INTEGRATED CFD-ACOUSTIC APPROACH TO THE SIMULATION OF TONAL AND BROADBAND NOISE GENERATED BY AXIAL AND CENTRIFUGAL FANS

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SUMMARY

An innovative computational approach for the simulation of noise generated by axial and centrifugal fans is presented, integrating mesh generation, CFD simulation and acoustic analysis. The simulation chain includes methods for the efficient analysis of tonal and broadband noise suitable in an industrial setting. The results obtained for two different axial fans and centrifugal fans indicate an accurate prediction of the tonal noise while a larger variability is obtained in the estimation of the broadband noise level depending on the propagation angle.

INTRODUCTION

Fan noise simulation requires the development and the application of CFD and CAA computational methods to accurately predict the noise emissions in operative conditions.

Dealing with “tonal noise” analysis of turbomachinery, traditional hybrid approaches based on URANS solutions [1] or alternative approaches like LBM [2], [3] require larger resources in terms of memory and computational time with respect to more efficient methods based on the Fourier decomposition of the flow perturbations and the solution of the transport equations in the frequency domain (e.g. as done in the Non-Linear Harmonic method). A clear evidence is provided by ref. [4] in which a stage of an axial compressor is successfully modeled with the NLH method and with a more traditional full-annulus unsteady approach. The mesh needed by the NLH calculation is almost 6 times smaller, although it has a much higher relative resolution. In order to reach convergence the full annulus computation required 66 times the CPU time than the NLH computation and about 1.7 times of main memory. Similar conclusions are reported in ref. [5] in which the NLH simulation of a turbine stage with flat casing was significantly faster than a phase-lag method.

The prediction of “broadband noise” is instead typically approached with DES, LES, LBM methods [6], [7], [8], [9], achieving various levels of fidelity in the reproduction of the turbulent scales.

These approaches provide a valuable insight into the turbulence structures however they are still too costly for day-to-day engineering design work.

In this paper two cost-efficient computational methods are described and applied to the simulation of tonal and broadband fan noise.

- The simulation of “tonal noise” is based on the application of the Non-Linear Harmonic (NLH) method for the fan noise sources related to the blade passing frequencies and to the relative harmonics, as well as for the sound propagation in the fan duct and in the duct near-field [10].
- The simulation of “broadband noise” is performed with the Adaptive Spectral Reconstruction (ASR) method [11] which provides a stochastic reconstruction of the turbulent noise sources. The method relies on the time-averaged mean-flow properties computed with a steady RANS solution, hence is computationally affordable in industrial environment. The noise sources are computed in the source region and propagated in the near-field with a Finite Element Method (FEM).

In the frame of this study the computational chain above mentioned is applied to the simulation of the noise generated by two different axial fans, respectively the Northwestern Polytechnical University (NPU) fan [12] and the Advanced Noise Control Fan (ANCF) [13] operated by NASA Glenn Research Center. A centrifugal fan is finally considered. For all these fans, tonal and broadband noise predictions are compared with experimental data in order to assess the level of accuracy achieved.

METHODOLOGY

Noise source identification method for tonal noise

The **Non-Linear Harmonic (NLH)** approach [14]-[15] can be considered as a bridge between classical steady state and full unsteady calculations providing an approximate unsteady solution at affordable calculation cost. The method solves the unsteady Reynolds Averaged Navier-Stokes (RANS) equations by applying a Fourier decomposition in time of the flow perturbations, as shown in equations (1) and (2).

$$U^{'}(\vec{r},t)=\sum_{k=1}^{N}\left[\widetilde{U}_k(\vec{r})e^{j\omega_k t}+\widetilde{U}_{-k}(\vec{r})e^{-j\omega_k t}\right] \tag{1}$$

$$U(\vec{r},t)=\overline{U}(\vec{r})+\sum U^{'}(\vec{r},t) \tag{2}$$

By a casting in the frequency domaintransport equations are obtained for each time frequency.

The user controls the accuracy of the unsteady solution through the order of the Fourier series. Alongside the solving of the **t**ime averaged flow steady-state equations, each frequency requires the solving of two additional sets of conservation equations (for the real and imaginary parts of each harmonic). The method is made nonlinear by the injection of the so called deterministic stresses, resulting from all the solved frequencies, into the time-averaged flow solver. They represent the full nonlinear effects of the flow unsteadiness on the time-averaged flow. Because of the transposition to the frequency domain, only one blade channel is required like a steady flow simulation. The method also features a treatment that enhances the flow continuity across the rotor/stator interface. A non-reflective treatment is applied as well at each interface.

The NLH methodology has been successfully to an integrated aero-engine including fan, OGV (outlet guide vane) and nacelle intake in presence of ground effects and crosswind conditions [16]. More recently the methodology has been extended to fully account for installation effects of pylons/nacelles on CROR aerodynamics and noise [17] and applied to the simulation of aero-engine fan noise [10], [18].

The Nonlinear Harmonic (NLH) method is implemented inthe FINE^{TM}/Turbo and FINE^{TM}/Open CFD software. It enables the simultaneous simulation of the tonal noise generation and propagation in the fan duct, also in presence of damping material. The method is applicable to the prediction of the rotor-stator interaction noise at the blade passing frequency and at its harmonics. The noise at frequencies multiple of the shaft frequency can be approached provided the full wheel is modeled.

Noise source identification method for broadband noise

The **Adaptive Spectral Reconstruction (ASR)** method [11] makes the assumption that the turbulent velocity in each point of the source domain can be reconstructed as a summation of Fourier components, and each component, also called mode, represents a convected planar wave. The frequency content of the reconstructed turbulent velocity u' at point x and time t is written as:

$$u'(x,t) = 2\sum_{n=1}^{N\max} u_n \cos[k_n \cdot (x - Ut) + \psi_n]\sigma_n \tag{3}$$

where k_n is the wave vector of the n^{th} Fourier component, u_n , σ_n and ψ_n are magnitude, direction and phase of the n^{th} Fourier component, and U is the convection velocity. A set of random angles is used to generate the Fourier components, and the magnitude u_n of each mode is computed as a function of the wavenumber using the Von Karman-Pao isotropic turbulence spectrum *E(k)* scaled to match the local mean kinetic energy computed in the CFD RANS analysis.

The main improvement provided by the ASR approach over the SNGR method is in the definition of the spatial correlation of the reconstructed turbulent velocities, that plays a fundamental role in the sound radiation. The spatial correlation of each Fourier mode is kept proportional to the mode wavelength which is proportional to the vortex size. Once the turbulent velocity field has been obtained, the aeroacoustic sources are evaluated in terms of Lamb vectors. The ASR method reconstructs the turbulent velocity on a dedicated fully isotropic Cartesian mesh, automatically built in the solver, adaptively refined on the basis of the local correlation length extracted from RANS. Details on the method are given in [11].

Noise propagation methods

The **Finite Element Method (FEM)** is used to solve the Pierce-Howe Convective Wave Equation in the frequency domain. The solver propagatesin the near-field region the noise sources computed with the ASR method, taking into account the presence of a non-uniform mean flow.

The **Boundary Element Method (BEM)** is used to compute the solution of the Helmholtz Equation in the frequency domain, in presence of a uniform mean flow. This solver radiates to the far-field the acoustic field computed by FEM (or NLH) exploiting the Green’s function approach.

The **Ffowcs Williams-Hawkings (FW-H)** solver computes the noise radiated to the far-field region from a “radiation surface” on which the flow properties have been computed by CFD.

The approaches above mentioned are implemented in a computational chain dedicated to turbomachinery applications and available in the NUMECA’s Flow Integrated Environment (FINE^{TM}) software suite, providing wizard automation driven by best practices.

SIMULATION OF THE NPU AXIAL FAN

Test case definition and computational approach

The NPU-fan is a highly-loaded single-stage axial-flow fan in the Turbomachinery Aerodynamics and Acoustics Lab (TAAL) of Northwestern Polytechnical University (China) [12]. The baseline configuration of the NPU axial fan consideredin this first simulation is shown in Figure 1.

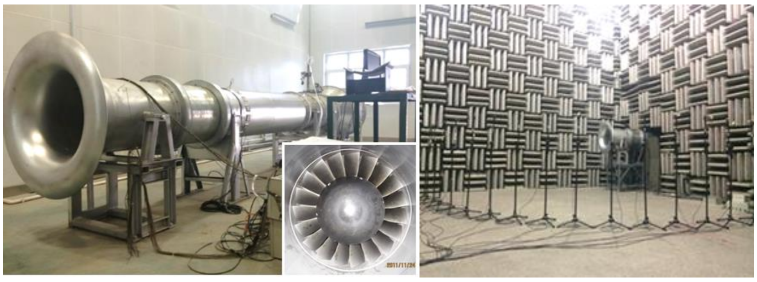

Figure 1: NPU fan rig tested in the semi-anechoic chamber

This experimental setup is currently being exploited in the frame of the IMAGE research project Details on geometry and working point are listed in Table 1. The unlined configuration of the duct is considered. The duct is equipped with a rotatable line array of microphones for duct mode analysis.

Table 1: fan geometry and working point

Parameter	Value	Parameter	Value
Rotation rate (RPM)	2973	External diameter (m)	0.5
Mass flow rate (kg/s)	5.30	Internal diameter (m)	0.285
Number of rotor blades	19	Blade profile	NACA 65
Number of stator blades	18		

The tonal noise source generation in the fan region is computed with the NLH method while the sound propagation is obtained applying the FEM method in-duct and in the near field region. The BEM method (Green’s function approach) is finally used to compute the sound radiation to the far-field. The broadband noise sources are evaluated using the ASR method relying on a steady RANS solution. The sources are propagated in-duct and in the far-field using FEM and BEM methods. Figure 2 shows the regions in which the different computational approaches are applied.

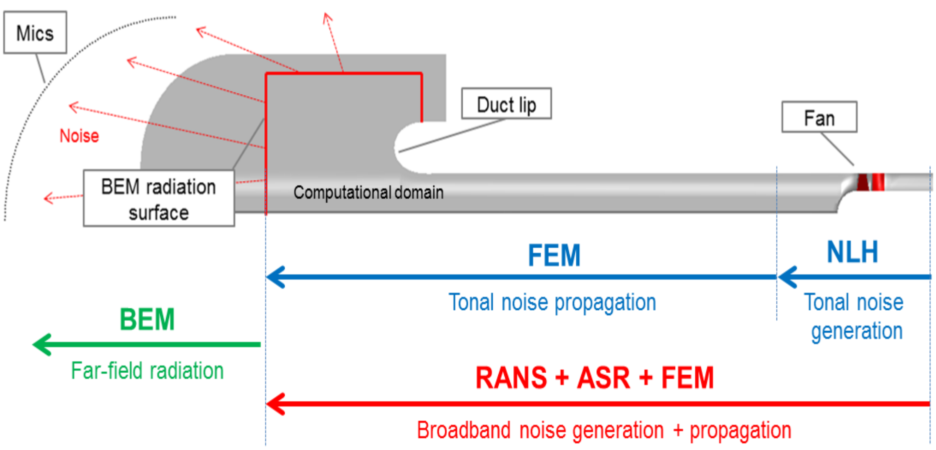

Figure2: Computational domain and numerical approaches considered

CFD model

The CFD model is based on a structured grid made by 16M hexahedral elements, providing a mesh resolution larger than 10 points per wavelength in the duct. The mesh is refined in the fan region in order to achieve a resolution of 40 points per wavelength at a frequency three times the blade passing frequency. This resolution is largely sufficient to avoid numerical dissipative effects that could potentially damp the propagating acoustic waves. The y+ on the rotor blades is lower than 6.3, on solid walls it is lower than 4.5, the minimum skewness is 36.2° while the maximum aspect ratio is lower than 600 in the blades region. Figure 3 shows the mesh in the duct inlet region (left) and in the fan region (right).

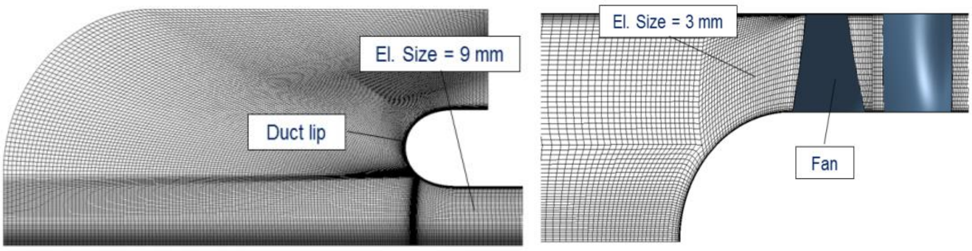

Figure 3: NLH computational mesh

The external boundary of the computational domain (near-field) is treated with a non-reflecting boundary condition. Periodicity is applied to the lateral boundary surfaces. The computational domain extends over a single blade/vane flow passage (Figure 4).

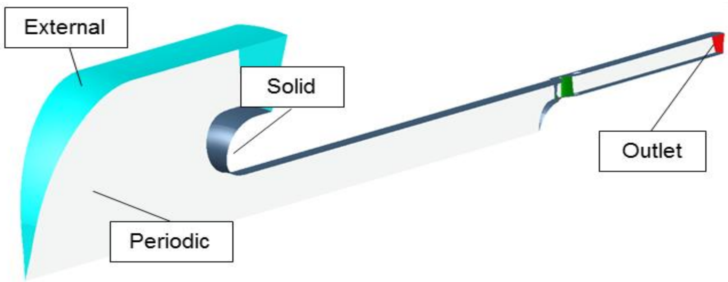

Figure4: NLH computational domain

The values of the boundary conditions are reported in Table 2.

Table 2: CFD boundary conditions

External surface	Static pressure = 101325 Pa		Static temperature = 288.15 K
	$V_x = V_y = V_z = 0$ m/s	K =0.11 m²/s²	ε =1.4 m²/s³
Outlet surface	Mass flow = 6.38 kg/s		
Solid surface	Rotating speed = 2973 RPM		

Three harmonics are used to simulate the perturbations exchanged through the rotor-stator interaction surface. A two equations k-epsilon turbulence model is considered.

Acoustic model

The FEM propagation model is based on an unstructured mesh made by hexahedral (dominant) and tetrahedral elements. The global mesh size is 2.2 M nodes, providing a spatial resolution larger than 7 points per wavelength at a frequency three times the blade passing frequency (BPF). The max elements aspect ratio is 3.6. The tonal noise source is applied in the FEM model interpolating the NLH harmonic solution over the acoustic meshin the fan region. A Perfectly Matched Layer

(PML) absorbing layer is used to reproduce the non-reflecting boundary (Figure 5). The broadband noise source is directly computed with the ASR solver and embedded into the FEM solving system.

The BEM method is finally used to radiate the sound in the far-field. The ground reflection is simulated with a symmetry plane applied in the BEM model.

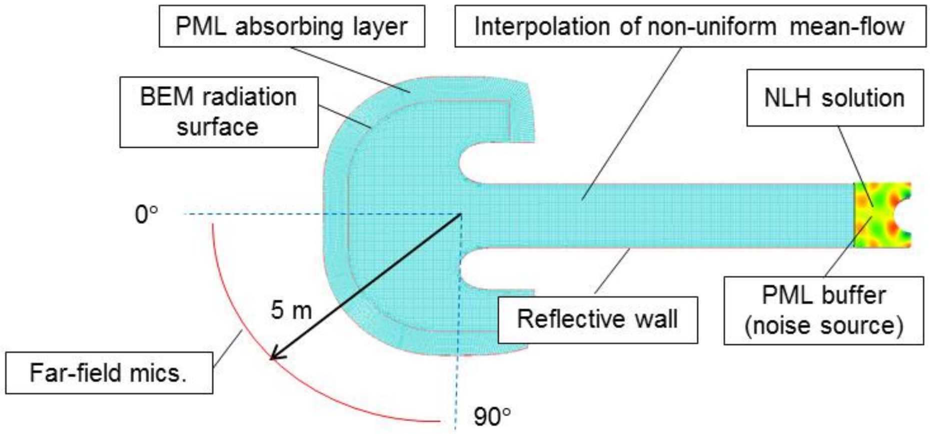

Figure 5: FEM-BEM computational domainand boundary conditions (acoustic mesh shown in blue)

Results

The solutions obtained for the acoustic field at the first three BPFs are shown in Figure 6.

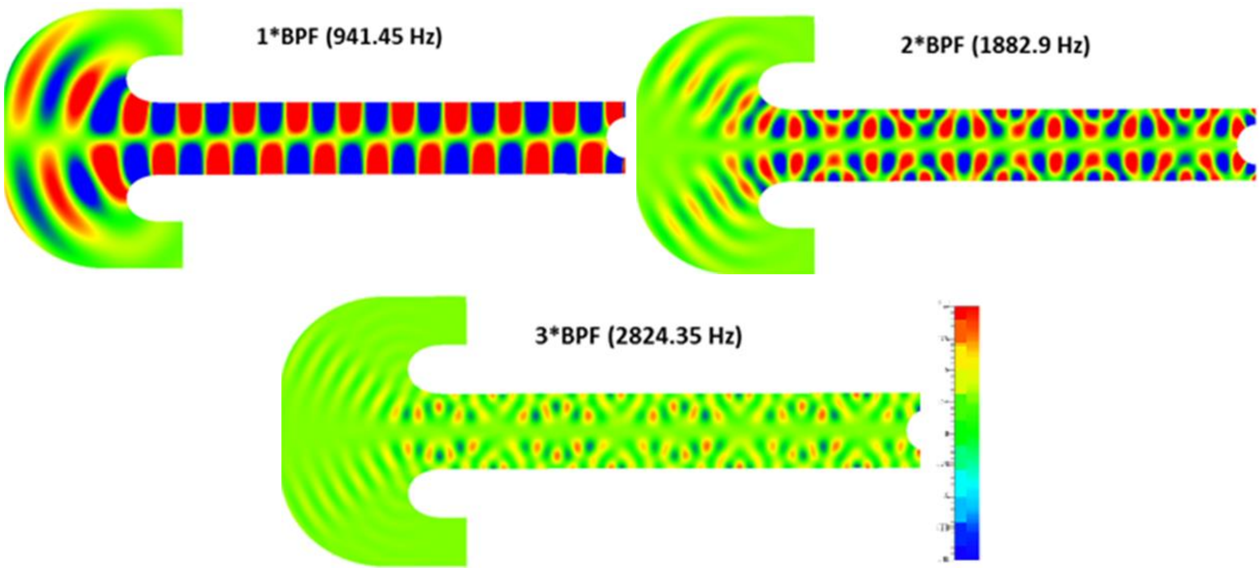

Figure 6: acoustic pressure field [Pa] inside the fan duct and in the near-field (tonal noise)

The tonal acoustic field is used to compute the propagating duct modes generated by rotor-stator interaction. For this purpose the Triple-Plane Pressure Matching Method [19] is applied considering three neighbouring planes located in the same duct section equipped with the rotatable line array of microphones for duct mode analysis. The results are shown in Figure 7, in which the mode amplitudes are split over azimuthal and radial orders for propagating modes. The detected rotor-stator interaction modes are in agreement with the theoretical expectations obtained from the Tyler-Sofrin formulation and with the measurements. The scattered modes present in the experimental results are likely due to not perfectly axisymmetric geometry and flow conditions during measurements. These modes cannot be reproduced in the NLH analysis made in this work, which is based on a model including an axisymmetric duct and a uniform distribution of the flow in the azimuthal direction. Duct modes scattering by azimuthal deviations of the flow from axisymmetric conditions have been observed in [20]-[21], while the presence of azimuthal periodicities of other types than rotor-stator interaction modes is reported in [22]-[23].

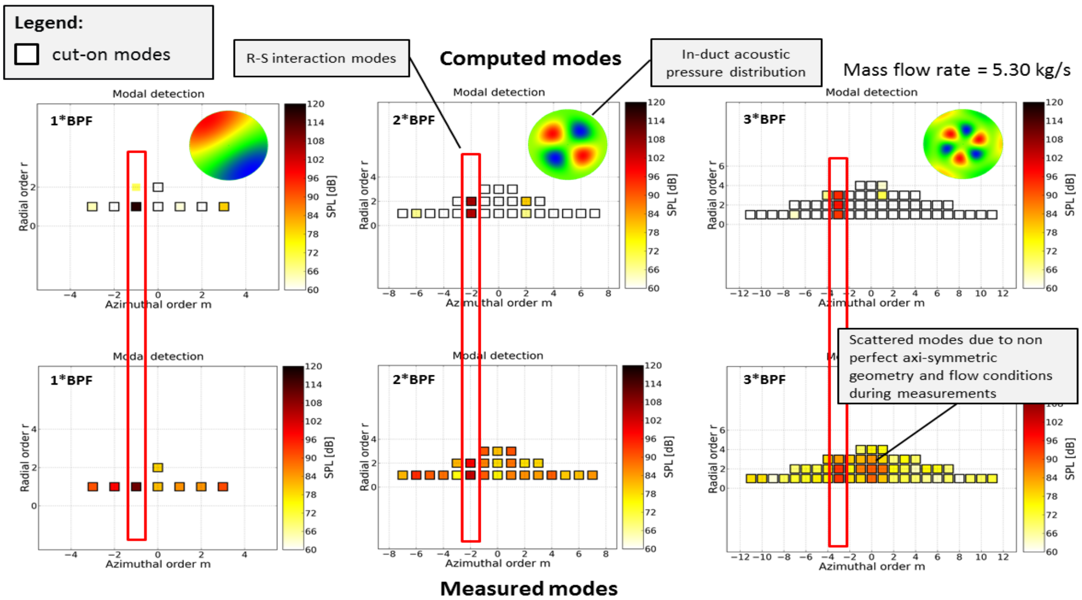

Figure 7: modal decomposition inside the fane duct (tonal noise)

Polar plots of the noise directivity at the first three BPFs in the far-field are shown in Figures 8, 9 and 10. The maximum noise level and peak directivity are reasonably predicted (within 3 dB at the angle of maximum noise radiation.). An angular shift of about 5° is observed between the predicted and measured peaks in the spectra at the second and third BPF.

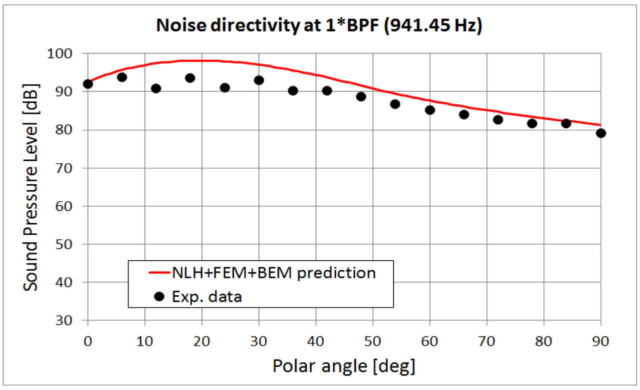

*Figure 8: tonal noise at 1*BPF*

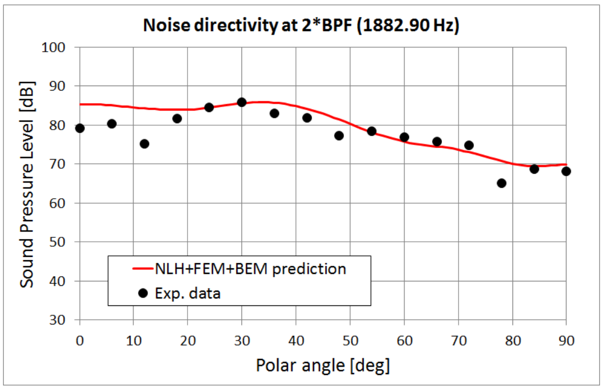

*Figure 9: tonal noise at 2*BPF*

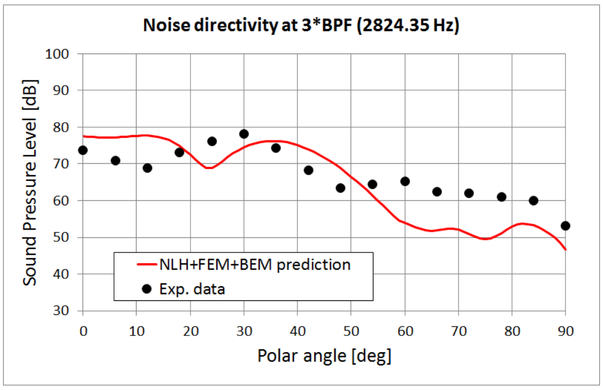

*Figure 10: tonal noise at 3*BPF*

The results for tonal and broadband noise are provided in Figure 11, which shows the noise spectra obtained at different far-field microphones up to a frequency of 1600 Hz for broadband noise. The accuracy of the broadband noise prediction has a large variability depending on the propagation angle. In particular the results obtained are in global agreement with the measurements at high radiation angles (60° and 90°) and within 15 dB from experimental data at low radiation angles (0° and 30°).

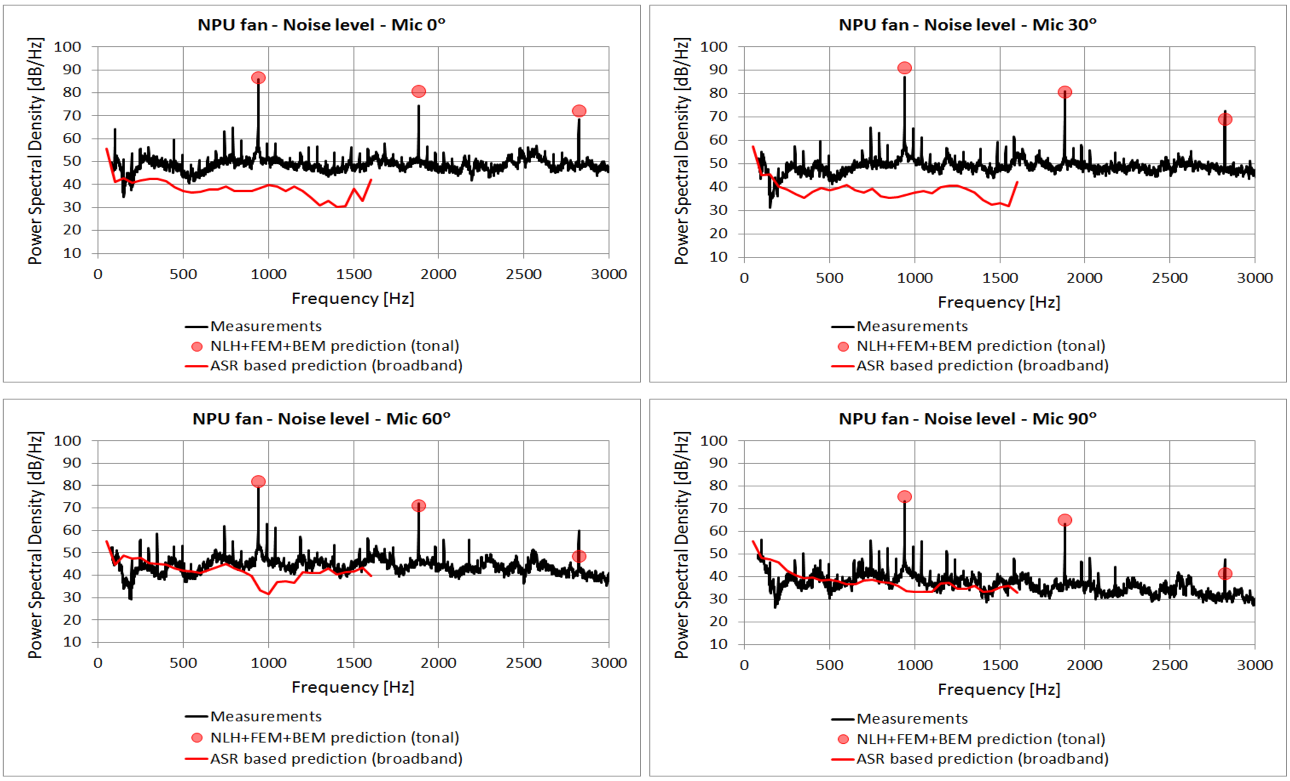

Figure 11: broadband noise spectra relative todifferent far-field microphones

SIMULATION OF THE NASA-ANCF AXIAL FAN

Test case definition and computational approach

This section shortly summarizes the acoustic results obtained from the simulation of the ANCF fan [13]. The ANCF is a 1.2 m diameter ducted fan used for aerodynamic and acoustic measurements formerly installed in the Aero-Acoustic Propulsion Laboratory (AAPL) at the NASA Glenn Research Center and currently located at the University of Notre Dame. Fan geometry and simulation approach are described in Figure 12. There are many ANCF configurations, the one considered in this paper corresponds to a rotor of 16 blades with pitch angle of 28° and to a set of 14 stator vanes located at 1-chord spacing downstream of the fan (the distance is measured between the rotor blade trailing edge and the stator-vane leading edge, at the hub, with chord length of 5.25 inches). The fan operating condition consists of a rotational speed of 1800 revolutions-per-minute-corrected (rpmc) resulting in a tip speed of 114 m/s and in an inlet duct Mach number of ~ 0.15. The fundamental blade passing frequency (BPF) is 480 Hz.

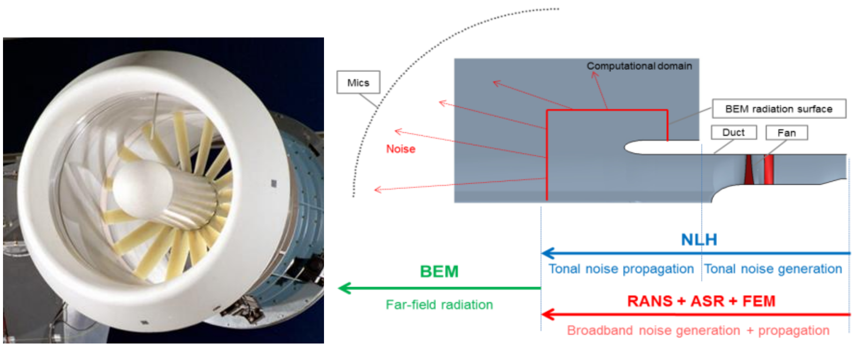

Figure 12: ANCF fan geometry (left) and relative computational domain (right)

The computational approach adopted is similar to the one previously shown for the NPU fan. In this case the tonal noise propagation in the near-field is fully computed with the NLH method.

Results

The solutions obtained for the acoustic field inside the duct and in the near-field are shown in Figures 13, 14 and 15. The first three BPFs are considered (tonal noise). The maximum noise levels at the peak directivity angles are in reasonable agreement with measurements at the first and second BPF, while a deviation of 5 dB is observed at the third BPF. The large under-prediction at 0° is likely due to the absence of scattered low-order modes in the NLH solution, which is obtained in presence of perfectly axi-symmetric geometry and flow distribution. For the first two BPFs the NLH predictions are compared with the results obtained with the LBM method [2].

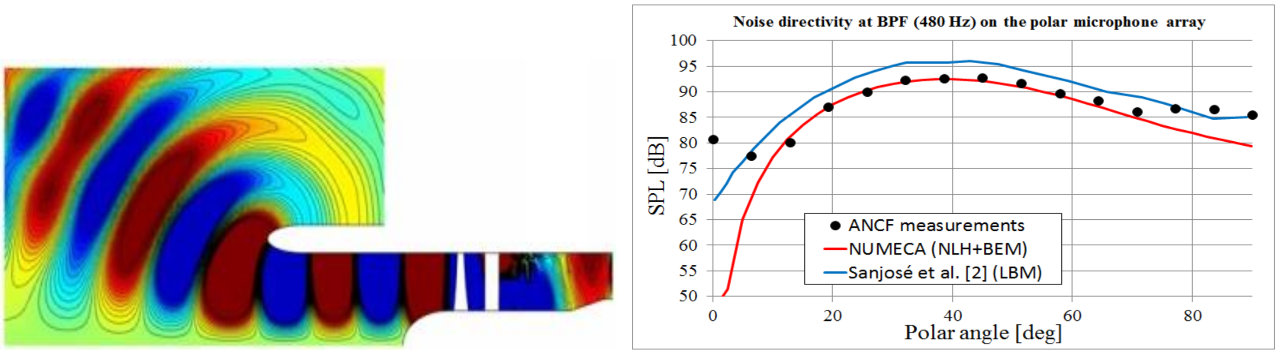

*Figure 13: acoustic pressure field [Pa] and noise directivity plots at 1*BPF (tonal noise)*

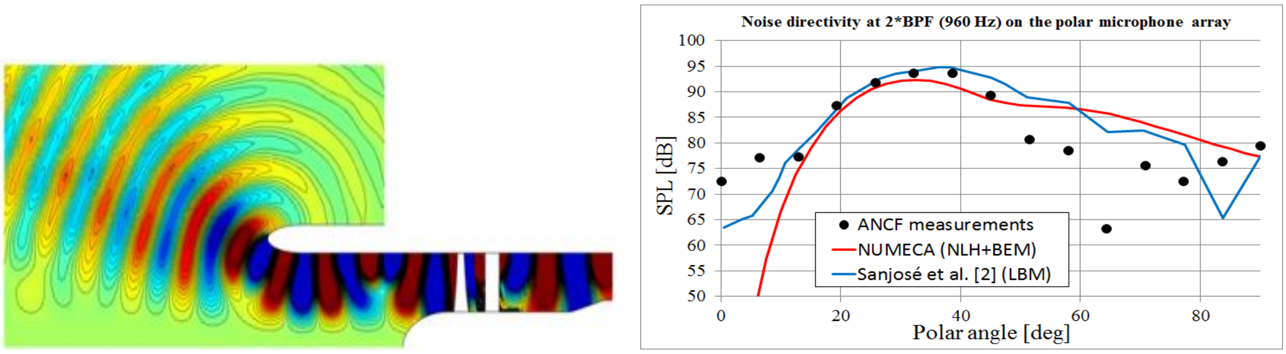

*Figure 14: acoustic pressure field [Pa] and noise directivity plots at 2*BPF (tonal noise)*

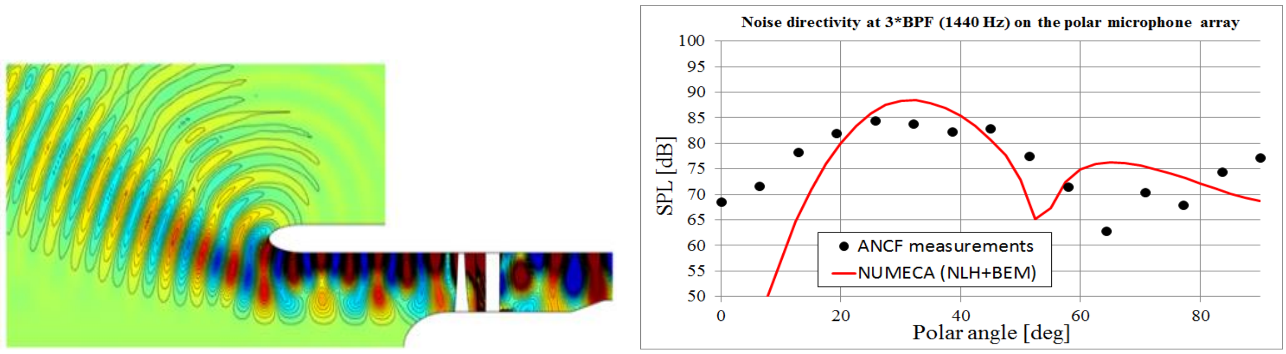

*Figure 15: acoustic pressure field [Pa] and noise directivity plots at 3*BPF (tonal noise)*

The results for broadband noise are provided in Figure 16 which shows the noise spectra obtained at different far-field microphones up to a frequency of 1600 Hz. The accuracy of the broadband noise prediction has a large variability depending on the propagation angle. In particular the results obtained are in global agreement with the measurements at low radiation angles (0° and 25°) and within 15 dB from experimental data at high radiation angles (64° and 90°). An overprediction of 15 dB is observed below 100 Hz.

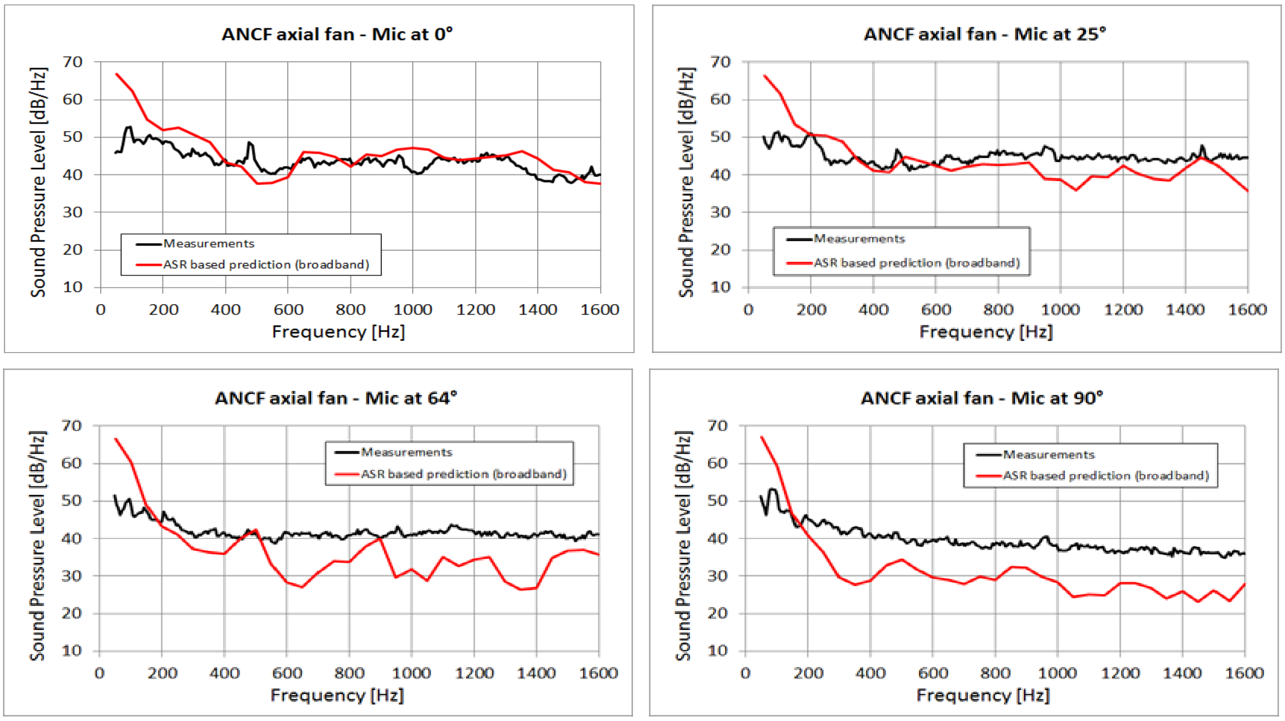

Figure 16: broadband noise spectra relative todifferent far-field microphones

SIMULATION OF CENTRIFUGAL FANS

Test case definition and computational approach / Results

The computational chain for broadband noise is finally applied to the simulation of the two centrifugal fans shown in Figures17 and 18, characterized by different size and rotational speed.

The time averaged mean flow required by the ASR method for the broadband noise reconstruction is provided by a NLH simulation relying on a computational mesh containing 5.3M grid points, a first cell size of 3.9e-6 m and a number of 12 viscous layers. The CFD results provide a very good simulation of the flow inside the impeller, with correct incidence on the fan blades, correct pressure loadings and torques. In particular the pressure rise in the impeller matches within 3-7 % with measured values and the torque also matches within 5 % of measured.

The noise sources are reconstructed using the ASR method and propagated with FEM and BEM solvers. The predicted sound power levels are within 10 dB from experimental data. The overall acoustic simulation (import of CFD solution, acoustic model setup, sources reconstruction, propagation analysis and post-processing) is automatically performed by a wizard dedicated to turbomachinery applications, available in FINE^{TM}/Acoustics. For each configuration the simulation time is 10 hours on a 16 cores desktop PC.

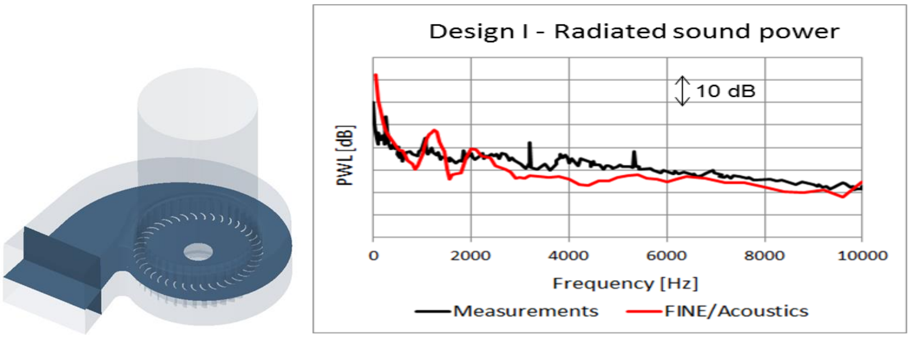

Figure 17: centrifugal compressor design I (size = 10x10x3.5 cm, RPM=8000, blades number = 40)

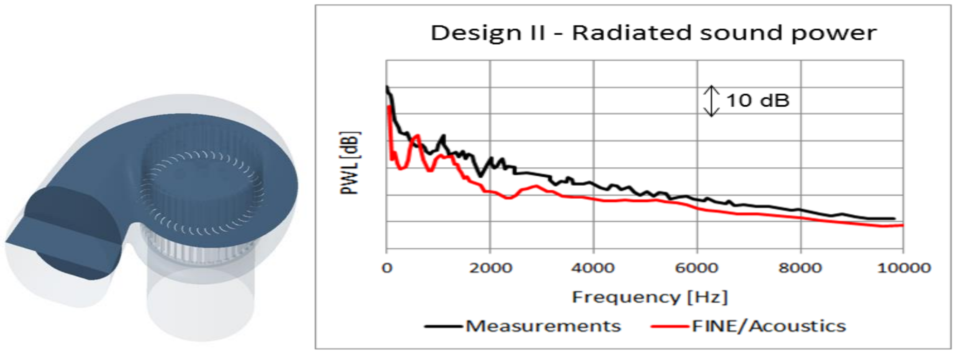

Figure 18: centrifugal compressor design II (size = 21x21x8 cm, RPM=3000, blades number = 44)

CONCLUSIONS

In this paper an efficient computational chains for tonal and broadband noise have been introduced and applied to the simulation of axial and centrifugal fans.

The results obtained indicate in general a reasonable prediction of tonal and broadband noise in terms of levels and trends with some exceptions for specific propagation angles. In particular:

- The tonal noise simulation of the axial fans (i.e. NPU and ANCF) provides numerical results with a maximum deviation from 3 dB to 5 dB in SPL (e.g. at the third blade passing frequency) with respect to experimental data, at the polar angle of maximum noise radiation.
- The modal analysis performed at the blade passing frequency and at its harmonics confirms the above mentioned accuracy, providing rotor-stator interaction modes with amplitudes in line with the experimentally detected ones. Scattered modes are not reproduced in the simulation.
- The broadband noise simulation of the axial fans (i.e. NPU, ANCF) provides accurate results for some propagation angles, while for others the differences can reach up to 10-15 dB.
- The broadband noise simulation of the centrifugal fans provides sound power level spectra correctly captured in terms of shape and levels, with maximum variations at isolated frequencies within 10 dB.

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