DEPARTMENT OF MECHANICAL & MECHATRONIC ENGINEERING

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The prediction of performance and noise in large diameter axial flow fans

Stellenbosch University

Clarise du Plessis, Johan van der Spuy and Hanno Reuter

Outline

- Introduction
- Fan performance testing
- Fan performance modelling
- Fan noise testing
- Fan noise modelling
- Conclusion

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Introduction

- Fan suppliers have their own fan performance and noise testing facilities and measurement techniques, which differ measurably.
- Some suppliers have full scale facilities whereas others have scale model facilities.
- It is therefore difficult for OEMs to evaluate fan performance and noise data from suppliers and implement the performance data in there thermal design and CFD models.
- The Stellenbosch University fan test facility is probably the only independent test facility in the world for economical comparative testing by OEMs.
- This facility has now been improved to also conduct accurate comparative noise testing.
- The results can be used by OEMs to develop inhouse virtual test rigs to evaluate fan performance (and noise) for implementation in CFD studies in order to improve thermal software, become more competitive and reduce risk.
- This paper discusses a study done on the M-fan, developed at Stellenbosch University.

Objectives

- Show the comparison between modelled and measured fan performance
- Show the comparison between modelled and measured noise
- Evaluate the mechanisms of fan noise
- Verify fan noise scaling laws
- Show the impact of reducing number of blades on fan noise.

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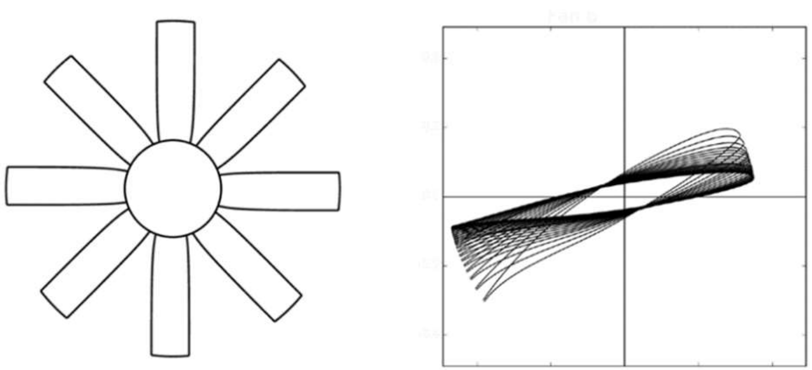
Fan description

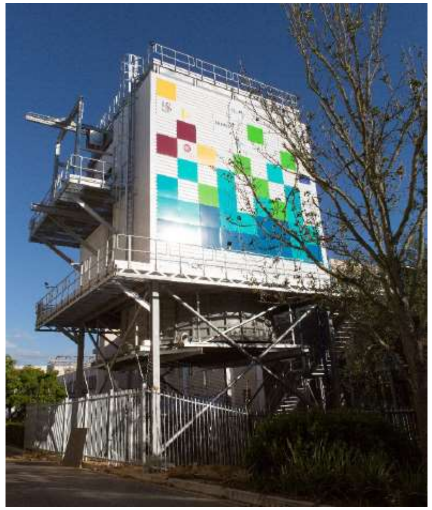
- The M-fan is designed as a large diameter (24 ft) axial flow fan, developed at Stellenbosch University, for forced draft air-cooled heat exchangers, to be used in the power generation industry.

- Blades are very rectangular in shape, with a camber of 3.5% at the blade root and 0.8% at the tip.



M-fan top view and blade stacking plan (Wilkinson, 2017)

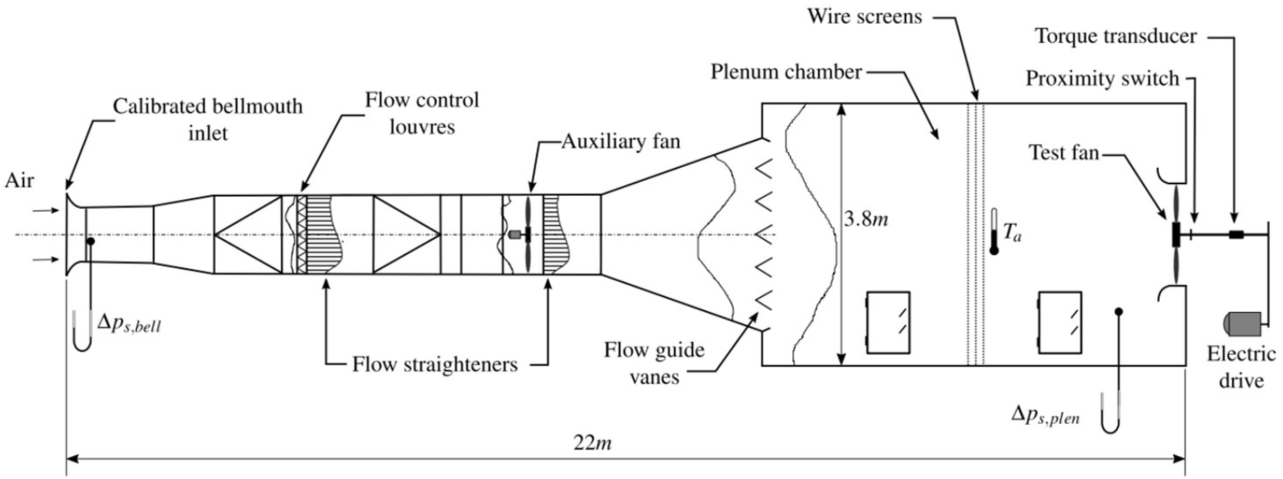
Installed scaled model M-fan



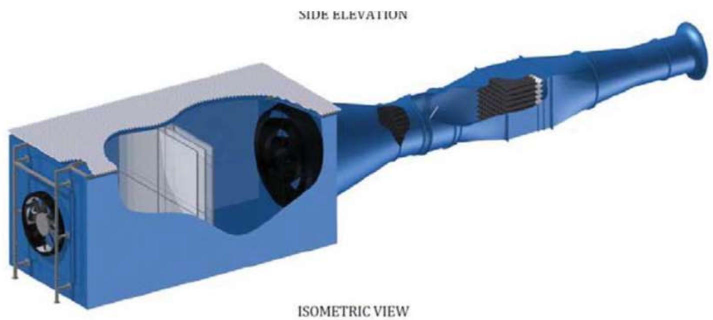
Installed full-scale M-fan

ISO 5801 Type A fan test facility

- Current configuration, 1.542 m casing ID. Facility equipped to measure flow rate, pressure rise, shaft power and running speed.



Schematic of test facility



3D model of fan test facility

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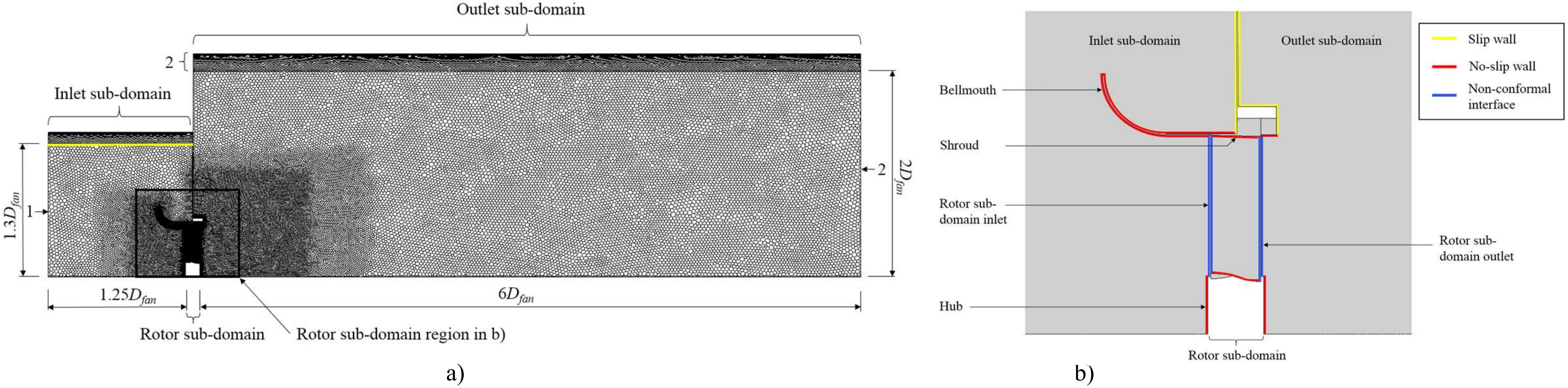
Fan numerical modelling

- Fan model corresponds with free inlet, free outlet fan test facility on which experimental measurements are taken (pictures of computational domain obtained from the work of du Plessis).

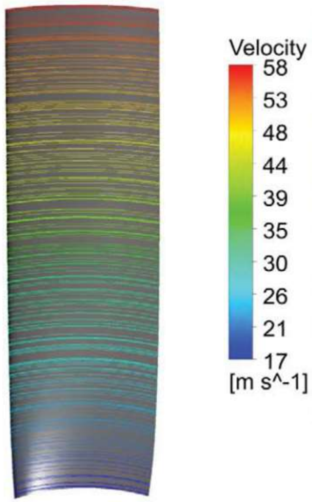
- Steady state simulations at various volume flow rates and fan tip clearances are completed with the realizable *k*-ε turbulence model.

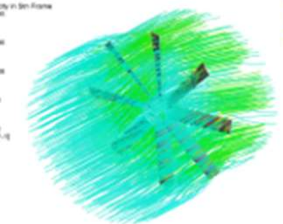


Fan computational domains of the free inlet, free outlet test facility: a) all domains; b) close-up of region surrounding rotor sub-domain

Visualised numerical results

- Visualised results for 8-blade M-fan at design flowrate at 34° (these results were obtained by Rohwer).





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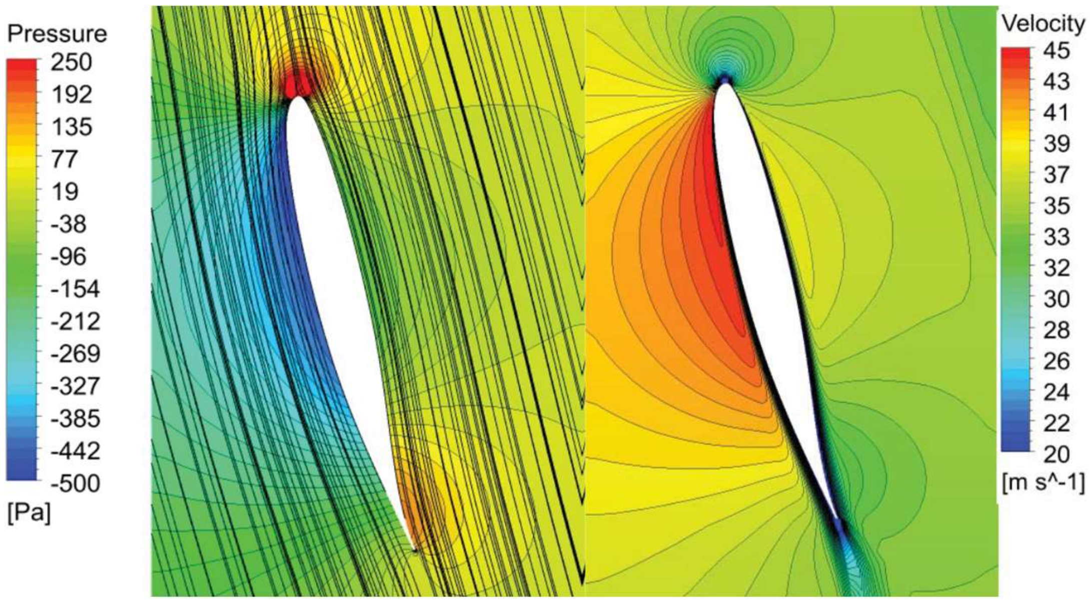
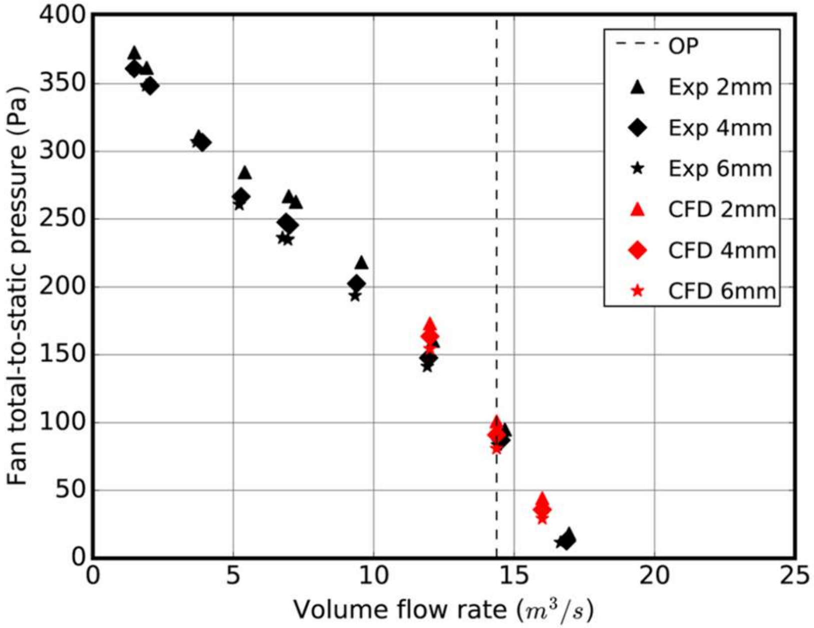


b)

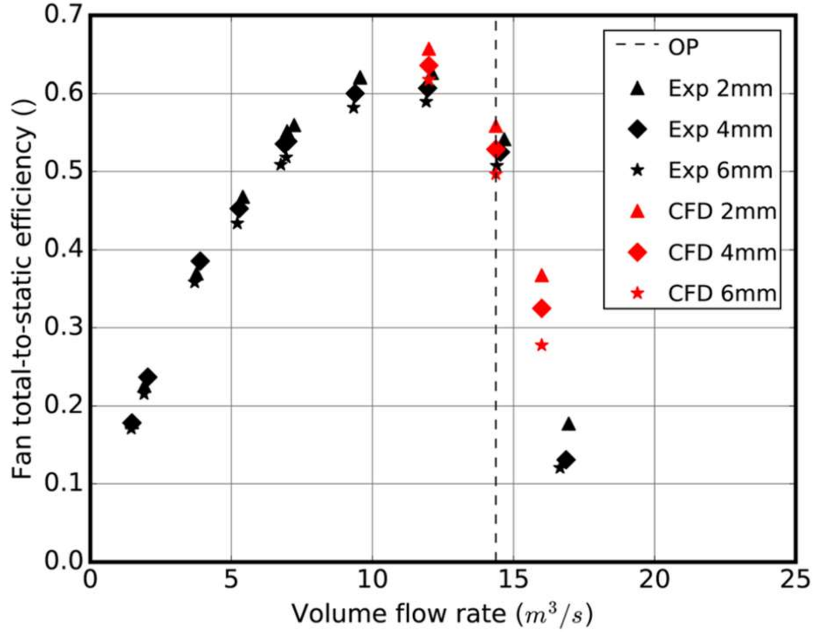
Streamlines over fan blades: a) full blade b) at 50% span

Experimental vs numerical results

- Included results for 8-blade M-fan at 34° at different TC values (these results were obtained by Wilkinson).



a)

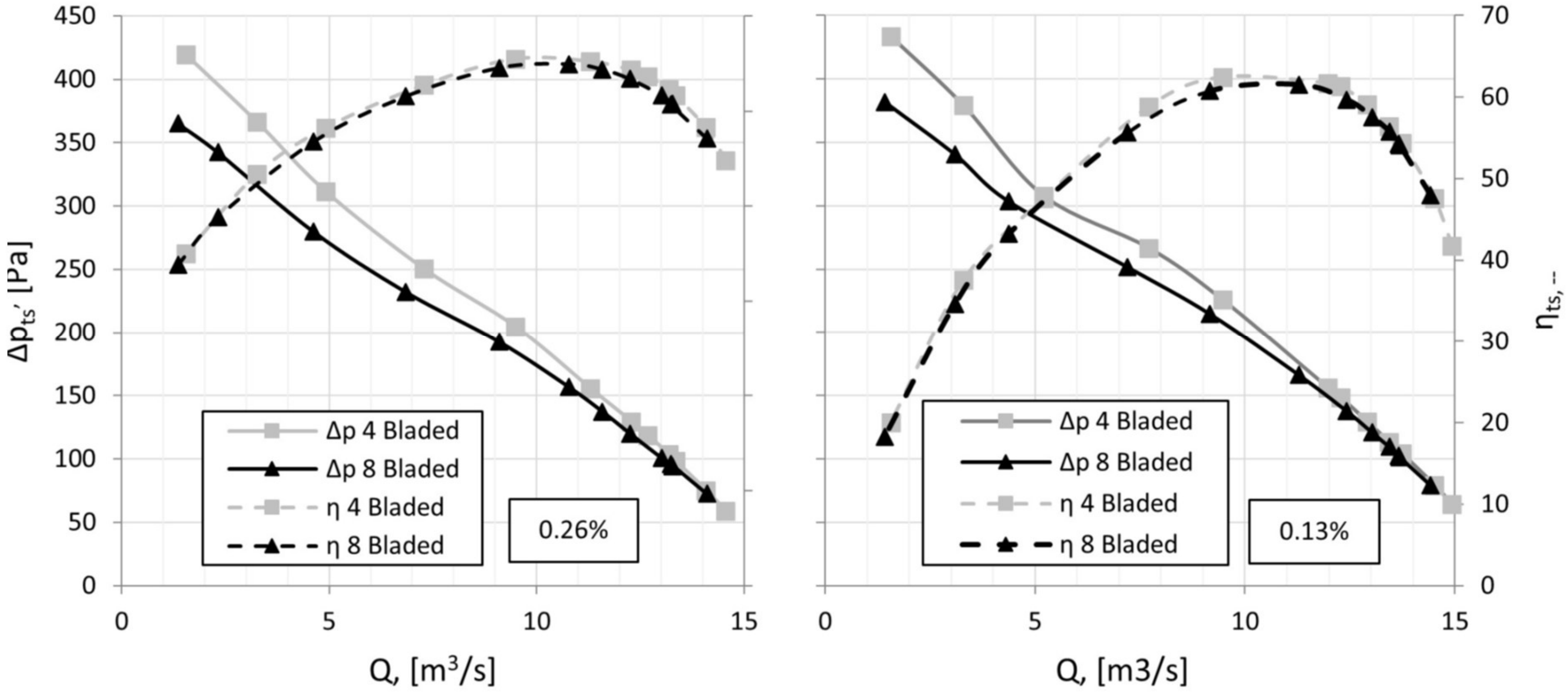


b)

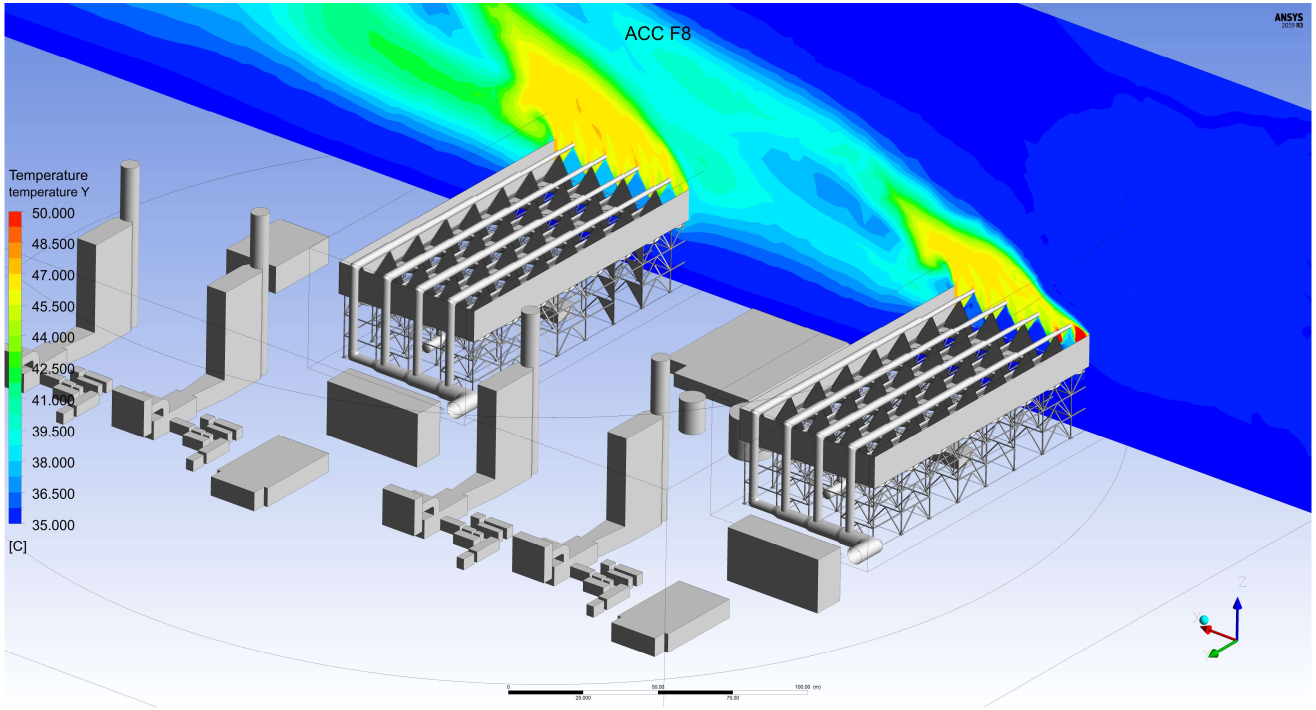
Simulated vs experimental results: a) Fan static pressure b) Fan static efficiency

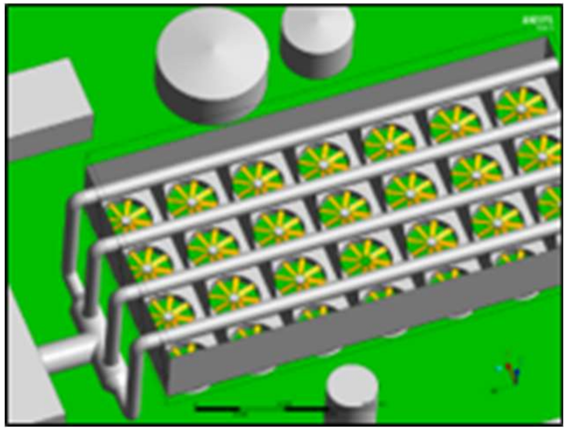
Fan performance measurement

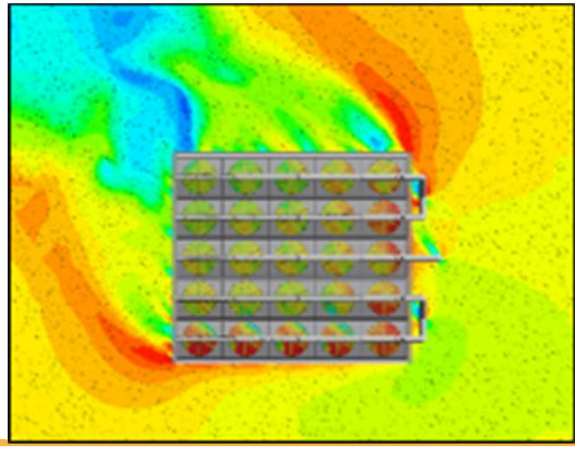
- Comparison of aerodynamic performance of 4- and 8-bladed fan at 2 mm and 4 mm tip clearance.



CFD analysis







ANSYS CFX Plots: Drs Markus Feldkamp and Christoph Schemmann (HAMON)

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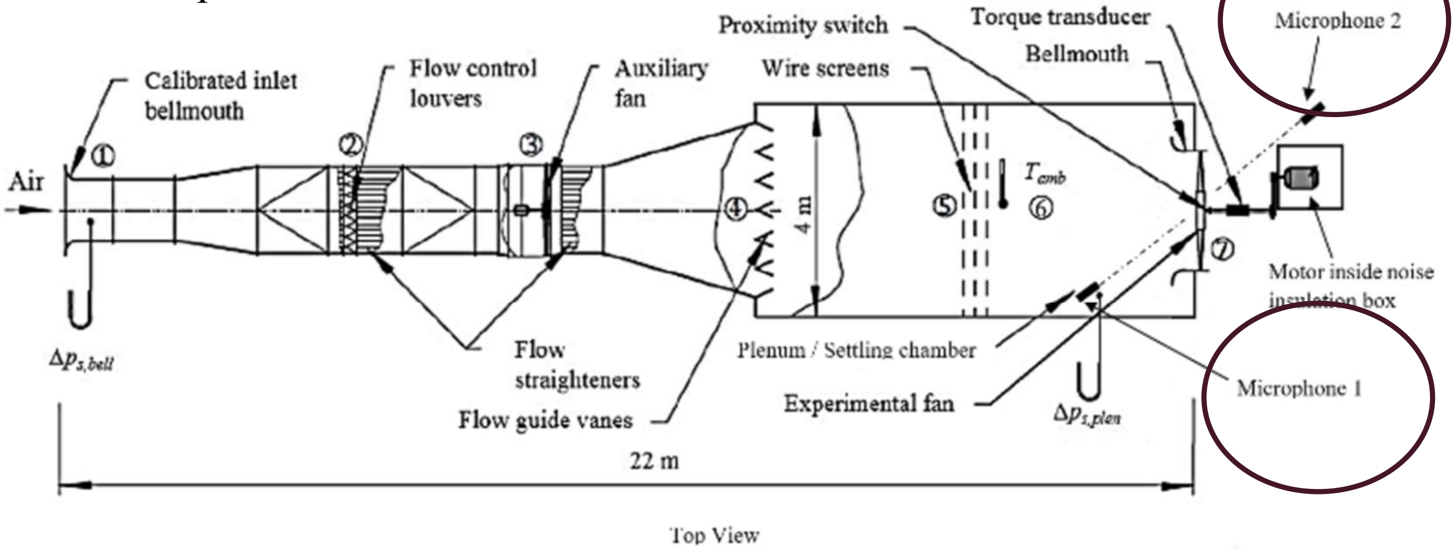
Fan noise measurement

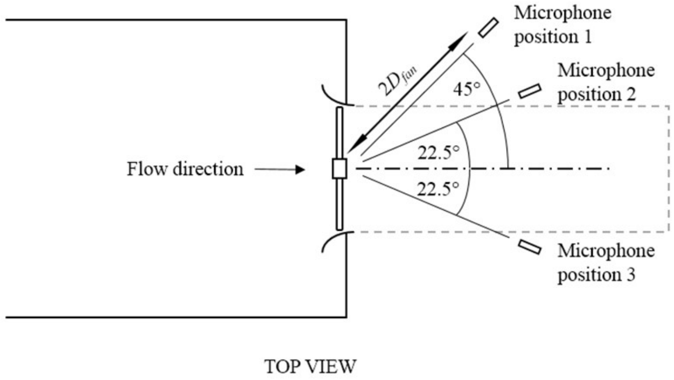
- Noise measurements performed on standard ISO 5801 Type A fan test facility.
- Facility was equipped with both in- and outside microphone – outside microphone used for correlation to numerical results.
- Fan motor covered with noise insulating box.
- Auxiliary fan run at reduced speed.



Fan noise measurement

- Effect of reflective surfaces are corrected for by comparing pure tone noise measurements in the test facility to the same measurements in an anechoic chamber.

- Fan noise is measured at three microphone positions.



Microphone positions for ISO 5801 facility

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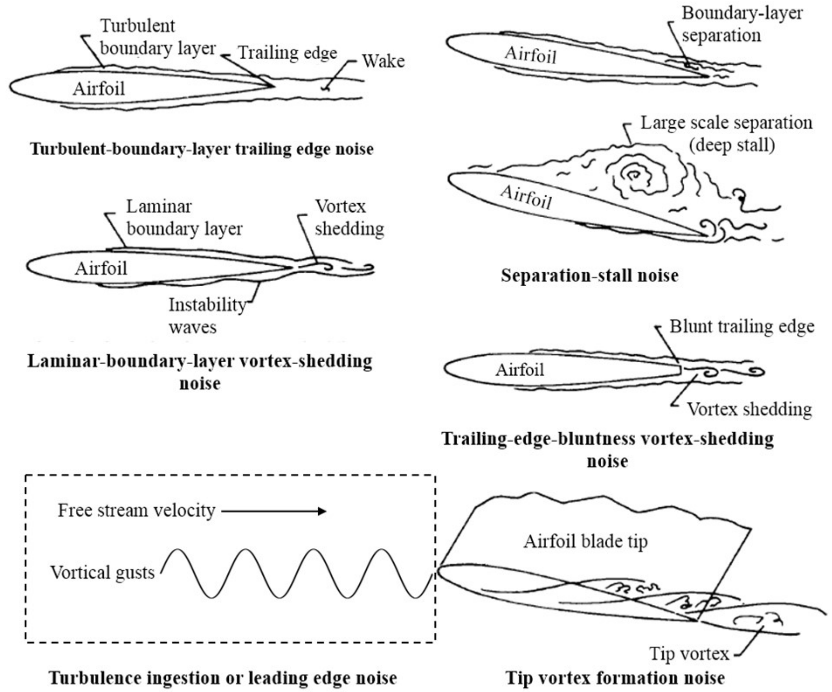
Fan aerodynamic noise mechanisms

- Rotational noise:
  - Blade interactions with inflow distortion, inflow turbulence and fixtures close to the fan
- Non-rotational noise:
  - Laminar boundary layer vortex shedding noise
  - Turbulent boundary layer trailing edge noise
  - Blade interactions with the tip clearance vortex
  - Blade stall (due to large scale separation)

Most dominant broadband fan noise mechanisms:

- Trailing edge noise (may also have tonal components if boundary layer is laminar)
- Turbulence ingestion noise due to blade interactions with tip clearance vortex



Flow conditions producing airfoil self-noise (adapted from Brooks et al, 1989)

Numerical fan noise prediction

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Axial fan noise can be predicted numerically by:

- Modelling the fan and its surroundings with scale-resolving numerical models such as LES, which is computationally expensive and time consuming.

- Breaking down the noise spectrum into components, making use of less computationally expensive scale-resolving numerical models and semi-empirical and analytical prediction methods. Added benefit of better understanding of individual noise mechanisms and how they can potentially be reduced.

Turbulence ingestion noise

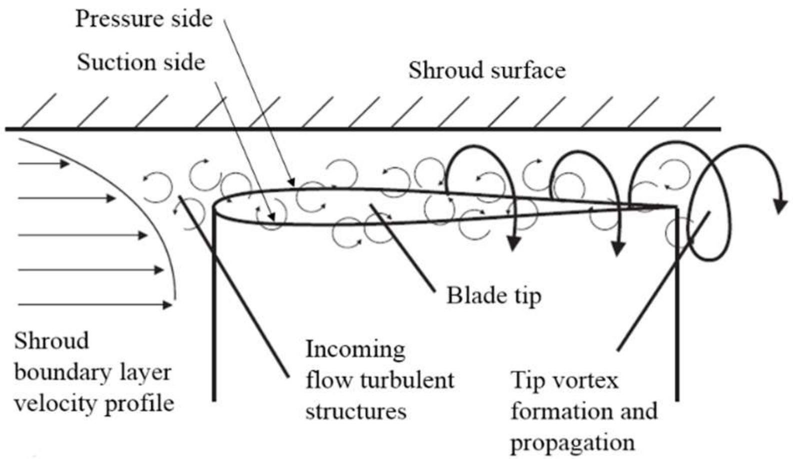
- Turbulent structures are stretched around the leading edge as they are convected downstream by the mean flow, causing fluctuating pressure on the airfoil surface.

- Turbulent structures larger than the airfoil thickness are responsible for the generation of leading edge noise.

- Broadband noise generated by incident turbulence on an airfoil leading edge dominates trailing edge noise when the turbulence intensity is above 1% (Roger et al, 2006).

- Turbulence can be ingestion from upstream flow, or generated by the rotor itself due to the tip leakage vortex.

- Analytical formulation proposed by Amiet (1975) enables prediction of far field noise due to incident turbulence on an airfoil.



Tip vortex formation (adapted from Higgens et al, 2018)

Analytical model for turbulence ingestion noise prediction

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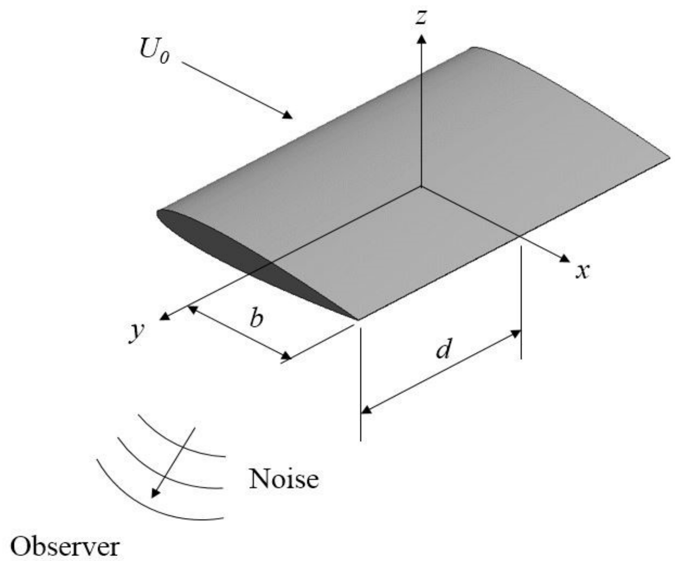
- Analytical formulation by Amiet (1975) enables prediction of far field noise due to incident turbulence on an airfoil.
- The equation for the far-field sound power spectral density for a far field observer is:

$$S_{pp}(\mathbf{x},\omega) = \left(\frac{\omega z \rho_0 b}{c_0 \sigma^2}\right)^2 \pi U_0 d \left|\mathcal{L}(\mathbf{r}, K_x, K_y)\right|^2 \Phi_{ww}(K_x, K_y)$$

ω: circular frequency (in rad/s)
z: coordinate of the observer normal to the airfoil chord
$\mathbf{x}$: observer position
ρ_0: air density
b: half of the airfoil chord
d: half of the airfoil span
c_0: speed of sound in air
σ: $\sigma^2 = x^2 + \beta^2(y^2 + z^2)$
U_0: mean velocity in the chordwise direction
$\mathcal{L}$: dimensionless effective lift.
K_x, K_y: aerodynamic wavenumbers
Φ_{ww}: wavenumber spectrum of the turbulent velocity component normal to airfoil



Coordinate system for turbulence ingestion noise model

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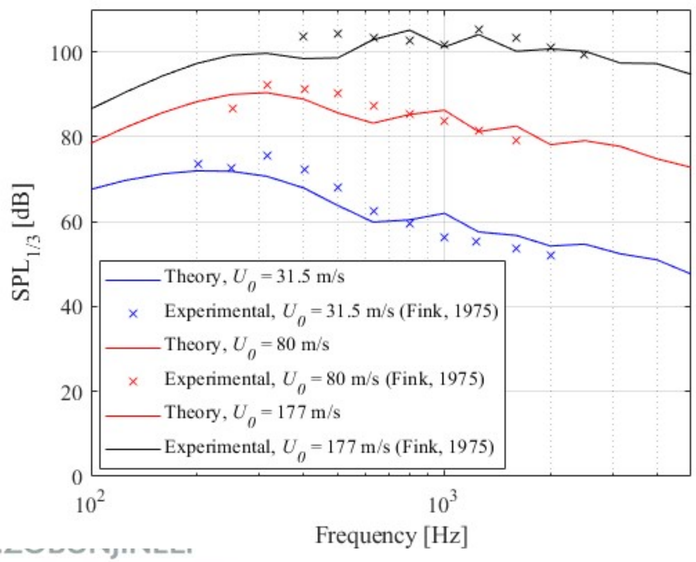
Turbulence ingestion noise implementation for airfoils

- Isotropic turbulence is assumed for the implementation of Amiet's model.
- A correction for the effect on airfoil thickness by Moriarty et al (2005) is applied, which reduces the predicted SPL in the high frequency region (thick airfoils produce less leading edge noise than thin airfoils).
- Model implementation is validated for various airfoil shapes. Some examples:

Flat plate



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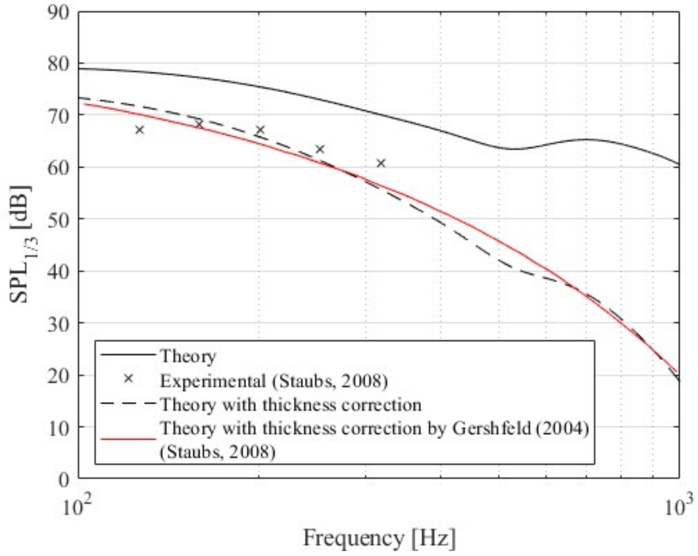


Turbulence ingestion noise implementation for fans

- Coordinates are created in Matlab® to represent the fan and the observer (corresponding to microphone positions in experiments)

- Fan blades are split into segments, with the center of each segment located mid-chord and mid-span.

- The third-octave SPL turbulence ingestion noise generated by each segment at the observer position is calculated and corrected for the fan blade thickness at the specific span position.

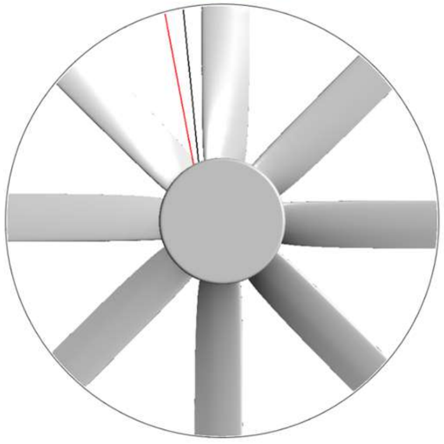
- The SPL of each segment of each blade is added logarithmically to find the total SPL due to turbulence ingestion at the observer.

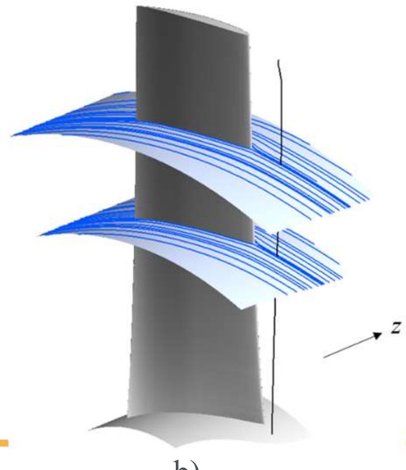
- Inputs to analytical model are determined from steady RANS CFD.

Turbulence ingestion noise implementation for fans

- For the fan implementation, the blade is assumed stationary and relative tangential velocity from the CFD is used as the free stream velocity. The turbulence intensity is calculated in the rotational frame of reference. Turbulent kinetic energy and turbulent dissipation rate are also obtained from CFD.

- Intersection of black plane in a) with streamline that approximately reaches leading edge is shown in b). Black line in b) is where inputs to turbulence ingestion noise model is read.


a)



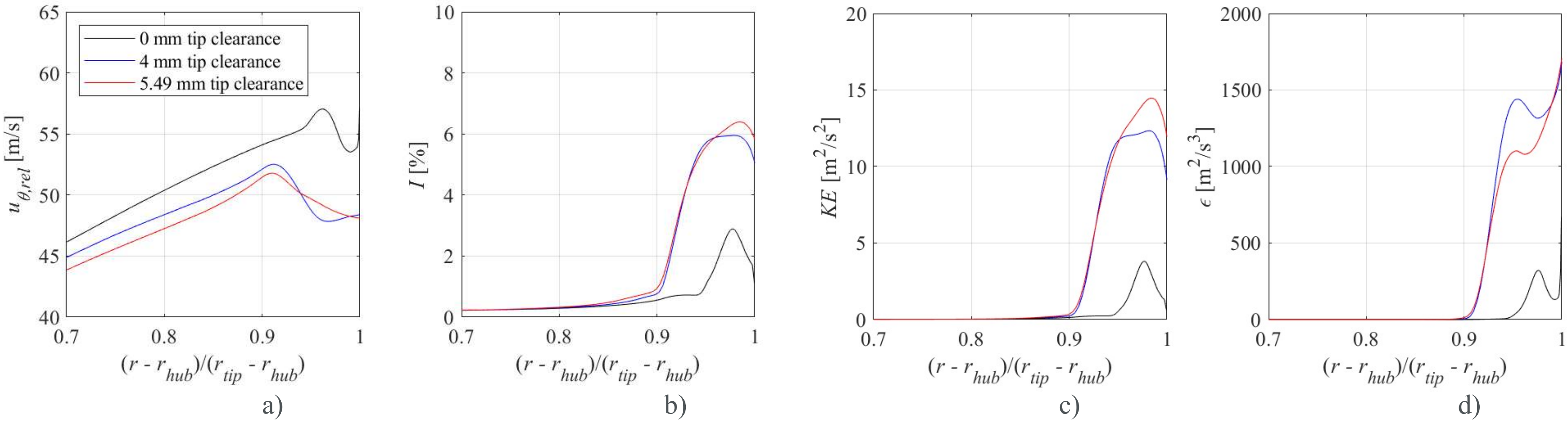
b)

8-bladed M-fan: a) view in the flow direction; b) plane intersection with streamlines

Turbulence ingestion noise implementation for fans

- The 8- and 4-bladed M-fan is investigated at a range of volume flow rates for two diameters, and 0 mm, 4 mm and 5.49 mm tip clearances.

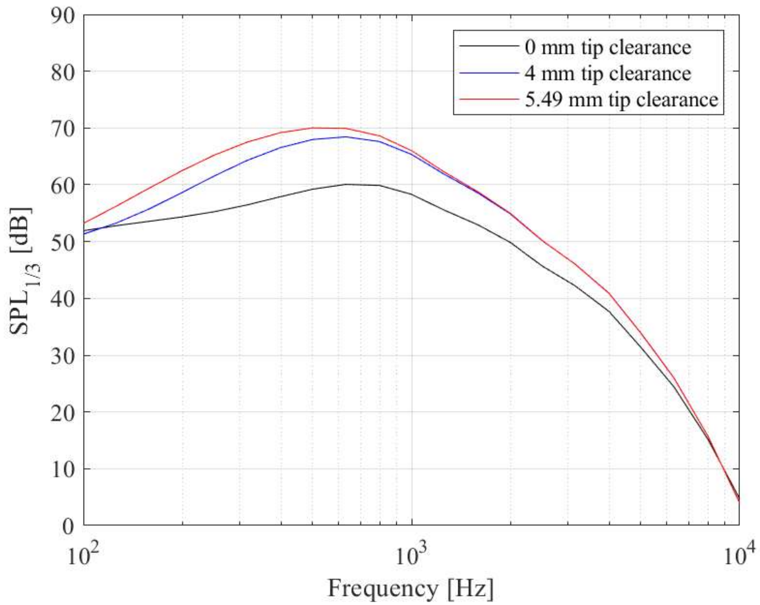
- An example of the inputs to the turbulence ingestion model for the 8-bladed M-fan with a 1.542 m diameter:



8-bladed M-fan with D_{fan} = 1.542 m and different tip configurations, at a volume flow rate of 12.91 m^3/s: a) relative tangential velocity; b) turbulent intensity; c) turbulent kinetic energy; d) turbulent dissipation rate

Turbulence ingestion noise implementation for fans

- The SPL for the 8-bladed M-fan with a 1.542 m diameter with different tip configurations is shown:



SPL of the 8-bladed M-fan at a volume flow rate of 12.91 m^3/s with different tip configurations

Turbulence ingestion noise implementation for fans

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Main conclusions from investigations:

- Turbulence ingestion noise increases with decreasing volume flow rate.

- For the same fan with a different diameter, the same tip speed and scaled volume flow rate and tip clearance, only the turbulent dissipation rate changes. The change is inversely proportional to the ratio of fan diameters. Fan noise for a fan of a certain diameter can be predicted from the input data of a different diameter fan by modifying ε and scaling the representative fan geometry in Matlab® accordingly.

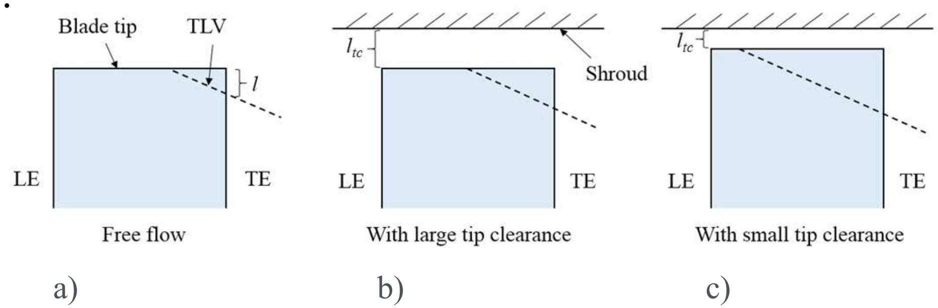
- If a fan chord is doubled and its number of blades halved (keeping solidity constant), turbulence ingestion noise of the fan with smaller number of blades is lower solely due to the decreased number of blades.

Tip vortex formation noise

- For a blade in free flow, two vortices originate at the leading edge, which move along the pressure and suction side edges at the tip of the blade.

- Near the trailing edge (TE), the pressure difference between the two sides of the blade drives the pressure side vortex over the tip, joining the more stable vortex on the suction side. This is known as the tip leakage vortex (TLV).

- When a solid surface is in close proximity to the blade tip, the characteristics of the TLV change. As the tip clearance is reduced, the pressure side tip vortex is shed closer to the leading edge (a-b) and the vortical structures become smaller (Higgens et al, 2019).



Effect of blade tip configurations on the spanwise extent of the tip leakage vortex on the blade suction side in a) free flow; b) with a shroud and large tip clearance; c) with a shroud and small tip clearance

Semi-empirical model for tip vortex formation noise prediction

- The spanwise extent of the vortical structure at the TE of the blade is an indication of the strength of the vortex and its propagated noise.

- Brooks & Marcolini (1986) developed an empirical prediction method for tip vortex formation noise based on airfoils in free flow.

- Tip vortex formation noise per 1/3-octave frequency can be calculated as:

$$\mathrm{SPL}_{1/3} = 10\log_{10}\left(\frac{M_0^2 M_{max}^3 l^2 \overline{D}_h}{r_e^2}\right) - 30.5\left(\log_{10}St + 0.3\right)^2 + 126$$

M_0: free stream Mach number
M_{max}: maximum Mach number of the flow within or about the separated flow region
l: spanwise extent of the thick viscous core of the tip vortex at TE
$\overline{D_h}$: directivity function
r_e: retarded observer distance
St: Strouhal number

Semi-empirical model for tip vortex formation noise prediction implementation

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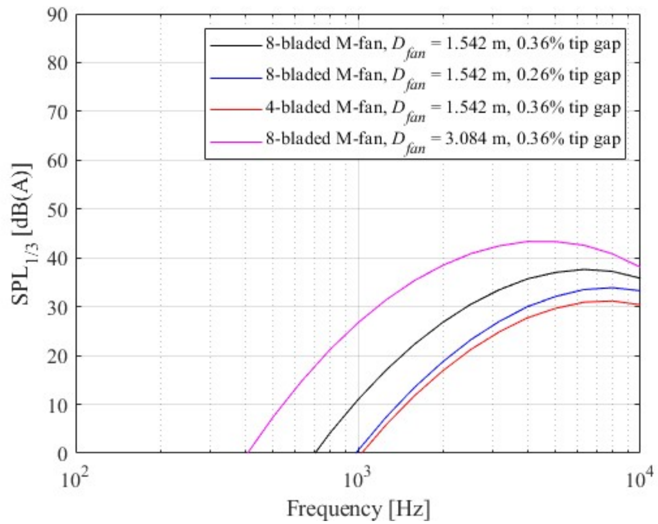
- In Matlab®, an observer is placed at the same positions as in the experimental noise measurements.
- Each blade tip has its own coordinate system of which the *x*-axis is aligned with the blade chord.
- The free stream Mach number is calculated using the relative tangential velocity from CFD.
- The SPL predicted for each blade tip is logarithmically summed to represent an entire fan.



Tip vortex formation noise for M-fan

Tip vortex formation noise

Main conclusions from investigations:

- Although the existence of the tip gap is the main cause of turbulence ingestion noise, it does not generate substantial noise; the tip vortex formation noise is negligible compared to the turbulence ingestion noise.

- The tip vortex formation noise model does not take turbulence interaction noise into account, which is generated as a product of the pressure fluctuations on the shroud.

Trailing edge noise

- Fan trailing edge noise is predicted using single-airfoil theory.

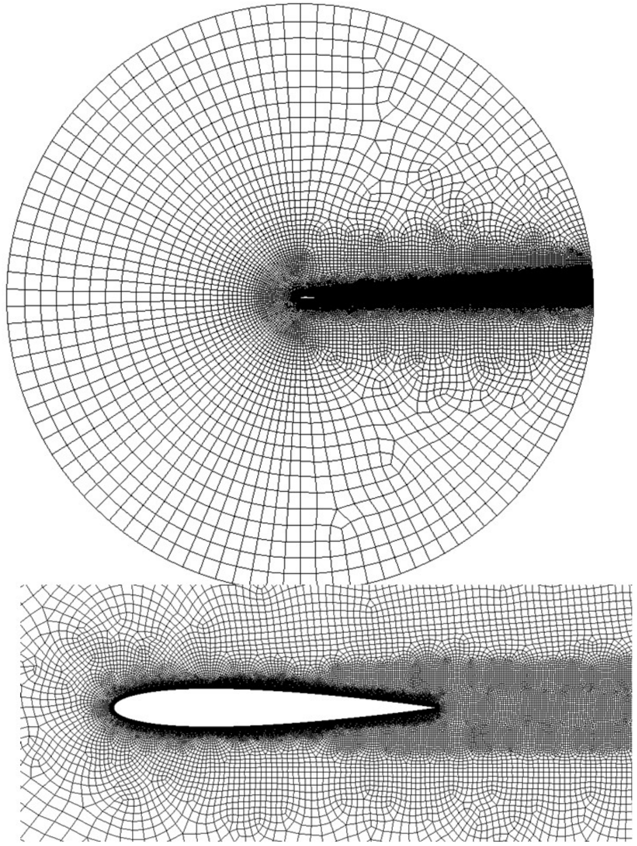
- The M-fan blade profile is a NASA LS 0413 at the hub, with an increased camber, tapered to a NASA LS 0409 at the fan tip.

- NASA LS 0409 and 0413, and NACA 0012 airfoil profiles are modelled corresponding with the chord length and tangential velocity of the blade at three span positions: the hub, center span and tip of the blade for the 1.542 m diameter fan rotating at 718 rpm with a tip clearance of 5.5 mm (conditions during experimental fan noise measurements).

- To investigate airfoil noise scaling, shorter and longer chord lengths are also modelled at the same free stream velocities.

Airfoil trailing edge noise modelling

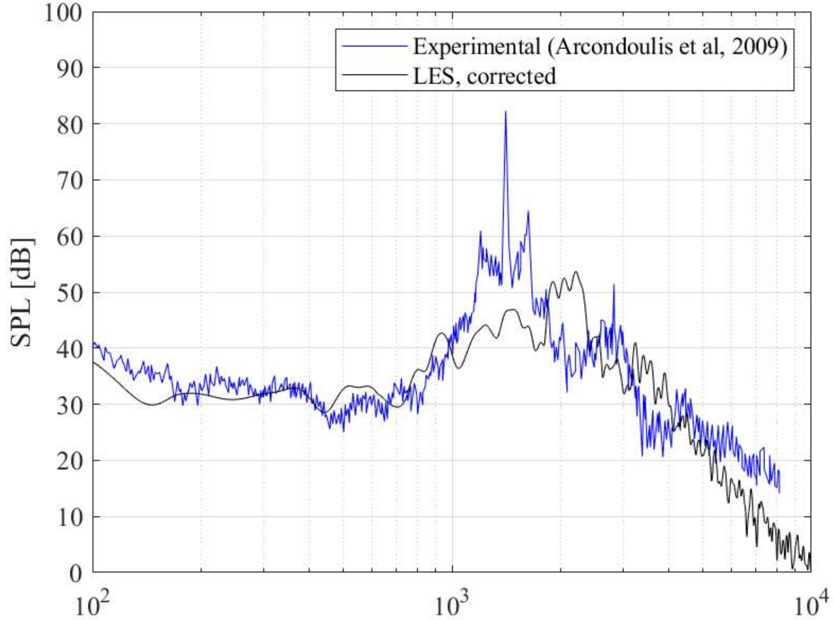
- Airfoil noise is modelled with Large Eddy Simulation (LES) in conjunction with the Ffowcs-Williams Hawkings acoustic analogy.
- The computational domains are circular with a radius of 16 chord lengths, with varying spanwise lengths.
- Unstructured mesh, hex dominant.
- Periodic boundaries in spanwise direction.
- Pressure fluctuations on airfoil surface is used to compute far field noise.
- A correction method is proposed to correct the SPL of the simulated spanwise length for a longer spanwise length (for example, to compare predicted noise to experimental measurements).



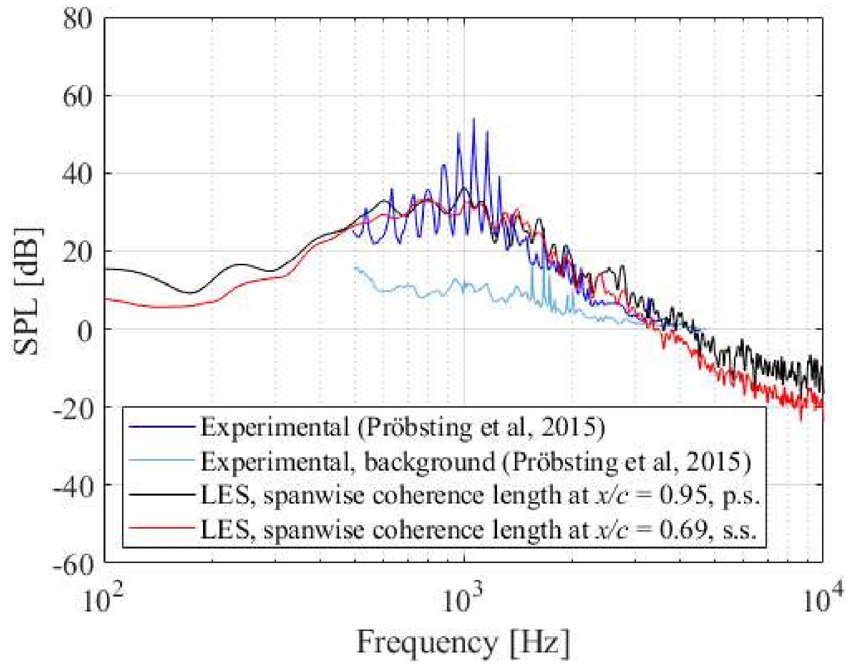
NACA 0012 airfoil mesh

Airfoil trailing edge noise modelling

- Noise modelling method is validated with experimental measurements for the NACA 0012 airfoil with 0° and 3° angle of attack.



0° angle of attack



3° angle of attack

Airfoil trailing edge noise modelling

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- Airfoil noise frequency is found to scale well with chord and free stream velocity, as described in literature:

$$f_2 = f_1 \left(\frac{\sqrt{c}}{u^{3/2}} \right)_1 \left(\frac{u^{3/2}}{\sqrt{c}} \right)_2$$

- Airfoil noise SPL is found to generally scale well with the boundary layer displacement thickness, δ^*, at the trailing edge:

$$\mathrm{SPL}_{\frac{1}{3},2} = \mathrm{SPL}_{\frac{1}{3},1} - \left(10 \log_{10} \left(\frac{M_0^5 \delta^* L}{r_e^2} \right) \right)_1 + \left(10 \log_{10} \left(\frac{M_0^5 \delta^* L}{r_e^2} \right) \right)_2$$

Trailing edge noise

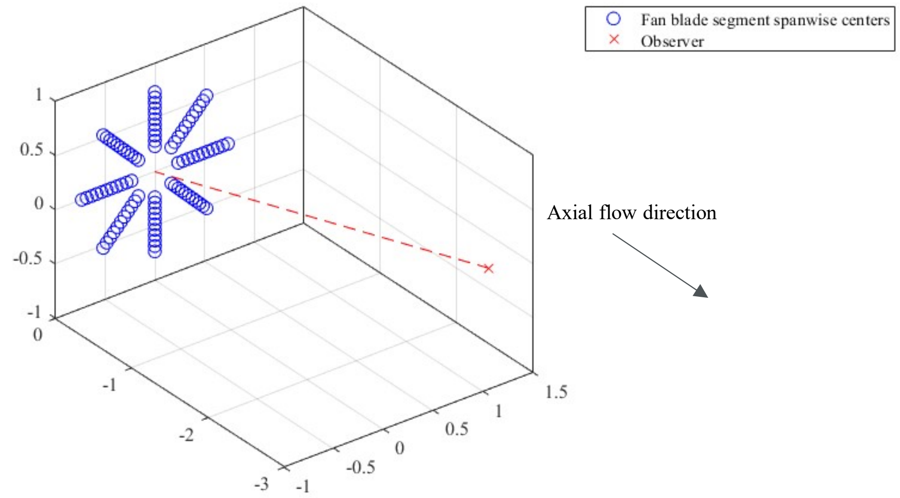
- For applying modelled airfoil noise to predict fan noise, the fan blade is divided into a number of segments in Matlab®.

- The average relative tangential velocity and the average angle of attack of each segment from the axial fan CFD is used to characterise the blade.

- The average camber and thickness of each segment is computed.

- The displacement thickness on the suction side for each segment is computed using XFOIL.

- For each segment, the closest match in thickness, free stream velocity and angle of attack is selected from the modelled airfoil noise.



8-bladed M-fan blade segments and an observer

Trailing edge noise

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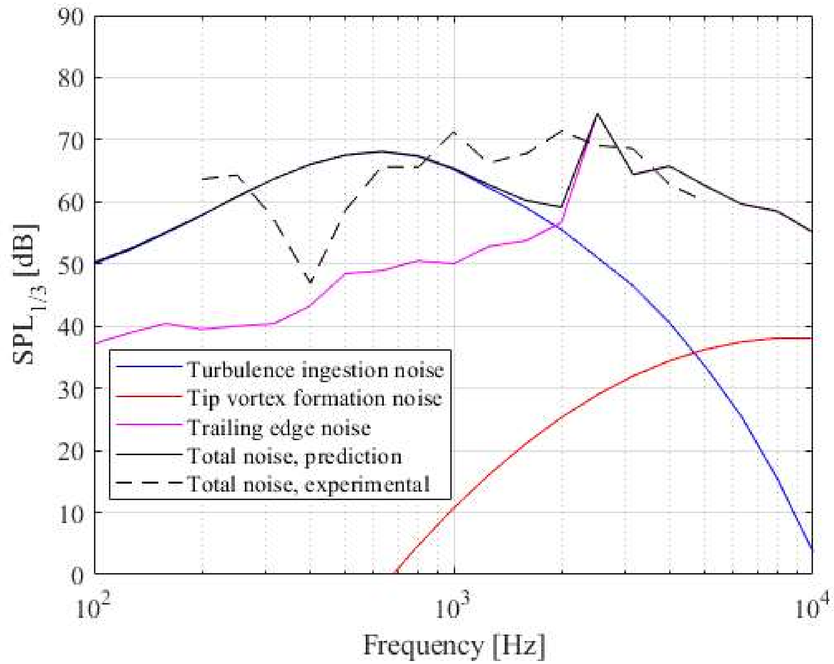
- A combination of weighted averaging and scaling of airfoil noise is used to compute the SPL generated by each section at the far field observer position.
- SPL of each segment is summed as uncorrelated sources; this assumption can be made as the segmentation method of Christophe et al (2008) is followed.
- The procedure is repeated for the same fan at the same tip speed and with a diameter of 3.084 m.

Total fan noise prediction

- Good agreement is found; predicted total A-weighted OASPL is 0.31 dB higher than that of the experimental measurements.



SPL generated by the 8-bladed M-fan with D_{fan} = 1.542 m, 5.49 mm tip gaps and volume flow rate of 13.80 m^3/s

Fan noise scaling

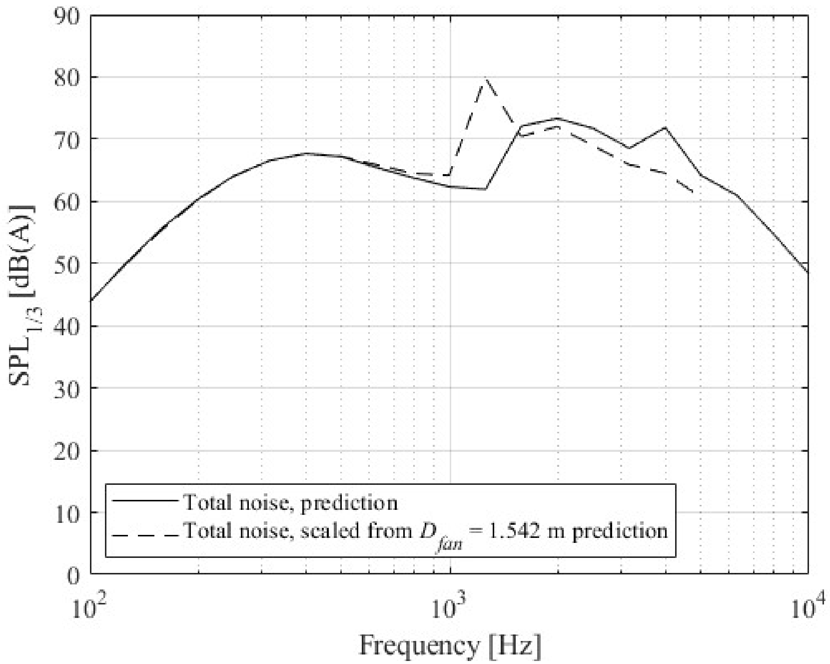
- The SPL predicted for the 1.542 m diameter fan is scaled as:

$$SPL_2 = SPL_1 + C \log_{10} \frac{D_{fan,2}}{D_{fan,1}}$$

  which corresponds to the form of a scaling method proposed by Graham & Hoover (1991), where the constant *C* is equal to 20.

- Total fan noise is found to scale well with *C* = 11.61, however, to be conservative, the entire spectrum can be scaled with *C* = 16.74, determined from the turbulence ingestion noise spectrum.

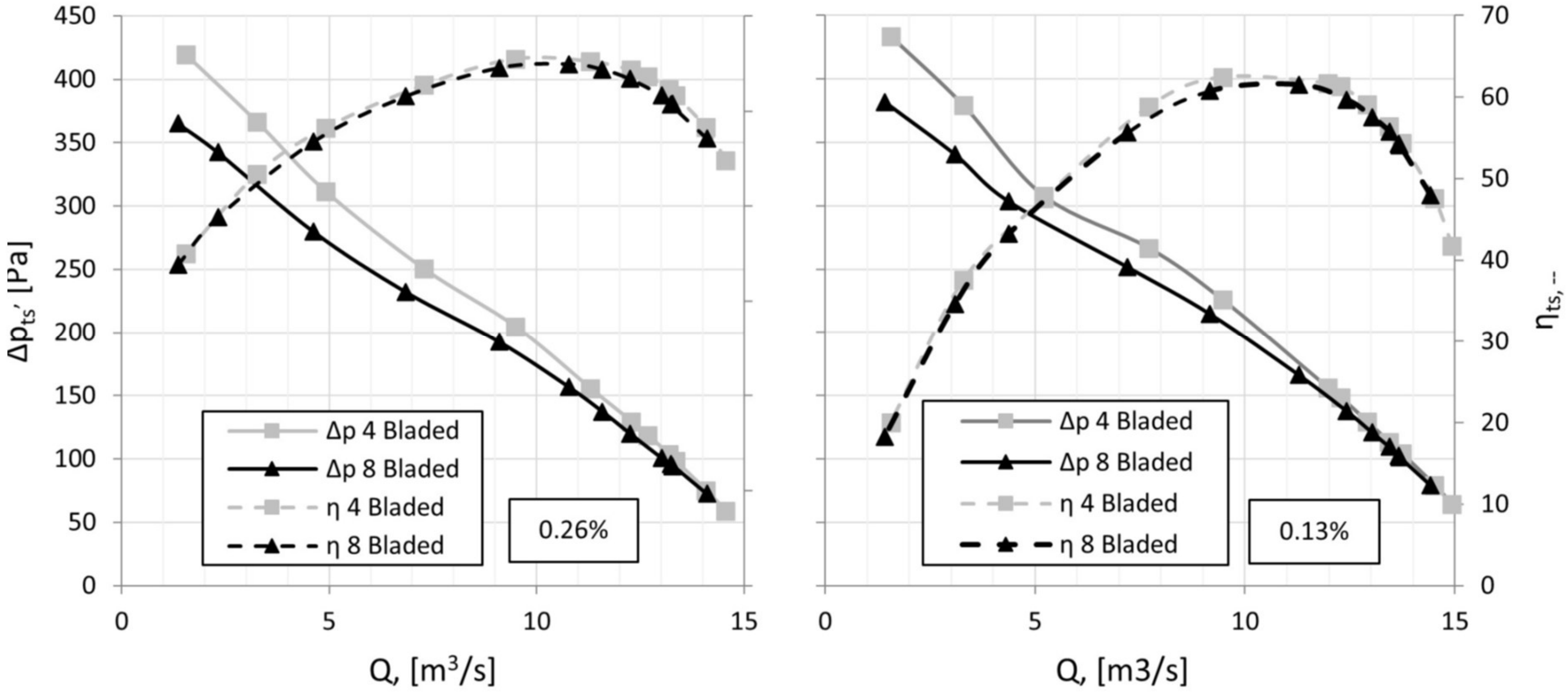
- Turbulence ingestion noise for the full-scale 7.3152 m diameter M-fan scales from 1.542 m diameter with *C* = 12.35.



SPL generated by the 8-bladed M-fan with D_{fan} = 3.084 m, 10.98 mm tip gaps and volume flow rate of 55.20 m^3/s

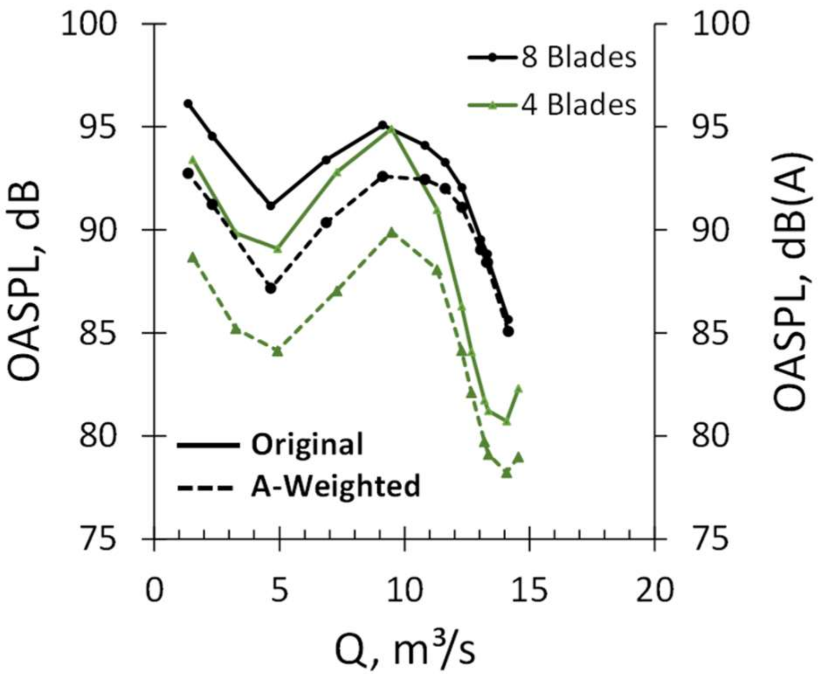
Fan noise measurement

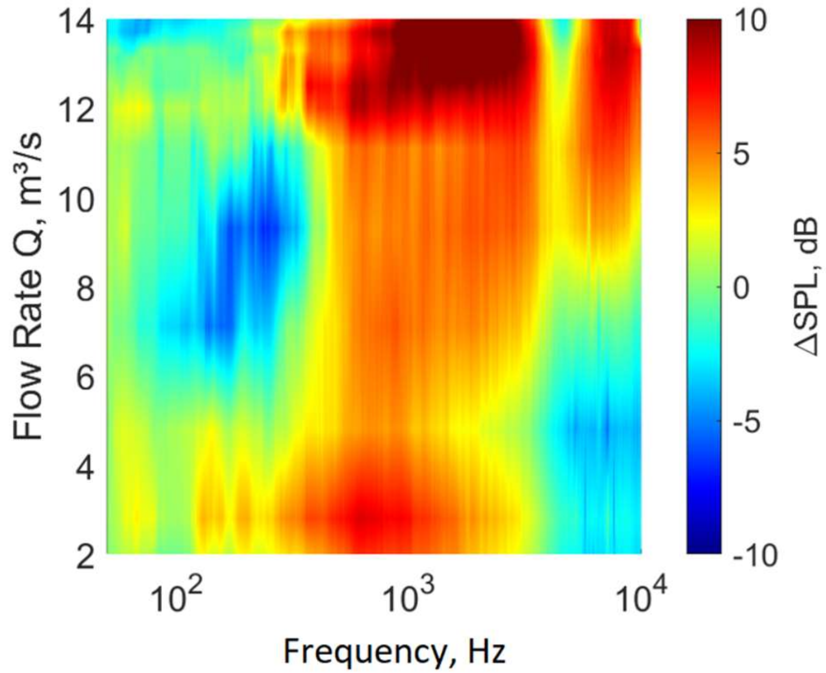
- Comparison of aerodynamic performance of 4- and 8-bladed fan at 2 mm and 4 mm tip clearance.



Fan noise measurement

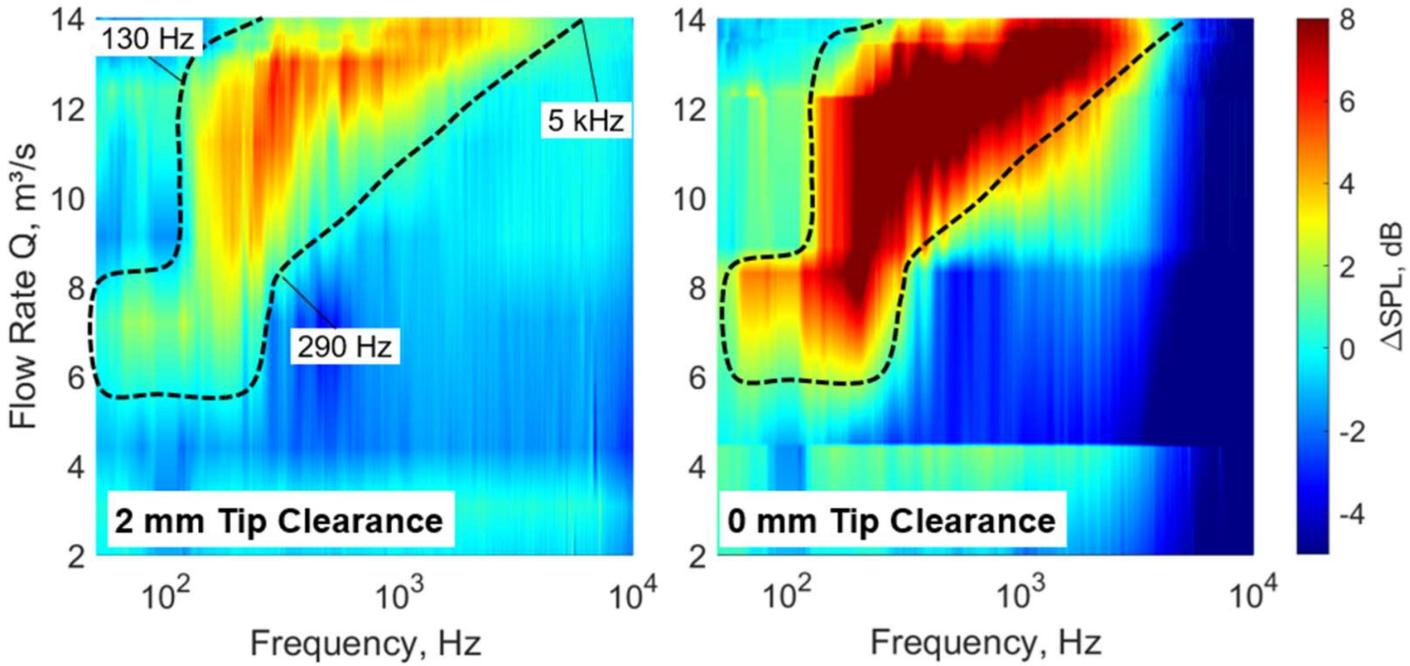
- Comparison of overall sound pressure level of of 4- and 8-bladed fan at 4 mm tip clearance (L) and spectral noise reduction from 8 to 4 bladed fan ®.





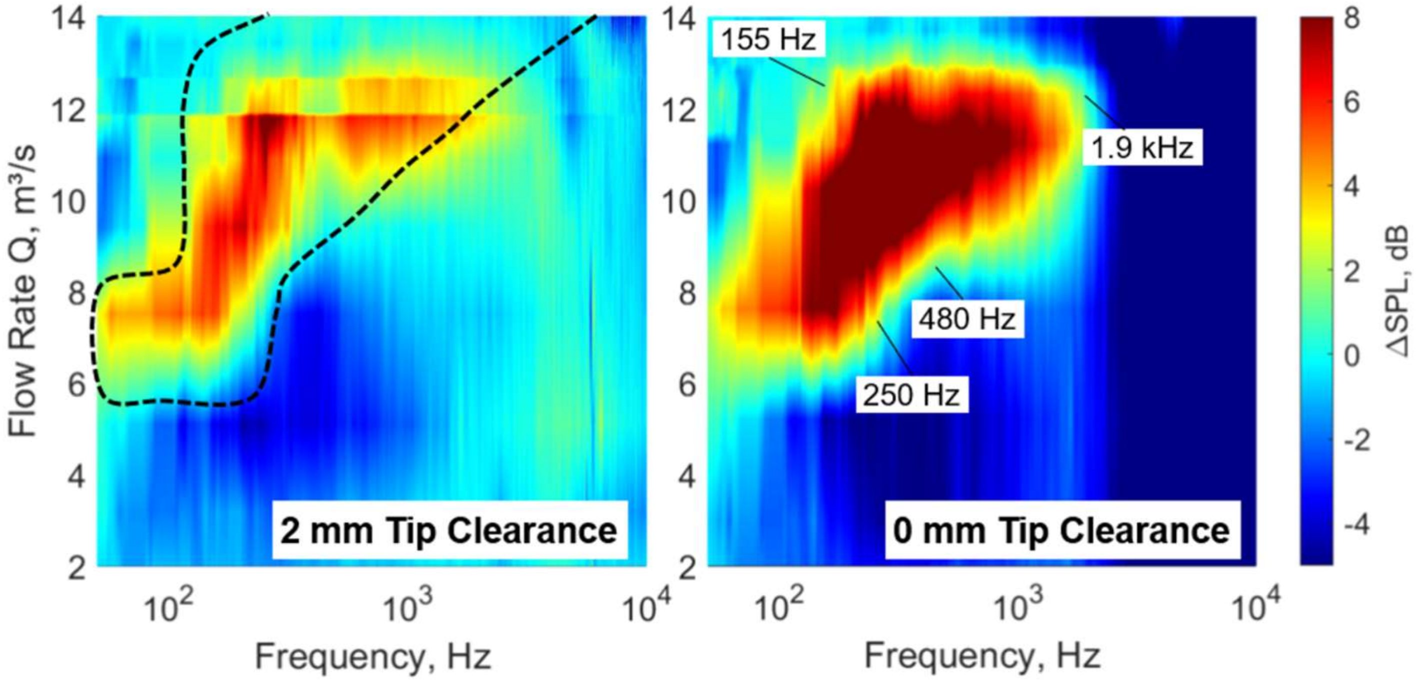
Fan noise measurement

- Comparison of tip clearance effects for 8-bladed fan, relative to 4 mm tip clearance.



Fan noise measurement

- Comparison of tip clearance effects for 4-bladed fan, relative to 4 mm tip clearance.



Conclusions

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- Fan performance can be modelled accurately in a 3-D CFD virtual test rig.
- By combining trailing edge noise strip theory and turbulence ingestion noise models, the total fan noise spectrum can be predicted numerically with good accuracy compared to the experimental measurements.
- The standard fan test facility can be used to perform comparative measurements to determine the noise characteristics of scaled fans.
- The fan tests facility will be modified further to reduce its self-noise characteristics during testing.

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VdSJ[0 These are all related to computational effects. What about other conclusions?
Van der Spuy, Johan [sjvdspuy@s, 2022-01-13T14:09:05.979