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Aeroacoustics research in Europe: The CEAS-ASC report on 2018 highlights

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Abstract

The Council of European Aerospace Societies (CEAS) Aeroacoustics Specialists Committee (ASC) supports and promotes the interests of the scientific and industrial aeroacoustics community on an European scale and European aeronautics activities internationally. In this context, "aeroacoustics" encompasses all aerospace acoustics and related areas. Each year the committee highlights some of the research and development projects in Europe.

This paper is a report on highlights of aeroacoustics research in Europe in 2018, compiled from information provided to the ASC of the CEAS. During 2018, a number of research programmes involving aeroacoustics were funded by the European Commission. Some of the highlights from these programmes are summarised in this article, as well as highlights from other programmes funded by national programmes or by industry. Furthermore, a concise summary of the CEAS-ASC workshop "Future Aircraft Design and Noise Impact" held in the Netherlands Aerospace Centre (NLR) Amsterdam in September 2018 is included in this report.

Enquiries concerning all contributions should be addressed to the authors who are given at the end of each subsection.

1 1. CEAS-ASC workshop

The 22nd CEAS-ASC Annual Scientific Workshop was held in NLR Amsterdam, on September 6-7, 2018. Its topic was "Future Aircraft Design and Noise Impact" and it was organized by Harry Brouwer of NLR and in co-operation with the EU project ANIMA (Aviation Noise Impact Management through Novel Approaches). The focus of the workshop was on the relationship between aircraft design and noise impact. Contributions were invited from both the domains of technology and impact assessment and thus the overarching objective of the workshop was to encourage discussion and cooperation between researchers in low noise technologies on one hand and on noise impact assessment and mitigation on the other.

Topics on which contributions were invited included: • Aircraft overall noise • Noise propagation • Auralization • Noise impact of new architectures • Boundary layer ingestion • Distributed

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propulsion • Single event models • Metrics • From wind tunnel data to noise impact assessment
 • Noise impact of drones • Non-acoustical factors

A total of 33 abstracts were received, 27 of which were accepted by the workshop scientific committee. In addition, 4 researchers accepted an invitation to present a keynote overview :

Lothar Bertsch, DLR: 10 years of joint research at DLR and TU Braunschweig toward low noise aircraft design - what did we achieve?

 Russell Thomas, NASA: Realizing NASAs Vision for Low Noise Subsonic Transport Aircraft.

Infrid Legriffon & Laurent Sanders, ONERA: Single Event Noise Prediction at ONERA Case of aircraft powered by contra-rotating open rotors.

The workshop was well-attended with 56 participants from 13 European countries and the USA. The participation from the USA was somewhat larger then on previous occasions with 6 participants from NASA, FAA, and Pennsylvania State University. Proceedings can be found at https://www.nlr.org/ceas-asc-2018-workshop/.

26 **2.** Airframe noise

27 2.1. Numerical study of fan noise installation effects using the Immersed Boundary Method

For several years, ONERA has been developing an innovative two-step CFD/CAA workflow 28 based on solid surfaces described by unstructured meshes immersed in volume Cartesian grids. 29 This so-called Immersed Boundary Method (IBM) is particularly efficient to evaluate acoustic 30 engine installation effects on novel aircraft architectures. The methodology consists in, first, 31 computing the mean flow around the geometry of interest with the CFD solver FastS [1], then 32 use the CAA solver sAbrinA_{v0} [2] to compute the propagation of acoustic waves generated by 33 any kind of noise source. Both solvers are used in Cartesian mode, and have their IBM pre-34 process based on the Cassiopee package [1]. The method allows to drastically reduce the mesh 35 design efforts as well as the computational costs for both CFD and CAA stages. First validations 36 of the methodology with no mean flow confirmed its efficiency and reliability [3]. 37

This methodology bas been successfully applied to study the installation effects, on the 38 fan/OGV interaction noise, of two different implementations OWN and UWN (Over- and Under-39 Wing-Nacelle) of classic turbofans on ONERAs NOVA aircraft, accounting for realistic non-40 uniform mean flows at M = 0.25 (i.e. take-off/landing flight conditions). Instantaneous pressure 41 fluctuations computed by the sAbrin A_{v0} solver are plotted in Fig. 1. for the two configurations. 42 Multiple interference patterns, mainly due to reflection/scattering effects on the solid surfaces 43 and refraction effects due to the mean flow gradients, are clearly noticeable. The comparison of 44 noise maps on the ground (see Fig. 2) shows that the OWN configuration brings noise reduc-45 tion of more than 15 dB, especially in front of the aircraft as could be expected from this noise 46 shielding effect. 47

These simulations demonstrate the capacities of the present numerical workflow. Parametric studies, dealing with acoustic efficiency for installation effects, are now affordable.



Figure 1: Instantaneous pressure fluctuations with one-sided engine aircraft in the vertical nacelle mid-section plane: UWN configuration (left); OWN configuration (right).



Figure 2: Extrapolated acoustical pressure maps (in dB) with a two-sided engine aircraft: UWN configuration (left); OWN configuration (right)

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⁵³ 2.2. The Air Curtain as a Fluidic Spoiler to Reduce Aerodynamic Noise.

The air curtain has been used in a number of diverse engineering applications, such as acting as 54 smoke, heat or contamination barriers. In aeronautics, it was first proposed for use for landing-55 gear noise reduction by Wickerhoff and Sijpkes [4], after which Oerlemans and de Bruin [5] 56 performed proof-of-concept research to validate it on a generic bluff body. In recent years, the 57 planar jet as a means to reduce noise has been further investigated and advanced by Zhao et al. 58 [6, 7], in which tandem rods were examined as a simplified representation of aircraft landing gear. 59 Subsequently, in order to minimise the additional noise source introduced by the air curtain itself, 60 the dual air curtain has been developed and investigated, in which improved acoustic and energy 61 efficiency have been achieved through the addition of a second upstream planar jet [8, 9]. Initial 62 research has been conducted into the development of the Fluidic Spoiler as a landing gear noise 63 reduction technology beyond representative academic configurations, see Fig 3. In addition to 64 the acoustical studies, the fluid mechanics of dual planar jets in a cross flow, which have received 65 little attention in the literature, have been extensively examined with PIV, hotwire and numerical 66

analysis, and proper orthogonal decomposition has been performed in order to characterise the

coherent structures of the flow field, particularly the large-scale vortices mainly occurring in the

⁶⁹ shear layers [10, 11, 12]. Further applications of the air curtain, also called: Fluidic Spoiler, have

⁷⁰ been studied such as the use of the air curtain to shield the aerodynamic noise of the pantograph

⁷¹ of a high speed train or to reduce cavity noise [13], see Fig 4.



(a) Fuselage Mounted: Elevation

(b) Fuselage Mounted: Isometric

Figure 3: Dual-jet air curtain concept for shielding nose landing gear. Not to scale.



(a) Cavity resonance baseline.

(b) Fluidic spoiler applied upstream of cavity opening showing dramatic reduction in cavity pressure across all resonant modes.

Figure 4: Sound pressure level [dB] inside a cylindrical cavity as a function of tunnel flow-speed. Superimposed on the plot are the theoretical shear layer modes (SL), the theoretical acoustic resonant modes, including azimuthal, (H1, AZ1...) and the Helmholtz resonance (HR).

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74 2.3. Full Scale Nose Landing Gear Analysis.

Recently research has been published based on the experimental results from the Clean Sky
 funded ALLEGRA Advanced LowNoise Landing (Main and Nose) Gear for Regional Aircraft

project. This project was developed to assess low-noise technologies applied to a full-scale 77 nose landing gear model and a half-scale main landing-gear model of a 90-seat configuration 78 regional aircraft concept. With regard to the nose landing gear (NLG) campaign, one of the 79 significant contributions of ALLEGRA is that a complete and highly detailed representation of 80 the landing-gear components and associated structures such as the complete wheel bay cavity 81 (wheel well), bay doors, nose fuselage and hydraulic dressings were included at full scale [14, 82 15, 16]. In 2018, results from a decomposition analysis was performed where LG components 83 were removed one after the other in order to assess their individual contribution [17]. In addition, 84 85 low noise treatments such as wheel hub caps, retractable fuselage fairings, perforated fairings and wire mesh was evaluated, see Fig. 5. Additional interesting findings such as the excitation and 86 radiation of wheel well noise was assessed, in particular the higher order modes of the large 87 volume wheel well which can be excited within the velocity range of a landing aircraft[18]; 88 modes that are usually ignored[19]. Also in 2018, windtunnel results were compared to flyover 89 results of real aircraft of a similar size and design as well as to standard semi-empirical models. 90 Particularly novel was the comparison to acoustic data extracted from CFD flow computations 91 which was propagated to simulated microphone arrays and processed using several beamforming 92 approaches [20]. Similar analyses were performed for the half scale MLG which also was found 93 to radiate noise from the wheel bay [21, 22]. 94



(a) Without hub-caps applied

(b) With hub caps applied

Figure 5: Hub-caps low noise technology applied to nose landing gear.

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98 2.4. Retro-Fit Noise Reduction Technology Assessment through Flyover Noise Measurements

The teams of the DLR Technical Acoustics and Engine Acoustics Departments achieved flight tests with the DLR Airbus A320 research aircraft ATRA (Fig. 6). The aim of this combined effort was to demonstrate the effect of selected retro-fit noise reductions means on the wings, landing gears and the engine exhaust nozzles. The measurements were taken at Cochstedt airport

in Saxony-Anhalt (Germany) with a phased microphone array for source localization (Fig. 7, 103 left) and widely distributed single farfield microphones in order to obtain absolute levels and 104 directivity information. The tested porous flap side edge provided a 2 dB noise reduction in 105 terms of the measured sound exposure level during flyover in about 600 ft height above the 106 microphone in gear-up configuration. Selected fairings on both the main and nose landing gear 107 showed a 1 - 2 dB noise reduction which strongly depends on the flight speed and high-lift system 108 configuration. Noise reductions are very weak at high flap settings with potentially high gear-109 wake flap interaction noise generation. This result indicates that both sources need to addressed 110 together. The engine nozzle trailing edge modification leads to a high frequency noise reduction 111 (Fig. 7, right) combined with the suppression of tonal engine noise components. The flight 112 test was a core activity of the DLR project Low Noise ATRA. Contributions were made by the 113 industrial partners Airbus and Safran. 114



Figure 6: ATRA approaching the measurement systems.



Figure 7: Source map for a fly-over in landing configuration calculated with a hybrid deconvolution method (left) and effect of the nozzle modification on the perceived noise level (right)

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117 2.5. Numerical Analysis of the Impact of Variable Porosity on Trailing-Edge Noise

The impact of permeability on the trailing-edge noise is analyzed by a constant and a variable 118 porous surface [23]. Porous media generate the Darcy drag force, i.e., the viscous effect of the 119 micro-structure inside a porous medium, which is numerically determined by the permeability 120 and the Forchheimer term. The permeability and the porosity of a baseline configuration are 121 defined based on the acoustic intensity quantified for various porous surfaces [24]. A variable 122 porous medium at a trailing edge is designed by an adjoint-based optimization. The constant 123 and the variable porous medium are applied to two flow configurations, one at zero deg. and 124 one at two deg. angle-of-attack (AOA), to indicate the impact of various loads on the suction 125 and pressure sides on the effectiveness of porous surfaces. In Fig 8 the directivity determined 126 by the overall sound pressure level is presented. The zero deg. AOA configuration shows that 127 the porous media reduce the noise generation independently from the direction. The acoustic 128 gain is determined by an induced drag force which leads to a lower convection velocity for the 129 turbulent flow passing over the trailing edge. The porous surface is extremely effective to reduce 130 the tone and the broadband noise [24]. The variable porosity configuration shows with the thick 131 arrows an additional noise reduction compared to the constant porosity medium. However, at two 132 deg. AOA the porous surface shows a lower impact on the noise reduction such that the acoustic 133 gain, which is obtained by the optimization at zero deg. AOA, is diminished. This sensitivity of 134 the porous-media effectiveness means that in future optimization approaches the AOA should be 135 considered an optimization parameter. 136



Figure 8: Overall sound pressure level determined by the acoustic perturbation equations black arrows indicate the noise reduction between impermeable (solid lines) and porous (dashed lines) surfaces color denotes the rounded (red) and the sharp (green) trailing-edge at zero deg. AOA and the rounded trailing-edge at two deg. AOA (blue).

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141 2.6. RANS-based trailing-edge noise prediction using Amiet's theory

Amiet's semi-analytical model [25] for trailing-edge noise prediction was performed by cou-142 pling it with Reynolds-Averaged Navier-Stokes (RANS) simulations which are used to determine 143 the wall-pressure statistics. Two families of wall-pressure spectrum models are compared: i) 144 based on a resolution of the Poisson equation by integrating velocity statistics over the boundary 145 layer thickness (Panton & Linebarger model [26]), or ii) directly addressing wall-pressure statis-146 tics through ad-hoc empirical models calibrated on experimental databases (Goody, Rozenberg, 147 Kamruzzaman, Catlett, Hu & Herr and Lee models [27]). As illustrative test cases, two different 148 configurations are treated in this work: a NACA0012 airfoil at 0 degree angle of attack (a.o.a) 149 and a DU96-W-180 airfoil at 4 degrees a.o.a, the key differences between both cases being the 150 importance of the wall-pressure gradient and symmetry between the pressure and suction sides. 151 The results, see Fig. 9, indicate that both the semi-empirical model developed for adverse pres-152 sure gradients and the integral model yield good predictions for the NACA0012 test case. For the 153

¹⁵⁴ Du96-W-180 airfoil, the Lee model which is modified for high adverse pressure gradient flow ¹⁵⁵ performs in the range of $\pm 3dB$. The Kamruzzaman model also exhibits a good performance in ¹⁵⁶ the range of ± 3 dB by considering its simple formulation. Lastly, Panton & Linebarger model ¹⁵⁷ predicts well the middle range whereas under-predicts around 2 dB for the higher frequencies.



Figure 9: Far-field noise prediction by Amiet's theory with different wall-pressure models and comparison with an experimental data the NACA0012 airfoil (left) and the DU96-W-180 airfoil (right).

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¹⁶¹ 2.7. The attenuation of the cavity tones induced by a low-speed flow using micro-perforated ¹⁶² panels

Experimental studies have been carried out to assess the effect on the pressure fluctuations 163 of micro-perforating [28] the base wall of cavities mounted in a low-speed wind-tunnel and 164 undergoing a fully-developed turbulent boundary layer [29], as shown in Fig 10. This passive 165 strategy has hardly been studied in shallow cavities in transitional flow regime, e.g. with a 166 length-to-depth ratio of about 10. The wall-pressure spectra acquired at Mach number 0.09 167 over the cavity base panel showed dominant peaks on one third of the cavity floor towards the 168 leading edge. Broadband pressure fluctuations dominate further downstream, with amplitudes 169 of about 10 dB above that of the first peak. The peaks are identified as transverse tunnel-cavity 170 resonances excited by the shear layer and coupled with the thin panel flexural modes. It can 171 be seen from Fig 10 that micro-perforating the floor of the cavity reduces by up to 8 dB the 172 dominant tonal peaks. This was also ob served for a closed-flow cavity, but to a lesser extent. 173 However, the micro-perforations are inefficient downstream of the reduction zone to attenuate 174 the broadband pressure fluctuations, which can even be enhanced. Two-dimensional Lattice-175 Boltzmann simulations were performed for a transitional cavity mounted in a waveguide and 176 undergoing a low-speed boundary layer. The calculated wall pressure spectra confirmed the 177 existence of transverse tunnel-cavity resonances as well as their attenuation at the base and at the 178 mouth of the cavity by inserting a micro-perforated floor. The dissipation of energy was found 179 to be concentrated within and at the inlet-outlet of the base-wall apertures which correspond to 180

regions of maximum velocity fluctuations. A strategy would be to microperforate only part of the base wall that extends over one third of the cavity length in order to achieve attenuation of

the dominant peaks without enhancement of the broadband wall-pressure fluctuations.



Figure 10: Views of a transitional flow cavity with micro-perforated base wall beneath a fully developed turbulent boundary layer: (a) sketch of the cavity with numbering of the 19 wall-pressure measurements positions evenly distributed over the centered length line of the base wall (b) photograph of the wind tunnel test section on top of which is mounted the micro-perforated cavity.



Figure 11: Effect of a microperforated floor on the pressure level (PL) spectra measured over the base wall of a transitional cavity with length-to-depth ratio 10.6: (a) at 18.2 cm and (b) at 9.8 cm from the cavity upstream edge. The solid curves correspond to a plain floor and the dotted curves to a microperforated floor the red dot in the sketches shows the measurement location.

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189 2.8. Airfoil noise reduction with add-ons and permeable materials

Leading-edge-impingement (LEI) noise and turbulent-boundary-layer trailing-edge (TBL-TE) 190 noise are amongst the most relevant sources for airframe and turbofan noise (i.e., rotor/stator in-191 teraction noise). They can be mitigated by using serrations or reducing the pressure imbalance 192 with permeable surfaces. Recent developments have confirmed that serrations reduce noise by 193 generating destructive interference between the scattered pressure waves for both TBL-TE and 194 LEI noise. For TBL-TE noise [30], it has been proven that the effect of the serrations on the flow 195 is to increase the spanwise coherence of the turbulent structures, which promotes destructive 196 interference for slanted edges. This is achieved by altering the flow features over the serration 197 surface, see Fig. 12, both the size of the turbulent structures and their convective direction, as 198 also proved experimentally [31]. Conversely, for rotor/stator impingement noise [32], the di-199 mensions of the turbulent structures in the slipstream of the fan is such that, to realise destructive 200 interference and to reduce noise more than 1 dB, large amplitude serrations are necessary, thus 201 affecting negatively both the aerodynamic performances and robustness of the stator. An alter-202 native approach to reduce noise is the application of permeable surfaces at both the leading and 203 trailing edge. In this case, the noise reduction mechanism is the reduction of the pressure imbal-204 ance. For TBL-TE noise [33], permeable materials have been shown to reduce noise up to 10 dB 205 in wind tunnel applications. It has been proven that the conventional model adopted for a solid 206 trailing edge cannot be applied for porous materials because additional noise sources are present. 207 Conversely, for LIN [34], the adoption of a permeable surface at the leading edge has shown that 208 the presence of flow through the insert that forces transition to turbulence, see Fig. 13. In this 209 case, alleviation of LEI noise has been obtained but with an increase of TBL-TE. 210



Figure 12: Streamlines representing the instantaneous flow field over a serrated trailing edge obtained with the lattice-Boltzmann method.



Figure 13: Instantaneous flow visualisation of the impingement of a propeller slipstream with on a pylon with solid (left) and permeable (right) leading edge

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214 **3. Fan and Jet Noise**

215 3.1. Aerodynamic noise of large-scale vortex ring produced by explosion

Aeroacoustic properties of large-scale turbulent vortex rings produced by means of explosion 216 in steel cylindrical chambers (Fig. 14) are considered [35]. Unlike the small-scale experiments 217 in which the noise of the ring is determined by spectra averaging over an ensemble of similar 218 realizations, in the case of large-scale rings generated by the explosion it is possible to investigate 219 the phenomenon on the basis of only a single realization. It significantly extends the range of 220 parameters that can be analyzed. The large-scale ring noise manifests itself by strong peaking 221 of the spectrum in a narrow frequency band as well as the small-scale one (Fig. 15). However 222 one could recognize two or even three narrow frequency bands which are close to the multiple 223 frequencies of the main peak (Fig. 16), but the amplitudes of these peaks are significantly lower. 224 The main frequency peak does not shift to a lower-frequency region while the ring moves. It 225 fundamentally differs from the case of the small-scale rings, which in turn is in agreement with 226 the self-similar theory of the vortex ring motion [36]. This difference means that the vortex 227 core behavior of such vortices has some peculiarities, although the presence of several peaks is 228 consistent with the results of the theory of vortex ring sound generation [37]. 229



Figure 14: High speed camera diagnostics of vertical movement of the vortex ring, duct diameter 80 cm.



Figure 15: Narrow band spectra for the vortex ring with time delay after explosion 10 s, duct 80 cm.



Figure 16: Multi-peaking structure of vortex ring noise for different conditions. Vortex ring moves along the ground surface, measurements produced by two different mics located at different distances from the trajectory (different colors).

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3.2. Shockwave Generation and Radiation from an UHBR Engine with Flow Distortion using a CFD/CAA Chaining Strategy

In the framework of the Clean Sky2 ASPIRE project, aeroacoustic investigations were 234 achieved on a full-scale Ultra High Bypass Ratio (UHBR) engine with inflow distortion at tran-235 sonic conditions [38]. Computational Fluid Dynamics (CFD) simulations were first realized to 236 compute the shocks in the vicinity of the fan, which were then radiated outside of the nacelle 237 thanks to Computational AeroAcoustics (CAA) simulations. The elsA solver [39] was used for 238 both CFD and CAA simulations and the coupling was done by injecting the shocks in terms of 239 usual conservative variables using a non-reflecting boundary condition [40]. The CAA solver 240 is based on the non-linearized Euler equations which allows to define the CFD/CAA interface 241 close to the fan where the propagation of shocks is highly non-linear. Both shock generation 242 and shock propagation mechanisms were investigated and the effects of inflow distortion were 243 highlighted by comparison with a baseline case without distortion. It was shown that the distor-244 tion, characterized by an acceleration of the flow at the bottom of the nacelle (17), is responsible 245 for a modification of the shock amplitudes that depends on the circumferential position. Thus, 246 azimuthal modes appear in addition to the rotor-locked mode present without distortion. The 247 near-field radiation is highly impacted with most of the noise being directed towards the sky 248 (18). This is shown to be caused by the blockage of shocks by a supersonic flow region in the 249 bottom of the nacelle (19). ONERA carried out this study in close cooperation with partners 250 Airbus, NLR, and DLR and received funding from the Clean Sky 2 Joint Undertaking under the 251 European Unions H2020 program (grant agreement no. 681856). 252



Figure 17: Inflow distortion map (axial velocity contours).



Figure 18: Pressure radiated through the inlet at the BPF (vertical plane).



Figure 19: Instantaneous density gradient magnitude contours and sonic isoline (in red) in the inlet (unwrapped radial slice, the fan is at the top, the nacelle entrance is at the bottom).

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256 3.3. A novel facility for the investigation of fan noise generation mechanisms: ECL-B3

The fan module is expected to be the major noise source of future Ultra-High-Bypass-Ratio 257 (UHBR) turbofan engines. Among the reasons are the increase in fan diameter, a reduction of 258 the exhaust jet speed and the shortening of the nacelle. The new ECL-B3 test rig shown in Fig 20 259 is dedicated to advanced research in aeroacoustics [41] as well as aero-dynamic and aero-elastic 260 instabilities of fan stages [42]. This facility, the result of a collaboration between the Fluid Me-261 chanics and Acoustics Laboratory and Safran Aircraft Engines, was inaugurated in 2018 at the 262 Ecole Centrale de Lyon. The first tested configuration was a scaled modern UHBR fan manu-263 factured by Safran Aircraft Engines within the ENOVAL European project. The noise generated 264 by the fan module was measured by in-duct wall-flush mounted microphones intended for the 265 characterization of the modal content. Part of the sensors are mounted on rotating rings allow-266 ing a fine spatial discretization. The angular steps have been optimized such as to minimize 267 the number of rotating steps while keeping modal basis parameters such as the mutual coher-268 ence and condition number as low as possible over a wide frequency band. The invariably lost 269 phase relationships between probes at the sequential positions is reconstructed. fixed reference 270 microphones have been used to estimate the complete cross-spectral matrix as if measurements 271 at sequential steps were recorded simultaneously. Modal amplitudes are estimated by using an 272 iterative Inverse Bayesian Approach [43]. The resulting algorithm allows to control the degree 273 of sparsity imposed on the solution. For instance at tonal frequencies the number of dominant 274 modes is expected to be small due to constructive interferences, a high degree of sparsity is 275 appropriate. For broadband noise a mild sparsity assumption would be more pertinent [41]. 276



Figure 20: Left, view of the Turbulence Control Screen (TCS) and the traversable microphone array for directivity measurements in the anechoic chamber of the ECL-B3 facility. Right, in-duct view from the downstream test section showing stator vanes.

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281 3.4. Multi-port eduction of installation effects applied to a small axial fan

In HVAC systems, the noise emitted by the fan is usually characterized in a test bench ensur-282 ing a relatively ideal constant and uniform inflow. In contrast, the implementation of this fan 283 in an industrial duct system will often result in a non-uniform and unsteady flow field due to 284 the presence of nearby bends, valves, etc. Those distorted inflow conditions are usually accom-285 panied by an increase of noise emissions [44]. An experimental investigation of aeroacoustic 286 installation effects was performed in the ALCOVES (Aeroacoustic Lab for COoling and VEnti-287 lation Systems) test bench of the von Karman Institute for Fluid Dynamics [45] for the case of an 288 axial fan such as found in domestic appliances. A multi-port methodology [46] has been used to 289 extract the active noise emitted by the fan in various inflow conditions, by decontaminating the 290 microphone measurements from the test bench acoustic reflections and turbulent boundary layer 291 pressure fluctuations. The inflow distortions were shown to have strong impact on the acoustic 292 emissions and aerodynamic performance of the fan. Using similarity laws, it was shown that 293 the alteration of the operating point is not sufficient to explain the impact of distorted inflows on 294 the acoustic power radiated by the fan. The broadband noise in particular was shown to be very 295 sensitive to the turbulence shed by the grids, with additional noise of the order of 10 dB at some 296 frequencies in Fig. 21. The results suggest the need for novel acoustic design guidelines ac-297 counting for inflow quality in addition to the classical indicators solely based on the performance 298 point. 299



Figure 21: Acoustic power upstream of the fan under different inflow conditions at the same rotational speed.

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304 3.5. Prediction of far-field sound of installed complex geometry ultra high bypass ratio jets in 305 flight using LES

Growing aero-engine bypass ratios means the noise directly generated by the jet has now de-306 creased significantly. Another consequence is that the relative importance of installation noise 307 has increased. Increasing engine diameters can lead the jet to directly interact with the wing 308 and flap generating significant noise sources. Using LES in a blind test, flow and resulting far-309 field sound has been accurately predicted for complex geometry installed configurations under 310 flight conditions [47]. This is difficult and costly to adequately achieve experimentally, yet well 311 defined numerically. Figure 22 shows the jet-wing-flap interaction and far-field sound directly 312 below the aircraft. Agreement with available measured sound data is clear. Isolated and installed 313 configurations, have been contrasted for round nozzles with two flap deflections [47] and noz-314 zles with serrations [48]. For round nozzles a 20dB increase in noise was predicted and greatly 315 reduced with nozzle serrations. This is due to increased turbulence dissipation reducing jet-flap 316 interaction. Using high-fidelity unsteady data sets, noise sources and their distribution have been 317 identified [47]. Furthermore, turbulence length and time scale distributions have been calculated 318 [47, 49] to inform lower fidelity modelling such as RANS, that can be used to guide rapid design 319 tools. A modelling framework has been defined for complex geometries [47] consisting of mod-320 ular hybrid structured-unstructured mesh generation, low dissipation numerical discretisation, 321

hybrid LES-RANS turbulence modelling, Ffowcs Williams-Hawkings (FW-H) surface genera-

tion and far-field propagation [47]. The same procedure has recently been successfully validated

in another blind test for large scale simulations including a pylon and fuselage. This highlights the ability of the approach to reliably replace significant amounts of rig testing, also providing

the ability of the approach to reliably replace significant amounts of rig testing, also providing greater consistency.

szo greater consistency.



Figure 22: Fig. 1 (a-c) Jet flow and interaction with wing-flap geometry, (d) isolated (Iso.) and installed sound pressure level for flap deflections 8 (F08) and 14 (F14) degrees with measured (Exp.) data.

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330 4. Helicopter Noise

331 4.1. Blade-Vortex Interaction Noise Controller Based on Miniature Trailing Edge Effectors

A methodology to suppress/alleviate the noise annoyance emitted by bladevortex interaction 332 (BVI) phenomena occurring on helicopter main rotors developed and validated in Refs. [50, 51] 333 has been presented. The proposed methodology is suitable for the identification of multi-cyclic 334 harmonic controllers based on the actuation of rotor blades equipped with Miniature Trailing 335 Edge Effectors (MiTEs). The low-power requirements make MiTEs particularly suited for this 336 kind of application. The objective of the control methodology is the direct suppression of the 337 aerodynamic noise sources by generation of localized high-harmonic unsteady aerodynamic 338 loads (as much as possible equal and opposite to those produced by BVI phenomena) aimed 339 at canceling out those caused by the BVI events. The set-up of control devices is selected on 340 the basis of the blade-vortex interaction scenario, taking into account a trade-off between effec-341 tiveness and power requirement. The control law is efficiently identified by means of an optimal 342 controller synthesized through suitable two-dimensional multi-vortex, parallel blade-vortex in-343 teraction problems. The proposed methodology is validated by the application to realistic heli-344 copter main rotors during low-speed descent flights, numerically simulated through high-fidelity 345 aerodynamic and aeroacoustic solvers based, respectively, upon a three-dimensional free-wake 346

³⁴⁷ boundary element method [52] for the solution of potential flows around rotors in blade-vortex
 ³⁴⁸ interaction conditions and the Farassat 1A formulation. Results demonstrate that the proposed
 ³⁴⁹ control approach is a promising method to reduce BVI noise.

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352 Submission Country: Italy

4.2. Rotorcraft comprehensive code assessment for blade-vortex interaction conditions

Computational methodologies applied to a comprehensive code for rotorcraft developed in re-354 cent years at Roma Tre University are presented in Ref. [52], along with an assessment of its 355 prediction capabilities focused on flight conditions characterized by strong blade-vortex interac-356 tion phenomena. This comprehensive code includes a detailed aeroelastic response analysis of 357 the blade within the trim procedure: a three-dimensional, potential-flow, an rotor aerodynamics 358 solver which is fully coupled with a bending-torsion beam model of blade structural dynamics, 359 and a harmonic-balance/modal approach is used to integrate the rotor aeroelastic equations [53]. 360 Hence, for a prescribed flight condition, the aeroelastic trim module provides pitch control set-361 tings and vehicle attitude, blade elastic response, mean and vibratory hub loads, as well as the 362 pressure distributions required to define the noise sources in the aeroacoustic module. The rotor 363 noise radiation is evaluated through the widely-used boundary integral Farassat 1A formulation. 364 The validation campaign of the comprehensive code has been carried out against the well-known 365 HART II database, which is the outcome of a joint multi-national effort aimed at performing wind 366 tunnel measurements of loads, blade deflection, wake shape and noise concerning a four-bladed 367 model rotor in low-speed descent flight. Comparisons with numerical simulations available in the 368 literature for the same test cases are also presented. It is shown that, with limited computational 369 cost, the results provided by the Roma Tre aero-acousto-elastic solver are in good agreement with 370 the experimental data, with a level of accuracy that is in line with the state-of-the-art predictions. 371 The influence of the vortex core modeling on aerodynamic predictions and the influence of the 372 inclusion of the fuselage shielding effect on aeroacoustic predictions are discussed. 373

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377 5. Aircraft interior noise

5.1. Parametric study on effects of wall pressure wavenumber spectra on aircraft fuselage vibra tion

The wall pressure wavenumber spectra in the front region of the aircraft fuselage at cruise 380 condition are formulated based on the wall pressure cross-spectral model [54]. The formulated 381 spectra are used as excitation sources for the calculation of the fuselage panel vibration with 382 the Statistical Energy Analysis method [55]. The coherence length, the convection velocity and 383 the flow angle are modified to study their effects on the wavenumber spectrum and the panel 384 vibration. Furthermore, the practical impact of parametrically important factors on the calculated 385 results such as the surface microphone array size and resolution, window functions and dealing 386 with noisy signal is studied, see [56]. Figs. 23 and 24 show the effect of coherence length 387

and convection velocity modifications on the wavenumber spectra and the panel vibration. For 388 the frequencies between 800 Hz and 2 kHz in which a possible coincidence between the flow 389 excitation and the panel vibration occurs, the wavenumber spectral peak region is important 390 for the excitation. A change in the spectral peak level results in a respective change in panel 391 vibration level. For frequencies outside of 800 Hz - 2 kHz, the lower streamwise wavenumber 392 spectral range is important for the excitation. Figs. 25 and 26 show the effect of the array size, 393 resolution and noise. A too small resolution or a too small size will strongly affect the calculated 394 wavenumber spectra and vibration. However, an overly large array size will increase the error 395 due to a reduction of the signal-to-noise ratio when dealing with noisy signal. 396



Figure 23: Contour plot of wavenumber spectra at 2500 Hz with levels between -54 dB and -35 dB (a) Smol'yakov model (b) $0.5 l_1$ (c) $0.5 l_3$ (d) $0.8 u_c$



Figure 24: Comparison of panel vibration (a) modification of coherence lengths (b) modification of convection velocities.



Figure 25: Comparison of streamwise wavenumber spectra at 2500Hz with different processing settings (a) array sizes (b) array resolutions (c) noisy signal.



Figure 26: Comparison of panel vibration with different processing settings (a) array sizes (b) array resolutions (c) noisy signal.

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400 **6. Propeller noise**

6.1. Contra-rotating open rotors (CROR) as a viable aircraft propulsion system: experimental,
 numerical and analytical studies.

Noise from contra-rotating open rotors is a major obstacle to the adoption of this fuel efficient 403 technology as a viable aircraft propulsion system. A better understanding of both contra-rotating 404 open rotor noise generation, reduction and shielding has been achieved recently due to ongo-405 ing research based on the WENEMOR data [57, 58, 59] where 288 test conditions of a 1:7 scale 406 green regional aircraft model were completed. A wide range of airframe configurations equipped 407 with two installed CROR engines operating in both pusher and tractor modes and operated at 408 both approach and takeoff settings were assessed as a function of windtunnel speed and angle 409 of attack. The geometric parameters which were varied included interchangeable tailpieces (T, 410 L and U empennage), variable fuselage length, engine pylon rotation, and engine pylon elonga-411 tion and these allowed shielding effects, pylon wake effects as well as the benefits to be gained 412 from moving the entire CROR out of the wing wake to be assessed [60]. In addition to the full 413 installation analysis set-up, a second campaign was conducted where only the installed-on-pylon 414

contra-rotating open rotor configuration was evaluated [61]. The experimental results were used 415 to validate an original numerical method for the calculation of engine noise installation effects 416 and its application to contra-rotating open rotor propulsion was demonstrated. This method is 417 based on the weak coupling between computational fluid dynamics, an integral method based on 418 Lighthills analogy for the calculation of acoustic radiation, and on a boundary element method 419 for the calculation of the acoustic diffraction by the aircraft fuselage and empennage [62, 63]. In 420 addition, the equal number of blades fore and aft for the CROR engines considered, has provided 421 interesting opportunities such as a study which approaches the question of counter-rotating open 422 rotor engine noise levels from a yet unexplored perspective, examining the radiation efficiency 423 properties of unducted turbomachinery acoustic modes in order to provide design guidelines that 424 mitigate the radiation of sound without the need for shielding [64]. 425

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429 7. Techniques and methods in aeroacoustics

7.1. The conditions of quadrupole moment conservation in the evolution of small perturbations of stationary flows

Perturbations of incompressible ideal fluid flows are described in terms of the Lagrangian 432 and Hamiltonian formalism [65]. Expressions for the Lagrangian and Hamiltonian in which 433 the displacement field and momentum density perturbation field are used as canonical variables 434 are obtained. Based on Noethers theorem, the conditions of conservation of the quadrupole 435 moment of perturbations of the flow are derived. It is shown that these conditions are satisfied 436 for any uniform jet flows both in the two- and three-dimensional cases. The results are of great 437 importance in aeroacoustics because the quadrupole moment of the flow is the principal term of 438 acoustic source expansion in the Mach number. Conservation of the quadrupole moment means 439 that the evolution of perturbations of uniform jet flows under arbitrary initial conditions makes 440 no contribution to quadrupole sound radiation in the linear approximation. Therefore, sound 441 sources of low-velocity jets may be related to finer effects, such as weak non-uniformity of the 442 flow in the streamwise direction or nonlinearity of perturbations. It is also possible that the idea 443 444 that sound sources in a turbulent jet are small perturbations on the background of the mean flow does not correspond to their real nature and generation of acoustic perturbations in the turbulent 445 flow is significantly affected by the local non-linear structure of the vorticity. 446

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450 7.2. Noise reduction of VEGA launch pad environment at lift-off

In 2015, ONERA performed the analysis of microphone array data measured during VV05 of VEGA launcher in Kourou, on behalf of ESA [66]. Approximately at the payload fairing level, a 2 m diameter circular array composed of 32 microphones, was implemented on one of the antilightning pylons, oriented toward the exhaust duct, aimed at identifying the location and level of the acoustic sources generated during lift-off. Based on this study, the contributions to the overall

noise from the engine jet, the table and the flame trenches were highlighted and as a trade-off 456 between acoustic benefits and costs, ESA decided to modify the launch table by closing existing 457 openings with heavy steel plates filled with porous materials. Two years later, in 2017, during 458 VV10, the same microphone array measurements were realized. Direct comparison of the acous-459 tic levels measured on the microphones pointed out a reduction of about 2 dB at the frequencies 460 of interest, and even more for higher frequencies. A deconvolution method developed in ONERA 461 [67], based on the well-known DAMAS [68], was applied to three scanning plans, including a to-462 tal of about 3000 sources. When the launcher is at the lowest altitudes, corresponding to the most 463 critical moment for acoustics, the source localization confirmed strong reduction of the sources 464 radiated from the table, with only slight change from the flame trenches (Fig 27). The last step 465 consisted in propagating the acoustic sources to the fairing. As the microphone array is in front 466 of one of the two ducts, the reasonable hypothesis that they generate similar noise (uncorrelated) 467 is made and the sources identified on the flame trench are symmetrized. Diffraction effect on 468 the fairing is taken into account thanks to correction of infinite cylinder. The results (Fig 28) are 469 coherent: the effect of the table covers progressively decreases with the increasing distance of 470 the launcher from the pad, leading to a corresponding reduction of the acoustic benefit. 471



Figure 27: Acoustic reduction on each scanning plan at 0 m



Figure 28: Acoustic attenuation at the fairing level Evolution with the altitude

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7.3. Duct azimuthal and radial modal deconvolution of CFD analysis of UHBR engine tonal noise.

A modal deconvolution method is used to characterize the main propagating acoustic duct 477 modes from non-intrusive measurements. In the framework of the ASPIRE-CS2 project, ON-478 ERAs modal deconvolution method ARMADA [69] is applied to numerical data from a generic 479 UHBR engine at the take-off sideline condition. The numerical simulation is provided by NLR 480 to quantify the tonal internal acoustic field by the application of a CFD approach for the config-481 uration with a clean fan channel [70]. The complex geometry of the nacelle implies a variable 482 Mach number through the fan duct, which is unfortunately not precisely known. As a first step, 483 an azimuthal Fourier transform is applied to determine the content of the dominant azimuthal 484 modes. In the bypass duct (downstream direction), they are shown to be quite constant, whereas, 485 upstream from the fan, they vary significantly in the vicinity of the inlet. Therefore, our decon-486 volution method [69], extended to an annular duct, is only applied on the bypass duct, using 487 data obtained at BPF2 on the wall as it would be for flush mounted microphones. We consider 488 a modal basis restricted to azimuthal mode orders from -1 to 11, which is relevant to explain the 489 main content of the total sound pressure. Considering a constant flow rate with two hypotheses 490 of Mach number (0.4 and 0.5), and under the correlated mode assumption, the results explain 491 more than 74% of the data. The more energetic modes correspond to azimuthal mode m=4 and 492 radial modes n=2 and 3, together with m=3 and n=2; they are found to be perfectly correlated. 493 Modes propagating in the upstream direction (k^{-}) point out possible reflections at the end of the 494 nacelle (see Fig. 29). 495

Finally, the acoustic pressure field (absolute value of the Fourier transform) is reconstructed from the estimated modes (cross spectral matrix of the amplitude), and compared to the initial numerical data (see Fig. 30). The black frames highlight areas where some modes, not included in the modal basis, go from cut-on to cut-off. Using only data obtained on the wall, ONERAs deconvolution method succeeds in providing a good representation of the acoustic field in the bypass duct.



Figure 29: Normalized power cross spectral matrix of the amplitude of the modes obtained by correlated ARMADA on the bypass duct @BPF2, considering M_0 =0.4 (left) and M_0 =0.5 (right).



Figure 30: Absolute value of the Fourier transform of the pressure field reconstructed on the bypass duct hub surface (left) and duct casing surface (right).

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505 7.4. Uncertainty quantification for direct aeroacoustics of cavity noise

Cavity noise has become a major concern in automobile exterior aerodynamics. Different 506 noise generation mechanisms have been identified, such as Helmholtz resonance, standing waves 507 and Rossiter feedback, which all lead to tonal noise emission. Both frequencies and sound pres-508 sure levels of cavity noise are highly sensitive to geometric and environmental uncertainties. 509 Those sensitivities can lead to deviating results between experiment and numerical simulations. 510 Uncertainty quantification (UQ) is therefore a promising tool to gain deeper insight into the fac-511 tors influencing the sound spectra. An UQ framework based on the deterministic high-order 512 discontinuous Galerkin solver FLEXI has been developed to quantify the influence of random 513 input parameters on cavity noise. UQ was realized through a non-intrusive spectral projection 514 method which revealed fast stochastic convergence in comparison to sampling based methods. 515 With the help of this framework, the system response of a cavity flow problem under the influence 516 of uncertain parameters has been analyzed. Uncertainties in the upstream boundary layer as well 517 as randomness in the cavity geometry have been investigated [71]. As an example, the acoustic 518 response to an uncertain cavity depth revealed strong non-linearities. For a given critical cavity 519 depth, sudden mode switching of the first two dominant Rossiter modes and the associated dis-520 tinct frequencies has been identified (Fig 31 left). The resulting pressure spectrum provided the 521 stochastic noise production which included all dominant, unstable modes and can be interpreted 522 as the superimposition of two distinct feedback regimes (Fig 31 right). 523



Figure 31: Influence of an uncertain cavity depth D on aeroacoustic feedback. Response surface plotted as a Campbell diagram (left). Stochastic pressure spectrum with expectation and variance (right).

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527 7.5. Simulating Tonal Fan Noise of an Aircraft in Flight

To ensure compliance with noise regulations, expensive fly-over tests are needed. No numer-528 ical alternative currently exists. Yet an accurate virtual fly-over would revolutionize the design 529 process of future aircraft as it can help to assess the most relevant noise sources at an early de-530 sign stage. As a first step towards enabling such a virtual fly-over, Mößner et al. [72] developed 531 a method capable of studying tonal rotor-stator-interaction noise from its generation in the fan 532 stage to its propagation to observer positions at ground level. Solving this problem with a single, 533 high-fidelity method is hardly realizable, particularly in terms of computation costs. Instead, 534 a computational chain consisting of multiple high-fidelity methods was established. The entire 535 task was split into smaller subtasks that can be handled by specialized tools with the aim of 536 performing each subtask as accurately and efficiently as possible. Different subtasks include the 537 fan noise generation, the propagation in the bypass and inlet ducts and the shielding and scat-538 tering effects due to the engines installation. Special care was taken to validate the accuracy of 539 the interfaces between the tools. To ensure that the entire computational chain delivers plausi-540 ble results, the results were compared to another simulation [73] using an established technique 541 for the case of an isolated engine and a good agreement was found. To prove the new methods 542 capability of predicting the tonal fan noise of an installed engine, the technique was applied to 543 a V2527 engine mounted underneath the fully equipped wing of an A320 aircraft in approach 544 conditions (shown in Fig 32). In Fig 33, the acoustic footprint on the ground is shown for the 545 isolated and installed engine cases. For the installed engine, scattering effects cause a complex 546 interference pattern. The overall magnitude of sound pressure level and general directivity of the 547 installed and isolated engine cases is, however, comparable for the investigated configuration. In 548 summary, the efficiency of the method as well its capability for computing complex scattering 549 effects was demonstrated. In future investigations, it is essential to incrementally increase the 550 complexity of the simulation to pinpoint the most relevant noise mechanisms of fly-over tests. 551



Figure 32: Sound pressure of the isolated (left) and installed (right) engine cases



Figure 33: Acoustic footprint of the isolated (left) and installed (right) engine configurations

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555 7.6. Enhanced HR-CLEAN-SC for resolving multiple closely-spaced sound sources

Enhancement of spatial resolution in acoustic imaging has been obtained by using an opti-556 mized acoustic array together with the Enhanced high-resolution (EHR) CLEAN-SC algorithm 557 [74]. The EHR-CLEAN-SC algorithm is based on the well-known CLEAN-SC algorithm [75] 558 that provides clean source maps in which sidelobes that are spatially coherent to the sources 559 are eradicated. Still, the resolution of CLEAN-SC is limited by the Rayleigh criterion. The 560 HR-CLEAN-SC algorithm [76] surpasses this limit, by explicitly accounting for the presence 561 of closely-located sources. To find the locations of these sources, the source markers are re-562 located away from the peak in the source map, to a location where the combined influence of 563 the other sound sources is minimal. The freedom of the source marker relocation is limited by 564 the sidelobe level. A first step to enhance the HR-CLEAN-SC performance is to ensure low 565 sidelobe levels by optimizing the array design. Secondly, the source marker relocation is done 566 such that it exploits the low-sidelobe design of the acoustic array. It was demonstrated that the 567 resulting EHR-CLEAN-SC algorithm could resolve four closely-spaced sound sources down to 568 more than half the frequency set by the Rayleigh criterion, using both synthetic and experimental 569

data [74]. An example is shown in Fig. 34 presenting the source maps of four closely-spaced 570 synthetic incoherent sound sources and using the standard Underbrink array. In subplots a to d, 571 the results are shown for conventional frequency-domain beamforming (CFDBF), CLEAN-SC, 572 HR-CLEAN-SC, and EHR-CLEAN-SC. Subplot e shows the results when the optimized array 573 is used together with the EHR-CLEAN-SC algorithm. The maps are shown at a frequency of 574 1.8 kHz, while, according to the Rayleigh criterion, the sources are expected to be resolved only 575 above 4.2 kHz. In practice, the EHR-CLEAN-SC algorithm is recommended for examining 576 closely-spaced aeroacoustic sound sources such as landing gear noise [77]. 577



Figure 34: Source maps showing the sound pressure level relative to the maximum sound pressure level (SPL-SPLmax) of four synthesized sound sources with 10 cm separation produced by using the Underbrink array and (a) CFDBF, (b) CLEAN-SC, (c) HR-CLEAN-SC, and (d) EHR-CLEAN-SC, compared with the same source setting resolved by EHR-CLEAN-SC with the optimized acoustic array (e) at 1.8 kHz. (The sources are at the intersections of the dashed lines.

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⁵⁸² 7.7. Statistical Inference Method for Liner Impedance Eduction with a Shear Grazing Flow

⁵⁸³ Understanding the effects of a complex flow on the acoustical response of nacelle liners is of ⁵⁸⁴ prime importance for current nacelle liner design. The acoustical response of a liner is char-⁵⁸⁵ acterized by its impedance ζ , whose measurement, in the presence of a grazing flow, can be ⁵⁸⁶ achieved through indirect eduction methods. These methods consist in matching an experimen-⁵⁸⁷ tal observation to a numerical simulation, via an optimization procedure. In practice, either the ⁵⁸⁸ pressure field is measured on the wall opposite the liner [78], or the velocity field is observed

above the liner via a Laser Doppler Velocimetry (LDV) measurement [79], see Fig. 35. A set 589 of equations (convected Helmholtz [78], linearized Euler [79]) is then chosen and solved numer-590 ically. The "numerical" pressure (or velocity) is then compared to its experimental counterpart 591 until a convergence is reached. One of the main concerns regarding this strategy is the valid-592 ity of the obtained impedance value, relative to the presence of different uncertainties. To take 593 into account uncertainties of the measurements or the numerical model, the eduction is recast 594 into a statistical inference problem. Using Bayes theorem, the posterior probability density of 595 the impedance is obtained, thus representing the information one has on this quantity, after hav-596 597 ing observed new experimental data [80]. This approach allows taking into account different sources of uncertainties, available prior knowledge, and to yield estimators on the impedance 598 that are more informative than the single impedance value returned by a classical deterministic 599 approach. The statistical eduction process has been successfully validated on NASA benchmark 600 data (from [78]). The results are shown in Fig. 36, for material CT57 (ceramic tubular material 601 of 57% porosity), at Mach 0.255. 602



Figure 35: Schematics of an aero-acoustic bench for liner impedance eduction, showing both the microphone measurement locations and the LDV window.



Figure 36: Left: probability density function of the impedance at f = 1000 Hz and Mach = 0.255. Right: comparison between NASA deterministic eduction method (markers) and Bayesian inference results (error bars), at Mach = 0.255

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7.8. Analysis and discretization of time-domain impedance boundary conditions in aeroacous tics

Improving the reliability of computational aeroacoustics (CAA) is one of the key drivers to 608 achieve the noise reduction levels targeted by international regulations. To reduce the noise emit-609 ted by an aircraft, one practical solution consists in mounting passive sound absorbing materials, 610 commonly known as acoustical liners. Practical computations of sound absorption are typically 611 done by abstracting the geometrical features of the material using an impedance boundary condi-612 tion, which in case of time-domain CAA simulations is called a TDIBC. The TDIBC used in the 613 numerical computation must be tailored to the absorbing material considered. [81] has shown 614 that the TDIBC can be derived from a mathematical study of the absorbing material, while being 615 shaped under an expression very close to an improved broadband multipole model. This fea-616 ture contrasts with the existing purely empirical one-size-fits all approach (consisting in using 617 a single numerical model postulated a priori), which can lead to computational difficulties for 618 adjusting the fit. The analysis carried out has delivered tailored TDIBCs for a wide range of 619 materials, which covers perforates, semi-infinite ground layers, as well as cavities filled with a 620 porous medium. A computationally-efficient way of performing the time-domain computation 621 has also been laid out in [82]. It relies on using transport equations and ordinary differential 622 equations, and is also a consequence of the mathematical analysis used for tailoring the TDIBC. 623 Moreover, a practical problem encountered in numerical computations is that some materials can 624 625 impose a stringent reduction in time step, leading to a costly simulation. The analysis presented in [82] has highlighted a way of canceling this time step reduction, i.e. of ensuring that the IBC 626 has a neutral impact on the simulation time step (see Fig. 37. This is done using a formulation 627 based on the reflection coefficient instead of the impedance or admittance. 628



Figure 37: Maximum allowable CourantFriedrichsLewy (CFL) number against SPL, in an impedance tube configuration. Hard wall (black), non-linear TDIBC with a formulation based on the reflecton coefficient (red), non-linear TDIBC with a formulation based on the impedance (blue). The dB levels of the incident wave are arbitrary.

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⁶³² 7.9. Improved Generalized Inverse Beamforming for Airframe Noise Applications

Thanks to their ability to deal with distributed and coherent acoustic sources, inverse beamforming methods have grown in popularity amongst the aeroacoustic community in the last few decades. An improved version of the Generalized Inverse Beamforming (GIBF) [83] has been developed at von Karman Institute for Fluid Dynamics (VKI) with the objective of ensuring an

accurate source localization and a robust source strength reconstruction for airframe noise appli-637 cations. Specifically, a method based on the Quasi-optimality criterion for the determination of 638 the optimal regularization parameters at each iteration of the algorithm has been implemented. 639 The validation of the technique has been carried out by applying the improved GIBF to an ex-640 perimental benchmark dataset labelled as NASA2. The test case, Fig. 38, refers to the analysis 641 of a small-scale open-jet facility, the NASA Langley Quiet Flow Facility (QFF), for the char-642 acterization of a NACA 63-215 Mod-B full-span airfoil self-noise. The study comprehends the 643 qualitative evaluation of the noise source distribution maps for several one-third octave frequency 644 bands and the quantitative estimation of the integrated one-third octave band spectra of the model 645 leading edge and trailing edge regions. All the maps and the spectra have been compared with 646 the ones obtained with other microphone phased array data processing techniques commonly 647 used in aeroacoustic applications [84]. Results show that, with a proper handling of the regular-648 ization strategy, GIBF can accurately resolve distributed acoustic noise sources. The sound maps 649 present improvements in terms of readability and reconstruction of the distributed nature of the 650 source, whereas the integrated levels are in close agreement with the ones predicted by the other 651 advanced methods Fig. 38. 652



Figure 38: Setup for the Leading Edge/Trailing Edge measurements of the NACA 63-215 Mod-B full-span airfoil in NASA Langley QFF. The airfoil is installed in a clean configuration at its zero-lift angle of attack (-1.2). The coordinate system origin is the center of the nozzle exit plane. Credits: Hutcheson and Brooks



Figure 39: Integrated leading edge and trailing edge one-third octave band spectra per-foot-span computed with various microphone phased array data processing techniques and GIBF noise source distribution maps referred to different one-third octave band frequencies. Credits: Christopher Bahr.

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7.10. Velocity-Potential Boundary-Field Integral Formulation for Sound Scattered by Moving Bodies

A novel boundary-field integral formulation suitable for the prediction of noise scattered by 659 moving bodies has been developed and validated in Ref. [85] in the framework of potential 660 subsonic potential flows. It allows for the appraisal of the role of nonlinear terms in the acous-661 tic scattering computations for those configurations where the nonuniform mean-flow past the 662 scattering body is not negligible. Such an issue is not trivial because it is proven that, starting 663 from the same flow modeling assumptions, linear formulations based on the wave equation for 664 the velocity potential or on the Lighthill equation and the Ffowcs Williams and Hawkings equa-665 tion for the pressure disturbance, provide different predictions when the scatterer is not at rest. 666 Hence, discrepancies reside in the different influence of the neglected nonlinear terms. The new 667 velocity potential-based approach is developed by extracting the first-order contributions from 668 the nonlinear terms. This yields a linearized boundary-field, frequency-domain formulation for 669 the scattered potential, that extends the standard linear boundary integral approach. The influ-670 ence of the additional field contributions is examined for different scatterer velocities, with the 671 aim of assessing the domain of validity of the fully linear formulation and the rate of grow of the 672 field contributions with increase of velocity. Specifically, the numerical investigation concerns 673 the noise scattered by a moving, non-lifting wing, when impinged by an acoustic disturbance 674 generated by a co-moving point source. 675

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679 8. Miscellaneous topics

680 8.1. Vehicle Cabin Noise

An important part of the noise inside vehicle cabins is emitted from window vibration. The 681 vibration is excited both hydrodynamically (due to exterior flow impingement on windows) and 682 acoustically (due to exterior flow-induced noise). The flows induced by side-view mirrors up-683 stream of the windows can significantly contribute to the excitation. As a simplification of a mir-684 ror, a hemisphere embedded in free stream was investigated using large eddy simulation (LES) 685 [86]. The wake was found to contain predominant exterior noise sources. Furthermore, wake 686 impingement was explored by placing a quarter-spherocylinder blunt body (termed the generic 687 side-view mirror) on a plate (Fig. 40) in a study on cavity interior noise using LES coupled 688 with a finite element method [87]. The analysis of wavenumber-frequency spectra addressed the 689 inhomogeneous feature of surface pressure fluctuations, of which the hydrodynamic component 690 has bent spectral energy ridges due to the inhomogeneous mean convection. The flow inhomo-691 geneity, however, has less influence on the noise magnitude distribution at natural frequencies, 692 as compared to the mode shapes of the window and cavity (Fig. 41). In addition, the efficiencies 693 of the hydrodynamic and acoustic components in the interior noise generation were quantified. 694 Since the quality of cabin noise prediction is dependent on the accuracy of the inputs to the 695 prediction (surface pressure fluctuations), a study on CFD methods for exterior flows and noise 696 was motivated regarding compressibility, turbulence modelling including improved delayed de-697 tached eddy simulation (IDDES) and LES, and grid topology [88]. The compressible IDDES was 698 down-selected based on its comparatively better performance. This method was then applied to 699 simulate real truck side-view mirrors, which are mounted on a simplified truck body [89]. It was 700 identified that intensive surface pressure fluctuations on the window are mainly caused by the 701 impingement of the free shear layers that initiate from the mirrors and A-pillar. 702



Figure 40: The configuration with streamlines of the time-averaged velocity. The streamlines past the mirror upper edge are colored in blue, and those past the side edges colored in red.



Figure 41: Contours of the interior noise magnitudes at 100Hz, 500Hz, and 1000Hz. From left to right, the red lines show the window mode shapes at 101.6Hz, 503Hz, and 998Hz the blue lines show the cavity mode shapes at 106.3Hz, 501.5Hz, and 1000.4Hz. The solid and dashed line patterns represent the normalized mode shape levels of 0.1 and -0.1, respectively.

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⁷⁰⁶ 8.2. Assessing the stochastic error of in-duct multi-microphone measurements

In-duct multi-microphone measurements are used to determine the acoustic properties of com-707 ponents such as acoustic liners. This can involve wave decomposition and determination of scat-708 tering matrices. To be able to compare measured results with model predictions, the quality 709 of the measurements have to be known. Uncertainty analyses are invaluable to assess and im-710 prove the quality of measurement results in terms of accuracy and precision. Linear analyses are 711 widespread, computationally fast and give information of the contribution of each error source to 712 the overall measurement uncertainty, however they can not be applied in every situation. The pur-713 pose of this study was to determine if linear methods can be used to assess the quality of acoustic 714 scattering matrices. A linear uncertainty analysis was applied to acoustic scattering matrix mea-715 surements and the results were compared against Monte-Carlo simulations. It was shown that 716 a linear uncertainty analysis, applied to the wave decomposition method, gives correct results 717 for plane waves when three conditions are satisfied. An example of a result, including a 95% 718 confidence interval, for the reflection coefficient of a rigid wall duct termination can be seen in 719 Fig 42. When higher order modes are present, the number of conditions that have to be simulta-720 neously satisfied increases with the number of cut-on higher order modes and it is better to resort 721 to a different method. The method was based on matrix perturbation theory, and gives qualitative 722 information in the form of partial condition numbers and the implementation is straightforward. 723 Using the alternative method, the measurements of higher order modes were analyzed and the 724 observed difference in the measured reflection coefficients for different excitation conditions was 725 explained by the disparity in modal amplitude. 726



Figure 42: Measured reflection coefficient of a rigid wall with 95% confidence interval. Left absolute value, right phase.

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729 8.3. Nonlinear Asymptotic Impedance Model for a Helmholtz Resonator of Finite Depth

In order to model the impedance of an acoustic liner composed of an array of Helmholtz resonators, a weakly nonlinear theory is developed for the resonance regime of a finite-length Helmholtz resonator, based on the acoustics of an organ pipe connected to the external excitation field via an acoustically small neck. The flow through the neck includes linear viscous friction and nonlinear dissipation due to flow separation and vortex shedding. This paper extends and refines the previous analysis [90], which considered an acoustically compact cavity.

The weakly nonlinear model allows a solution, asymptotic for small, but also moderate, excitation amplitudes. This enables analytically obtaining an expression for the impedance that includes nonlinear effects for frequencies close to the fundamental resonance frequency.

Considering the small number of modelling assumptions, the obtained results compare very
 well with experimental data by Motsinger & Kraft [91] in the linear and nonlinear impedance
 regimes. See Figure 43



Figure 43: Comparison of impedance resistance $\Re(Z)/\rho_0 c_0$, as given by new theory (solid lines), with measurements (squares) and predictions (dash-dotted lines) by Motsinger & Kraft in [91]

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745 8.4. Analytical prediction of limit-cycle oscillations amplitude in solid rocket motors

⁷⁴⁶ In large Solid Rocket Motors (SRMs), vortex-driven indirect sound leads to the establish-⁷⁴⁷ ment of a feedback loop resulting in self-sustained limit-cycle pressure pulsations [92, 93, 94]. ⁷⁴⁸ Paramount to this mechanism is the interaction of vortices, created near a geometric feature of ⁷⁴⁹ the combustion chamber, with the nozzle as they exit [95]. For vortex-driven self-sustained pres-⁷⁵⁰ sure pulsations, the presence of a cavity around the choked nozzle inlet has been demonstrated ⁷⁵¹ to have a major influence. Indeed, cold-gas experiments of a scale model of the Ariane 5 SRM

have shown that the limit-cycle amplitude of vortex- driven self-sustained pressure pulsations 752 are proportional to the nozzle cavity volume [92]. Hirschberg et al. [95] have used dedicated 753 vortex-nozzle interaction simulations, based on a frictionless compressible model proposed by 754 Hulshoff et al. [96], to develop a new scaling law for this indirect sound source. Hirschberg et al. 755 identified key parameters, viz., the nozzle inlet Mach number, the vortex circulation and the dy-756 namic pressure upstream from the nozzle [95]. Using an energy balance approach, Hirschberg et 757 al. [94] formulated an analytical model which predicts, within an order of magnitude, pulsation 758 amplitudes observed in cold gas-scale experiments of Ariane 5. Both this analytical model and 759 the numerical study of vortex-nozzle interaction, confirmed the importance of the nozzle cavity 760 volume. 761

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765 8.5. Light Electrospun Polyvinylpyrrolidone Blankets

Traditional sound absorption materials (foams, fibres, membranes, etc..) have good noise re-766 duction abilities at high frequency range, but exhibit insufficient sound absorption properties in 767 the low and medium frequency range in which human sensitivity to noise is fairly high. There-768 fore, materials with excellent noise reduction properties in the low and medium frequency range 769 are highly desirable for acoustical purposes. Polymeric soundproofing materials have been fabri-770 cated by electrospinning polyvinylpyrrolidone (PVP) [97]. The mats were produced in the form 771 of thin disks of 10 cm in diameter with a fibre diameter of (1.6 ± 0.5) or $(2.8 \pm 0.5) \mu m$. The 772 sound absorption coefficients were measured using an impedance tube instrument. For a given 773 set of disks (from a minimum of 6) the sound absorption coefficient changed with the frequency 774 (in the range 200-1600 Hz) following a bell shape curve with a maximum (where the coefficient 775 is greater than 0.9) that shifts to lower frequencies with an increasing number of piled disks 776 and with greater fibre diameter (Fig. 44). The acoustic behaviour can be continuously tuned by 777 changing the mass of the blanket (number of plies). 778



Figure 44: Sound absorption coefficient as a function of frequency for various β disk piles. Curves a, b, c, d, e and f refer, respectively, to samples β 1, β 1-4, β 1-6, β 1-10, β 1-17 and β 1-22, (β i-j means the pile made of all disks from the i-th to j-th

Moreover, in view to improve flame retardancy that often, because of very severe regulations 779 (as in aerospace engineering), prevents the applicability of materials, the addition of graphene 780 in the PVP blanket has been considered [97, 98] and the sound absorption coefficient has been 781 evaluated for different concentrations [[99]]. Results, reported in Fig. 45 for a PVP blanket 782 (mass of about 7.5 \pm 0.5 g), reveal that the addition of graphene does not lower the very high 783 sound absorption coefficient value but it affects, in a non-monotonous manner, the bell shaped 784 curves versus frequency becoming sharper and moving to higher frequency at the lower graphene 785 addition. The opposite is observed when the graphene content is further increased. 786



Figure 45: Comparison of sound absorption coefficient as a function of frequency of PVP blankets without and with the addition of graphene of different concentrations

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