
- to do investigations of the fundamental mechanisms between actions, actuators and jet exhaust,
- to define strategies of jet noise reduction by theoretical, CFD and experimental studies,
- to develop open and closed loop control laws depending on the needs of noise control.

WP2 – Investigation of instability waves concept physics

Instability wave is the physical mechanism exploited by some plasma actuators concepts in ORINOCO. This dedicated Work Package deals with the instability waves concept physics to define its parameters in the vicinity of the nozzle and the characteristics of actuators to generate anti-phase waves. Theoretical, numerical and experimental studies is carried out to select plasma actuators configurations from WP1 and to prepare their implementations for assessment in WP3.

In details, the objectives of WP2 are the following:

- to elaborate of the plasma actuator active control strategy which is realized with two steps: (i) Suppression of Artificially excited Instability Wave (SAIW, T2.1); (ii) on this base formulation of control strategy for the instability waves of different azimuthal structures developing downstream in free high speed jet (Suppression of Natural Instability Wave, SNIW, T3.3).
- To develop the instability wave concept physics for determination of instability wave parameters via near-field jet characteristics.
- To evaluate the influence of temperature effect on instability wave dynamics (to T3.1)
- To develop experimental tools for diagnostic instability wave parameters
- To develop experimental diagnostics of the flow-field parameters of instability waves including unsteady CFD simulations
- To evaluate the actuators characteristics for generation instability waves from the point of view noise suppression (to T3.3)
- To carry out RANS-MFD simulation of plasma control effects on instability waves
- To provide closed-loop system for artificial instability wave control to T3.3
- To select plasma actuators for testing in T3.1 and T3.3 for acoustic measurements

WP 3 – Concept assessment

The objective of this work package is to assess the various control strategies developed in T1.3 and T2.1. Experiments are performed at the CNRS, ECL and TsAGI, and the results will be compared in terms of noise reduction and changes in flow/source mechanisms:

- Noise suppression based on arc plasma actuators technique (APAT) and azimuthal mode coupling technique (AMCT, T1.3.1) performed at CNRS and ECL,
- Suppression of natural instability wave (SNIW) with DBD, corona and gliding discharges based on suppression of artificial instability wave (SAIW, T2.1) performed at TsAGI,

The analysis of the experimental data has two objectives: the first is to understand the changes which are produced by the actuators, both in terms of the flow structure and the sound-source mechanisms ; the second objective is to understand how the concepts should be scaled up to large-scale (T4.2).

WP4 – Exploitation and dissemination

WP4 is dedicated to the synthesis of the results and their dissemination outside the project. In details, the objectives are:

- To make a synthesis of the results of the project;
- To prepare the industrial exploitation of these results, through communication of the results to the Industrial Expert Panel and thanks to recommendations for an implementation of the plasma actuators on a full scale;
- To disseminate the outputs of the project in the aeronautics and scientific community, to ensure the proper exploitation of outputs complying with the consortium agreement terms;
- To organise an international workshop to present the results of ORINOCO.

WP 5 – Coordination & Management

The objective of WP5 is to lead the program, harmonizing all partners' works and efforts so that all the objectives of the project are reached, and its program fully achieved. In particular, the coordinators endeavour to carry out on arbitrage of all strategic and tactical decisions, continuously trying to adjust the Consortium means to the program needs, and controlling the costs and the respect of the schedule. It is also to ensure a proper communication among partners, and the control of exploitation and dissemination circumstances.

In practical terms, Work Package 5 has two main goals:

- To support an efficient coordination of the Consortium according to the specificity of the bicephalous coordination.
- To secure the prompt initiation and smooth running of the project activities and the timely production of all deliverables, to the EC as well as to the partners, within the budget, and according to the EC rules.

1.3 A description of the main S&T results/foregrounds

1.3.1 WP1 Plasma Actuators Concept for Jet Noise Reduction

a) Overall objectives of the WP for all the project

The objectives of the work package are:

- to do investigations of the fundamental mechanisms between actions, actuators and jet exhaust,
- to define strategies of jet noise reduction by theoretical, CFD and experimental studies,
- to develop open and closed loop control laws depending on the needs of noise control.

b) Description of the methodology

This WP breaks down into 4 tasks.

- Scientific workshop (Georgy A. Faranosov, TsAGI),

→ participation of all the partners

- Development and Optimisation of Plasma actuators set-up (Ivan Belyaev, TsAGI),

→ participation of TsAGI, ONERA, ECL, CNRS, JIHT RAS, TRINITI, GPI-RAS

- Definition of Control Strategies (Nikolay N. Ostrikov, TsAGI),

→ participation of TsAGI, ONERA, ECL, CIRA, CNRS

- Development of the plant model and control laws (Peter Jordan, CNRS).

c) Description of the WP results

➲ Task 1.2

Task 1.2	**Development and Optimisation of Plasma Actuators set up**	**TsAGI, ONERA, ECL, CNRS, JIHT RAS, TRINITI, GPI RAS**

This task was devoted to the development, adaptation and optimization of plasmas actuators based on different types of electrical discharges. Designs and properties of actuators under development were presented in Deliverable D 1.2-1, D1.1-2, D 1.2-3, D1.2-4 and Project periodic reports.

→ Activity 1.2.1 - Elaboration of plasma discharge actuators as an effective tool for instability wave control (TsAGI, JIHT RAS, TRINITI, GPI RAS, CNRS)

Several types of plasma actuators were designed, manufactured and improved in frameworks of project. These actuators are based on different types of gas discharges (high frequency dielectric barrier discharge (HF DBD), slipping surface discharge, surface barrier corona discharge, arc discharge in magnetic field, combined discharge) (D1-2.1,3,5).

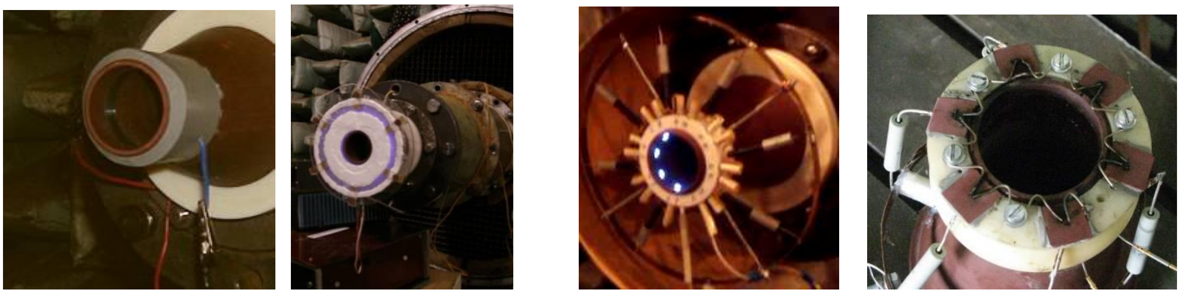
The classical two-electrode surface DBD scheme was used for HF DBD plasma actuator (Fig.1a). High frequency (up to 300 kHz) power supply was used for its operation. The internal plasma-generating electrode was located at the distance of 3 cm upstream from the nozzle exit. The discharge developed downstream direction.

Surface barrier corona discharge plasma actuator (Fig.1b) allows one to take basic advantages from both a corona discharge and dielectric barrier discharge. Such discharge combination gives an opportunity to diminish a distance between corona needles without giving rise to spark formation. This actuator creates pulsing ionic wind near the nozzle edge.

Slipping surface discharge plasma actuator (Fig.1c) has eight plasma forming spark gaps on inner nozzle surface at 1 cm distance from nozzle edge. Discharge duration was about 1 μs.

The effect of these three actuators on the jet shear layer near the nozzle edge was investigated. The results of these experiments are presented in deliverable D2-1.4. In all cases actuators materially affect the jet shear layer resulting in instability waves excitation and were used for instability wave control.

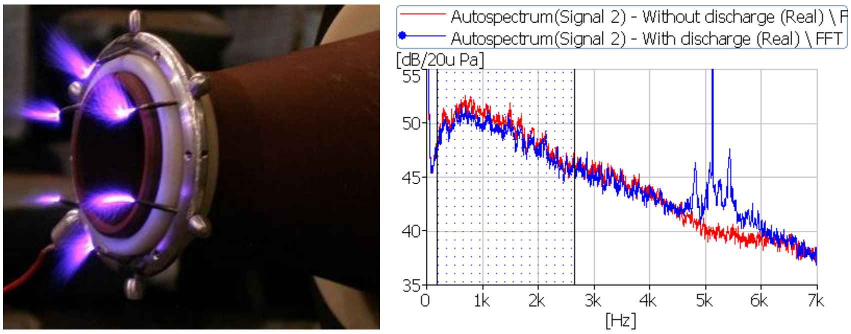
Magnetically driven arc plasma actuator (Fig.1d) has six discharge gaps. The discharge was created along ceramic plate surface between wire electrodes, normally to the flow direction. Ceramic plates are required for electric and thermal insulation of the magnets from the discharge. It has been revealed that magnetically driven arc discharge actuator creates coherent structures in the shear layer of turbulent jet. But it was not used for instability wave control experiments due to frequency power supply limit.



a b c d

Figure 1 – Dielectric barrier, surface barrier corona, slipping discharges and magnetically arc plasma.

Combined discharge plasma actuator has six needle plasma forming electrodes (Fig. 2a). The combined discharge plasma actuator didn't create distinguishable coherent structure in jet shear layer due to azimuthal nonuniformity. It is necessary to notice, that high-frequency combined discharge actuator excitation led to jet noise suppression in low-frequency range of noise spectrum (Fig.2b).



a b

Figure 2 Combined discharge

Surface Dielectric Barrier Discharge (DBD) actuators powered by nanosecond pulsed high voltage are investigated as potential candidate for jet noise reduction. This type of actuator produces a localized pressure wave propagating at sound speed. This pressure wave results from the sudden temperature increase at the wall surface due to the plasma propagation. So, the strength of the pressure wave is directly correlated with the amount of electrical energy deposited on the wall surface. The objective in WP1 for PPRIME contribution is an optimization of the actuator geometry in order to maximize the deposited energy and subsequently in order to reinforce the pressure gradient created by the actuator at the dielectric wall. In context of jet noise reduction, it is expected that the produced pressure waves can interact with the axisymmetric shear layer and more specifically it is presumed that pressure wave may modify the organization of the coherent flow structures responsible for a part of the radiated noise.

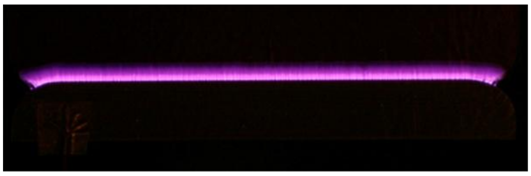


Figure 3 – nano-second pulsed DBD

→ Activity 1.2.2 - Improvement and development of arc plasma actuators – Investigation on the actuator behaviour (ONERA, ECL)

- The Plasma Synthetic Jet has been developed and improved. The frequency varies from a few Hertz up to 2 kHz. For Orinoco applications, the generated micro-jet velocity can reach 200 m/s with a temperature around 400 to 600 K.

A 3-scale numerical model has been successfully developed in order to describe the aerodynamics PSJ aerodynamic effect on a flow. The PSJ effect is described using a volumic source term computed by a coupled solver for both the PSJ cavity aerodynamics and the non-confined arc discharge creating the exhausted jet.

Two dedicated models have been developed in order to understand both the microscopic development of the arc discharge and the evolution of the flow inside the cavity due to the heating by this discharge. Thanks to an accurate Real Gas Thermodynamics [2], these models have proven to be able to estimate the amount of energy really transferred to the exhausted jet during one pulse and also to determine the characteristics of this jet [1,3].

The key point is about determining the source term representing the periodic behaviour of the PSJ as it has been pointed out that the exhausted mass and momentum after 30 periods differ from the first pulse, due to the modifications of the pressure and densities inside the PSJ cavity. Our coupled model has proven to be able to capture this particular behaviour. A first numerical test-case accounting for the aerodynamics effects of the PSJ has been constructed and showed promising results both in qualitative and quantitative ways. This test-case does validate the methodology proposed. In order to completely validate the model in terms of physical aspects, more complex numerical simulations involving both refined meshes and turbulence models need still to be performed (see D 1.2-4).

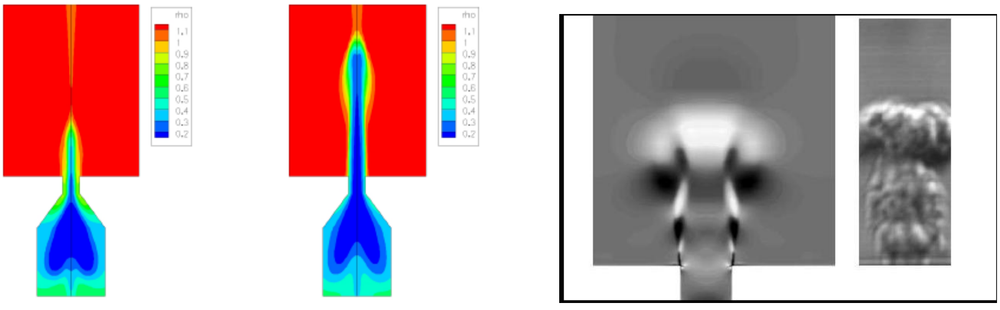


Figure 4 – Cavity and micro-jet simulation – Schlieren visualization comparison.

- Two types of nozzle based on JEAN geometry, □=50mm, have been defined and manufactured, Lip and VG nozzles (fig. 5). They correspond to two types of control strategy acting on the shear layer characteristics at the sources of noise. These two interactions generate two different types of vortices which modify the characteristics of the shear layer.

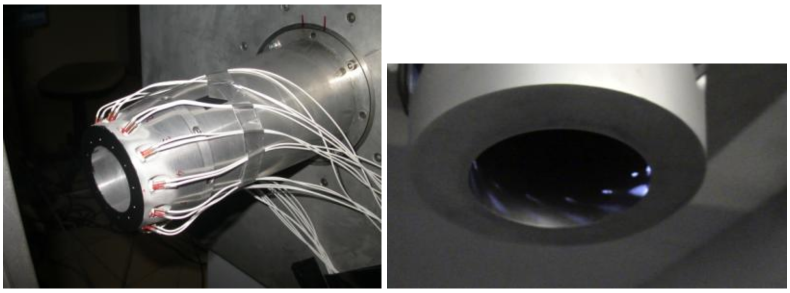


Figure 5 - Lip and VG nozzles

➲ **Task 1.3**

Task 1.3	Definition of Control Strategies	**TsAGI, ONERA, ECL, CIRA, CNRS**

→ Activity 1.3.1 – Numerical and experimental optimisation of jet noise reduction based on azimuthal modes decomposition (ONERA, ECL, CIRA, CNRS)

ONERA performed noise and aerodynamic characterisation, both experimentally and numerically, of high Reynolds number subsonic jets manipulated by means of PSJ actuators. The objectives are to highlight the configurations providing the most pronounced jet noise modifications, which may help in identifying the underlying mechanisms of jet noise production with and without actuators. The comprehensive presentations of the results can be found in deliverables D1.2-4, D1.2-6 and D1.3-1.

The application of the PSJ actuator on the lip region of the nozzle is able to generate coherent structures by forcing and driving the natural instabilities of high-Reynolds number subsonic jets, which would alter the noise radiated at low emission angles. A 2-Dimensional- 2-Components (2D-2C) Particle Image Velocimetry (PIV) measurement campaign was performed in order to explore the generation of the coherent structures. Schlieren visualisations were also performed to complete the aerodynamic measurements. It was observed that strong coherent structures are generated, locally increasing the thickness of the mixing layer and changing the repartition of energy in the mixing layer (fig. 6 & 7)

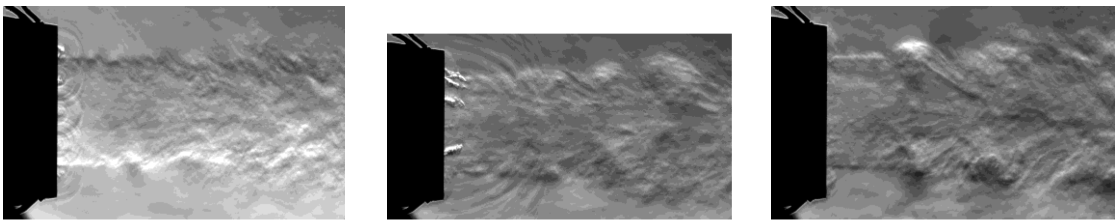


Figure 6 - Schlieren visualisation of pulsed generated vortexes

Lip nozzle - M=0,4- f_{JSP}=10 Hertz – t=130□s, 250□s and 800□s

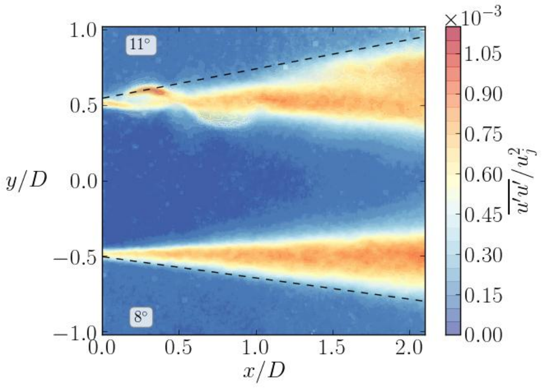
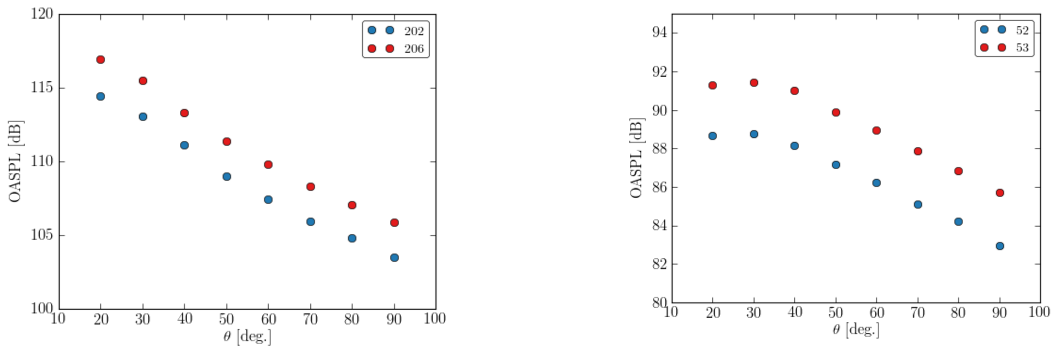


Figure 7 - Strong coherent structure visualisation and divergence (forced by PSJ = 11°, natural = 8°) M= 0,6 – PIV measurements.

Far-field acoustic measurements were performed at ONERA Toulouse prior to a second and more accurate aeroacoustic measurement campaign that was later performed in the anechoic chamber of the ECL/LMFA (WP3). The acoustic measurements have shown that the PSJ actuators were able to increases the noise of high-Reynolds-number subsonic jets by interacting either with the mixing layer (Lip-Nozzle, fig. 8-a), or with the boundary layer (VG Nozzle, fig. 8-b)



(a) (b)

Figure 8 – Effect of PSJ actuation, f=820Hz,- a) Lip nozzle, M=0,9 – b) VG_nozzle, M=0,4

Near-field pressure fluctuations of high Reynolds number subsonic jet under PSJ actuation were also performed. One can observe the generation of tonal components when the PSJ actuators are activated, with the first peak corresponding to the main actuation frequency, followed by harmonics (fig. 9). It shows that the peaks observed in the near field of the forced jets are not directly resulting from the acoustic signature of the actuators, but rather translate an aerodynamic of aeroacoustic response of the jet.

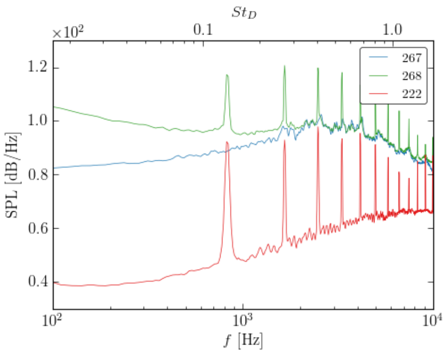


Figure 9 - *Example of near-field spectra - microphone #2 (x = 1D)*

267; M = 0:9 - baseline, 268; M=0,9 - f_{PSJ} = 820 Hz; 222: M=0 - f_{PSJ} = 820 Hz.

Onera performed RANS simulations to provide the mean flow fields used for PSE analysis [4] and investigated numerically the action of the Plasma Synthetic Jets on the development of a jet flow and noise [5]. The flow simulated is similar to the one investigated experimentally, with an exhaust Mach number of 0.9. The control is made with 12 PSJs located at nozzle exit with the forcing frequency f_F = 820 Hz and with the azimuthal mode m = 0. Both configurations without and with PSJs are computed; large eddy simulations and noise radiation (Ffowcs Williams & Hawkings) are performed with the codes CEDRE and KIM developed at Onera.

Aerodynamically, mean and turbulent flow modifications have been observed with the PSJs, as an evidence of the action of the control on the jet development. Especially, the vortical structures growing in the shear layer, observed experimentally with PSJs, were successfully reproduced numerically, as visible in 0.

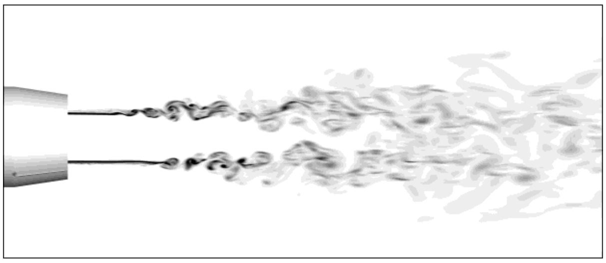
	
(a) without PSJs	(b) with PSJs

Figure 10 – Vorticity snapshots. The vortex generated by the PSJs is indicated with an arrow.

In the far field, the broadband noise increase observed with the PSJs, reproduced in 11 (b) at 90°, is in very good agreement with the experimental results, 11 (a), as well as the OASPL modification (+2 dB experimentally, + 1.5 dB numerically).

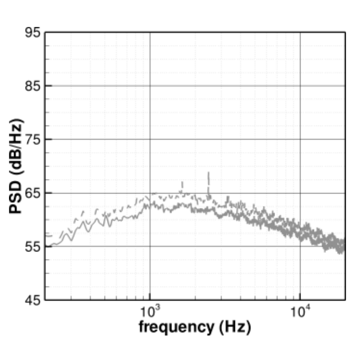
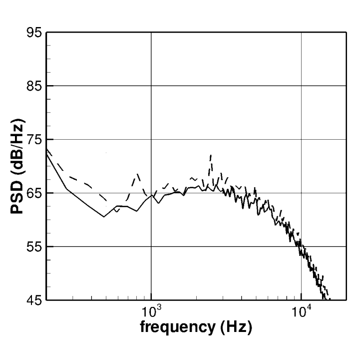
	
(a) experiments	(b) simulations

Figure 11– Power Spectral Densities at 90° — without PSJs and – – – with PSJs.

These results illustrate the capacity of the numerical simulations to reproduce the flow and noise modifications in the presence of PSJs, to help understanding the mechanisms occurring in the jet for further noise reduction. Detailed results on the simulations are described in [5] and are planned to be presented at the AIAA/CEAS Aeroacoustics Conference in 2014.

Activity 1.3.2 Theoretical and experimental investigation of jet azimuthal structure influence on the instability wave development

Theoretical investigation of the instability waves developing within jet mixing layer having weak azimuthal nonuniformity was carried out. It was shown for corrugated jet (Fig.12); initial natural excitations are expanded near the orifice into series over eigensolutions. Due to each eigen-solution contains a mixture of different azimuthal modes, the contribution of eigensolution can decrease with respect to round jet. Corrugation effect of mean flow decreases downstream, so every eigen-solution tends to the form characterized for round jet, but some has less amplitude with respect to round jet. As a result, it is possible to suppress radiating instability waves. A result of this investigation shows that it cans to suppress axisymmetrical instability wave given the main contribution to the sound. (D1-3.2)

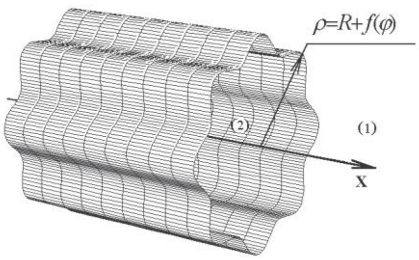


Figure 12 - Corrugated jet with an s-lobed cross-section of the form f(φ)=ε cos(sφ), where ε - dimensionless parameter characterized a weak azimuthal nonuniformity.

The possibility of reducing the noise of a subsonic turbulent jet by using a corrugated nozzle was experimentally demonstrated. The sound fields of subsonic jets issuing at a rate of 240 m/s from six tab corrugated nozzles with different corrugation amplitudes were compared with the sound field of an equivalent circular jet (Fig.13). It was shown that an increase in the corrugation amplitude leads to a noise decrease in the far field of the jet within the Strouhal number interval 0.1 < St < 0.7, which contains a maximum of the jet radiation spectrum, and to a slight noise increase in the high frequency region. The use of a corrugated nozzle leads to a noise decrease of 2.3 dB, as compared to the case of a circular nozzle with the same area of the output section. (D3-3.1)

Figure 13 - Photographs of the corrugated nozzles and the circular nozzle with the equivalent area of the output cross section.

➲ **Task 1.4**

Task 1.4	**Development of the plant model and control laws**	CNRS

The search for simplified models of subsonic turbulent jets and the noise they produce continues to be driven by the need for low-cost-prediction and design-guidance tools; while a more recent interest in closed-loop control motivates the search for time-domain models. In both cases the crux of the problem is to understand the underlying mechanisms, such that the Navier Stokes equations can be distilled down to some simplified form that captures these with accuracy sufficient for the job at hand (prediction, control, design,. . .). PPRIME WP1 activity was devoted to the search for such models, and a number of approaches were pursued in this regard.

Initial investigations were based on the POD-Galërkin approach, where we used numerical data to distill the full flow solution down to a simplified dynamic model. A comibation of conditional structure eduction (using linear stochastic estimation), Proper Orthogonal Decomposition and system-identification allowed us to obtain a non-linear, 20-degree-of-freedom model that reproduces both the flow dynamics and sound-source activity of the turbulent jet. This is reported in deliverable 1.4-1.

The problem of how best to integrate a externally imposed actuation, for the purpose of control, was then investigated theoretically in the framework of Galêrkin projection, where the formalism was adapted to incorporate unsteady boundary conditions. This work is reported in deliverable 1.4-2.

The above developments were accompanied in WP2 by an extensive exploration of the capacity of linear stability theory to explain the evolution of wavepackets (coherent turbulent structures) over the first 5 diameters of both actuated and un-actuated jets (cf. D2.1-1 ; D2.1-5). These results suggested that models simpler than those derived using the POD-Galërkin approach might be appropriate for the purpose of control; though non-linearity can not be entirely neglected, it might be possible to include it in a simpler, appropriately crafted, dynamic Ansätz. This way of approaching the problem was felt to be more promising than the rather arbitrary rank-reduction philosophy of the POD-Galërkin framework and so we began to explore the possibility of constructing a, simpler, more experimentally-adapted ROM using ARMAX (Auto-Regressive Moving

Average eXogeneous) system identification. The simplicity of this linear input-ouput model makes it an attractive choice for the implementation of closed-loop control. This approach was implemented experimentally on an unactuated jet and showed very promising results: the model is capable of providing a surprisingly good prediction of the downstream evolution of wavepackets based on measurements in the near-nozzle region.

The ARMAX model is not of course perfect; its performance deteriorates considerably around the end of the potential core, precisely the region where linear stability theory (cf. D2.1-5) also shows poor agreement with measurement. The latest analysis of these different results leads us to believe that simplified (linearised) models require something more, and may prove promising for ROM design and control provided the non-linear mechanisms essential for sound generation, which take the form of wavepacket jitter and axial coherence decay, are clearly understood and then explicitly incorporated in the linearised model. The most recent work is based on the use of the non-linear , one-dimensional, Burgers' equation which we solve subject to deterministic, stochastic and mixed deterministic-stochastic upstream forcing; we then use the solution to understand what kind of distilation leads to a simplified, linearised model that reproduces the said non-linear signatures (jitter and axial coherence decay). Initial results shows that by performing a linearisation about a slowly time-varying base flow (obtained by low-pass filtering the complete non-linear solution), the resulting linear model can indeed reproduce the said behaviour. This encouraging result will next be tested in the framework of the Navier-Stokes equations using a Large Eddy Simulation and subsequent Linearised Euler Equation solution using an unsteady base-flow obtained from the LES solution.

d) Global conclusions for the WP

During Orinoco project, different devices using plasma technology have been developed, manufactured and improved for jet exhaust noise control, "Gliding surface multi-spark discharge", "Closed Barrier Corona", "Magnetically Driven Arc", "Dielectric Barrier Discharge", "Plasma Synthetic Jet" and Nano-Second Dielectric Barrier Discharge".

Numerical and experimental investigations on the fundamental mechanisms between actuations, actuators and jet exhaust have shown the capabilities of such devices to create coherent structures by forcing and driving the natural instabilities of high-Reynolds number subsonic jets, which would alter the noise radiated at low emission angles.

This work gave an important input to WP3 activities. The mechanisms of noise reduction with unsteady devices are not completely understood but this project allowed a big advance in the understanding of the physic phenomena. The obtained results are very promising.

1.3.2 WP2 Investigation of Instability Waves Concept Physics

a) Overall objectives of the WP for all the project

WP2 deals with the instability waves concept physics to define its parameters in the vicinity of the nozzle and the characteristics of actuators to generate anti-phase waves. Theoretical, numerical and experimental studies are carried out to select plasma actuators configurations from WP1 and to prepare their implementations for assessment in WP3:

- Elaboration of the plasma actuator active control strategy which is realized with two steps:
    - (i) suppression of artificially excited instability wave;
    - (ii) on this base formulation of control strategy for the instability waves of different azimuthal structures developing downstream in free high speed jet.

- To develop the instability wave concept physics for determination of instability wave parameters via near-field jet characteristics.
- To evaluate the influence of temperature effect on instability wave dynamics
- To develop experimental tools for diagnostic instability wave parameters
- To develop experimental diagnostics of the flow-field parameters of instability waves including unsteady CFD simulations
- To evaluate the actuators characteristics for generation instability waves from the point of view noise suppression
- To carry out RANS-MFD simulation of plasma control effects on instability waves•
- To provide closed-loop system for artificial instability wave control
- To select plasma actuators for testing in T3.1 and T3.3 for acoustic measurements

b) Description of the methodology

TsAGI activity was corresponded with achievement of the following WP2 objectives: elaboration of the plasma actuator active control strategy, development of the instability wave concept physics for determination of instability wave parameters via near-field jet characteristics, development of experimental tools for diagnostic instability wave parameters, development of the experimental diagnostics of the flow-field parameters of instability waves, evaluation and experimental assessment of plasma discharge actuators' capability to generate the instability wave of necessary parameters and suppress the artificial instability wave, the selection of plasma actuators for testing in T3.1 and T3.3 for acoustic measurements, the providing of the closed-loop system for artificial instability wave control.

PPRIME-CNRS activity was corresponded with achievement of the following WP2 objectives:

development of the instability wave concept physics for determination of instability wave parameters via near-field jet characteristics, development of the experimental tools for diagnostic instability wave parameters, development of the experimental diagnostics of the flow-field parameters of instability waves.

NLR activity was corresponded with achievement of the following WP2 objectives: the developing of the experimental diagnostics of the flow-field parameters of instability waves including unsteady CFD simulations.

CIAM activity was corresponded with achievement of the following WP2 objectives: the evaluating of the influence of temperature effect on instability wave dynamics and the developing of the experimental tools for diagnostic instability wave parameters.

CIRA activity was corresponded with achievement of the following WP2 objectives: the carrying out RANS-MFD simulation of plasma control effects on instability waves.

c) Description of the WP results

TsAGI’s team presented in D2.1-1 theoretical and experimental results on developing of the instability wave concept physics for determination of instability wave parameters via near-field jet characteristics together with experimental verification of the theory from far field measurements by means of azimuthal decomposition technique. The good agreement between theory and far field measurements was obtained. In the whole, these results show that artificially excited instability waves can be founded from near field measurements. Moreover, this theory allows the instability wave parameters to be determined for concrete way of their excitation. Therefore, it was used at following experimental investigation on the determining near-field parameters of instability waves excited artificially by plasma actuators and acoustically by use of different experimental tools.

TsAGI's team presented in D2.1-3 theoretical results on actuators characteristics required for instability waves generation. Corresponding solutions obtained by means of the Wiener-Hopf technique shows that

- the effectiveness of instability wave excitation substantially depends upon the localization of the external disturbance;

- instability wave amplitude reaches its maximum when the nozzle edge lies in the zone of maximal excitation;

- the dependence of the instability wave amplitude on the angle of incidence becomes weaker when the width of the excited zone of the shear layer diminishes;

- in order to increase the effectiveness of instability wave excitation, it seems reasonable to concentrate actuator's impact on the nozzle edge.

A rough estimation of the actuators intensity required for effective instability wave generation was performed in D2.1-3. It has been shown that plasma actuators should be capable to create a pulsing gas stream with amplitude of speed pulsations about 1m/s concentrating actuator's impact on the nozzle edge.

For quantitative diagnostics of artificially excited coherent structures/instability waves in jets, phase-locked PIV has been used (D2.1-5). Results of phase-locked PIV demonstrate the appearance of periodic spatial structure (especially in V_y field) which can be associated with the most excited instability wave for high-speed jet in consideration. In the case of mismatch between acoustical excitation frequency and PIV sampling frequency the orderly structure of velocity field disappears and the flow picture looks like for the unforced jet. With the velocity increase the period and amplitude of excited instability wave also increase, as well as the spatial range of the wave-packet. Both facts are in agreement with conclusions of instability wave theory. The conducted experimental campaign provides an experimental technique and database on acoustically forced and unforced turbulent jets, which can be used for identification and analyses of instability waves. An acoustic control over artificially excited instability wave was realized. The goal of the experiment was twofold: 1) verification of the results of theoretical approach developed in D2.1-1; 2) application of the experimental tool based on PIV technique to the instability wave diagnostics in the controlled jet.

For instability waves control in a jet shear layer near to a nozzle exit some variants plasma actuators were developed and created. Theoretical research results were regarded for plasma actuator elaboration. These actuators were based on different types of gas discharges (combined discharge, high-current gliding surface discharge, high frequency dielectric barrier discharge, surface barrier corona discharge). All actuators had been described in detail in deliverables D1.2-1, D1.2-3 and D1.2-5. For comparability of received results identical ceramic nozzles with a profile Vitoshinsky were used for all actuators.

For quantitative diagnostics of artificially excited instability waves in jets, phase-locked PIV has been used. The principal idea of phased-locked PIV consists in averaging the PIV results over a sequence of images with the same phase shift relative to the excitation signal. This allows us to separate a periodic component of velocity field from the uncorrelated pulsations. The results of phase-locked PIV measurements demonstrated the possibility of three elaborated plasma actuators (based on high frequency dielectric barrier discharge, on barrier corona discharge, on multy-spark gliding surface discharge) to create periodic spatial structure which can be associated with the most excited instability wave for high-speed jet.

These actuators were used in instability wave control experiments (D2.1-4). The main goal of these experiments was to clearly demonstrate the plasma actuators possibility of control over artificially excited instability waves in turbulent jet which is the basic idea of the ORINOCO project. Instability wave was excited by plane acoustic wave coming from the settling chamber, and then this instability wave was cancelled by the external plasma actuators forcing. The experiments were carried out in TsAGI's anechoic chamber AC-2. Firstly, the intensities of acoustical and plasma excitation were adjusted so as to give approximately equal levels of instability wave amplitude. For this adjustment we provided PIV measurement of instability wave amplitude created by plasma actuator and loudspeaker separately.

The experiments with three types of plasma actuators shown that the variation of the phase shift between the adjusted acoustical and plasma excited sources leads to approximately sinusoidal variation of instability waves amplitude, so that there exists a phase shift corresponding to maximal amplification and maximal attenuation (shifted by 180^0) of the coherent structures, the difference between minimum and maximum amplitudes being up to fourfold depending on the actuator type. The proposed systems of actuators allow effective controlling of artificially excited instability waves in the whole shear layer of the jet. The highest level of variation was reached for HF DBD plasma actuator and jet velocity – 200m/s (more than fourfold). At 100m/s velocity the jet is very sensitive to actuator impact intensity.

As a result, the main WP2objective was achieved by experimental evidence of the plasma actuators possibility of control over artificially excited instability waves in turbulent jet.

An initial series of experiments were performed by CNRS's team in D2.1-1 on forced jets (pulsed fluidic actuators were used). The flow was forced with a perturbation comprising three dominant frequencies and the response of the flow explored by means of phase-averaged hotwire measurements. This classical technique allows the wavepacket component to be educed in the framework of the triple decomposition. The educed component was then compared with the results of a linear stability calculation based on the locally-parallel formulation of Michalke. Favorable results for the lower amplitude component of the forcing function suggest that for low-amplitude perturbations the response of the jet can be understood in the framework of linear stability theory. Evidence of non-linearity was observed for the higher amplitude forcing.

The second series of experiments were devoted to the unforced jet, issuing from a nozzle with fully turbulent boundary layers, in order to establish if linear hydrodynamic wavepackets exist in such flows. The work is described in D2.1-5. TRSPIV was used to perform velocity measurements in planes normal to the jet axis for a large range of axial positions and Mach numbers. In this way the velocity field was decomposed into frequency—azimuthal-mode components which could be confronted with the results of a hydrodynamic stability computation. Extensive measurements of both the acoustic and hydrodynamic pressure fields were made for the same jets, the objective being to see if the complete jet-noise puzzle, fig. 1, can be assembled.

Results show that the linear stability theory agrees well with the 0 and 1st order azimuthal modes of the turbulent velocity field down to the end of the potential core. After this point agreement is poor, suggesting either that the wavepacket dynamics have become non-linear, or that the linear waves are masked by axisymmetric turbulent fluctuations. These hypotheses were checked using the nearfield pressure measurements reported in the D3.1-1 and the latter scenario was verified. This shows that the wavepacket dynamics can be under control. The question regarding far field noise generation is addressed in WP3.

The NLR WP2 activities in collaboration with the TU Delft state of the art volumetric PIV measurement techniques were employed to be used as a tool for the study of large scale structures in jets. Furthermore, Large Eddy Simulations were carried out in order to study the large scale flow structures that occur in jets. Jet inflow conditions were extracted from the PIV data, which was furthermore used for validation of the LES simulation. Fourier azimuthal mode decomposition and Proper Orthogonal Decomposition (POD) was used to extract large scale structures from the turbulent flow field. The details of this work were reported in D2.1-2. The understanding of jet dynamics is considered a prerequisite for the successful application of plasma actuators for the reduction of jet noise. The feasibility of the application of Tomographic PIV for the measurements of high-speed jets was demonstrated for the first time, unlocking a new tool for the study of large-scale instability modes and its 3D organization (D2.1-5). LES computations of an isothermal jet have been presented for two subsonic Mach numbers (0.3 and 0.9) in D2.1-5. The results have been validated with hotwire and PIV measurements, showing good comparisons. As a first analysis of the large-scale flow structures, POD analysis has been performed that demonstrated the existence of large scale flow structures.

CIAM results presented in D2.2-1 deals with the elaboration of up-to-date measuring techniques including PIV, LDA, microphones arrays for investigation of jet noise nature. In particular the phase average technique, when flash of PIV laser is synchronized with microphone (or CTA) signal, was used to state the relation between instability waves and jet noise. The investigation of turbulent characteristics of submerged single jet was considered. It was shown that pulsation of velocity in the initial region jet axis can be used as the reference signal for phase conditional averaging technique. Phase conditional averaging technique of PIV pictures for diagnostics of unsteady processes in turbulent round jet was developed and realized. Pulsation of the velocity in the initial region can be used as synchronization signal for phase averaging.

CIAM results presented in D2.3-1 deals with the investigation of mechanisms of jet noise generation using method, elaborated in TsAGI, based on statistical, correlation and spectral processing of signals between two microphones placed in two points diametrically opposite relative jet. The goal of this investigation is to obtain primary information on non-stationary pressure pulsation in acoustic field of a jet issuing with near-sonic velocity. In the experiments the free jet was be heated from ambient temperature to temperature about 800K at constant nozzle pressure ratio (NPR). In this case acoustical Mach number was be varied in the range 1-1.6 under constant gas dynamic Mach number. These experiments suppose to make clear the mechanisms of the noise generation in high velocity and high temperature jets (e.g. contribution of instability waves to jet noise). An experimental study of acoustic fields of hot and cold jets at transonic velocity was carried out at an open acoustic facility. Correlation between the signals of microphones placed on opposite sides of the heated jet at $X/D<15$ is small ($\approx$0.05), then the correlation coefficient increases to a value of about 0.5. Correlation function at $X/D>15$ has a certain asymmetry, apparently this non-uniformity is connected with sound generation by instability waves.

The theoretical basis of the Linear Stability Theory (LST) and Parabolized Stability Equations (PSE) were presented by CIRA in D2.4-1 and their numerical implementation developed and validated. Despite its higher computational cost, the standard five-equations version of the model was preferred to alternative approaches involving a lower number of variables and equations. Such formulation allows to retain the higher computational accuracy arising by the use of lower order operators. In order to take also into account the spreading effects of the mean flow field, an inverse-iteration algorithm approach is presented allowing to compute the exact eigenvalues once an approximate solution is known. The numerical implementation of the proposed methodologies, were finally validated by analyzing the stability analysis results obtained considering an analytical base flow solution.

d) Global conclusions for the WP

The theoretical studies of TsAGI allow a control strategy for instability waves in jet mixing layer to be formulated. It has been theoretically shown that a harmonic instability wave can be mitigated (or amplified) by an exterior harmonic action, providing the appropriate choice of its amplitude and phase. The experimental studies carried out by TsAGI have shown feasibility of the proposed strategy. It has been demonstrated that an instability wave can be excited with both acoustic action, interior and exterior (system acoustic generator – acoustic generator), and plasma actuators developed in the project (system acoustic generator – plasma actuator). One of overall objectives of the project of Orinoco consists in development of system for the active control of waves of instability in jet mixing layer. The demonstration of instability waves control possibility in experiment was done by TsAGI's team and presented in D2.1-4 and D3.3-1.

The main result of the CNRS WP2 work is that hydrodynamic instabilities, in the form of convected wavepackets, exist in both forced and unforced jets.

NLR developed a new tool for the study of large-scale instability modes and its 3D organization, and the analysis of the large-scale flow structures, POD analysis has been performed that demonstrated the existence of large scale flow structures.

Phase conditional averaging technique of PIV data for diagnostics of unsteady processes in turbulent round jet developed in Tasks 2.2 was applied in Tasks 2.1 for extracting instability wave characteristics.

As a whole, the investigations carried out in WP2 shows that the main objectives of WP2 were achieved: the instability wave's signature from the near-field measurements was founded by different experimental methods, the suppression of instability waves was achieved experimentally by forcing of different plasma actuators and the possibility of active control of artificial instability waves was demonstrated also.

1.3.3 WP3 Concept assessment

a) Overall objectives of the WP for all the project

The objective of this workpackage was to assess the control strategies developed. Experiments were performed by CNRS-PPRIME, ECL and TsAGI using different actuation and analysis techniques. Arc plasma actuators developed by ONERA were used by ECL. Nanosecond pulsed DBD actuators were developed and tested by CNRS-PPRIME. TsAGI used a variety of plasma discharge actuators. While the testing of the effects of these different actuation techniques and associated strategies was one objective of WP3 an equally important aspect of the work was the development and implementation of analysis methodologies.

b) Description of the methodology

CNRS-PPRIME and UR3 developed acoustic measurement (acoustic and hydrodynamic) and analysis techniques dedicated to educing and understanding sound source mechanisms ; ECL and ONERA performed spectral analysis of both acoustic and aerodynamic measurements in order to shed light on the nature of the changes produced by the arc-plasma actuation ; TsAGI developed and implemented a closed-loop system for the control of artificially excited instability waves.

c) Description of the WP results

Task 3.1 Source mechanism diagnostics (CNRS-PPRIME & UR3)

1. Investigation of instability-wave dynamics and their sound generation.

Based on the modelling efforts undertaken in WPs 1 and 2, that demonstrating both the existence and importance of wavepackets (hydrodynamic instabilities) in the generation of jet noise, a specially-adapted experiment was designed in order to provide easy access to extended space-time signatures of these instability waves.

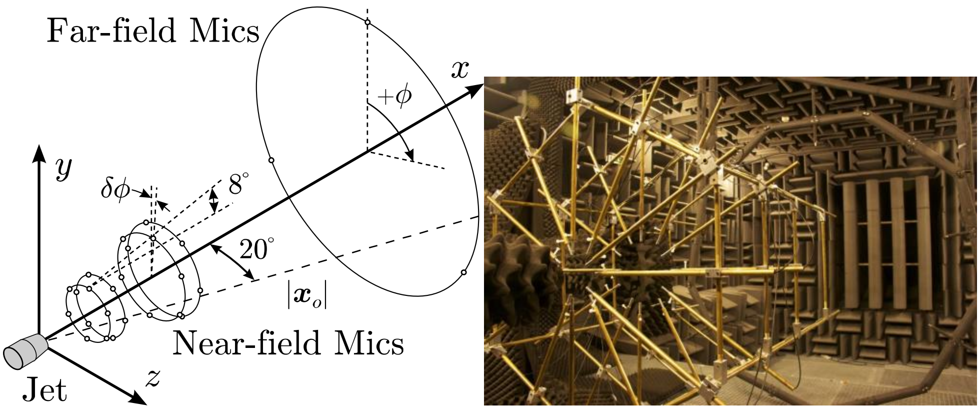


Figure 14 - Schematic and photo of experimental setup.

The diagnostic tool is shown in figure 14 in a reduced 4-ring setup (24 microphones). A more elaborate, 8-ring array was also used, holding a total of 48 microphones. CNRS and UR3 used this data to explore wave-packet and source mechanism dynamics.

Analysis of jets data was performed for Mach numbers ranging from 0.3 to 0.6. The main results demonstrate that instability wave signatures can be educed from the turbulent jet using the array, and that these can be connected to the far-field sound in two ways: (1) by direct correlation between azimuthal Fourier modes of the near (hydrodynamic) and far (acoustic) pressure field; and, (2) by projection using a tailored Green's function (provided by O. Leon of ONERA).

Subsequent analysis of the data and comparison with *linear* hydrodynamic stability theory showed that linear-instability signatures could be educed from the measurement by axial POD (Proper Orthogonal Decomposition).

However, this educed component of the pressure field appears to be insufficient to capture the essential sound producing dynamics. When used compute the sound field an error of about 30dB is observed; a similar error occurs when the PSE solution is projected to the farfield. When the complete pressure signal of the array is projected the amplitudes in the downstream direction have the correct order of magnitude.

An extended analysis, and comparison in particular with supersonic predictions, indicates that this 30dB difference may be attributable to the jittering wave-packet behaviour modelled in deliverable D1.4-1. This jitter is believed to be due to non-linear wave-packet dynamics which it will be necessary to model in order to correctly account for the acoustic efficiency of instability waves. This is a key result of the work performed by CNRS-PPRIME.

2. Separating acoustic and hydrodynamic components of the pressure field

A novel method of analysis aimed at the characterization of the pressure fluctuations in the near field region of incompressible and compressible jets, was developed by UR3. The method is based on the application of the wavelet transform to pressure.

In the proposed method it is assumed that the hydrodynamic contribution, being related to localized vortices, compresses well onto a wavelet base. This means that the wavelet transform of the hydrodynamic component leads to wavelet coefficients of much larger amplitude with respect to those associated to the acoustic one. Therefore, the part of the signal associated with the hydrodynamic pressure can be extracted by selecting the wavelet coefficients exceeding, in absolute value, a proper threshold, the remaining part of the signal being associated to the acoustic component. Thanks to the use of orthogonal wavelets, the set of coefficients below/above the threshold are anti-transformed so that an acoustic/hydrodynamic signal is retrieved in the physical space. The selection of the threshold is crucial and it is based on an iterative process where the propagation velocities associated to the acoustic and the hydrodynamic components are estimated. To this purpose, the procedure requires the simultaneous acquisition of two pressure signals by a microphone pair located in the near field.

With respect to other methods available in literature, the procedure proposed by UNIROMA TRE during the ORINOCO project permits one to use a very simplified configuration since only two microphones (or two virtual probes in a numerical simulation) positioned close to each other in the near field are necessary.

The method has been preliminary applied to experimental data obtained in a small scale facility available to UNIROMA TRE and consisting of a transonic single stream jet installed in a semi-anechoic chamber. Under the framework of the ORINOCO project, an exchange of data with other partners has been implemented as well allowing new databases, either experimental or numerical, to be analyzed.

The results obtained in those analyses demonstrated the capability of the method to separate acoustic from hydrodynamic pressure. This ability has been demonstrated through several indicators, including power spectra, cross-correlations, statistical conditioning and conditional averages. From the physical viewpoint, among several outcomes, it has been shown that the preferential radiation direction of the acoustic pressure is located at angles that, with respect to the flow axis, are larger than those of the hydrodynamic counterpart. The signature of the cone of silence has been also evidenced providing evidence of the main directivity feature of the acoustic near field. Also the decay rate of the acoustic and hydrodynamic components in terms of the radial distance from the jet axis and at selected frequencies, follows, even though qualitatively, the expected behaviour. The simultaneous measure or computation of velocity and pressure permitted us to determine the flow regions exhibiting maximum correlation levels with the near field acoustic or hydrodynamic components of the pressure fluctuations. In the acoustic case, the largest correlations are determined at the end of the potential core. Conversely, the largest hydrodynamic pressure–velocity correlations are located close to the nozzle exit and in the far region, between x/D=6 and x/D=9, where turbulence is known to be strongly intermittent. Also the correlation between acceleration and acoustic pressure gives support to the idea that acoustic sources are located in a region close to the end of the potential core. Further analyses supported the idea that the potential core contractions induced by large scale structures in the shear layer play an essential role into the generation of jet noise.

Task 3.2 Assessment of arc-plasma actuators for jet noise reduction (ECL & ONERA)

LMFA and ONERA-DMAE performed experimental noise and aerodynamic characterisation of jets manipulated by means of PSJ (Plasma Synthetic Jet) actuators. The experimental study follows the WP1 tasks 1.2 led by ONERA which were devoted to the development and improvement of PSJ system. The comprehensive presentation of the results can be found in deliverables D3.2-1 and D3.2-2.

Acoustic effects

The main acoustic effect of the PSJ actuation, for the parameter range studied, can be summarised using the figure 2 below (taken from figure 14 of deliverable D3.2-1).

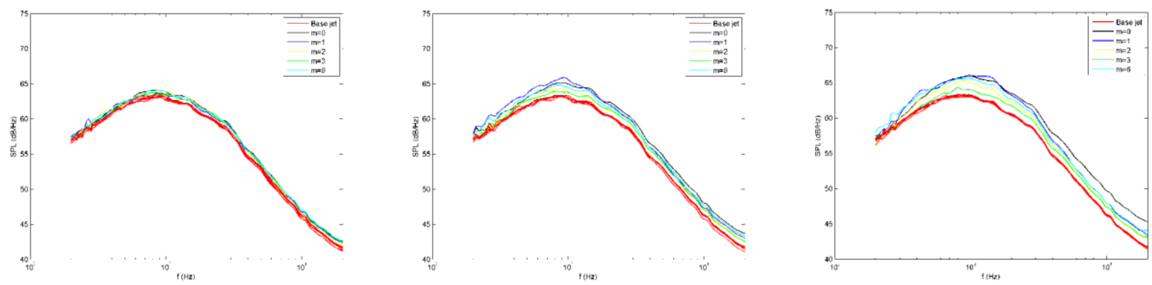


Figure 15 - Acoustic effect of PSJ actuation on M=0.6 jet. Spectra are measured at 30°. From left to right the actuation Strouhal numbers (St=fD/U) are 0.06, 0.13 & 0.2. The red line is the baseline, the coloured lines correspond to different azimuthal modes of forcing.

Over the range of forcing frequencies explored, the main effect of the PSJ actuation is to increase the broadband jet noise. This effect is most marked when the jet is forced at azimuthal mode 0 and St=0.2, which corresponds to the most amplified mode of the jet. Forcing at other frequency/azimuthal mode combinations produces a lesser amplification of the jet noise.

Aerodynamic effects

In deliverable D3.2-2 the aerodynamic effects of PSJ forcing were explored. The mean flow of the jet is modified by PSJ forcing, which is found to enhance entrainment; an increase in the shear layer thickness is visible in the velocity profiles. The velocity fluctuation levels in the shear layer are also enhanced.

In terms of the power spectral densities of the velocity fluctuations the following observations are made.

- high-level tonal components are manifest at the forcing frequency and its harmonics
- the axial amplification and decay characteristics of the tonal components differ depending on the forcing frequency,
- the fact that the tonal peaks remain higher than the broadband component demonstrates, similar to the acoustic results, that the jet responds to the actuation: i.e. the PSJ actuators have control authority over both the jet and sound-source dynamics,

A further analysis of the data was performed with an eye to verifying that the peaks in the hot-wire signal are due to coherent structures produced by the forcing and not electromagnetic contamination. The analysis was based on a phase analysis between the reference signal and the hot-wire measurement. This analysis showed clearly that the peaks are associated with coherent structures produced by the PSJ actuation and which persist to downstream distances of x/D=7.

Task 3.3 Assessment of plasma-discharge actuators for instability wave generation and noise control (TsAGI)

TsAGI developed a closed-loop control strategy for the mitigation of artificially generated instability waves based on the theoretical studies of D2.1.1 and D2.1.3 that show how a harmonic instability wave can be mitigated (or amplified) by an exterior harmonic action, providing the appropriate choice of its amplitude and phase. Experiments have corroborated the idea (D2.1.5) of the feasibility to mitigate an instability wave, excited due to the action from inside the jet, with an action from outside. It has been experimentally demonstrated (D2.1.4) that an instability wave can be controlled with acoustic signal, as well as (due to the identity of the physical mechanisms) with plasma actuators. The effect of instability wave mitigation has been achieved through adjustment of the amplitude and then the phase of exterior control signal.

The instability wave amplitude and its dependence on the phase difference between excitation and control signals have been measured by making use of two methods: hot-wire and PIV measurements. Data from a hot-wire located at some distance downstream from the nozzle in the jet mixing layer provide a local characteristic, but allowing the real-time measurements of instability wave parameters, which is of fundamental importance for a closed-loop feedback control system.

Selection of the amplitude and phase of the exterior control signal that leads to instability wave mitigation has been performed manually by the sweep method in the search for minimization of hot-wire signal. It turns out that one hot-wire (or microphone), which is located in the jet near-field and measures the signal level at the instability wave frequency, is sufficient for selection of the amplitude and phase of the control signal. Further measurements with the PIV system have shown that for given flow parameters not only local (near the hot-wire), but also global mitigation of the instability wave in the jet flow.

Therefore, a closed-loop feedback control system has been simplified to a system prototype that controls the level of interference signal at one sensor in the presence of reference and control signals. Namely, a signal from the hot-wire has been substituted with a signal from a microphone, a block scheme of the experiment is shown in Fig. 1. The problem has been formulated as mitigation of a reference harmonic acoustic wave in a space point (where the microphone or hot-wire is located) with a control signal. In this experiment, a signal from generator 1 (reference signal) and a signal from generator 2, which is controlled with the closed loop, have been used to minimize the total signal at the microphone. As mentioned above, this corresponds to mitigation of instability wave in the experiment performed in D2.1.5.

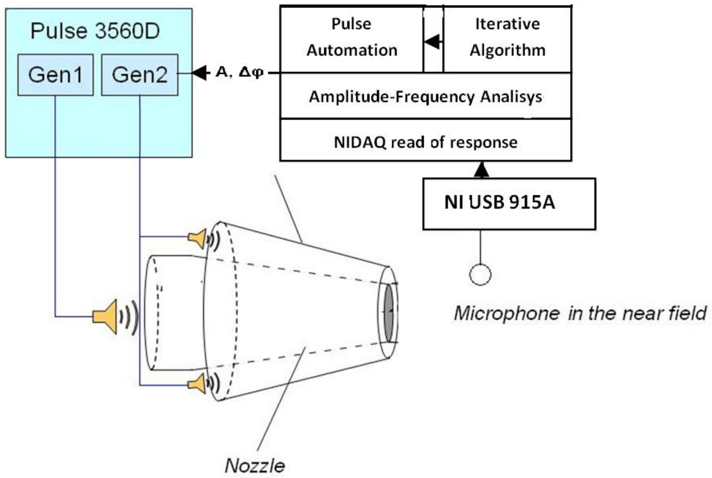


Figure 16 - A prototype of active control system. A block scheme of control and response analysis for the system "acoustic generator – acoustic generator".

Figure 16 depicts the block scheme of the software and hardware complex. The control action consists in measuring the amplitude in volts and shifting the phase in degrees of the control signal generator with respect to the reference generator. The reference signal has a constant frequency. The iteration algorithm is based on a cyclic search for a signal minimum at a control parameter surface (amplitude - phase).

The control system was shown to be capable of producing significant reductions in the amplitude of artificially-generated, harmonic, instability waves, thus demonstrating the possibility of active, closed-loop flow control in a turbulent jet.

Task 3.4 Benchmark with alternative concepts from OPENAIR

The strategies developed in ORINOCO are dedicated to plasma actuators concepts for jet noise reduction. In the framework of OPENAIR, several active technologies are studied on similar conditions as in ORINOCO: single stream nozzle at small scale.

In T3.4, the objectives are to highlight the progress performed in the plasma actuators techniques since OPENAIR and to compare the results obtained in both projects.

The comparison is made between the three most promising techniques identified in OPENAIR: the "fluidevrons" (CNRS), the Dielectric Barrier Discharge (TsAGI, IVTAN) and the Plasma Synthetic Jet (Onera).

Since OPENAIR, the actuators have been improved in terms of integrations and efficiency on the jet. Thanks to the tests performed in T3.2 and T3.3, it has been showed that the plasma actuators succeed in modifying the jet behaviour. In OPENAIR, the fluidevrons reduced the jet noise by an order of 2 db. In ORINOCO, 0.8 dB is obtained with HF DBD on the low frequency. As with the fluidevrons, the levels in high frequency are increased. It was pointed out that the DBD was able to suppress an instability wave. Concerning the PSJ, the tests confirm that the actuator has a strong action on the jet, generating a vortex convected by the flow. Nevertheless, due to limitation of the Strouhal number of the excitation, it was not able to obtained jet noise reduction.

d) Global conclusions for the WP

The existence of instability waves in turbulent jets, which while theorised for over 40 years has, up until very recently, been contested by many, has been convincingly demonstrated thanks to work performed in the ORINOCO project and in particular the efforts of WP3 (supported by the work of WP2).

The efforts of the CNRS-PPRIME allowed the eduction of instability waves and their connection to the radiated sound using appropriately adapted experimental and signal-processing techniques. The identification of the importance of non-linear instability wave dynamics for the acoustic efficiency of the jet is an important result which will underpin future modelling and control efforts.

TsAGI developed a real-time, closed-loop, control strategy based on the generation of instability waves. This study is a concluding step in development of the global system of jet noise within the framework of ORINOCO project and consists in development of a prototype of a closed-loop feedback active control system for mitigation of artificially excited instability waves in turbulent jets. In fact, this study puts an end to the preliminary research on active system development by demonstrating the feasibility of active control of high-speed subsonic jet noise based on mitigation instability waves.

ECL & ONERA demonstrated that arc-plasma actuators have control authority over turbulent jets, producing coherent structures (instability waves) that survive downstream to distances of up to seven jet diameters. For the limited frequency range explored, ranging from St=0.06 to 0.2, the main acoustic effect of PSJ actuation comprises a broadband increase in the sound radiation. This increase is maximum when the forcing is at frequency and azimuthal wavenumber pairs that correspond to the most unstable modes of the jet.

1.3.4 WP4 Exploitation and dissemination

a) Overall objectives of the WP for all the project

The objectives of the work package were:

- To make a synthesis of the project results.
- To consider the possibility for the industrial exploitation of these results.

- To disseminate the project outputs in the aeronautics and scientific community, to ensure proper exploitation of the project outputs in accordance with the consortium agreement terms.
- To organise an international workshop to present the results of ORINOCO.

b) Description of the methodology

WP4 included 3 tasks:

Task 4.1: Final Results Assessment (M33 – M35)

Participants: Aviadvigatel, Onera, TsAGI, CIAM

Task 4.2: Full Scale Recommendations (M36 – M38)

Participants: Aviadvigatel, Onera, TsAGI

Task 4.3: Dissemination Workshop (M35 – M38)

Participation of all the partners.

c) Description of the WP results

The main aim of ORINOCO is theoretical, numerical and experimental investigations for an efficient implementation of plasma actuators for jet noise reduction on the basis of instability waves control. During the project, several concepts of plasma actuators for noise reduction have been evaluated on isothermal single jet at small scale. A large amount of experimental data have been obtained. In order to disseminate the scientific results of the project in the aeronautics community, a dissemination workshop have been organised in Onera (Chatillon) on the subject of Jet noise reduction with active technologies. 12 presentations were made, pointing out the different plasma techniques that were developed within the project and showing the technical activities of each partner.

The results assessment carried out in WP4 shows that the main objectives of ORINOCO project were achieved. The six plasma actuators were developed and improved in the project. These actuators are based on different types of gas discharges (high frequency dielectric barrier discharge (HF DBD), slipping surface discharge, surface barrier corona discharge, arc discharge in magnetic field, combined discharge, arc plasma synthetic jet). All the actuators were implemented on nozzles and their ability to generate coherent structures in the turbulent shear layer of the jet was proved. Overall objectives of the project of Orinoco consisted in development of system for the active control of waves of instability in jet mixing layer. Three concepts of instability waves control have been investigated. Test results obtained in WP3 demonstrate perspectivity of developing concepts. The main results of TRM and IEP meetings discussions can be formulated as follows:

1. Conducted researches have shown the ability of developed plasma actuators to effectively influence the shear layer near the nozzle edge, generating instability waves. Obtained experimental results on plasma actuators action agree with theoretical and numerical investigation. Developed actuators are perspective for creation of a jet noise control system. The scientific value of the obtained data is evident considering results on instability waves physics and jet noise mechanism.
2. For configuration being developed based on plasma actuator technology for jet noise reduction were analysed compared to chevron nozzles based on data received from the program partners (on Paris meeting). Based on these actuators jet noise reduction technologies can be derived which may result in efficiency of 1-3 dB per 0,1-0,3% of engine

net thrust loss that surpasses better parameters of acoustic mechanic systems. The ORINOCO methods compared to chevron nozzles may allow to avoid engine thrust losses that means 1-3 % and not be involved at engine operation conditions where negative acoustic efficiency is possible.

3. Practical result for full-scale tests may come out during further scientific investigations and further clarification of received data. It is highly probable to expect the practical results for jet flows, instability waves in other investigation directions such as tasks not associated with aircraft noise emission.
4. For further scientific investigations, clarification of existing data and possibility to use plasma actuator noise reduction technology for a future implementation on full size engine it is reasonable to proceed with:
   - experiments on larger nozzle models with definition of scaling factor;
   - works on estimation of technology feasibility for two contour nozzle
   - works on refinement of energy consumption data and cost of the developed technologies scaling.
5. As have shown the spent estimations, transition to full-scale models will demand increase in load-supplying capacity of plasma actuators to 15-50 kW. Such values are acceptable for the modern aircraft.

To date, the concept of instability waves control in the jet shear layer using plasma actuators has passed stages from TRL1 to TRL3. At the moment of the beginning of works there were theoretical notions about the existence of instability waves in the turbulent jet and their possible role in the noise generation, indirectly confirmed in experiments. That has allowed to offer at TRL1 the concepts of instability waves control. As a result of theoretical studies the concept of the reference experiment has been formulated and the theoretical and hardware base was developed for its carrying out in order to demonstrate control of artificial instability wave. At that stage the control strategy has been actually formulated at theoretical level, allowing to create new technology, i.e. has been reached TRL2. Theoretical studies have been continued regarding a more detailed modeling of the actuators impact on a jet. Theoretical researches of noise emission by instability waves with the aim of creating a noise control active system of the jet were carried out. It has allowed to construct a laboratory prototype of the instability waves active control system for jet noise reducing. At the moment, control of artificial instability waves was realized with different types of plasma actuators which are capable periodically to affect on nozzle edge, i.e. concept have been confirmed on small-scale model and TRL3 was reached. For TRL increasing it will be necessary to appropriately modify the plasma actuators both in terms of their own characteristics (increased power), and in terms of their location (the problem of their integration with the layout). This will increase the complexity of the models, and technical difficulties related to the integration of actuators in the nozzle may appear. All these problems can be solved and, apparently, are not insurmountable barriers to transition TRL3 →TRL5-6. The main difficulties that may arise are likely to be related with the physical mechanisms underlying the concepts; namely, the transition to bypass nozzles, hot jets, accounting for the pylon (TRL4-5), as well as flow swirl and heterogeneity (TRL 5-6). It may result in new features of the origin and development of instability waves, which are absent or not detected in cold single jets. Therefore, tests at an open test bench should be preceded by extensive research at a facility with TRL 5.

d) Global conclusions for the WP

The assessment test results demonstrate that developed plasma actuators and proposed strategies are perspective for creation of a jet noise control system. Practical result for full-scale tests may come out during further scientific investigations and further clarification of received data. Developed in the project plasma actuators allow to increase considerably scales of models, up to the dimensions of full-scale nozzle at reasonable increase in power consumption (not more 50 kW).

1.4 *Impacts of the project*

1.4.1 Socio-economic impact

ORINOCO is an answer to the coordinated call Aeronautics and Air Transport (FP7-AAT-2010-RTD-RUSSIA) and more specifically the field of "advanced engine noise control based on plasma actuators (AAT.2010.1.1-7) of the "AREA 7.1.1.1 Green Aircraft".

The Green Aircraft is connected to ACARE objectives at the horizon 2020 which define in particular a target of reduction by 10 EPNdB of the average Decibel per Aircraft Operation (see figure below). Projects such as SILENCE(R) have contributed to significant noise abatement thanks to passive solution but jet noise remains the main source of engine noise at take-off. Recently, OPENAIR proposed to go a step further with the assessment of several innovative active technologies (mechanical, fluidic and plasma). The great interest of OPENAIR is to evaluate the potential of each of these concepts, but the time allowed for their development is not sufficient to make specific investigations for jet noise. By focusing on more fundamental considerations, ORINOCO has studied the interaction between the actuators and the nozzle jet and the best control strategy to reduce the jet noise. ORINOCO is clearly addressing the necessary technology Breakthrough (Generation 2 Noise Technologies). The implementation of plasma actuators concepts developed in the framework of ORINOCO opens the way to new generations of reduction devices that could lead to attractive solution for future concept of engine. Therefore, ORINOCO has participated to reduce external noise by 10 EPNdB per operation of fixed-wing aircraft by 2020 taking 2001 as a baseline.

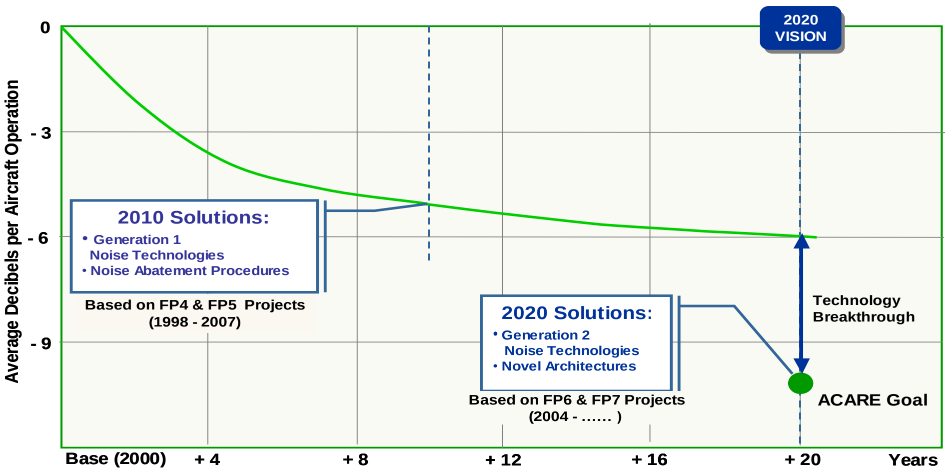


Figure 17: ACARE Noise Reduction goals

Passive reduction devices such as chevrons result in noise reduction but, also, in engine performance decrease during cruise (due to the increase of the drag). Fluidic micro-jets also succeed in reducing jet noise. As active reduction devices, they can be switched off after take-off, and therefore do not present the drawbacks of the chevrons. Nevertheless, the air used by the micro-jets has to be taken from the engine (typically from the secondary duct), exactly at the moment when the maximum thrust is necessary. Plasma actuators devices only use electric power and thus do not present this drawback; even if it will impact the global consumption of the aircraft. The output power necessary to implement plasma actuators on full scale engine has been roughly estimated and was considered as acceptable by several members of the Industrial Expert Panel.

As an answer to AAT.2010.1.1-7 ('Enhancing strategic international co-operation with Russia in the field of advanced engine noise control based on plasma actuators'), ORINOCO project was built on the basis of strong cooperation between Europe and Russia Federation. Therefore, two coordinators ensured the good progress of the project with respect of its objectives, its schedule and its budget. As the coordinators are from Onera and TsAGI, ORINOCO project reinforced the cooperation agreement already signed by these two parties in 2001. Thus, during the project life, ORINOCO results were several times presented at the annual Onera-TsAGI seminars. Involving additional partners has contributed to enlarge this cooperation to Europe and Russia Federation.

The objectives of ORINOCO were to develop and enhance plasma actuators technologies dedicated to jet noise reduction, to investigate instability waves concepts for jet noise, to formulate noise control strategy and to implement jet noise control based on plasma actuators

These objectives include and extend the aspects mentioned in the FP7 Cooperation Work Programme for the field AAT.2010.1.1-7. In particular, WP2 (Investigation of Instability Waves Concept Physics) investigated three aspects specific to instability waves: theoretical investigation of instability waves signature on the nozzle surface, experimental characterization of the initial amplitude of instability wave and methodology for the generation of instability waves in anti-phase, based on robust theoretical formulas.

Several plasma actuators concepts were evaluated in WP3 (Concept Assessment) in anechoic test facilities to measure the jet noise reduction. These measurements provide a good experience about the aerodynamic effects of plasma actuators on the jet and their consequences on the jet noise.

Investigate the plasma actuators concepts for the control of instability waves is one mean to reduce jet noise. ORINOCO has proposed to extend the engine noise control based on plasma actuators to other approaches. The results obtained with the different solutions were compared within the project and with other technologies thanks to the scientific workshop organized at the end of project. The technology impact answered the work programme and go beyond.

1.4.2 Wider societal implications of the project

ORINOCO focuses on fundamental aspects of plasma actuators and jet noise mechanisms. For the actuators, the next step should be to increase the Technology Readiness Level and give the opportunity for the aeronautics industries to exploit these new techniques. Concerning the jet noise mechanisms, the physical understanding brought by the project can already been used to develop or improved noise reduction devices (passive or active).

The use of plasma actuators fully integrated in the inner surface of the nozzle would be of high interest for the aeronautical industries in comparison with passive devices such as chevrons. This would results in noise reduction without any thrust penalty (having for consequence an increase of fuel consumption and Nox emission).

ORINOCO has participated to the ACARE goals (as mentioned above) and therefore has added its contribution to the reduction of the overall noise level of aircrafts. If we go further on the societal implications of the project, noise abatement contributes to the improvement of competitiveness of the European and Russian Aeronautics Industries. The regulation rules being more and more restrictive on noise levels, noise reduction devices will be a strong commercial argument to remain competitive.

As the overall noise decreases in the vicinity of the airport, the transport policy has two possibilities:

- The airport is among the most important air transport hubs. The reduction of noise per aircraft operation would give the opportunity to increase the traffic, with respect to the regulation rules. The overall noise level would remain the same, but the number of flights could be increased; as a consequence, the airport would grow, offering much more employments on the platform.

- The airport is saturated and has no possibility to increase the number of flights or to extend. In this case, the noise benefits would directly have an impact on the quality of life around the airport. This is typically the case for airports located close to town center. A balanced compromise could also be found between the noise benefits on environment and the increase of traffic.

1.4.3 Dissemination and exploitation activities

Dissemination of ORINOCO results have taken various and complementary forms and addressed three parties: the scientific community, the aeronautics industry and the public.

Dissemination to scientific community

As the best way to communicate to scientific community and leave a trace of our results, 10 peer reviewed publications were written on basis of activities performed in ORINOCO:

- Journal of Fluid Mechanics (4)
  - Wavelet analysis of Near-Field Pressure Fluctuations Generated by a Subsonic Jet, *S. Grizzi, R. Camussi,* JFM, vol. 698, pp 93 - 124 (May 2012)
  - Axisymmetric superdirectivity in subsonic jets, *A.V.G. Cavalieri, P. Jordan, T. Colonius, Y. Gervais*, JFM, vol. 704, pp 388 - 420 (August 2012)
  - Educing the source mechanism associated with downstream radiation in subsonic jets, F. Kerherve, P. Jordan, A.V.G. Cavalieri, J. Delville, C. Bogey, D. Juve, JFM, vol. 710, pp 606 - 640 (Nov. 2012)
  - Wavepackets in the velocity field of turbulent jets” Journal of Fluid Mechanics, *A.V.G. Cavalieri, D. Rodriguez, P. Jordan, T. Colonius, Y. Gervais, JFM, Vol. 730 - pp 559-592* (Sept. 2013)
- Acoustical Physics (3)
  - A theoretical study of the efficiency of instability wave excitation in a two dimensional nozzle edge model, G. Faranosov, Acoustical Physics, 2012, Vol. 58, No. 4, pp. 503–509
  - Acoustic control of instability waves in turbulent jet, V.F. Kopiev, I.V. Belyaev, M.YU. Zaitsev, V.A. Kopiev, G.A. Farasonov, Acoustical Physics, 2013, vol. 59, N° 1, pp. 16-26
  - Subsonic jet noise reduction by means of corrugated nozzles, V. Kopiev, M. Zaitsev, N. Ostrikov, Acoustical Physics, 2013, Vol. 59, No. 2, pp. 207–209
- Journal of Physics
  - Experimental investigation of the Near-Field Noise generated by a Compressible Round Jet, *S. Grizzi, R. Camussi, 318* (2011)
- Journal of electrostratics
  - Geometrical optimization of a surface DBD powered by a nanosecond pulsed high voltage, C. Aba'a Ndong, N. Zouzou, N. Benard, E. Moreau, Journal of Electrostatics, Vol. 71, N° 3, pp. 246-253 (June 2013)
- Annual Review of Fluid Mechanics
  - Wave Packets and Subsonic Jet Noise, P. Jordan, T. Colonius, Vol. 45, pp. 173-195 (Jan. 2013)

In addition to these existing publications, a summary of the results obtained in ORINOCO is about to be integrated in the CEAS-ASC Aeroacoustics Highlights 2013 of the Journal of Sound and Vibration.

Communications in scientific conferences were highly used to disseminate the results in front of an audience of experts. Partners of ORINOCO participated to several Aeroacoustics Conference, including the main annual event of AIAA/CEAS Aeroacoustics Conference. 25 participations have already been identified:

- General Conferences:
  - 6th Aerodays in Madrid, Spain (2011)
  - Euronoise, Prague (2012)
  - European Conference for Aerospace Sciences - Munich, Germany, 1-4 July 2013 (2 part.)
- AIAA/CEAS Aeroacoustics Conference:
  - 2012 Colorado Springs: 5 participations
  - 2013 Berlin: 4 participations
- Russian Aeroacoustics Conference (2011): 7 participations thanks to the organisation of ORINOCO Technical Review Meeting at the same place.
- Russian Aeroacoustics Conference (2013): 1 participation
- CEAA (Computational Experiment in Aeroacoustics) (2012): 2 participations
- International Symposium on Particle Image Velocimetry (2013): 2 participations

Even if the project is completed, the ORINOCO results continue to be communicated. Four communications are already planned in 2014:

- 2 participations to 20th AIAA/CEAS Aeroacoustics Conference (Aviation 2014), 16th-20th June 2014, Atlanta, USA
- 2 participations to the 4th X-Noise EV Scientific Workshop / 18th CEAS-ASC Workshop about "Aircraft noise reduction by flow control and active/ adaptive techniques" Kyev, Ukraine, 25-26th September 2014

Parts of the work performed in ORINOCO were used in Lecture Series:

- R. Camussi, “Application of time-frequency tools in aeroacoustics: identification of noise sources and theoretical modelling”, invited plenary lecture at the European Turbulence Conference ETC14, Lyon 1-4 September 2013.

- R. Camussi, “Wavelet analysis and applications in aeroacoustics” in Advanced post-processing of experimental and numerical data, VKI Lecture Series, 12-15 November 2013.

- P. Jordan, “Wavelet analysis and applications in aeroacoustics” in Advanced post-processing of experimental and numerical data, VKI Lecture Series, 12-15 November 2013.

Dissemination to aeronautics industry

ORINOCO was presented under the X-Noise cluster flag which co-ordinates noise projects in the European Aeroacoustics field. Therefore, the project coordinators had the opportunity to present their progress in 3 Full Network Meetings (2011, 2012, 2013) and contributed to 2 X-Noise EV Newsletters (Feb. 2012, June 2013). Another contribution to this newsletter is already planned for the issue of Spring 2014.

The participation to X-Noise cluster is an excellent mean to communicate the main results of the project to the European Aeronautics Industries and to the European Research Institutes.

A deeper communication to Industries was performed through the Industrial Expert Panel. As a reminder, during the mounting process of the project, an Industrial Expert Panel (IEP) has been composed with 6 representatives of European and Russian Aeronautics Industries: Airbus France, Alenia Aermacchi, Beriev, Snecma, Sukhoi and Tupolev.

The agreement between the Industrial Expert Members and ORINOCO Consortium was that they were invited in several meeting (Travel costs being paid by the coordinators) to give their feedback about the progress of the project through the technical presentations. As they are not members of the Consortium, they did not have access to the deliverables of the project.

The members of the Industrial Expert Panel were invited to the Kick-Off Meeting, 6 technical meetings and the Final Review:

- Nov. 2010: Kick-Off Meeting (Onera, Palaiseau, France)
- March 2011: TRM1 (TsAGI, Moscow, Russia)
- March 2012: TRM3 – First Period Review (CNRS, Poitiers, France)
- Sept. 2012: TRM4 (Svetlogorsk, Russia)
- April 2013: TRM5 (University of Roma Tre, Roma, Italy)
- Sept. 2013: TRM6 – Dissemination workshop (Onera, Châtillon, France)
- Dec. 2013: IEP meeting – Final Review (TsAGI, Moscow, Russia)

For ORINOCO partners, it was the opportunity to have an external feedback on the work performed in the project from aeroacoustics and plasma experts and to disseminate ORINOCO results to the aeronautical industries (even if TRL is still low).

For IEP members, the agreement gave them an access to recent works on plasma actuators and jet noise mechanisms and the possibility to give their point of view on the project results.

The IEP members appreciated the high level of technical discussions during the Technical Review Meeting and the results obtained in the project. Even if some of them regret that they did not have access to the deliverables and notice than the jet studied in ORINOCO are far from industrial configurations, they all considered that ORINOCO made a step forward on jet noise mechanisms that would be useful for them.

Public dissemination

Since the beginning of ORINOCO, a dedicated website was created (http://www.orinoco-project.org/) with a private part providing data to the Consortium (especially the deliverables) and a public part describing the Consortium and the objectives and providing the list of communications performed in the framework of the project.

Finally, a Dissemination Workshop was organized in Onera (Châtillon-France) on 25th September 2013. This workshop was open to public and announced on Onera external website and in the French Aeroacoustics Cluster (IROQUA) through newsletter and website. During one day, 13 presentations of ORINOCO results were made with an audience of 35 persons.

1.4.4 Contact details

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List of beneficiaries:

1. Office national d'études et de recherches aérospatiales, France
2. Federal state unitary enterprise the central aero hydrodynamic institute named after prof. N.e. zhukovsky, Russian federation
3. Aviadvigatel oao, Russian federation
4. Central institute of aviation motors, Russian federation
5. Centro italiano ricerche aerospaziali scpa, Italy
6. A.m. prokhorov general physics institute of Russian academy of sciences, Russian federation
7. Institution of the Russian academy of sciences joint institute for high temperatures ras, Russian federation
8. Centre national de la recherche scientifique, France
9. Ecole centrale de Lyon, France
10. Stichting nationaal lucht- en ruimtevaartlaboratorium, Netherlands
11. State research centre of Russian federation troitsk institute for innovation and fusion research, Russian federation
12. Universita degli studi roma tre, Italy
13. Erdyn Consultants, France

References:

[1] *Hardy, P., Dufour, G., Quint, G. and Rogier, F. «* Plasma Synthetic Jet modelling », *Technical Report ONERA/DMAE and ONERA/DTIM, Toulouse* (2010)

[2] *D'Angola, A., Colonna, G., Gorse, C. and Capitelli, M.* « Thermodynamic and transport properties in equilibrium air plasmas in a wide pressure and temperature range », *J.Eur. phys. D: Atomic, molecular and optical phys. Vol. 46, No. 1:129-150* (2008)

[3] *Ko, H.S., Haack, S.J., Land, H.B., Cybyk, B., Katz, J. and Kim, H.J.* « Analysis of flow distribution from high-speed flow actuator using particle image velocimetry and digital speckle tomography », *Flow Measurement and Instrumentation Vol. 21:443-453* (2010)

[4] O. Léon, J.-P. Brazier, M. Huet, D. Caruana, *D1.3-1: Report on numerical and experimental optimisation of jet noise reduction based on azimuthal modes decomposition*, ORINOCO Technical Report (2013)

[5] D. Caruana, M. Huet, O. Léon, *D1.2.6 – Post tests modification or validation of the arc plasma actuator*, ORINOCO Technical Report (2013)

2 Use and dissemination of foreground

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	Axisymmetric superdirectivity in subsonic jets	A.V.G. CAVALIERI	Journal of Fluid Mechanics	Vol. 704			2012	pp. 388-420		
2	Galerk in projections for fluid mechanics with unsteady boundary conditions	A.V.G. Cavalieri	Journal of Fluid Mechanics				October 2011			
3	Educing the source mechanism associated with downstream radiation in	F. Kerhervé	Journal of Fluid Mechanics				November 2012			

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
	subsonic jets									
4	Wavelet analysis of Near-Field Pressure Fluctuations Generated by a Subsonic Jet	S. Grizzi, R. Camussi	Journal of Fluid Mechanics	Vol. 698	Cambridge University Press	GB	2012	pp. 93-124		no
5	Statistical analysis of the pressure field in the near region of a M=0.5 circular jet	R. CAMUSSI	International Journal of Aeroacoustics							
6	Acoustic control over instability waves in turbulent jet	V.F. KOPIEV	Acoustical Physics							
7	Subsonic jet noise reduction by means of corrugated	V.F. KOPIEV	Acoustical Physics							

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
	nozzles									
8	Geometrical optimization of a surface DBD powered by a nanosecond pulsed high voltage	C. ABA'A NDONG	Journal of Electrostatics							
9	Wavepackets in the velocity field of turbulent jets	A.V.G. CAVALIERI	Journal of Fluid Mechanics	Vol. 730			2013	pp. 559-592		
10	Educing the source mechanism associated with downstream radiation in subsonic jets	F. KERHERVE	Journal of Fluid Mechanics	Vol 710			2012			
11	Wave Packets and Turbulent Jet Noise	P. JORDAN	Annual Review of Fluid Mechanics	Vol. 45			2013			

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
12	Experimental investigation of the Near-Field Noisegenerated by a Compressible Round Jet	S. Grizzi	Journal of Physics: Conference Series	Volume 318 Section 9			2011			
13	Coherent structures in aeroacoustics	P. JORDAN	Von Karmen lecture series Advanced post-processing of experimental and numerical data				2013			
14	Analysis techniques for aeroacoustics: noise source identification	P. JORDAN	Sound sources in turbulent shear flows, CISM courses and lectures	Volume 545	Springer – Verlag	Berlin	2013	197-287		
15	Inlet conditions and wave-pockets in subsonic jet	A.V.G. CAVALIERI	TSFP Ottowa				2011			

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
	noise									
16	Jet noise reduction using pulsed fluidic actuation	R. Maury	TSFP Ottowa				2011			
17	Experimental Investigation of pressure fluctuations in the near field of subsonic jets at different Mach and Reynolds numbers	S. Grizzi, R. Camussi	AIAA paper	2012-2257	AIAA	USA	2012			no
18	Experimental investigation of the Near-Field Noise generated by a Compressible	S. Grizzi, R. Camussi	Journal of Physics: Conference Series	Vol. 318	IOP	GB	2011	092003-1 092003-11		no

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
	Round Jet									

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
1	Conference	A.V.G. Cavalieri	Axisymmetric superdirectivity in subsonic jets	5-8 June 2011	AIAA/CEAS Aeroacoustic Conference and Exhibit Portland			
2	Conference	F. Cléro (ONERA), V. Kopiev	ORINOCO Advanced Engine Noise Control	30th March-1st April 2011	6th European Aeronautics Days Madrid, Spain	Scientific Community	500	European countries

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
		(TsAGI)	Based on Plasma Actuators					
3	Conference	F. Cléro (ONERA), V. Kopiev (TsAGI)	Presentation of ORINOCO Project	12th October 2011	X-NOISE 2011 Full Network Meeting Lausanne, Switzerland	Scientific Community and aeronautical industries	50	European countries
4	Conference	F. Cléro	Contribution to the Project synopses Aeronautics and Air Transport	November 2011	Second volume of European Commission			European countries
5	Conference	F. Cléro (ONERA), V. Kopiev (TsAGI)	ORINOCO Advanced Engine Noise Control Based on Plasma Actuators	27th-30th September 2011	Open Russian conference on aeroacoustics, Zvenigorod, Russia	scientific community	100	Russia
6	Conference	Yu.S. Akishev	The pulsating flow generation by a corona barrier	27th-30th September 2011	Open Russian conference on aeroacoustics,	scientific community	200	Russia

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
			discharge		Zvenigorod, Russia			
7	Conference	P. Jordan	On the response of subsonic jets to fluidic perturbation	27th-30th September 2011	Open Russian conference on aeroacoustics, Zvenigorod, Russia	scientific community	200	Russia
8	Conference	G.A. Faranosov	A theoretical investigation of the efficiency of artificial excitation of instability waves in a two-dimensional model of nozzle edge	27th-30th September 2011	Open Russian conference on aeroacoustics, Zvenigorod, Russia	scientific community	200	Russia
9	Conference	D. Caruana, P. Hardy, Ph Barricau (Onera)	The Plasma Synthetic Jet for Jet Exhaust Noise Control	27th-30th September 2011	Open Russian conference on aeroacoustics, Zvenigorod, Russia	scientific community	200	Russia

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
10	Conference	A.P.Kuryachi i	On generation of velocity pulsations in subsonic jet by dielectric barrier discharge actuator	27th-30th September 2011	Open Russian conference on aeroacoustics, Zvenigorod, Russia	scientific community		
11	Conference	E.M. Barhudarov	Acoustical and shock-wave characteristics multi-electrode ring plasma actuator RING-1	27th-30th September 2011	Open Russian conference on aeroacoustics, Zvenigorod, Russia	scientific community		
12	Conferences	S. GRIZZI	Experimental Investigation of pressure fluctuations in the near field of subsonic jets at different Mach and Reynolds numbers	6/2012	18th AIAA/CEAS Aeroacoustics Conference, Colorado Springs (USA)			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
13	Conference	GEORGY A	Theoretical Investigation of the Effectiveness of Artificial Instability Waves Excitation in Subsonic Jets	4 - 6 June 2012	18th AIAA/CEAS Aeroacoustics Conference, Colorado Springs (USA)			
14	Conference	VICTOR F. KOPIEV	Axisymmetrical instability wave control due to resonance coupling of azimuthal modes in high-speed jet issuing from corrugated nozzle	4 - 6 June 2012	18th AIAA/CEAS Aeroacoustics Conference, Colorado Springs (USA)			
15	Conference	A. V. G. CAVALIERI	Low-speed jet dynamics and sound radiation	4 - 6 June 2012	18th AIAA/CEAS Aeroacoustics Conference, Colorado Springs (USA)			
16	Conference	A. V. G. CAVALIERI	Wavepackets in the velocity field of	4 - 6 June 2012	18th AIAA/CEAS Aeroacoustics			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
			turbulent jets		Conference, Colorado Springs (USA)			
17	Conference	A. C. ABA'A NDONG	Effect of the dielectric aging on the behavior of a surface nanosecond pulsed DBD		IEEE TDEI			
18	Conference	F. Cléro (ONERA), V. Kopiev (TsAGI)	Advanced engine noise control based on plasma actuators	10 – 13 june 2012	Euronoise 2012 Conference, Prague Czech Republic	Scientific community	200	European countries
19	Conference	CEGLIA, G	High-resolution PIV analysis of compressibility effects in turbulent jets", International Symposium on Particle Image Velocimetry	July 1-3, 2013	Delft, The Netherlands			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
20	Conference	VIOLATO, D	3D organization of high-speed compressible jets by tomographic PIV", International Symposium on Particle Image Velocimetry	July 1-3, 2013	Delft, The Netherlands			
21	Conference	V. KOPIEV	Instability Wave Control in Turbulent Jet	27-29 May	19th AIAA/CEAS Aeroacoustics Conference, Berlin			
22	Conference	D.E. BREAKEY	Near-field wave packets and the far-field sound of a subsonic jet	2013	AIAA/CEAS Aeroacoustics conference			
23	Conference	D. RODRIGUEZ	Wave-packet eduction in turbulent jets based on eigenmode decomposition of	2013	AIAA Aeroacoustics conference			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
			PIV data					
24	Conference	F. KERHERVE	A twenty degree of freedom model of sound source dynamics in a turbulent jet	2012	AIAA Aeroacoustics conference			
25	Conference	S. Krasheninnikov, A. Mironov, V. Maslov, D. Zakharov	An investigation of Dynamic of Ordered Structure in Excited Jet Using PIV - based phase averaging technique		5th Eur. Conference for Aeronautics and Space Sci., Munich	Scientific Community		European countries
26	Conference	V. Kopiev (TsAGI), F. Cléro (Onera)	Numerical analysis for jet noise reduction with plasma actuators in ORINOCO Project	19-22 September 2012	CEAA2012 Conference, Svetlogorsk, Russia	Scientific Community	100	European countries + USA
27					International Symposium on			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
					Particle Image Velocimetry			
28	Lecture series	R. Camussi	Application of time-frequency tools in aeroacoustics: identification of noise sources and theoretical modelling	1-4 September 1 – 4 September 2013	the European Turbulence Conference ETC14, Lyon, France			
29	Lecture series	R. Camussi	Wavelet analysis and applications in aeroacoustics" in Advanced post-processing of experimental and numerical data	12-15 November 2013.	VKI Lecture Series			
30	Lecture series	P. Jordan	Wavelet analysis and applications in aeroacoustics in Advanced post-processing of	12-15 November 2013	VKI Lecture Series			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
			experimental and numerical data					
31	Conference	F. Cléro (ONERA), V. Kopiev (TsAGI)	Progress of ORINOCO project	10th October 2012	X-Noise 2012 Full Network Meetings, Braunschweig, Germany	Scientific community and aeronautical industries	50	European countries
32	Conference	F. Cléro (ONERA), V. Kopiev (TsAGI)	Progress of ORINOCO project	24 – 25th September 2013	X-Noise 2013 Full Network Meetings, Sevilla, Spain	Scientific community and aeronautical industries	50	European countries
33	Seminar	D. Caruana, C. Gleyzes, P. Barricau (Onera)	Aerodynamic Control using Plasma Synthetic Jet	30 january/ 1st február 2012	TsAGI-Onera Seminar, Meudon, France	Scientific Community	30	France, Russia
34	Seminar	F. Cléro, J-P. Brazier, M. Huet, D. Caruana (Onera)	Stability analysis for the implementation of plasma actuators for jet noise reduction	9-12 October 2012	TsAGI-Onera Seminar, Saint-Petersbourg, Russia	Scientific Community	30	France, Russia
35	Newsletter	F. Cléro (ONERA), V.	3rd X-Noise EV Newsletter,	Feb. 2012		Scientific community and		European

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
		Kopiev (TsAGI)	Progress of ORINOCO Project			aeronautical industries		countries
36	Newsletter		5th X-Noise EV Newsletter, Progress of ORINOCO Project	June 2013		Scientific community and aeronautical industries		European countries
37	Forum	F. Cléro (Onera), V. Kopiev (TsAGI) represented by A. Joulia (Onera)	ORINOCO Project	26-27th September 2013	AirTN Forum 2013, Cranfield University, UK	Scientific Community and aeronautical industries	100	European countries
38	Workshop			25th September 2013	Onera Châtillon			
39	Industrial Panel		Industrial Expert Panel	Participation to 7 meetings during the				

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NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
				project				
40	Conference	Kopiev V.F.	Instability wave control in turbulent jet by acoustical and plasma actuators	July, 2013	5th Eur. Conference for Aeronautics and Space Sci., Munich	Scientific Community		
41	Conference	Clero F. Kopiev V.F.	Advanced engine noise control based on plasma actuators	2011	Six European Aeronautics days AERODAYS 2011, Madrid	Scientific Community Industry		
42	Conference	Kopiev V.F.	Instability wave control in turbulent jet	June, 2013	19th AIAA/CEAS Aeroacoustics Conference, Berlin	Scientific Community		
43	Conference	Kopiev V.F.	Instability wave control in turbulent jet by plasma actuators	September , 2013	3d Conference on Aviation Acoustics, Zvenigorod			
44	Workshop	Kopiev V.F.	Direct control of instability waves in	September , 2012	International Workshop “Computational	Scientific Community		

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NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
			turbulent jet.		Experiment in Aeroacoustics", Svetlogorsk			
45	Workshop	Kopiev V.F.	Feasibility of instability wave control in turbulent jet with active actuators	March, 2013	12th Int. Workshop on Magneto-Plasma Aerodynamics? Moscow	Scientific Community		
46	Symposium	Kopiev V.F	Acoustical control of instability wave in turbulent jet	June, 2013	SYMPOSIUM "Waves In Fluids: Effects Of Non-Linearity, Rotation, Stratification And Dissipation», Moscow	Scientific Community		
47	Conference	Faranosov G.A.	Theoretical Investigation of the Effectiveness of Artificial Instability Waves Excitation in Subsonic Jets	May, 2012	18th AIAA/CEAS Aeroacoustics Conference Colorado	Scientific Community		

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
48	Conference	Akishev Ya.S.	The pulsating flow generation by a barrier crown	September, 2011	18th AIAA/CEAS Aeroacoustics Conference, Zvenigorod	Scientific Community Industry		
49	Conference	Kossyi I.A.	Acoustical and shock wave characteristics of multi-electrode circular plasma actuator RING-1	September, 2011	2d Conference on Aviation Acoustics,Zvenigorod	Zvenigorod Scientific Community Industry		
50	Conference	Clero F. Kopiev V.F.	Advanced engine noise control based on plasma actuators (ORINOCO)	September, 2011	2d Conference on Aviation Acoustics Zvenigorod	Zvenigorod Scientific Community Industry		
51	Conference	Faranosov G.A.	Theoretical investigation of the efficiency of artificial excitation of instability waves in a two-	September, 2011	2d Conference on Aviation Acoustics Zvenigorod	Zvenigorod Scientific Community Industry		

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
			dimensional model of nozzle edge					