A NUMERICAL AND EXPERIMENTAL TEST-BED FOR LOW-SPEED FANS

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SUMMARY

An extensive experimental and numerical data base provides detailed information on some transition and noise mechanisms encountered in the low-Reynolds number flows of low-speed axial fans for the first time. Two different similarly-instrumented mock-ups built from the same industrial Controlled-Diffusion airfoil have allowed the first consistent comparison of wall-pressure and near-field velocity statistics on the same geometry with and without rotation in perfect similitude of Mach and Reynolds numbers. The experimental and numerical results on the stationary airfoil constitute the largest unique aeroacoustic data set for airfoil trailing-edge noise characterization including installation effects. A similar experimental aeroacoustic data base has been built on the Rotating Controlled-Diffusion Blade in the MSU-AFRD test facility for different fan configurations, rotational speeds and flow rates. This yields a unique test-bed for fan code validation. The comparisons between the stationary and rotating airfoils suggest that the wall pressure statistics are hardly influenced by rotation in the trailing-edge region, and that the differences in the velocity statistics in the near-wake are a more energetic wake with smaller velocity deficits and diffusion, and far-less uniform inviscid region in the rotating case.

INTRODUCTION

The present study focuses on an experimental and numerical data base for low-speed axial fans that has been built in the course of the Ultra High-Efficiency Quiet (UHEQ) Fans Consortium. The latter gathers three universities (Michigan State University, University of Notre Dame and Université de Sherbrooke) and six companies (fan manufacturers and a software developer), and has three main missions: research, engineering and technological support, and advanced degree support (training of highly qualified people). The main objective is therefore to establish focused and funded research projects that provide value to client members through the duration of a research thesis. The collective wisdom and insights, expressed in the annual Consortium meetings and other interactions, is then used to guide Consortium activities to provide maximum benefit to both the members and the university participants. Finally the Consortium provides well documented and accurate data that can be used to validate computational results, and reveal mechanistic bases for observed phenomena and feed analytical models that can later be implemented at the design stage.

The Consortium started from the fully documented and quite extensive experimental data sets collected in the course of Neal's PhD dissertation at Michigan State University (MSU) [1], and the already existing numerical and experimental data base on a Controlled-Diffusion (CD) airfoil at low Reynolds number based on the chord length (Re_c about 10^5), representative of the flow conditions encountered in most low-speed axial fans used in many ventilation applications. The latter involved several series of experiments run in the anechoic wind tunnels at Ecole Centrale de Lyon (ECL) [2, 3, 4, 5], and many Large Eddy Simulations (LES) with both research and commercial codes [6, 7, 8, 9, 10, 11, 12, 13, 14]. Collectively this provides the most extensive data base for low Reynolds-number airfoil aerodynamics and aeroacoustics in a quiet anechoic open-jet wind tunnel. The same airfoil was then used as the base for the design of a Rotating Controlled-Diffusion Blade (RCDB) [15]. Modulable blades and hub could then be used to yield fans from 2 to 9 blades. In Neal's work only the 3-blade configuration was considered at a single flow condition from an aerodynamic point of view [1]. Since then, several fan configurations have been considered and a full range of operating conditions have been tested. Moreover additional acoustic measurements have been made to characterize some of these fan and flow conditions.

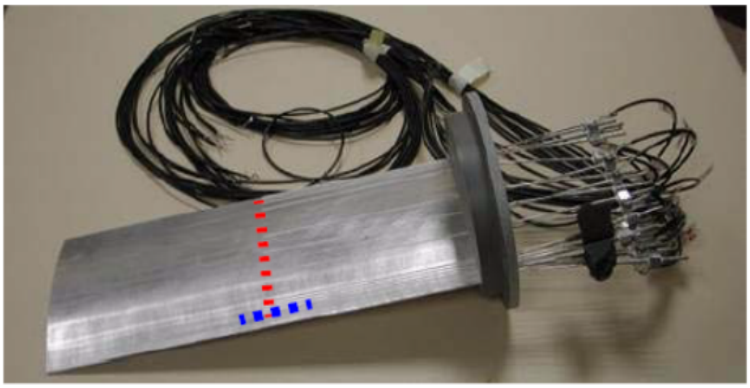
The present work first summarizes the methodology that has been followed by the Consortium. In this first section the tested configurations, the experimental facilities and measurement devices that have been used are then presented. Some special attention is put on the design of the modular RCDB fans and its close relationship with the stationary CD airfoil, which makes it a unique configuration. The numerical approaches and the simulated configurations that have been considered in parallel are also developed. In the following section, the main results are summarized on both the stationary and rotating mock-ups. A systematic comparison between the stationnary and rotating CD profiles is provided on both mean flow and unsteady flow statistics. Some first validations of the numerical simulations are also shown. Some preliminary conclusions are finally drawn.

METHODOLOGY

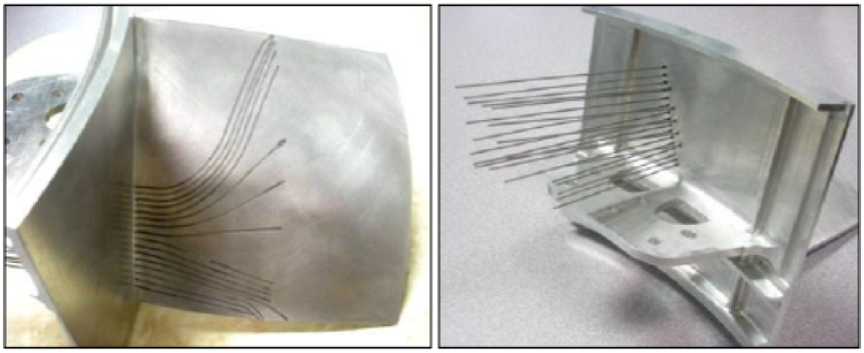
Low-speed axial fans are characterized by relatively low Reynolds-number flows that will involve transition to turbulence, partially or over most of the blade span. This transition can occur naturally through instabilities growing in the blade boundary layer, or triggered by either inflow turbulence or flow separation on the blade. In the former regime, Tollmien-Schlichting waves can yield a whistling noise characterized by a broadband hump with possibly several tones on top of it, and its harmonics. In the latter regime, the flow recirculation can trigger intense wall-pressure fluctuations near the reattachment point, and consequently a secondary noise source. Shear-layer instabilities in this recirculation bubble can also yield tonal components. Moreover, low-speed axial fans generally operate in a very disturbed upstream and downstream environment that will add many additional tonal and broadband noise sources. Consequently the noise signature of low-speed fans is the result of complex flow phenomena, and generally involve both tonal and broadband noise with similar levels.

In order to decipher several of these transitional phenomena and noise sources, two types of experimental and numerical set-ups have been considered within the Consortium: a more canonical set-up that studies low-speed aerodynamics and acoustics around airfoils and a dedicated fan set-up that allows checking how specifically rotation or the inherent additional secondary flow-features of a rotating machine affects the unsteady flow features triggering transition and noise radiation. The preliminary measurements can then validate detailed flow simulations, which in turn require additional detailed experimental verification. As shown below, unique features have been implemented in the tested mock-ups to have as consistent flow features as possible between the stationary and rotating configurations. Similar instrumentations and measurements are performed on both rigs to again yield consistent relevant flow statistics. Ultimately both flow and noise control can be implemented to improve both efficiency and noise emission of such rotating machines.

Experimental set-ups and data collection



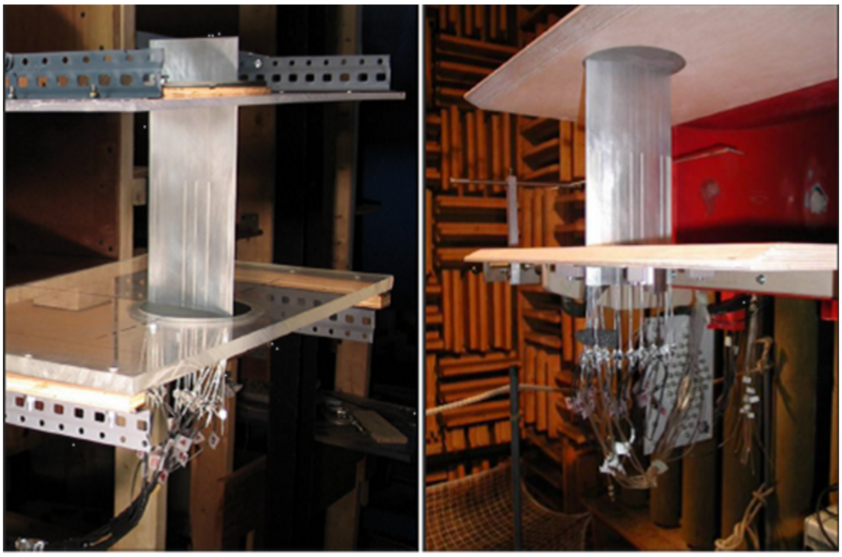
(a) CD Airfoil with RMP probes (pressure taps at mid-span region).



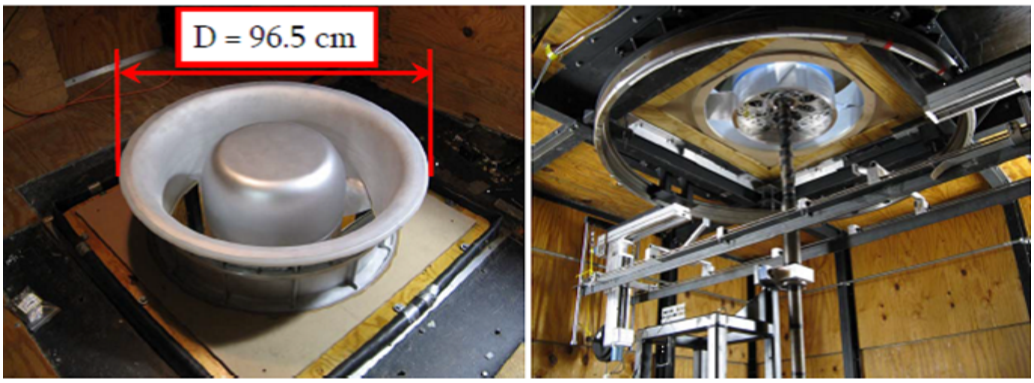
(b) Pressure taps embedded into RCDB.

Figure 1: Some of the instrumentation of the Consortium mock-ups: steady and unsteady pressure sensors.

The Consortium has focused around two specific mock-ups that are representative of modern low-speed fans [16]. The stationary mock-up involves an extruded industrial cambered airfoil with moldable thick leading and trailing edges as shown in Fig. 1(a). It was specifically designed for automotive engine cooling applications to yield as little drag as possible by controlling the boundary-layer diffusion and growth on the airfoil suction side. The same methodology as for modern high-speed compressors was thus applied to yield a Controlled-Diffusion airfoil dedicated to low-speed fans. Its thickness was also kept low and very-slow varying for optimal plastic injection molding. This same CD airfoil has been used over the whole blade span for the RCDB fans to be able to compare for the first time the same geometry with the perfect flow similitude in Reynolds and Mach numbers. This was made possible by using a unique generalized radial equilibrium design procedure and code, that limited any radial flow [17]. To have a flexible rotating setup, the large hub assembly contains the instrumentation packages and the modular blades and spacers installed on the hub of the RCDB (Fig. 1(b)). The instrumentation is laid out in three different levels to include the in-board pressure sensors, the in-board anemometer, a pressure cavity and the hard-drive to store all the measured data (no rotating collector to limit noise). Another distinctive attribute of the RCDB measurements is the use of ``flying" hot-wires that are supported by the rotating shaft. A contoured inlet nozzle has also been designed to provide an inlet flat velocity profile. Both stationary and rotating mock-ups are equipped with the same maximum number of wall-pressure probes on a given profile (a radial cut for the RCDB fan), namely 21 on both pressure and suction sides including a spanwise network of 4 sensors at the trailing edge. Five instrumented blades provide such a network at five radial positions, which makes the RCDB fan a unique research tool. The pinholes on both mock-ups can be connected to either mean static-pressure sensors or remote microphone probes that are flush-mounted on the capillary tubes coming out of the mock-up foot (Fig. 1). Note that the clustering of sensors near the trailing edge allows collecting all the necessary information for testing the simplest broadband self noise models based on pressure statistics [18, 19], and confirming what was found by Rozenberg *et al.* [20, 21].



(a) The free jet configuration for the CD airfoil (left - MSU, right - ECL).

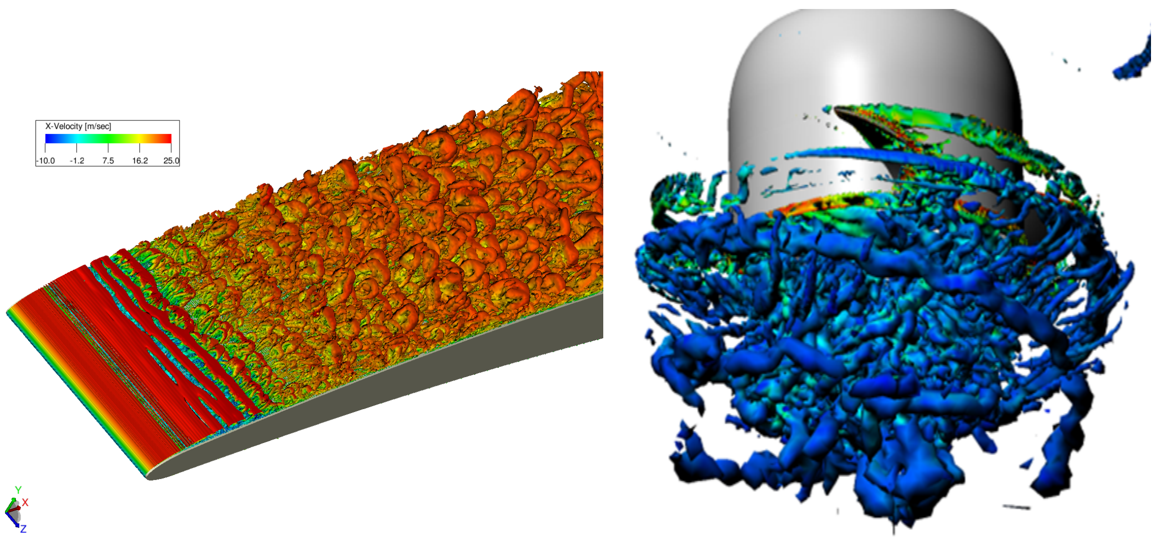


(b) RCDB mounted in MSU-AFRD (left - upstream view, right - downstream view).

Figure 2: Consortium mock-ups in test-facilities.

The CD airfoil has been tested in two different wind tunnels as shown in Fig. 2(a): the former MSU Engineering Laboratory Design tunnel whose open test section (61×61 cm^2) was contracted to achieve the same cross-sectional configuration as that used for the companion measurements at ECL anechoic tunnel to mimic the same confinement effect of the jet on the CD airfoil loading [2]. In the future, it will also be tested in the newly built anechoic wind tunnel at Sherbrooke. Collectively, the different measurements include for one particular flow condition: mean and fluctuating wall pressure at all sensor locations; mean and fluctuating velocity measurements in the suction-side boundary layer above all pressure sensors, in the near wake, in the far wake and across the full jet width, at the inlet, in the suction-side jet shear layers developing from the nozzle lips and on the boundaries of the limited domain used for most LES inside the jet potential core; the full Reynolds-stress tensor in the near wake (obtained with a specific double-X hot-wire probe); complete velocity fields near the trailing edge by both 2D and stereo Particle Imaging Velocimetry (PIV); far-field acoustic radiation maps providing the noise spectra all around the airfoil. The latter data has been gathered simultaneously with all the wall pressure data providing pressure coherence information. They also have been obtained for additional flow angles and velocities [4]. The modulable RCDB has only been tested in the Axial Fan R&D (AFRD) Facility at Michigan State University that has provided the parallel test data in rotation. Its unique use of the net moment-of-momentum flux to determine the mass flux of air through the fan plane accurately is fully described by Morris *et al.* [22]. The full setup is shown in Fig. 2(b), on the left showing the dedicated inlet nozzle and the RCDB fan from the top of the test-rig, on the right from inside the AFRD under the RCDB fan. The full set of traverses downstream of the fan has allowed measuring all velocity components (mean and rms) and the Reynolds stress tensor in the near wake. The ``flying" hot-wire has also produced velocity spectra. The on-board RMPs have yielded the wall-pressure data (mean pressure coefficients and spectra). The latest results involve acoustic measurements upstream of the RCDB fan as described below. Reynolds-Averaged Navier-Stokes (RANS) simulations have first been performed, then some unsteady Lattice Boltzmann Method (LBM) results have been obtained as explained in the next section.

Numerical simulations



(a) DNS of CD airfoil. (b) VLES of RCDB blade.

Figure 3: Instantanneous Λ_2 *contours in LBM simulations with Powerflow [23, 17].*

Initial simulations on the CD airfoil focused on steady RANS predictions first in free stream and then in the full wind tunnel with various turbulence models. It was shown that the flow around an airfoil in an open-jet wind tunnel differs significantly from that around an isolated airfoil in a uniform stream [2]. For instance, the jet shear layers (and consequently the jet width) had a similar effect as the solidity effect in a cascade. To account for this effect, a RANS simulation is first performed in a large computational domain which includes the airfoil, the nozzle and the jet. Velocities extracted from this RANS calculation are then used to provide boundary conditions for the incompressible LES, performed in a smaller domain embedded in the potential core of the jet. The final acoustic predictions are obtained by different acoustic analogies [11]. Several incompressible LES have been run since then on the same limited computational domain with several research codes and all major commercial codes [8, 10, 12, 24, 14]. More recently a Direct Numerical Simulation (DNS) has been performed on the airfoil for the reference case, using the Lattice Boltzmann Method (LBM) as implemented in the PowerFlow solver [25, 23]. This approach is naturally transient and compressible, providing a direct insight into hydrodynamics mechanisms responsible for the acoustic sources but also into acoustic propagation in the test-rig. Instead of studying macroscopic fluid quantities, the LBM tracks the time and space evolution on a lattice grid of a truncated particle distribution function. The particle distribution evolution is driven to the equilibrium by the so-called collision operator, approximated by the BGK model. The discrete Lattice-Boltzmann equations needs to be solved for a finite number of particle velocity. The discretization retained in Powerflow involves 19 discrete velocities for the third order truncation of the particle distribution function, which has been shown sufficient to recover the Navier-Stokes equations for a perfect gas at low Mach number in isothermal conditions [26, 27, 28]. In Powerflow, a single relaxation time is used, which is related to the dimensionless laminar kinematic viscosity [29]. In Fig. 3(a) the Λ_2-invariant contours of the DNS clearly show the thin recirculation bubble at the leading edge and the consequent transitional process with formation of hairpin vortices.

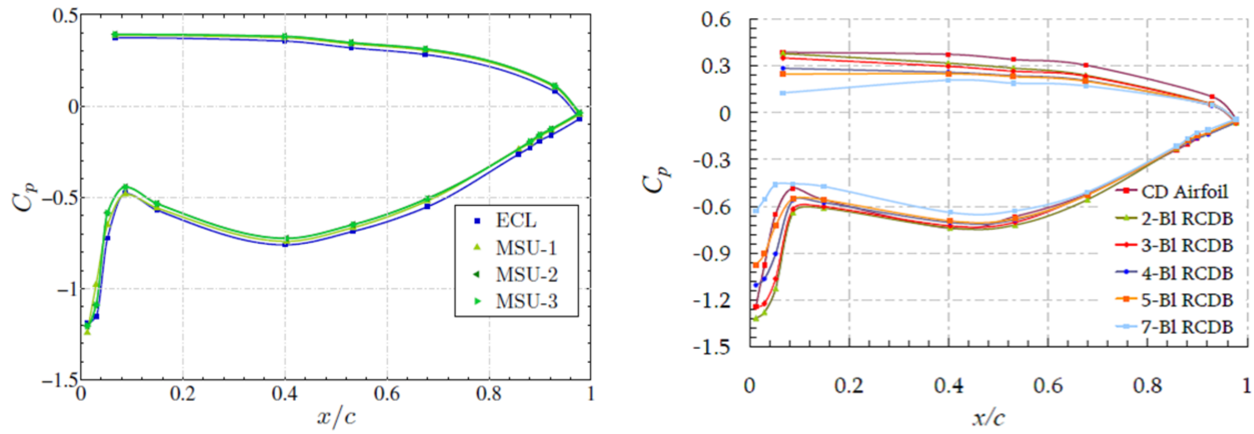
The first RCDB simulations were steady RANS simulations that allowed checking the blade pre-design [15]. The inlet nozzle provided the proper flat inlet profile with a minimum boundary-layer thickness. The expected radial equilibrium and minimum tip flow were also found. The effect of the blade number was also assessed. More recently unsteady simulations have been achieved with the LBM only, in a Very Large Eddy Simulation (VLES) mode. In the latter the relaxation time is replaced by an effective turbulent relaxation time that is derived from a systematic Renormalization Group procedure detailed in [30]. It captures the large structures in the anechoic room but also the small turbulent scales that develop along the blade and duct surfaces. Further details of the method and the particular extension developed for rotating machines can be found in Perot *et al.* [31]. With this method, the flow field was computed on the full AFRD test-rig, where the actual laboratory is replaced by a very large anechoic room (about 10^6 m^3) from which the air is ingested. The configuration included the precise geometry for the bellmouth and the hub. The study focused on the nominal 3-blade fan conditions at $\Omega = 467$ rpm. The finest grid resolution around the rotor is 0.5 mm yielding a total number of cells or voxels of about 30 millions. A total physical time of 2.5 s, corresponding to about twenty complete fan rotations, is simulated and is sufficient to obtain converged pressure and flow values inside the plenum. Excellent overall performances were predicted and detailed flow features as shown by the Λ_2-invariant contours in Fig. 3(b). Further details on these simulations can be found in Lallier-Daniels *et al.* [17].

RESULTS

In this section only sample results of the large experimental and numerical database are shown. More details on the recent experimental studies can be found in Foss *et al.* and the associated dissertations [1, 32, 33, 16, 34].

Aerodynamic results

The mean wall-pressure distributions, represented by the pressure coefficient C_p, on both the CD air-foil and the RCDB blade are first shown in Fig. 4. As expected Fig. 4(a) shows excellent repeatability and agreement with the previous ECL measurements [4]. The latest LES and DNS results have also been shown to match such a pressure distribution quite nicely. The plateau seen in the first 8% of the chord length is identified with the thin recirculation bubble. Fig. 4(b) features the same pressure distributions on several RCDB configurations with increasing number of blades. As expected the blade load increases with reduced solidity and identical suction-side profile is found with that of the CD airfoil for 3 blades, which justifies the initial focus on this particular configuration. Only the pressure side level is slightly shifted on the rotating blade. Recent measurements by Cawood have also shown that the wall-pressure spectra on most RMPs (except at the leading-edge where large variations are also seen on the CD airfoil [4]) are also similar between the CD airfoil and the 3-blade RCDB fan, suggesting that the wall pressure fluctuations are hardly or not affected by rotation especially near the trailing-edge where the trailing-edge noise sources are [32].

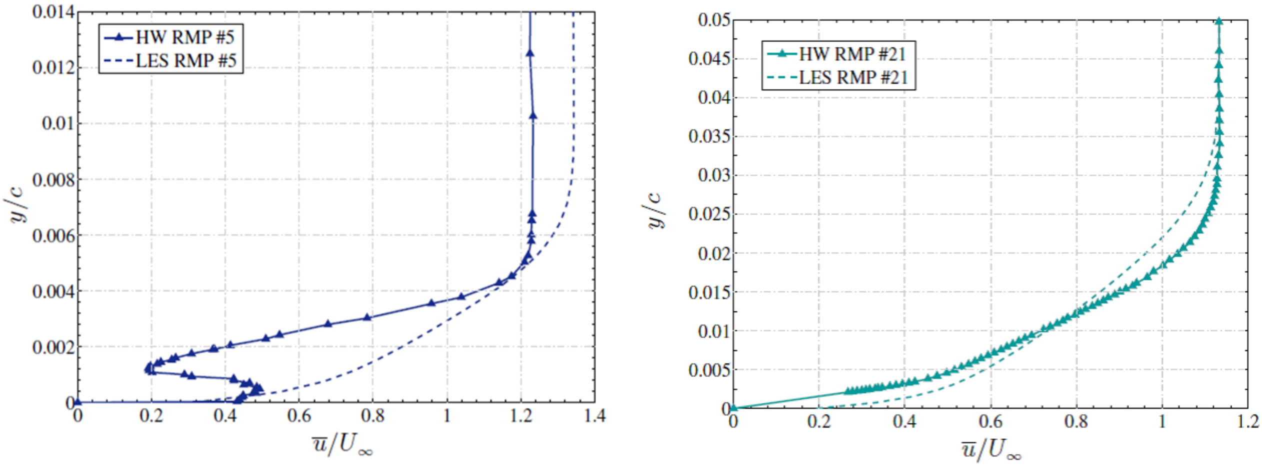


(a) CD Airfoil C_p data in the MSU and ECL wind tunnels. (b) Comparison of the C_p distributions for various RCDB configurations and the CD airfoil.

Figure 4: Mean wall-pressure distribution [1].

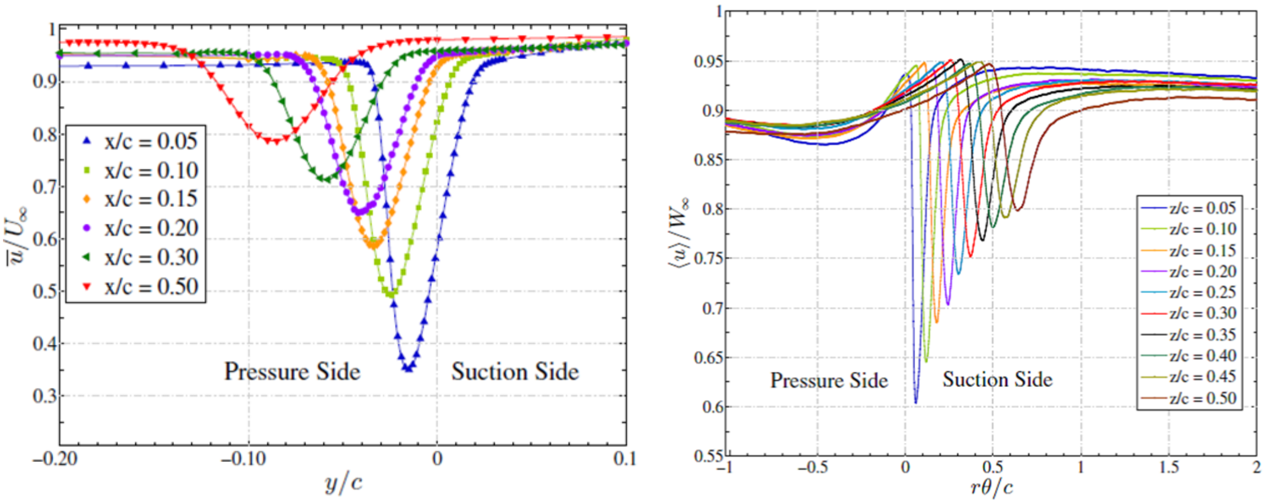
Boundary-layer velocity profiles above the RMPs have also been measured by single hot-wire on the stationary airfoil. Figs. 5(a) and (b) provide wall-normal velocity profiles near the leading and trailing edges of the airfoil respectively. The former suggests a reversal flow and provides an evidence of the extent of the laminar recirculation bubble at the leading edge. The latter exhibits an attached flow with a fully developed turbulent boundary layer. They are compared with the reference LES performed by Wang *et al.* on the limited computational domain embedded in the jet potential core [11]. Significant discrepancies are noticed particularly at the leading edge where the flow recirculation is underpredicted. Much better agreement has been found recently by Sanjose *et al.* in their DNS simulation [25, 23]. At the leading edge the reversal flow is captured and the trailing-edge velocity profile is fuller as in the experiment.

Cross-wire measurements have also been acquired in the near-wake region. Fig. 6(a) shows the mean wake evolution along the direction of the chord line of the CD airfoil, starting from its trailing edge. The expected diffusion of the wake is observed (smaller velocity deficit and broader wake downstream) and it is also apparent that the wake centerline is shifting to the airfoil pressure side because of the flow deflection induced by the cambered airfoil. Most LES and the DNS capture both the mean and rms profiles in the wake correctly [8, 25]. Similar behavior is also seen in the mean wake of the RCDB blade in Fig. 6(b). The same sharp asymmetric profile of the phase-averaged streamwise velocity is found behind the trailing edge. Yet, the diffusion of the wake seems much slower behind the rotating profile with smaller velocity deficits downstream, and larger variations are seen outside of the wake on the pressure side. The wake centerline is now shifting to the blade suction side because of the high blade stagger angle and the measurement was performed in the plane of rotation. Current LBM simulations are still too coarse and predict too wide wakes [17].



(a) RMP #5 (leading-edge location). (b) RMP #21 (trailing-edge location).

Figure 5: Hot-wire and LES boundary-layer mean velocity distribution for the CD airfoil [11].

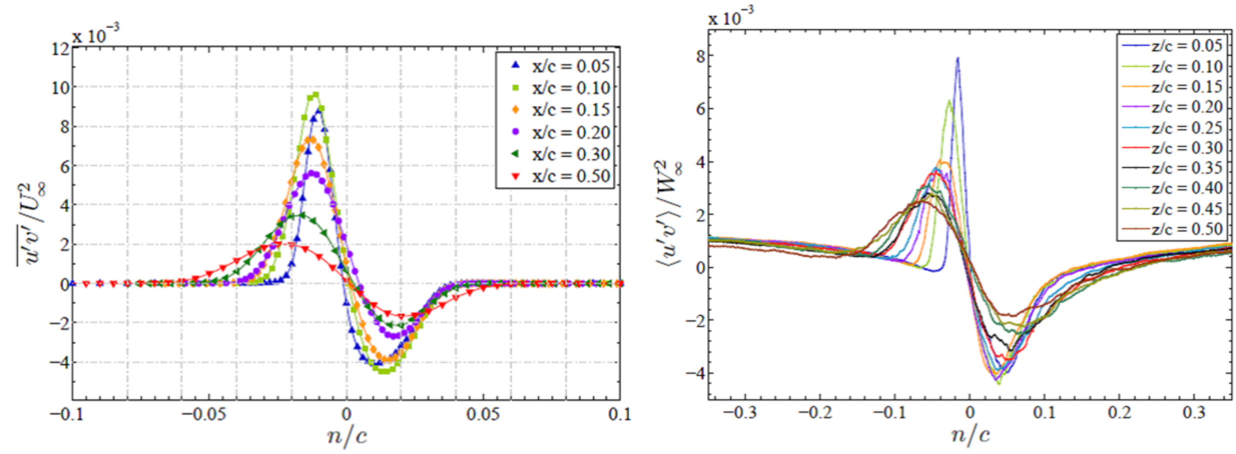


(a) CD airfoil data. (b) Phase-averaged data for a RCDB blade.

Figure 6: Mean streamwise wake-velocity profiles at multiple downstream locations [1].

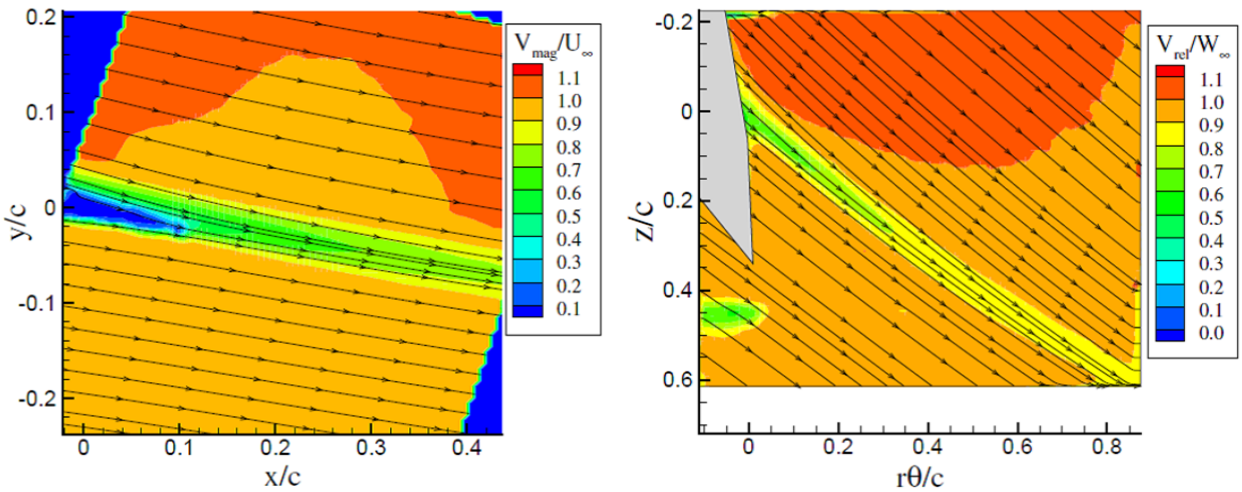
In the near-wake, the Reynolds shear stress tensor was also measured with a dedicated double-X hot-wire probe [1]. Figs. 7(a) and (b) display the crosswise term $\overline{u'v'}$ of the tensor using a shifted coordinate $n = y - y_c$ (y_c is the location of the minimum mean streamwise velocity $\bar{u}$) for the CD airfoil and the RCDB blade respectively. In both cases, this component is negative on the suction side and positive on the pressure side with similar amplitudes. Again a smaller wake diffusion and more variations outside of the wake are seen in the rotating case, which seems to be the two main modifications induced by rotation. No comparison have been made with simulations yet.

A final comparison between the two setups is provided by two-dimensional two-components (2D-2C) PIV observations where (u,v) velocity components were acquired in the near wake. Contours of velocity magnitude and streamlines are given in Figs. 8(a) and (b) for the CD airfoil and the RCDB blade respectively. Both plots show similar thin wakes and the CD airfoil measurement even the recirculation bubble behind the blunt trailing edge. The corresponding velocity deficits are consistent with those obtained by cross-wire measurements, and confirm the smaller velocity deficits seen on the rotating blade.



(a) CD airfoil data. (b) Phase-averaged data of a RCDB blade.

Figure 7: Reynolds shear stress distribution in the near wake [1].



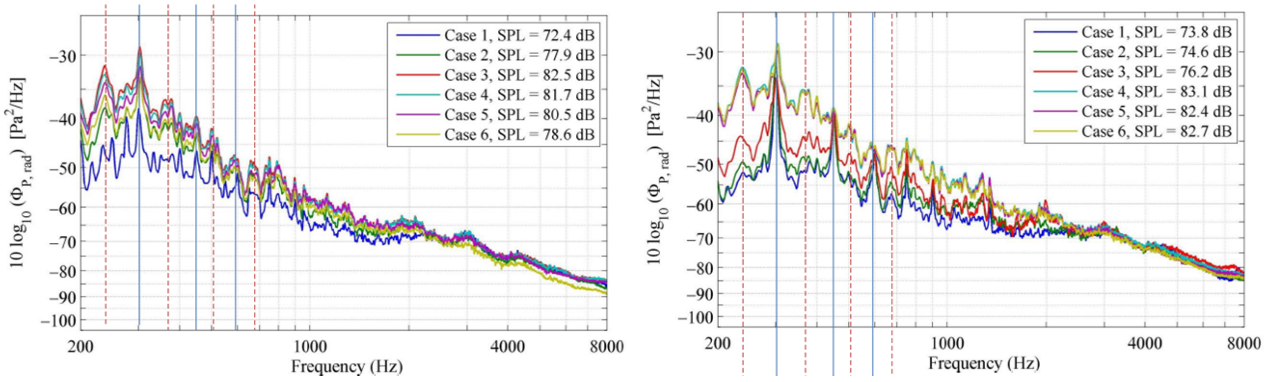
(a) CD airfoil data. (b) RCDB blade data in the relative velocity frame.

Figure 8: Wake normalized velocity magnitude close to the trailing edge from PIV measurements [1].

Acoustic results

Aeroacoustic characteristics of the RCDB blades configured as a 3 and a 9 blade fan have also been obtained. Six cases (flow rates) were identified for each fan configuration based on its performance curve, in order to cover situations with attached flow, slightly separated flow, a deeply separated flow and finally stall. These acoustic measurements were obtained with two Panasonic microphone arrays arranged at two different elevations above the mid-span of the blades. A beamforming technique was employed to properly measure the radiated acoustic pressure in a non-anechoic environment of the AFRD test-facility.

Figs. 9(a) and (b) show the far-field acoustic spectra for the six operating conditions for the 3-blade and 9-blade configurations respectively. As expected the overall noise level is increased as the flow rate is reduced with a significantly larger broadband noise for the lowest flow rates and a growth of subharmonic humps indicated as red dashed lines for both fans. Conversely at higher flow rates, the tonal content is dominant with a clear blade passing frequency and its harmonics indicated as solid blue lines (especially for the 9-blade case). The transition between the two regimes clearly marks



(a) 3-blade fan. (b) 9-blade fan.

Figure 9: RCDB fan far-field acoustic spectra at different operating conditions [34].

significant flow separations (observed in parallel hot-wire measurements in the wake and seen as a discontinuity in the performance curve) and a move towards stall, and consequently a jump in the overall noise. This transition is all the quicker as the solidity is low (the 3-blade configuration). It should also be emphasized that the low flow-rate spectra have very similar levels and shapes for both fans suggesting that in this mode the noise sources become independent of the number of blades.

CONCLUSIONS

In the course of the UHEQ Fans Consortium gathering three universities and six companies, a detailed experimental and numerical data base for low-speed axial fans has been built, which, for the first time, provides detailed information on some transition and noise mechanisms encountered in such low-Reynolds number flows. Two different consistent mock-ups have been built: an extruded two-dimensional stationary CD airfoil typical of modern industrial low-drag aerodynamic profiles, and a rotating blade (RCDB) made with the same CD profile with a proper radial equilibrium at the same flow condition as the stationary airfoil. These two mock-ups are equipped with the same wall pressure sensors (RMPs) at the same chordwise and spanwise locations. Similar hot-wire measurements have also been performed in the wake of the two mock-ups. This provides the first consistent comparison of the same geometry with and without rotation in perfect similitude of Mach and Reynolds numbers.

Several test campaigns have been performed on the stationary CD airfoil in four different open-jet wind tunnels. Consistent results have been obtained both on the wall-pressure and the near-field velocity statistics. Hot-wire velocity measurements include profiles of the boundary-layer, the near wake, the far wake, the nozzle exit, the suction-side nozzle shear layer and a closed-contour within the potential core corresponding to the restricted computational domain used in the parallel incompressible LES. Additional 2D-2C PIV measurements have been achieved in the near wake. Far-field acoustic pressure maps have also been collected. Overall this constitutes the largest unique data set for airfoil trailing-edge noise characterization (including installation effects). Consequently this configuration at this particular flow condition has been considered for code validation of several research codes and all commercial packages. Capturing the thin recirculation bubble at the leading edge correctly, has been found to be critical to yield the proper forced transition to turbulence and the consequent boundary-layer growth up to the trailing edge. Moreover, a nominally two-dimensional cambered airfoil has been shown to induce strong three-dimensional effects on an upstream two-dimensional flow.

Even though more limited because far more challenging, the experimental measurements on the RCDB blade performed in the MSU-AFRD test facility have already provided a unique wealth of information mostly for the 3-blade configuration: mean and fluctuating wall-pressure at midspan with the RMPs, detailed hot-wire velocity and Reynolds stress components in the near wake at midspan, and 2D-2C PIV measurements in the near wake at midspan. Full performance surveys and mean wall pressure measurements have been achieved for different fan configurations and rotational speeds. Similarly single-wire mean and fluctuation velocity maps have been collected in the near-wake for this large matrix of fan configurations and flow conditions. Finally acoustic measurements have also been collected for six flow rates covering all flow regimes of the 3-blade and 9-blade fans with two arrays of microphones and a beamforming de-convolution algorithm. The comparisons between the stationary and rotating airfoils have suggested that the wall pressure statistics are hardly influenced by rotation in the trailing-edge region, and that the differences in the velocity statistics in the near-wake are a more energetic rotating wake with smaller velocity deficits and wake diffusion, and far-less uniform inviscid region in the rotating case.

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REFERENCES

[1] D.R. Neal. *The effects of rotation on the flow field over a Controlled-Diffusion airfoil.* Phd thesis, Michigan State University, **2010**.

[2] S. Moreau, M. Henner, G. Iaccarino, M. Wang, and M. Roger. *Analysis of Flow Conditions in Freejet Experiments for Studying Airfoil Self-Noise*. AIAA J., 41(10):1895--1905, October **2003**.

[3] M. Roger and S. Moreau. *Broadband Self Noise from loaded fan blades*. AIAA J., 42(3):536--544, **2004**.

[4] S. Moreau and M. Roger. *Effect of Airfoil Aerodynamic Loading on Trailing-Edge Noise Sources*. AIAA J., 43(1):41--52, January **2005**.

[5] S. Moreau and M. Roger. *Back-scattering Correction and Further Extensions of Amiet's Trailing Edge Noise Model. Part 2: Applications*. J. Sound Vib., 323(2), **2009**.

[6] M. Wang, S. Moreau, G. Iaccarino, and M. Roger. *LES Prediction of Pressure Fluctuations on a Low Speed Airfoil*. In *Annual Research Briefs*. Centre for Turbulence Research, Stanford Univ./NASA Ames, **2004**.

[7] S. Moreau, G. Iaccarino, S. Kang, Y. Khalighi, and M. Wang. *Numerical Simulation of a Low Speed Fan Blade*. In *Proceedings of the Summer Program 2004*. Centre for Turbulence Research, Stanford Univ./NASA Ames, **2004**.

[8] S. Moreau, D. Neal, Y. Khalighi, M. Wang, and G. Iaccarino. *Validation of Unstructured-Mesh LES of the Trailing-Edge Flow and Noise of a Controlled-Diffusion Airfoil*. In *Proceedings of the Summer Program 2006*. Centre for Turbulence Research, Stanford Univ./NASA Ames, **2006**.

[9] J. Christophe and S. Moreau. *LES of the Trailing-Edge Flow and Noise of a Controlled-Diffusion Airfoil at High Angle of Attack*. In *Proceedings of the Summer Program 2008*. Centre for Turbulence Research, Stanford Univ./NASA Ames, **2008**.

[10] Y. Addad, R. Prosser, D. Laurence, S. Moreau, and F. Mendonca. *On the use of embedded meshes in the LES of external flows*. Flow, Turb. Comb., 80:393--403, **2008**.

[11] M. Wang, S. Moreau, and M. Roger. *LES Prediction of Wall-pressure Fluctuations and Noise of a Low-speed Airfoil*. International Journal of Aeroacoustics, 8(3):177--198, **2009**.

[12] J. Christophe, J. Anthoine, and S. Moreau. *Trailing Edge Noise of a Controlled-Diffusion Airfoil at Moderate and High Angle of Attack*. In *15th AIAA/CEAS Aeroacoustics Conference*, **2009**. AIAA-2009-3196.

[13] S. Moreau, M. Roger, and J. Christophe. *Flow Features and Self-Noise of Airfoils Near Stall or in Stall*. In *15th AIAA/CEAS Aeroacoustics Conference*, **2009**. AIAA-2009-3198.

[14] L. Corriveau, S. Moreau, M. Roger, and J. Christophe. *Experimental and Numerical Unsteady Acoustic Sources and Self-noise of a Katana Blade*. In *16th AIAA/CEAS Aeroacoustics Conference*, **2010**. AIAA-2010-3804.

[15] S. Moreau, G. Meauze, D. Lallier-Daniels, and Y. Mercadier. *Design of turbomachines by a novel full radial equilibrium method*. In *46th 3AF Symposium of Applied Aerodynamics: Aerodynamics of Rotating Bodies*, Orleans, France, March **2011**.

[16] J. Foss, S. C. Morris, S. Moreau, and W. Rockwood. *The Ultra-High Efficiency Quiet (UHEQ) fans consortium*. In *AMCA International Engineering Conference 2013*, San Antonio, Texas, June **2013**.

[17] D. Lallier-Daniels, S. Moreau, F. Perot, M-S. Kim, D. Neal, and J. Foss. *Experimental and numerical investigation of the flow generated by a 3-blade axial fan*. In *AMCA International Engineering Conference 2013*, San Antonio, Texas, June **2013**.

[18] R. K. Amiet. *Noise due to Turbulent Flow past a Trailing Edge*. J. Sound Vib., 47(3):387--393, **1976**.

[19] M. Roger and S. Moreau. *Back-scattering correction and further extensions of Amiet's trailing-edge noise model. Part 1: theory*. J. Sound Vib., 286(3):477--506, **2005**.

[20] Y. Rozenberg. *Modélisation analytique du bruit aérodynamique à large bande des machines tournantes : utilisation de calculs moyennés de mécanique des fluides.* PhD thesis, Ecole Centrale de Lyon, **2007**.

[21] Y. Rozenberg, G. Robert, and S. Moreau. *Spectral model accounting for pressure gradient and Reynolds effects for the prediction of trailing-edge noise using RANS simulations*. AIAA J., 50(10):2168--2179, **2012**.

[22] S. C. Morris, D.R. Neal, J. Foss, and G.L. Gould. *A Unique Air Flow Measurement Device*. Meas. Sci. Technol., 12(2):N9--N13, **2001**.

[23] M. Sanjosé and S. Moreau. *Direct numerical simulation of self-noise of an installed Control-Diffusion airfoil*. Can. Acoust., 39(3):177--197, **2011**.

[24] S. Kang, G. Iaccarino, F. Ham, and P. Moin. *Prediction of Wall-Pressure Fluctuation in Turbulent Flows with an Immersed Boundary Method*. J. Comput. Phys., 228:6753--6772, **2009**.

[25] M. Sanjosé, S. Moreau, M.S. Kim, and F. Pérot. *Direct Self-noise Simulation of the Installed Controlled Diffusion Airfoil*. In *17th AIAA/CEAS Aeroacoustics Conference*, **2011**. AIAA-2011-2716.

[26] U. Frisch, D. D'Humiéres, B. Hasslacher, P. Lallemend, Y. Pomeau, and J-P. Rivet. *Lattice gas hydrodynamics in two and three dimensions*. Complex Syst., 1:649--707, **1987**.

[27] S. Chen and G. D. Dooler. *Lattice Boltzmann method for fluid flows*. Ann. Rev. Fluid Mech., 30:329--364, **1998**.

[28] S. Marié, D. Ricot, and P. Sagaut. *Comparison between lattice Boltzmann method and Navier-Stokes high order schemes for computational aeroacoustics*. J. Comput. Phys., 228:1056--1070, **2009**.

[29] E. Vergnault, O. Malaspinas, and P. Sagaut. *A lattice Boltzmann method for nonlinear disturbances around an arbitrary base flow*. J. Comput. Phys., 231:8070--8082, **2012**.

[30] H. Chen, S. A. Orszag, I. Staroselsky, and S. Succi. *Expanded analogy between Boltzmann kinetic theory of fluids and turbulence*. J. Fluid Mech., 519:301--314, November **2004**.

[31] F. Pérot, M.-S. Kim, S. Moreau, M. Henner, and D. Neal. *Direct Aeroacoustics Prediction of a Low Speed Axial Fan*. In *16th AIAA/CEAS Aeroacoustics Conference*, Stockholm, Sweden, June 7--9 **2010**.

[32] A.F. Cawood. *Surface pressure measurements on a Rotating Controlled-Diffusion Blade.* Msc thesis, Michigan State University, **2012**.

[33] D. Hower. *Unsteady pressure fluctuations on the surface of a Controlled Diffusion airfoil.* Msc thesis, RWTH University, **2012**.

[34] B. Davoudi. *Aeroacoustic and wake measurements on a Rotating Controlled-Diffusion Blade.* Msc thesis, Michigan State University, **2014**.