ME5106 Online Presentation:

# Aeroacoustics Simulation and Experimental Study based on IDDES/LES and On-the-fly FW-H Method:

*Taking Cooling Fans as an Example*

*Presenter:*
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*08. April 2024*

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# Contents

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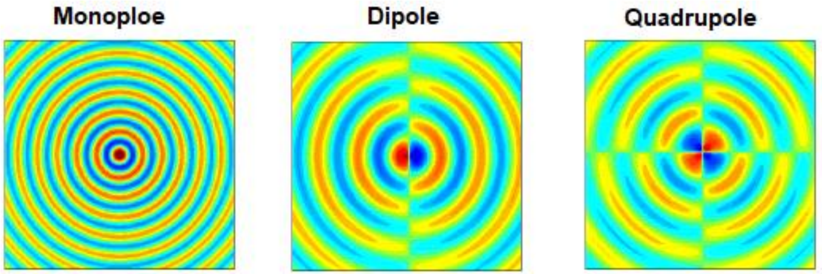
# **Theoretical Basis:** *Aeroacoustics Basis and Acoustic Analogy*

***Aeroacoustics Basis.***

*Source Type.*




Turbulent noise sources *(quadrupoles),* rotor surface pulsating force noise sources *(dipoles),* and aerodynamic noise sources caused by rotor motion *(monopoles)*

***Acoustic Analogy.***

- Kind of analytical method for flow-induced noise. Obtain acoustic information from flow fields.
- Main methods: Lighthill [1], Ffowcs Williams-Hawkings (FW-H) [2], Powell [3], etc. based on different terms.
- FW-H equation was used in this CAA case in STAR-CCM+.

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# Theoretical Basis: *CFD Platform and IDDES*

***Platform for CFD.***

*Software.* CFD platform used is Siemens STAR-CCM+*, which is a part of Siemens Simcenter, providing a multiple-condition CFD ability. Hardware. Case physics model: IDDES based on k-ε SST.

*Hardware.* The simulations were configured on a personal computer (Windows, 4C-8T), and computations were conducted on firstly a CFD server (Ubuntu, 128C-256T), later on Sugon Cluster (5Nodes, 320C-640T).

**License from PACE center, Tongji University, at which I am a part-time RA.*

***IDDES.***

Improved Delayed Detached Eddy Simulation (IDDES) [4] based on k-ω SST was used for this unsteady Computational Aeroacoustics (CAA) simulation.

- Good for vortices and eddies, which are strongly related to aeroacoustics
- Satisfactory computational power need
- Active RANS and LES in different regions
- Combines the advantages of DDES and WMLES models

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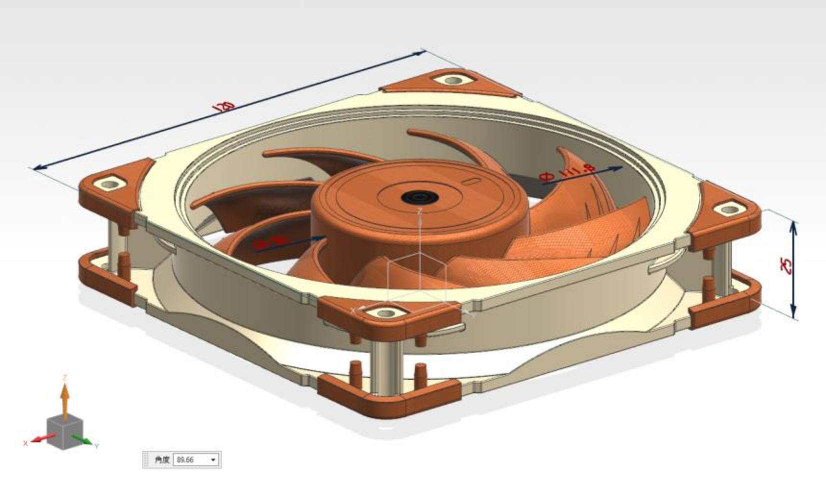
# Computational Aeroacoustics (CAA): *Model of Fans*

*Real Fans: Noctua NF-A12*25 .*

*CAD Model (with geometric parameters).*



*As the CAD model is announced by the original manufacture, it aligns preciously with the corresponding real fans!*

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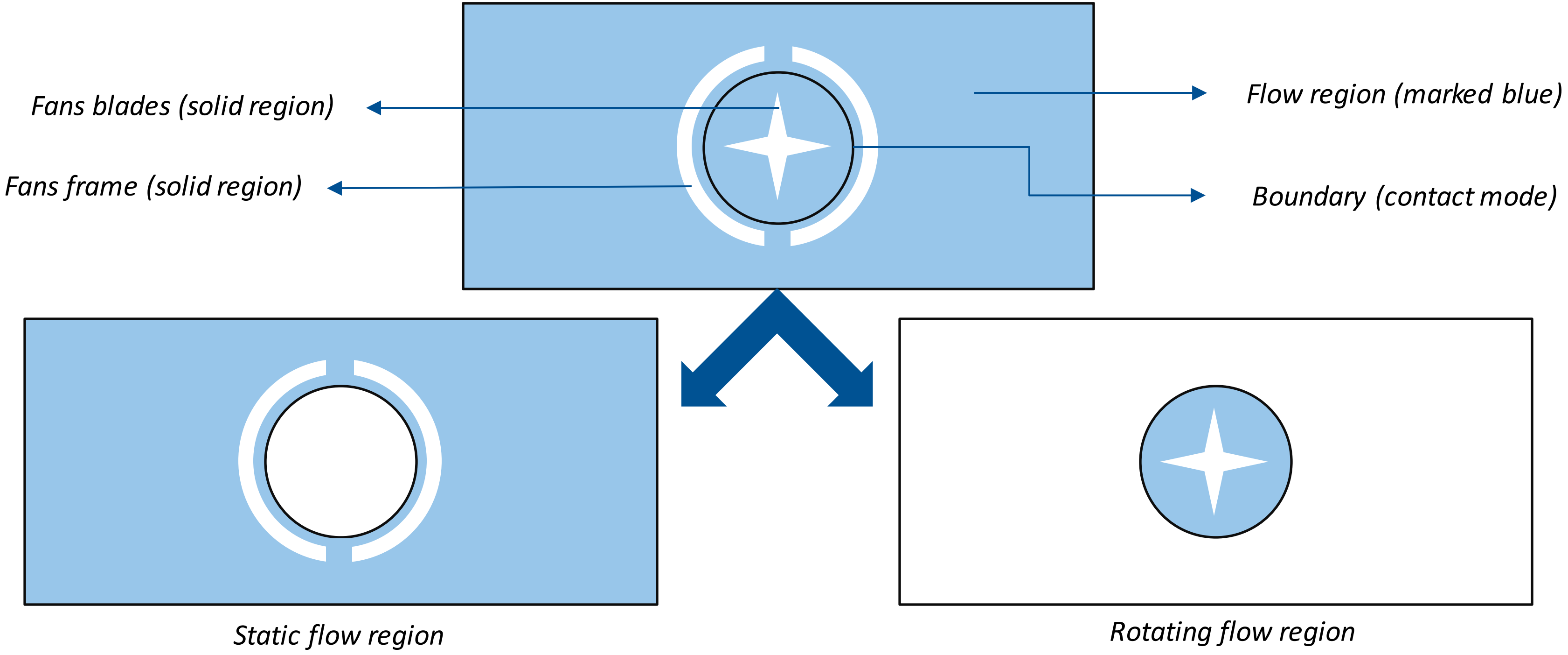
# Computational Aeroacoustics (CAA): *Rigid Body Motion*



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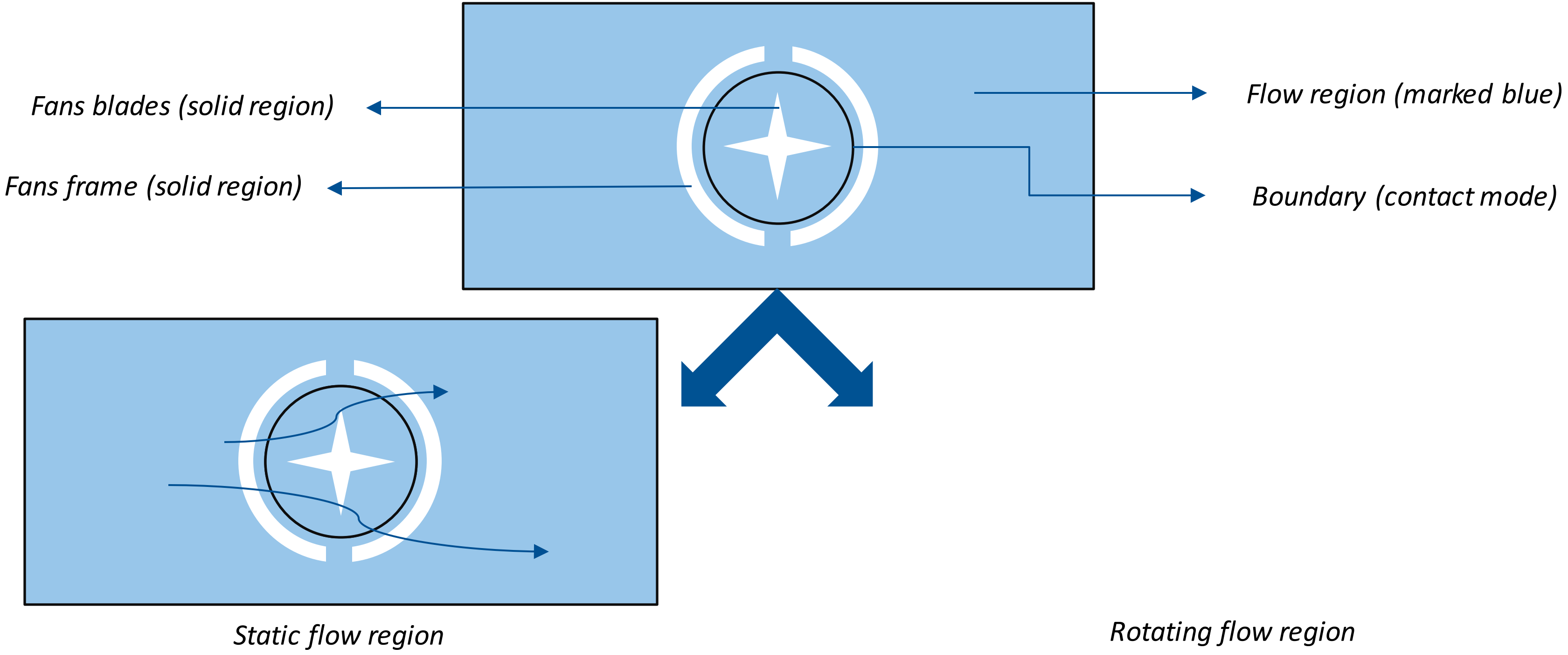
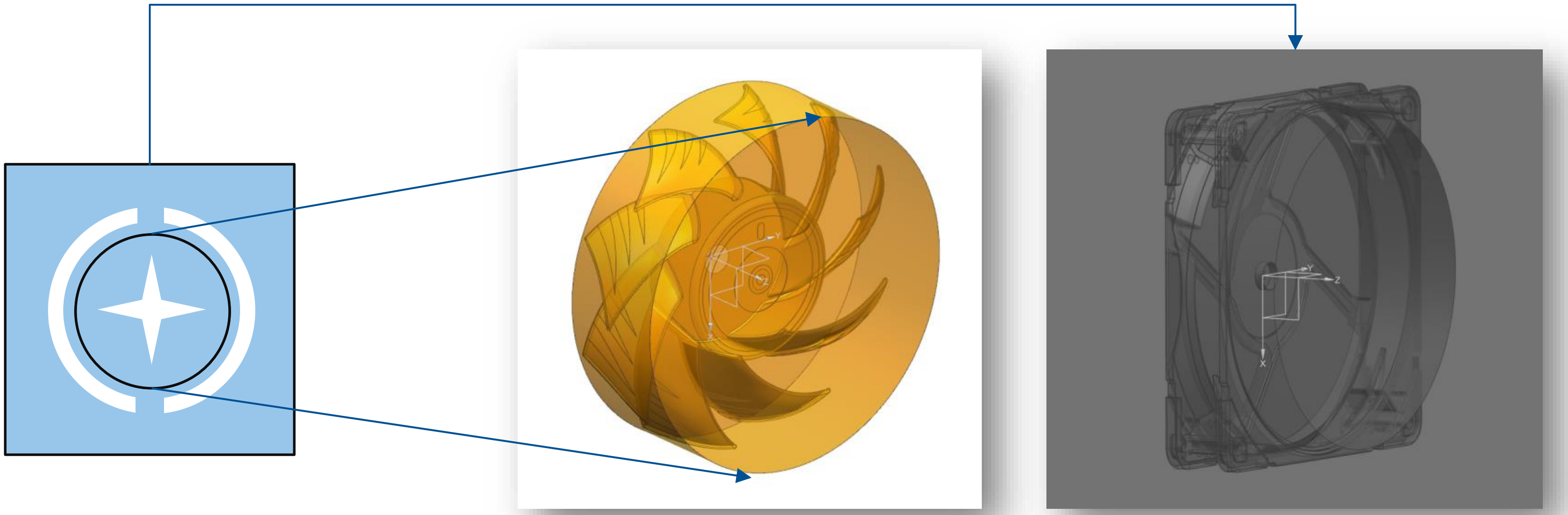
# Computational Aeroacoustics (CAA): *Rigid Body Motion*



# Computational Aeroacoustics (CAA): *Rigid Body Motion*



*Rotating flow region* *Static flow region (partly)*

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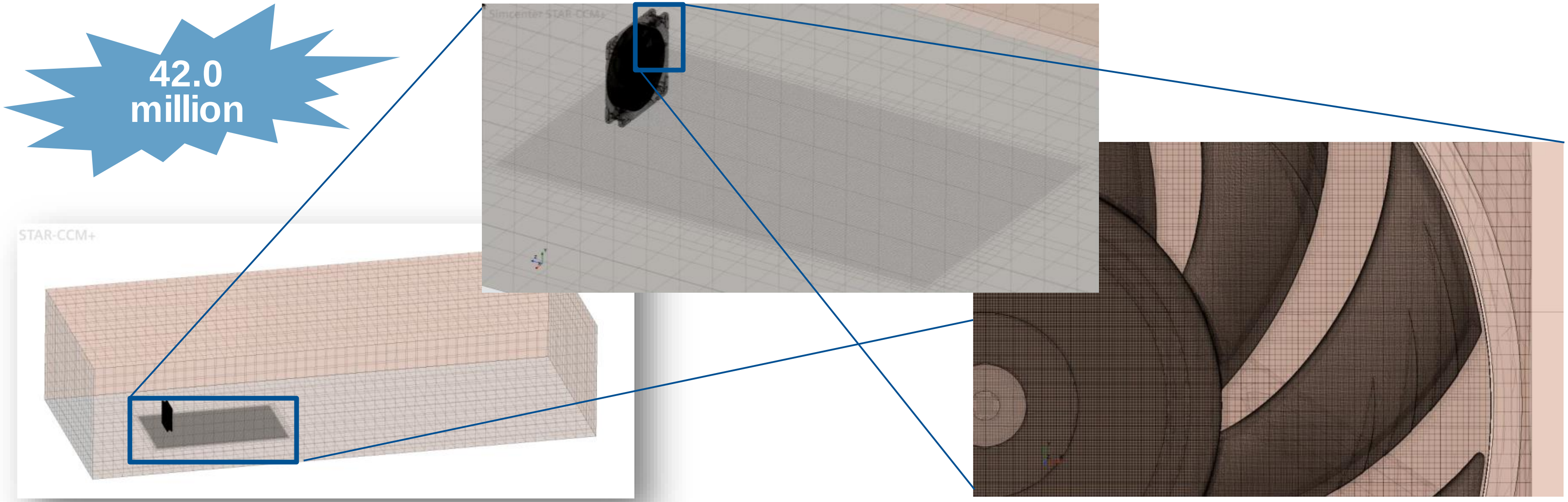
# Computational Aeroacoustics (CAA): *Meshing and Conditions*

**42.0 million**




*Why so high mesh number? Results of convergence check.*

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# Computational Aeroacoustics (CAA): *Meshing and Conditions*

## CFD Solver

Stop: *10,000* iterations, *10* iteration per dt

dt = *5e-4* s (first 10000 iter.s, 0.5 s), IDDES

dt = *1e-4* s (last 10000 iterations, 0.1 s), LES

Direct frequency resolution: *5,000* Hz

## Boundary

Blades, ground, frame: *Wall* (no-slip)

Five far boundary: pressure outlet *0 Pa*

Rotation region boundary: *imprint* (internal)

Contact update strategy: per time step

## FW-H Model

Mode: *On-the-fly* (real-time analogy)

Start: t > *0.05* s

FW-H surfaces: blades, ground

FW-H receivers: points (matching exp.)

## Initial Conditions

Velocity: *0 m/s*

Pressure: *0 Pa*

Turbulence intensity: *0.5%*

Relaxation Factor: *P 0.7, V 0.2*, warm-up

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# Computational Aeroacoustics (CAA): *FW-H Configurations*

FW-H mode: On-the-fly

FW-H surfaces: fans (blades, framework), wall

FW-H receiver: matching the experimental setups

FW-H solver execution time: 0.5s – 0.6x s

**Resolution frequency**

Lower range:

1 second / (0.6s – 0.5s) = 10 Hz

Higher range:

1 second/dt/2 = 5000 Hz

Finally: **10 Hz – 5000 Hz**

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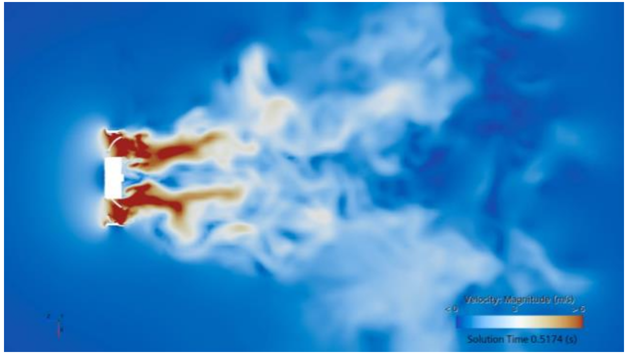
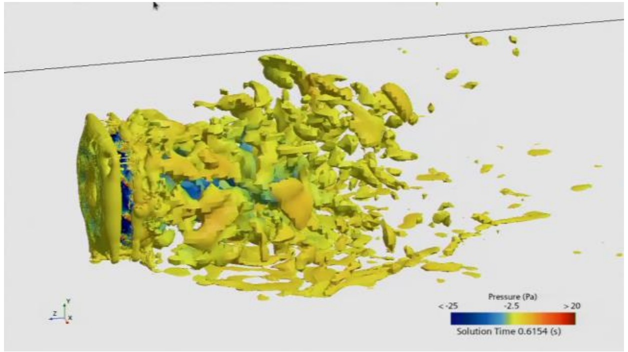
# Computational Aeroacoustics (CAA): *Results – Aerodynamics*

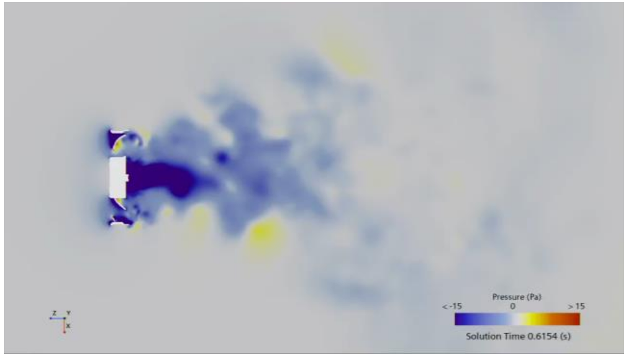
Velocity Magnitude

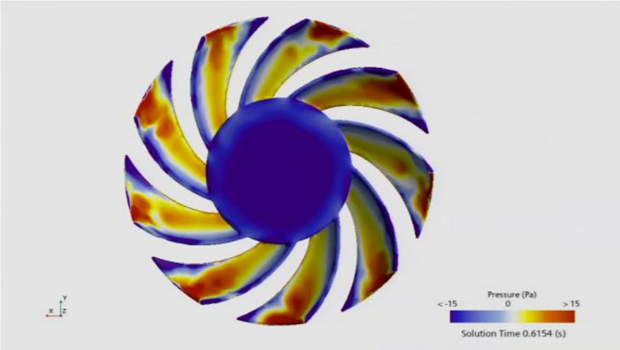



Q-criterion Iso-surface

Pressure (wake)




Pressure (blades)

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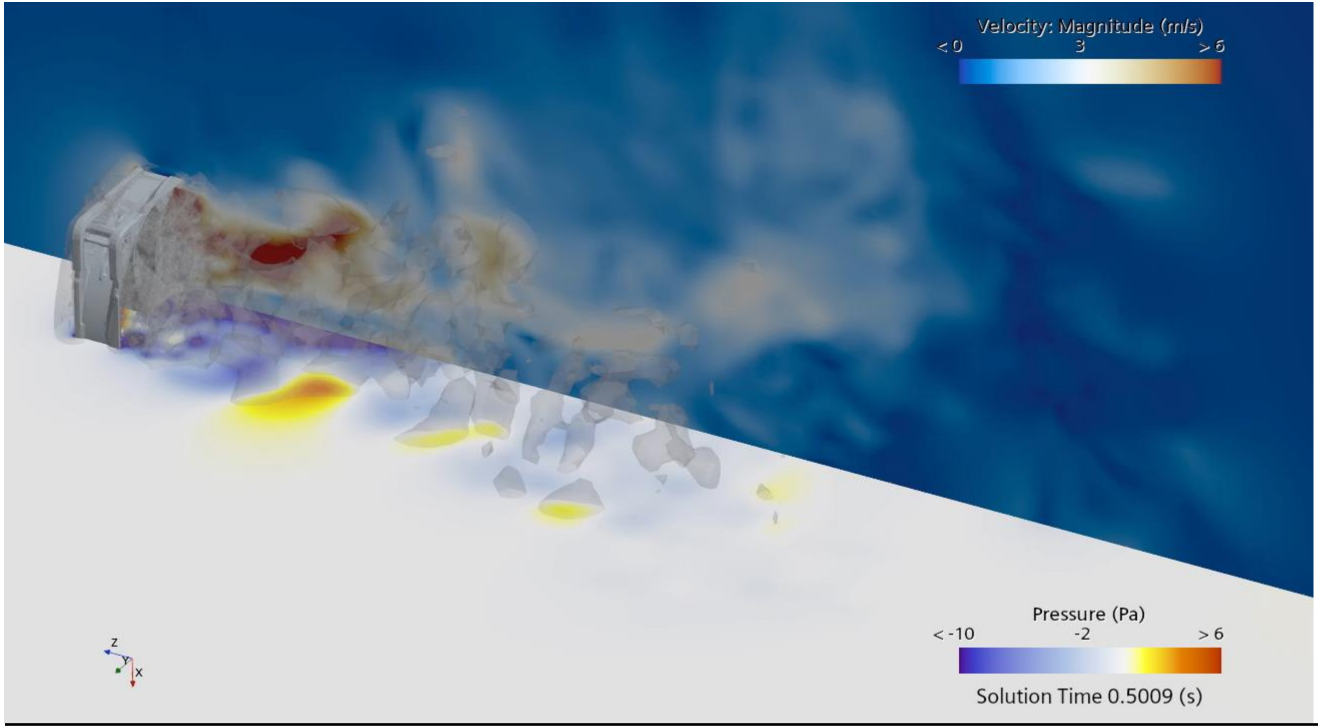
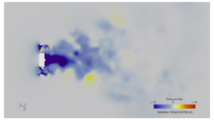
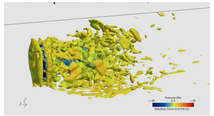
# Computational Aeroacoustics (CAA): *Results – Aerodynamics*





COLORFUL

FUNNY

DRAWING

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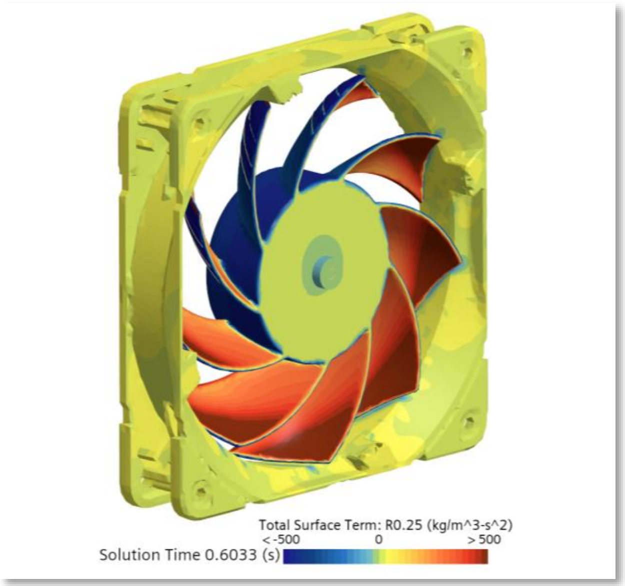
# Computational Aeroacoustics (CAA): *Results – Aeroacoustics*




*Total Surface Term from the fans**


*Total Surface Term from the ground surface**

* FW-H receiver at measurement point #3 (0.25m, 0 m, 0.06m).

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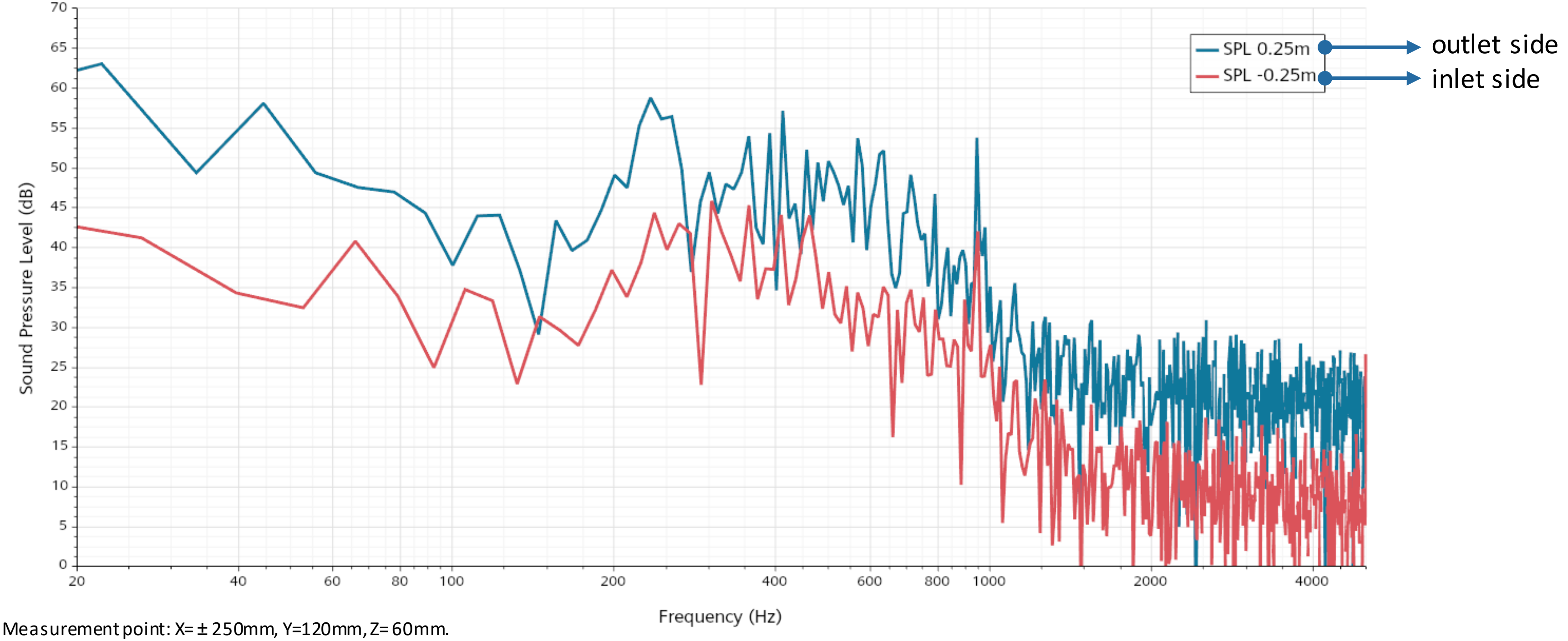
# **Computational Aeroacoustics (CAA):** *Results – Aeroacoustics*




Measurement point: X= ± 250mm, Y=120mm, Z= 60mm.

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# **Experimental Study:** *Equipment*

| | | | |
|---|---|---|---|
| *Photo* |  |  |  |
| *Name* | *Measurement Microphone* | *Hot-wire Anemometer* | *Contactless Tachometer* |
| *Model* | *MiniDSP UMIK-1* | *BENETECH GM8903* | *DT2236C* |
| *Output* | Varies of acoustic data | Velocity (single direction, m/s) | Revolutions per minute (RPM) |

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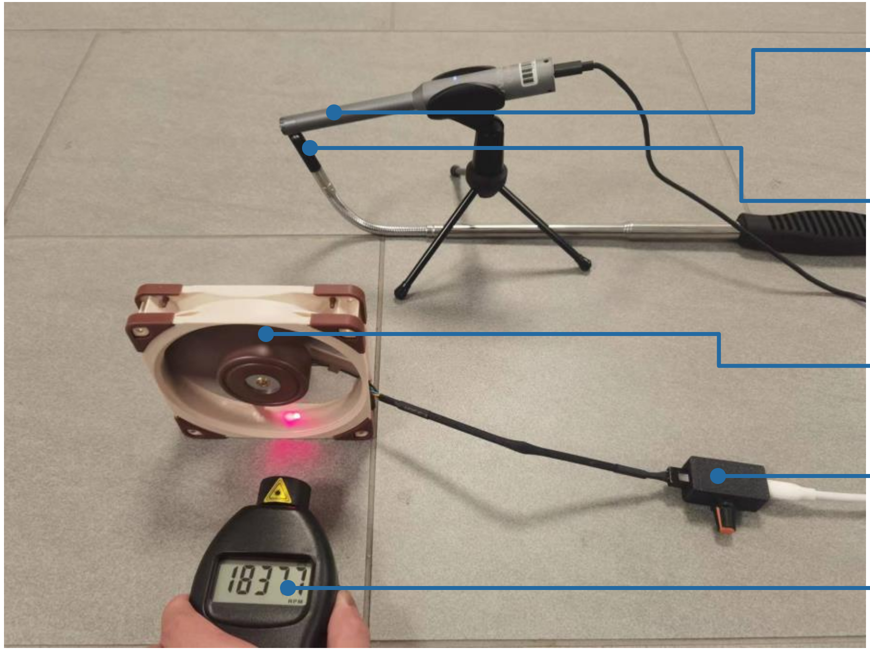
# Experimental Study: *Setups*




*Measurement Microphone **
*(to PC software REW)*

*Hot-wire probe*
*(to hot-wire DAQ)*

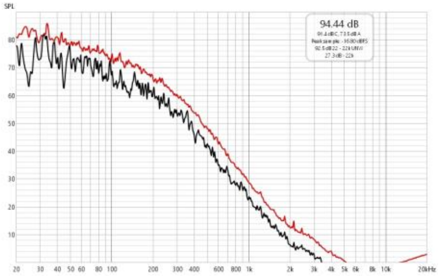
*Fans*

*PWM controller for Fans*
*(also serves as power supplier unit)*

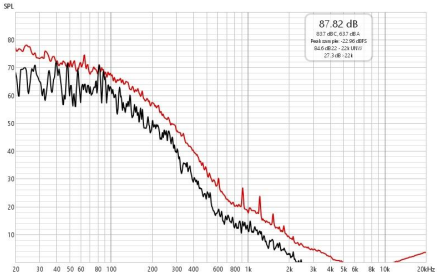
*Tachometer*
*(laser non-contact measuring mode)*

* Why not point to the fans? Air flow will affect the precision. For this case, 90-deg calibration file (instead of the general 0-deg one) was loaded, ensuring the reliability of this experiment.

# **Experimental Study:** *Results – Fans Position (Outlet)*



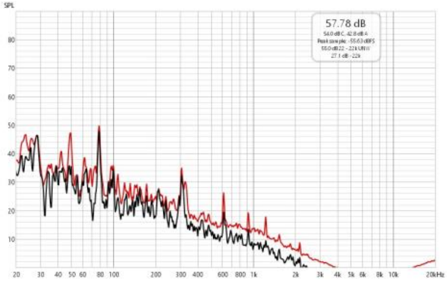

(0.10, 0)



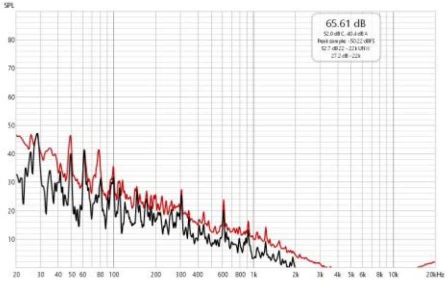

(0.25, 0)


(0.50, 0)

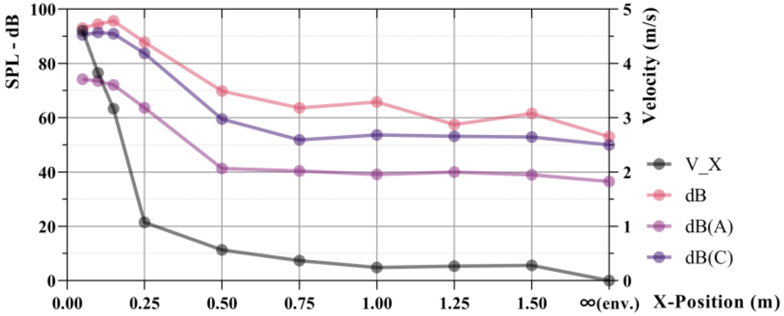

(0.75, 0)




(0.25, 0.40)




(0.50, 0.40)



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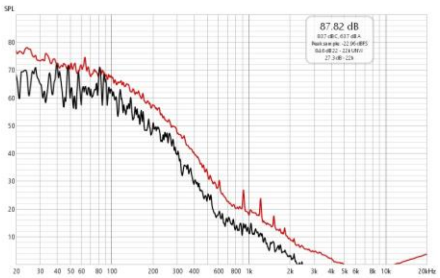
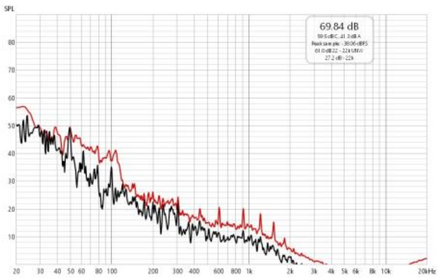
# **Experimental Study:** *Results – Fans Position (Outlet)*

(0.10, 0)

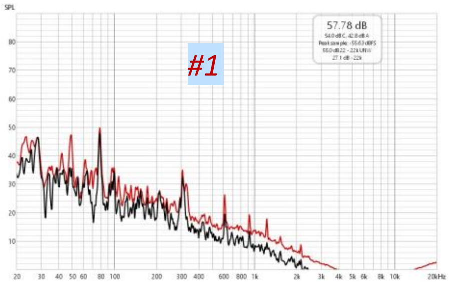


(0.25, 0)

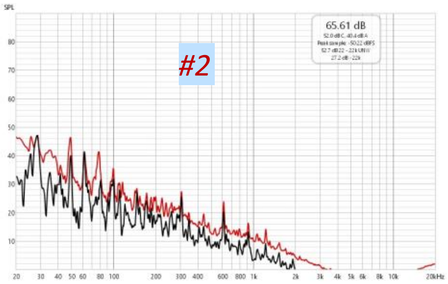


(0.50, 0)

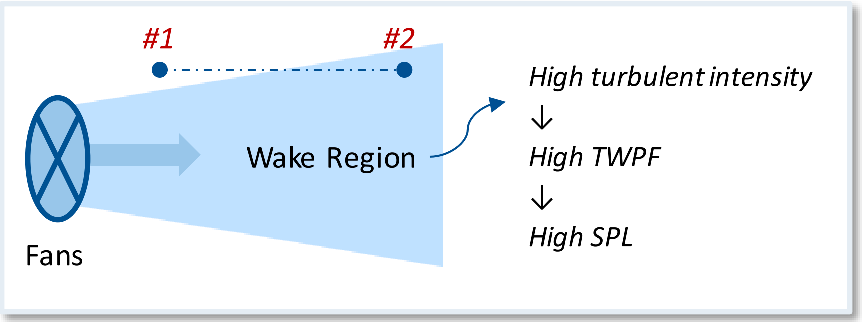
(0.75, 0)



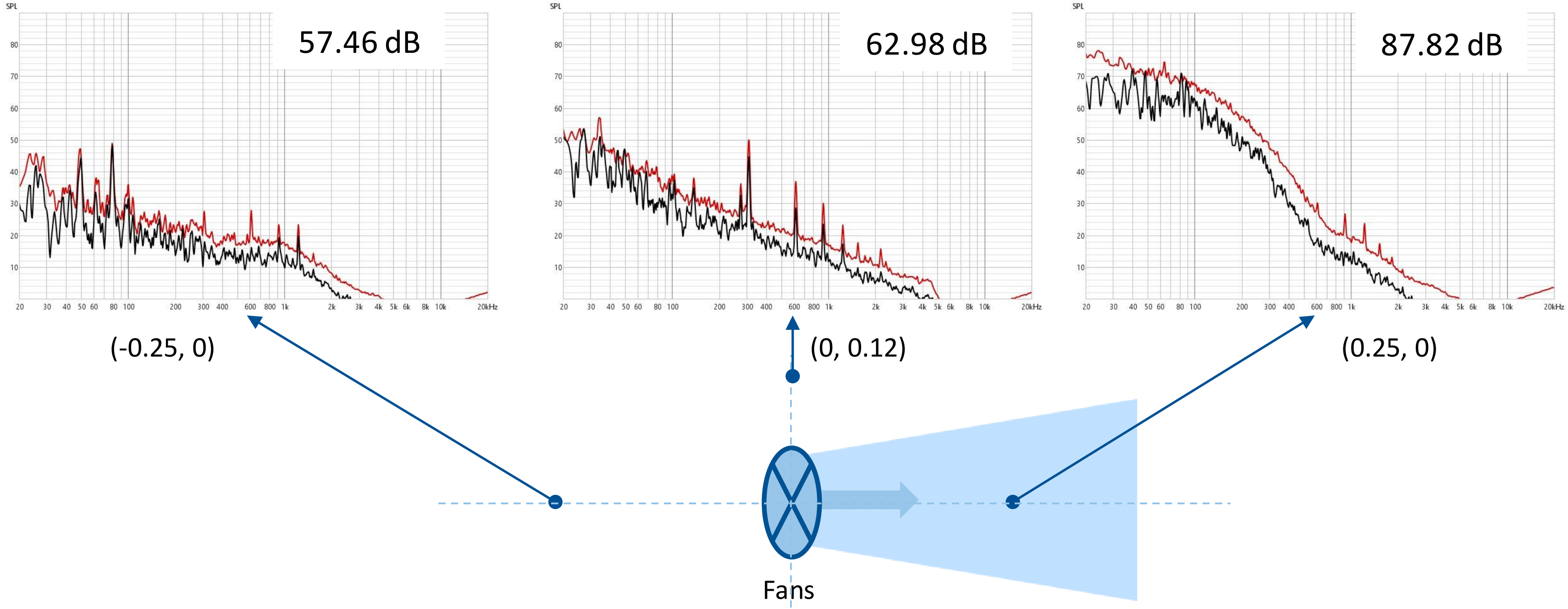
(0.25, 0.40)



(0.50, 0.40)



# Experimental Study: *Results – Fans Position (Inlet)*



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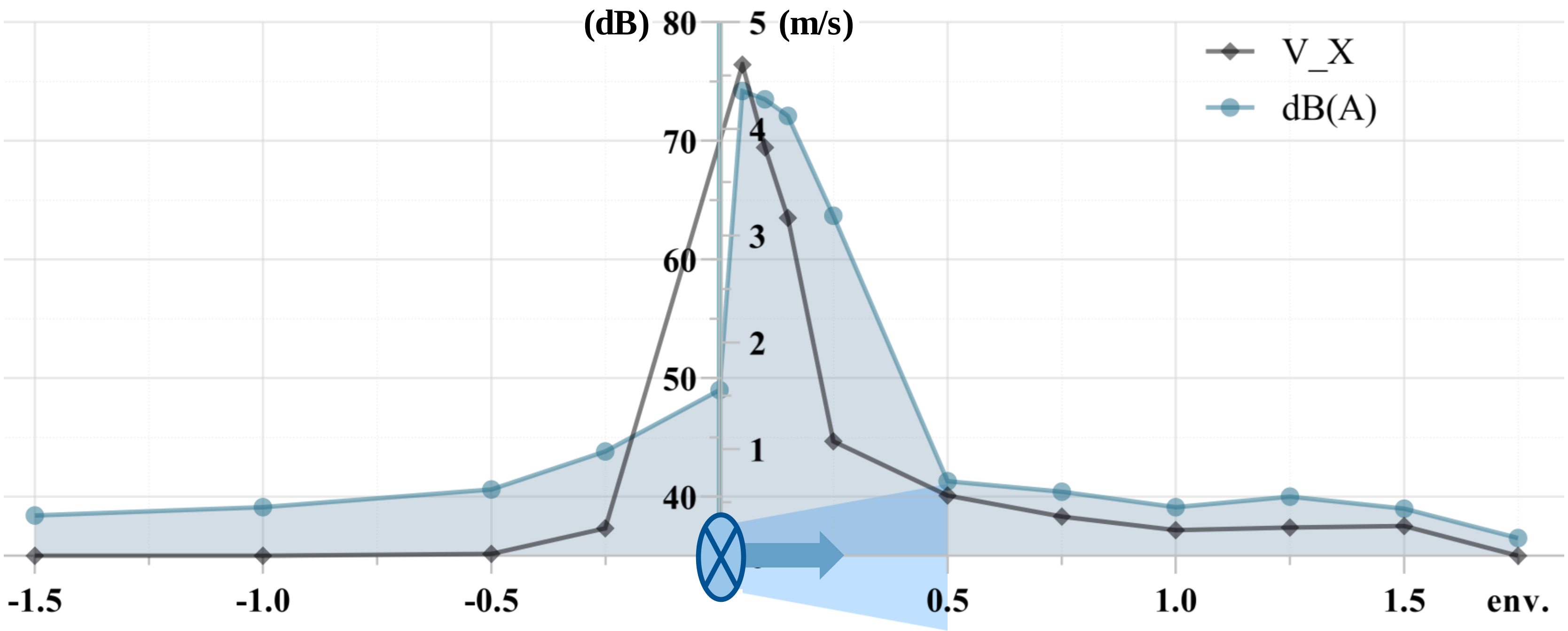
# Experimental Study: *Results – Fans Position*



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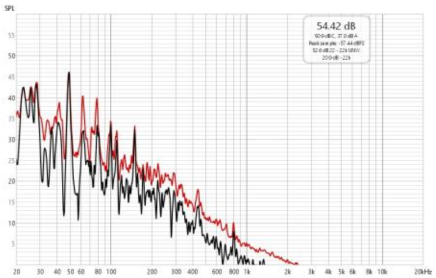
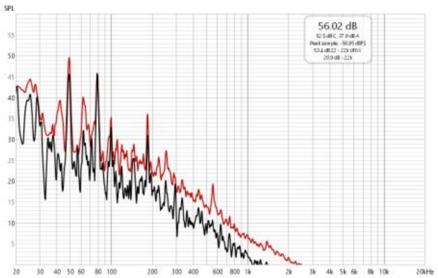
# Experimental Study: *Results – Fans RPM*


500 RPM

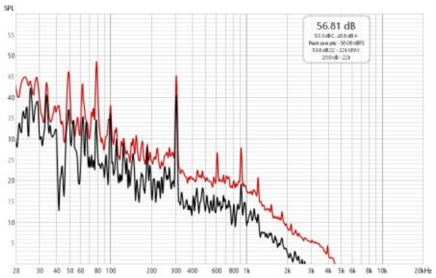



1000 RPM

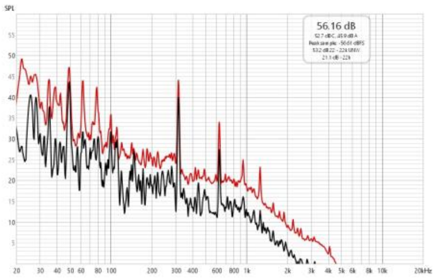



1250 RPM

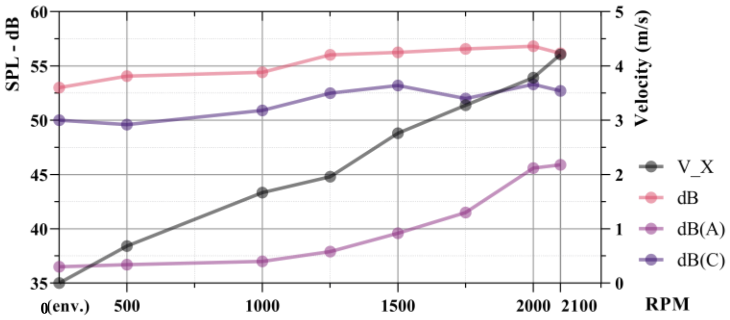

1500 RPM




2000 RPM




2100 RPM (max power)




*Measurement point: X=—250mm, Y=120mm, Z=60mm.

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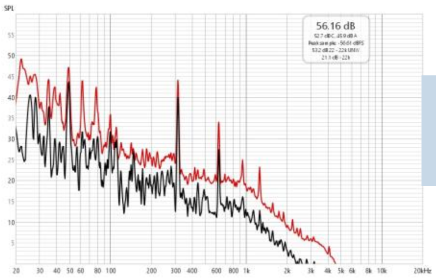
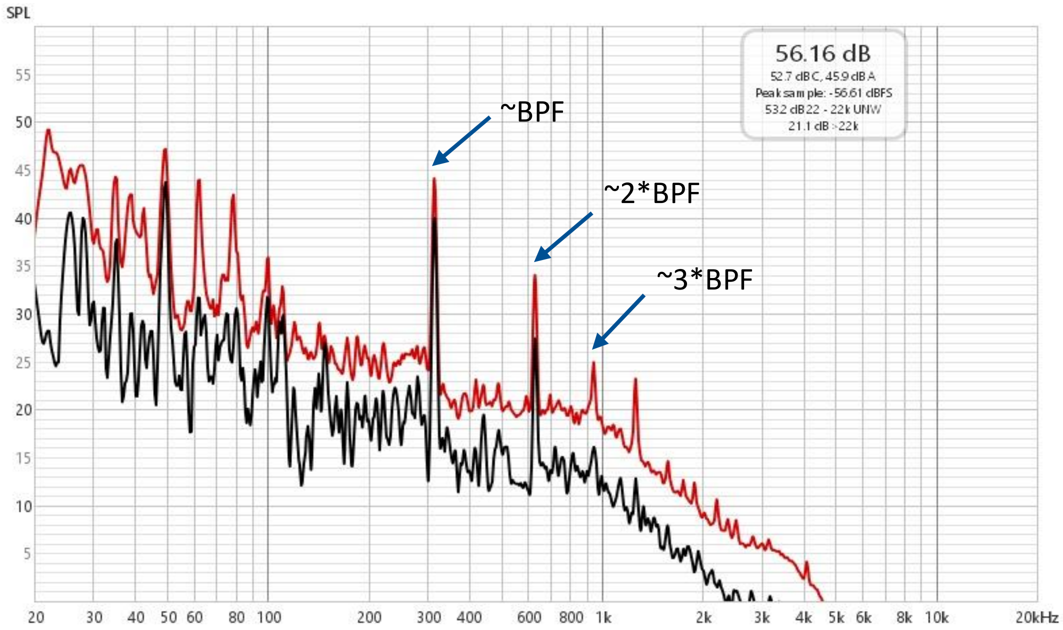
# Experimental Study: *Results – Fans RPM*

Blade Passing Frequency (**BPF**)
= RPM / 60 Hz * 9 blades

For this case, RPM = 2100,
Therefore, BPF = 315 Hz.



*zoom in …*



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# Experimental Study: *Results – Fans RPM*

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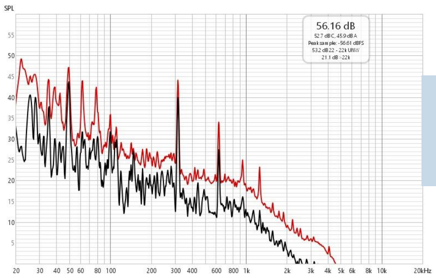
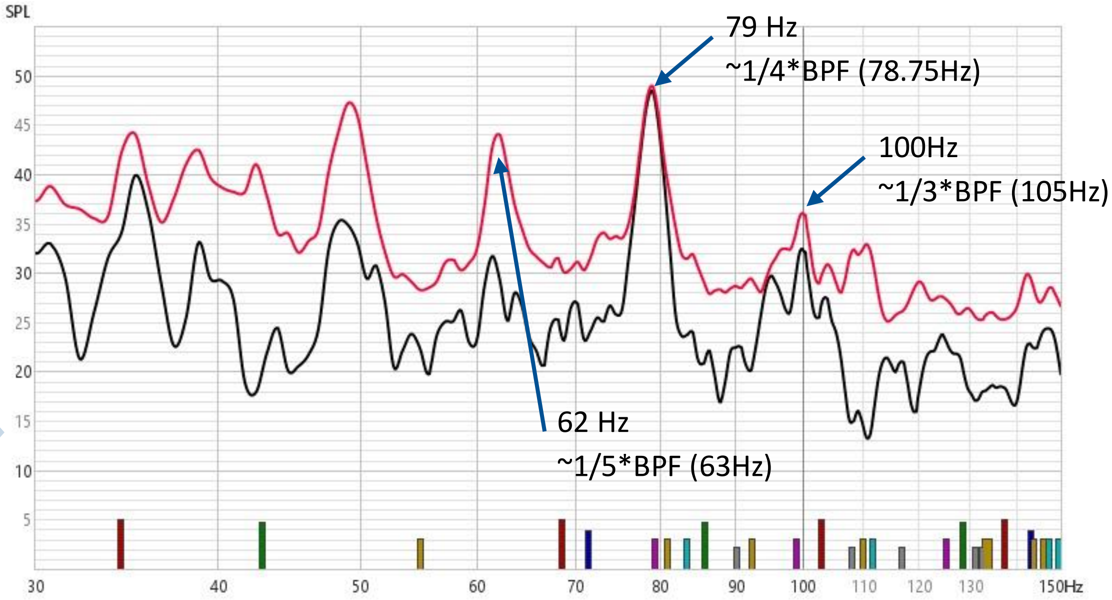



*zoom in …*



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# Experimental Study: *Results – Different Fans*

**Slimmer**: Arctic P12 Slim PWM PST
120mm × 120mm × 15mm

**Baseline**: Noctua NF-A12×25 PWM
120mm × 120mm × 25mm

**Bigger**: Noctua NF-A14 PWM
140mm × 140mm × 25mm

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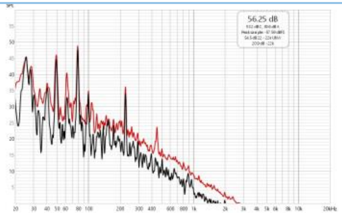
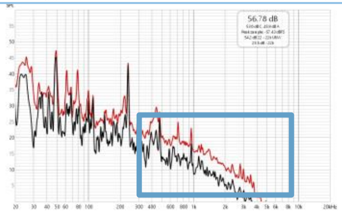
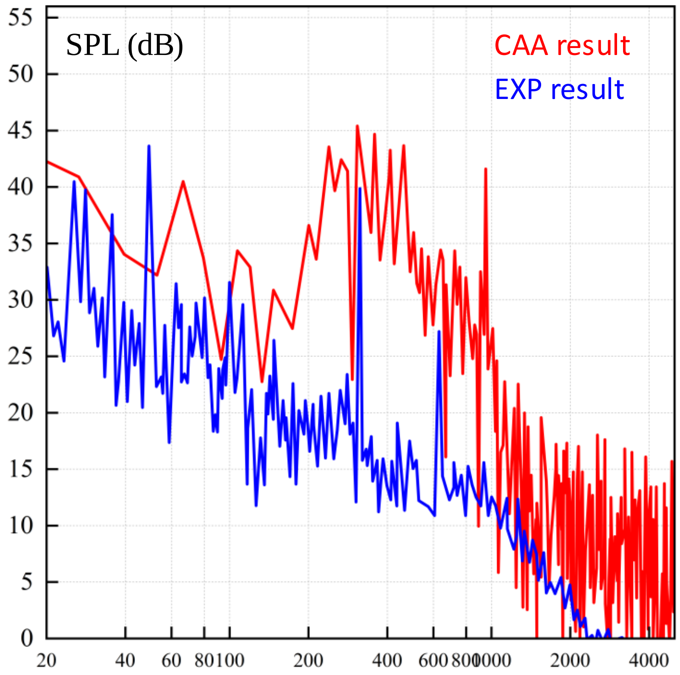
# Experimental Study: *Results – Different Fans (Same Flow Rate)*

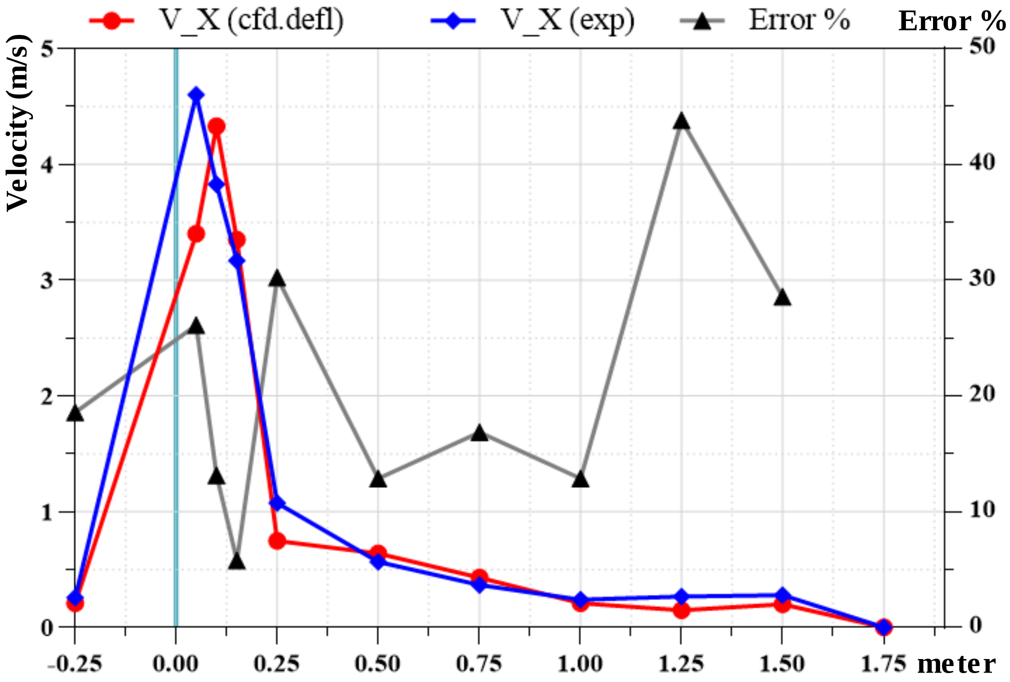
| **Fans Type** | Photo | Frequency | SPL – dB | SPL – dB(A) | Velocity |
|---|---|---|---|---|---|
| *"Baseline"* |  |  | 56.25 dB | 39.6 dB | 2.76 m/s |
| *"Bigger"* |  |  | 55.06 dB | 39.7 dB | 2.04 m/s |
| *"Slimmer"* |  |  | 56.78 dB | 45.9 dB* | 2.80 m/s |

*Congrat! Winner of ANNOYING PRIZE!

*Measurement point: X=120mm, Y=120mm, Z=60mm.

# **Compare:** *Between Simulations and Experiments*



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# Conclusion

1. Based on k-ε SST IDDES and on-the-fly FW-H, CAA shows reliable computational results, which generally match the experimental results (for spectrum, error still exists).
2. Mid-high rotation rate is the “sweet zone” for cooling fans, demonstrating a balance between aeroacoustics noise (SPL) and performance (air flow rate).
3. Significant peaks occur at frequencies that are multiples or fractions of the Blade Passing Frequency (BPF) of the fans.
4. The outlet side is dominated by turbulent wall pressure fluctuation (TWPF), while in the inlet region, acoustic wall pressure fluctuation (AWPF) is the leading modal.
5. As having higher turbulence intensity, jet wake region has higher TWPF components, exiting the noise, especially at the low-frequency range.
6. As for same cooling effect (air flow rate), bigger fans has little better acoustic performance, while slimmer ones are noisier.

# References

## Cited in Slides


1. N. Curle and M.J. Lighthill, *The influence of solid boundaries upon aerodynamic sound.* Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 1997. **231**
2. J.E. Ffowcs Williams, et al., *Sound generation by turbulence and surfaces in arbitrary motion.* Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 1997. **264**.
3. A. Powell, *Theory of Vortex Sound.* The Journal of the Acoustical Society of America, 1964. **36**.
4. M.S. Gritskevich, et al., *Development of DDES and IDDES Formulations for the k-ω Shear Stress Transport Model.* Flow, Turbulence and Combustion, 2012. **88**.


## Referred without citation


1. F. Farassat, *The Ffowcs Williams-Hawkings Equation — Fifteen Years of Research.* Aero- and Hydro-Acoustics, 1986.
2. Siemens Group, *Tutorials for Siemens NX: Aeroacoustics.* 2024.
3. N. Zhang, H. Shen, H. Yao, *Numerical simulation of cavity flow induced noise by LES and FW-H acoustic analogy*. Journal of Hydrodynamics, 2010. **22**.
4. E. Liu, et al., *Large Eddy Simulation and FW-H acoustic analogy of flow-induced noise in Elbow pipe*. Journal of Computational and Theoretical Nanoscience, 2015. **12**.
5. V. Strouhal, Ueber eine besondere art der tonerregung. Annalen der Physik und Chemie, 1878. **5**.
6. H. Oertel, Jr., Wakes behind blunt bodies. Annual Review of Fluid Mechanics, 1990. **22**.
7. C. H. K. Williamson, Vortex dynamics in the cylinder wake. Annual Review of Fluid Mechanics, 1996. **28**.
8. O. Inoue, N. Hatakeyama, Sound generation by a two-dimensional circular cylinder in a uniform flow. Journal of Fluid Mechanics, 2002. **471**.
9. A. Travin, M. Shur, Detached-Eddy Simulations Past a Circular Cylinder. Combustion, 2000. **63**.

# Thank you for your listening !

Huanxia WEI

08. Apr. 2024

# Backup: *IDDES Governing Equations*

## *Governing Equations.*

Incompressible N-S equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad (1)$$

Momentum conservation equation

$$\frac{\partial(\rho u)}{\partial t} + div(\rho u u) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_u$$
$$\frac{\partial(\rho v)}{\partial t} + div(\rho v u) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_v$$
$$\frac{\partial(\rho w)}{\partial t} + div(\rho w u) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + S_w \qquad (2)$$

Dissipation term introducing IDDES length scale

$$D_k = \rho \frac{k^{\frac{3}{2}}}{l_{IDDES}} \qquad (3)$$

IDDES length scale (the **switcher**)

$$l_{IDDES} = \tilde{f}_d (1 + f_e) l_{RANS} + (1 - \tilde{f}_d) l_{LES} \qquad (4)$$

Grid Correlation

$$\Delta = min\{max[C_w \Delta w_{min_{max}}, \Delta_{max}]\} \qquad (5)$$

## *Definitions in Equations.*

$$l_{DDES} = \tilde{f}_d l_{RANS} + (1 - \tilde{f}_d) l_{LES} \qquad (6)$$
$$l_{WMLES} = \tilde{f}_d (1 + f_e) l_{RANS} + (1 - f_B) l_{LES} \qquad (7)$$
$$\tilde{f}_d = max[(1 - f_{dt}), f_B] \qquad (8)$$
$$f_{dt} = 1.0 - tanh[(8 r_{dt})^3], \ f_B = min[2\,exp(-9\alpha^2), 1] \qquad (9)$$
$$\alpha = 0.25 - \frac{d}{\Delta_{max}} \qquad (10)$$
$$f_e = f_{e2} \cdot max[(f_{e1} - 1), 0] \qquad (11)$$
$$f_{e1} = \begin{cases} 2\,exp(-11.09\alpha^2); & \alpha \geq 0 \\ 2\,exp(-9\alpha^2); & \alpha < 0 \end{cases} \qquad (12)$$
$$f_{e2} = 1 - max(f_t, f_l) \qquad (13)$$
$$f_t = tanh[(c_t^2 r_{dt})^3], \quad f_l = tanh\left[(c_l^2 r_{dt})^{10}\right] \qquad (14)$$
$$r_{dt} = \frac{v_t}{\kappa^2 d^2\, max\left[\left(\sum_{i,j}\left(\frac{\partial u_i}{\partial x_j}\right)^2\right)^{0.5}, 10^{-10}\right]} \qquad (15)$$
$$r_{dl} = \frac{v_l}{\kappa^2 d^2\, max\left[\left(\sum_{i,j}\left(\frac{\partial u_i}{\partial x_j}\right)^2\right)^{0.5}, 10^{-10}\right]} \qquad (16)$$

Normally, the values of constants are: $C_W = 0.15$, $\kappa = 0.41$, $C_t = 1.87$, $C_l = 5.00$.

# **Backup:** *LES Governing Equations (Incompressible Version)*

## ***Governing Equations (Partly).***

Filtered N-S equation

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u_i u_j}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + 2\nu \frac{\partial}{\partial x_j}\bar{S}_{ij}; \quad (1)$$

Filtered Advection Term

$$\overline{u_i u_j} = \tau_{ij} + \bar{u}_i \bar{u}_j \quad (2)$$

Transformed Filtered N-S equation

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_i \bar{u}_j\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + 2\nu \frac{\partial}{\partial x_j}\bar{S}_{ij} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (3)$$

filtered governing equation for a passive scalar

$$\frac{\partial \bar{\phi}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u_j \phi}\right) = \frac{\partial \bar{J}_\phi}{\partial x_j} + \frac{\partial q_j}{\partial x_j} \quad (4)$$

## ***Derivations.***

Using Einstein notation, the Navier–Stokes equations for an incompressible fluid in Cartesian coordinates are

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}.$$

Filtering the momentum equation results in

$$\overline{\frac{\partial u_i}{\partial t}} + \overline{\frac{\partial u_i u_j}{\partial x_j}} = -\overline{\frac{1}{\rho}\frac{\partial p}{\partial x_i}} + \nu \overline{\frac{\partial^2 u_i}{\partial x_j \partial x_j}}.$$

If we assume that filtering and differentiation commute, then

$$\frac{\partial \bar{u}_i}{\partial t} + \overline{\frac{\partial u_i u_j}{\partial x_j}} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j}.$$

This equation models the changes in time of the filtered variables $\bar{u}_i$. Since the unfiltered variables $u_i$ are not known, it is impossible to directly calculate $\overline{\frac{\partial u_i u_j}{\partial x_j}}$. However, the quantity $\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j}$ is known. A substitution is made:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \left(\overline{\frac{\partial u_i u_j}{\partial x_j}} - \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j}\right).$$

Let $\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j$. The resulting set of equations are the LES equations:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}.$$