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Advanced Transitional Modelling for Calculation of Aerodynamic Self-Sustained Noise

Michele De Gennaro
AIT Austrian Institute of Technology G.m.b.H.
michele.degennaro.fl@ait.ac.at




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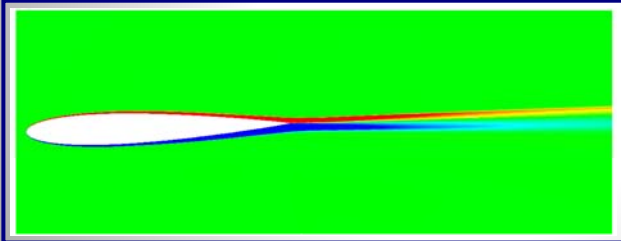
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- **Fundamentals of Computational Noise**
- **LBL-VS Noise**
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Introduction to Airfoil S-S Noise 


Airfoil Self-Generated Noise is the noise produced an aerodynamic surface in certain

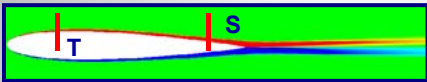
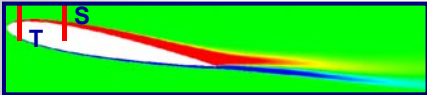
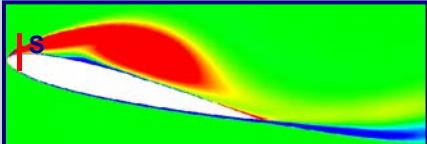
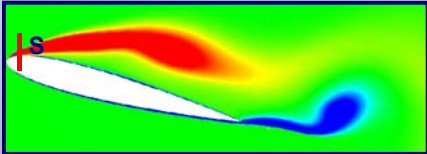


**NACA 0012
Dynamic Sinusoidal Pitch
(from -5deg to +15 deg)**


**Vortex Shedding
Vorticity Contours
(URANS)**

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Introduction to Airfoil S-S Noise 

0 deg		<p>Small Wake Structure Late Separation - Vortex $O(Re^{-1/2})$</p>
10 deg		<p>Defined Wake Structure Early Separation - Vortex $O(0.1c)$</p>
13 deg		<p>L.E. Vortex Generation Immediate Separation - Vortex $O(c)$</p>
15 deg		<p>Vortex Convection and T.E. Vort. Vortex $O(c)$</p>

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In this problems we have different scales of vortex

from **O(chord)** to turbulent scales **O(10^{-6/7} m)**

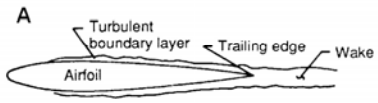
Macro-Scales from [m] to [mm]	}	Mass-Displacement (Monopole Sources)
		Body-Flow Interaction (Dipole Sources)
Micro-Scales from [mm] to [μm]	→	Unsteady Stresses Turbulence and Transition (Quadrupole Sources)

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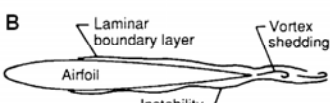
Airfoil Self-Generated Noise Classification [1]

A



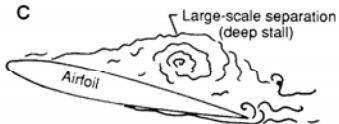
Turbulent-boundary-layer—trailing-edge noise

B



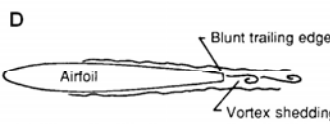
Laminar-boundary-layer—vortex-shedding noise

C



Separation-stall noise

D



Trailing-edge-bluntness—vortex-shedding noise


[1] Brooks, T.F., Pope, D. and Marcolini, M.A., “Airfoil Self-Noise and Prediction”, NASA Reference Publication 1218, 1989.

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Introduction to Airfoil S-S Noise

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Airfoil Self-Generated Noise concerns...



B737 – 40deg Flap Down
Landing Configuration



HAWT / Propeller in
Cruise Conditions



Cooler Fan
for Automotive,
HVAC and Electronic
Applications

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Fundamentals of Comp. Noise

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- > Sound is a fluctuating pressure disturbance of the flow that the human ear can hear
- > From a mathematical point of view it is a solution of N-S Equations

**Pressure =
Hydrodynamic Pressure + Acoustic Pressure**


$p' = 4.4934739 \text{ Pa}$
hydrodynamic field acoustic field

Direct Computation
Unfeasible

We need models ...

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Fundamentals of Comp. Noise



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A Milestone: The Lighthill's Equation, a rearrangement of the N-S equations into an inhomogeneous wave equation bridging the fluid dynamics with the acoustics.

$$\frac{1}{a_o} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2 L_{i,j}}{\partial x_i \partial x_j}$$

Quadrupoles

$$T_{i,j} = \rho u_i u_j + \tau_{ij} + (p - c_o^2 \rho) \delta_{ij}$$

Convection


Fluctuating part of the Reynolds Stress Tensor

Non-Linearities

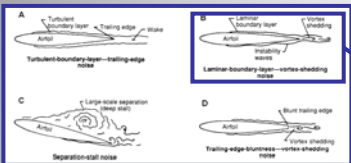
- + Solid Boundaries → Curle's Analogy
- + Relative motion between a fluid and a hard surface → Ffowcs Williams-Hawkings Analogy (Mono-Dipoles)

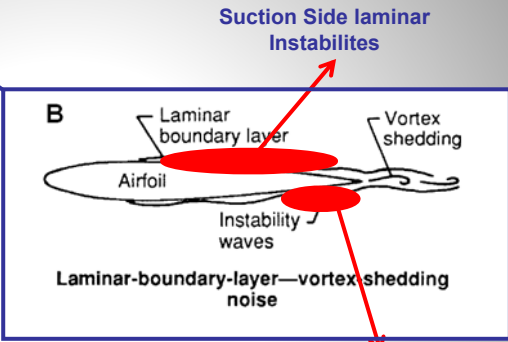
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LBL-VS Noise



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Laminar-boundary-layer—vortex shedding noise

LBL-VS Test Matrix

	AoA [deg]	Speed [m/sec]	Reynolds	Mach
Run-1	4	40	0.6M	0.11
Run-2	4	70	1.1M	0.20
Run-3	5	40	0.6M	0.11
Run-4	5	70	1.1M	0.20

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CFD and CAA Modelling



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Aerodynamic Modelling:


- NACA 0012, AoA = 4 deg - V = 70 m/sec
- 2D CFD Transient RANS (SIMPLE Segregated Solver)
- k- ω transitional (4-eqs) turbulence model
- 110 kCells grid ($y^+ = 1$)
- ANSYS-FLUENT 12.1

Aeroacoustic Modelling:

- (1) FWH Acoustic Analogy (embedded in FLUENT)
- (2) Volumetric Approach to Lighthill's Equation solved by FEM (External Solver, CFS++ from UniKlu)
- Simulation Time = 0.1 Sec \rightarrow Freq. Res. = 10 Hz
- Sampling Frequency = 50 kHz
- **LBL-VS \rightarrow Peaked Tonal Noise**

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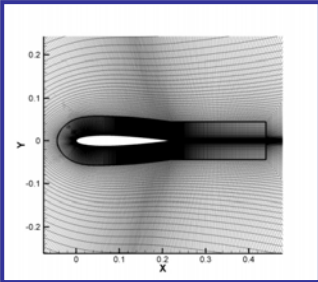
CFD and CAA Modelling



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- **FWH Acoustic Analogy, Surface Approach (ANSYS-Fluent)**
- Farassat-Brentner Formulation, Surface Approach, Propagation via Green's function.

$$\frac{1}{a_o} \frac{\partial^2 H(f)p'}{\partial t^2} - \nabla^2 [H(f)p'] = \frac{\partial^2}{\partial x_i \partial x_j} [\cancel{L_{i,j}} H(f)] + \frac{\partial F_i}{\partial x_i} \delta(f) + \frac{\partial Q}{\partial t} \delta(f)$$




Acoustic Surface Sources are computed on-the-fly at each time-step.

Then propagation is performed and the Acoustic pressure computed at microphone locations.

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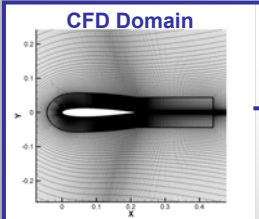
CFD and CAA Modelling




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- **FEM Approach (CFS++)**
 - Integral Formulation of the Lighthill Equation, resolution via FEM.

$$\int_{\Omega} w \frac{\partial^2 \rho'}{\partial t^2} d\Omega + \int_{\Omega} c_o^2 \frac{\partial w}{\partial x_i} \frac{\partial \rho'}{\partial x_i} d\Omega - \int_{\Gamma} c_o^2 w \frac{\partial \rho'}{\partial n} d\Gamma = - \int_{\Omega} \frac{\partial w}{\partial x_i} \frac{\partial L_{i,j}}{\partial x_j} d\Omega$$



CFD Domain




Acoustic Domain
PML

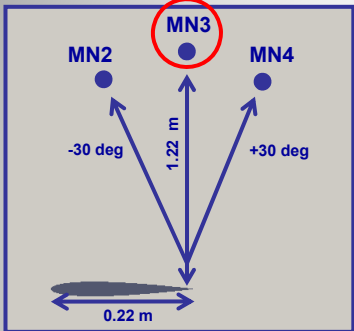
- Sources are computed and saved at each time step on the whole CFD grid (Right hand side term of equation above).
- Sources are interpolated and filtered (optional) on the acoustic grid.
- Propagation is computed via FEM in the whole domain with a PML B.C. (Non-Refl.).

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CFD and CAA Modelling



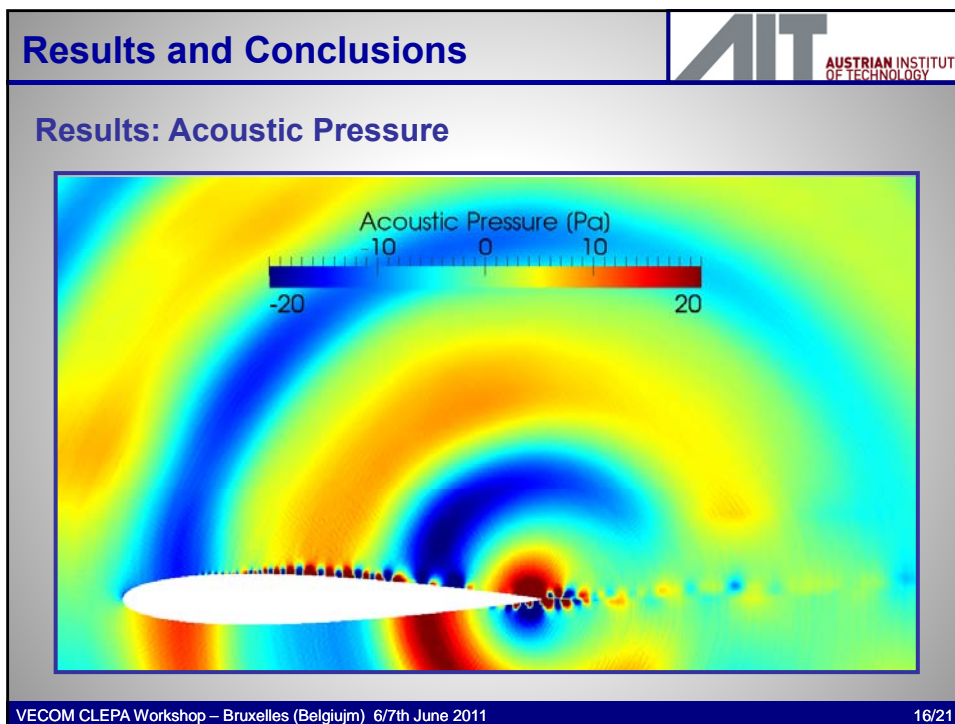
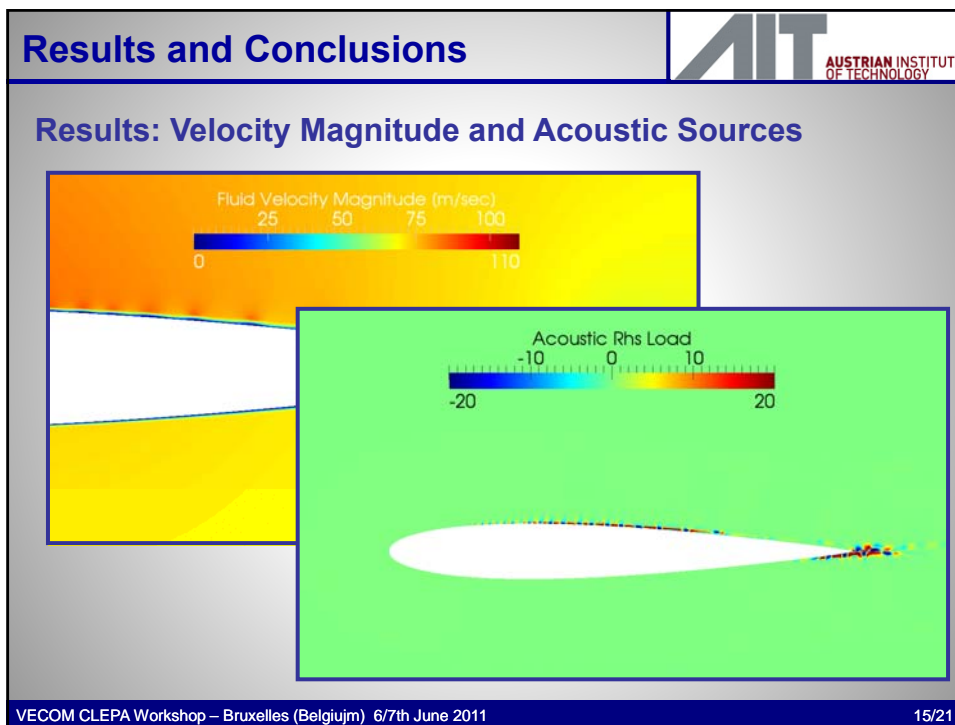
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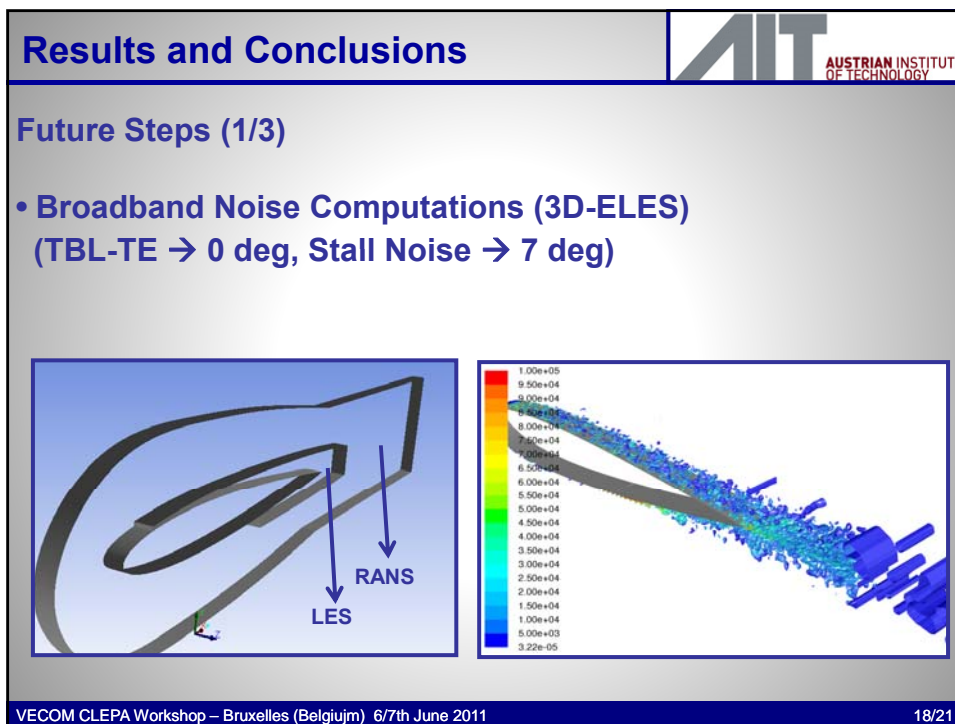
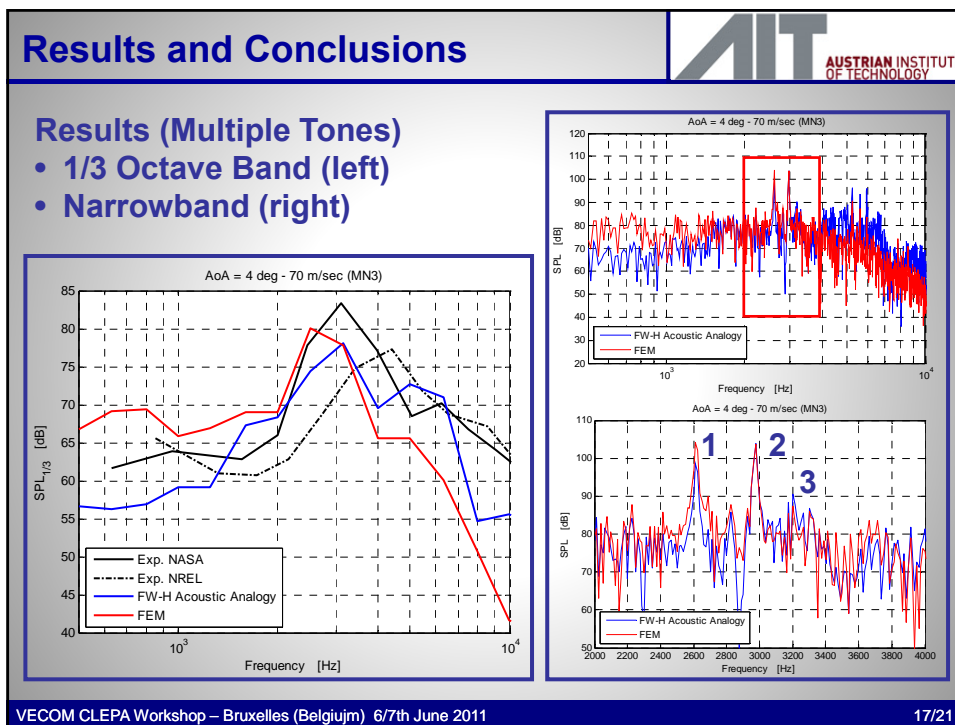


- All Computations are scaled to NASA Mic. Positions (≈ 5 chords of distance). Scaling law provided by Bies and Hansen [4].
- Computational results have been compared with 1/3 octave band experimental data from [1,2,3].


[1] Brooks, T.F., Pope, D. and Marcolini, M.A., "Airfoil Self-Noise and Prediction", NASA Reference Publication 1218, 1989.
 [2] Oerlemans S., Migliore P., Aeroacoustic Wind Tunnel tests of Wind Turbine Airfoils, AIAA Paper 2004-3042, 2004.
 [3] Oerlemans S., Wind Tunnel Aeroacoustic tests of Six Airfoils for use on Small Wind Turbines, National Aerospace laboratory NRL, NREL/SR-500-35339, 2004.
 [4] Bies, D.A., Hansen C.H., Engineering Noise Control 4th Edition, Taylor & Francis Spon Press, 2009.

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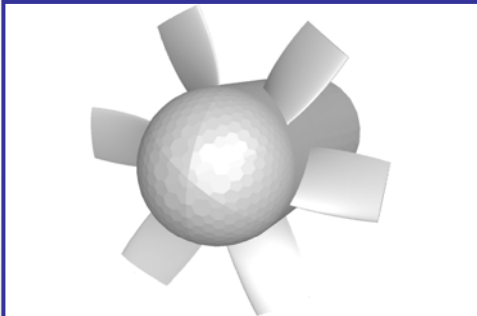
Results and Conclusions



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Future Steps (2/3)

- **Semi-Empirical Modelling (BPM) of Broadband Noise implemented as UDF into FLUENT for Fan Applications [5,6].**




[5] Carolus, T., Schneider, M., Review of Noise Prediction Methods for Axial Flow Fans, Internoise Conference Proceedings, 2000.

[6] Carolus, T., Stremel, M., Schneider, M., Tragflügelschall: Anwendung der Messungen von Brooks, Pope und Marcolini auf Ventilatorlärm, DAGA Proceedings, 2000.

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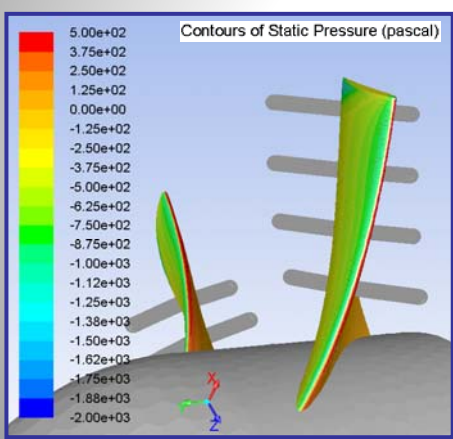
Results and Conclusions



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Future Steps (3/3)

- **Raked Blade and Computed Noise Spectrum**

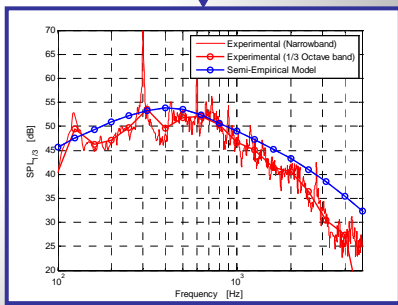


Contours of Static Pressure (pascal)

5.00e+02
3.75e+02
2.50e+02
1.25e+02
0.00e+00
-1.25e+02
-2.50e+02
-3.75e+02
-5.00e+02
-6.25e+02
-7.50e+02
-8.75e+02
-1.00e+03
-1.12e+03
-1.25e+03
-1.38e+03
-1.50e+03
-1.62e+03
-1.75e+03
-1.88e+03
-2.00e+03

B.L. Detection and Computation of :

1. B.L. Thickness
2. Displacement Thickness
3. Momentum Thickness



SPL_{1m} [dB]

Frequency [Hz]

Experimental (Narrowband)
 Experimental (1/3 Octave band)
 Semi-Empirical Model

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Thank You for the Attention

Questions ???

