Trinity College Dublin
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B-Fluid
Buildings Fluid Dynamics

Future Aircraft Design and Noise Impact
22nd Workshop of the Aeroacoustics Specialists Committee of the CEAS

September 6th - 7th 2018, Amsterdam

Characterisation and Reduction of Aircraft Landing Gear Noise

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Introduction

Aircraft Noise

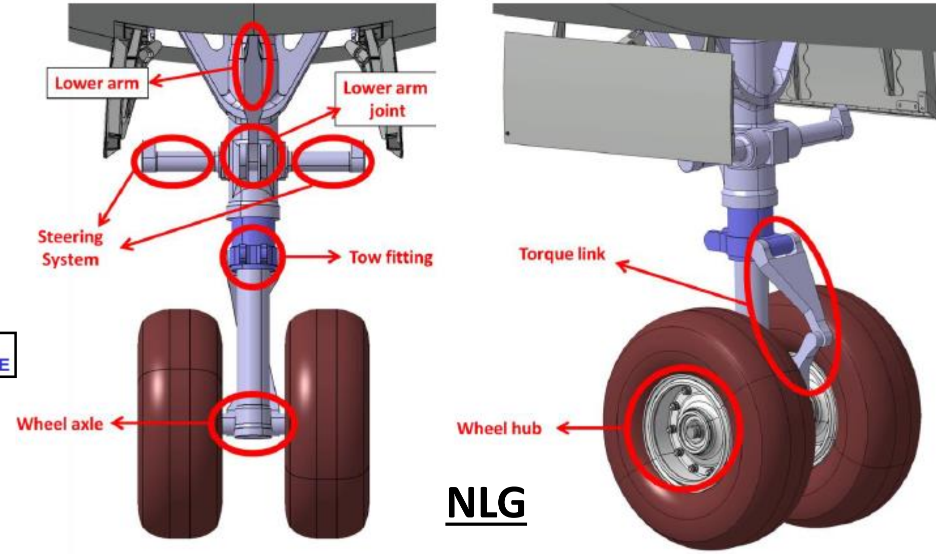
Aircraft noise sources

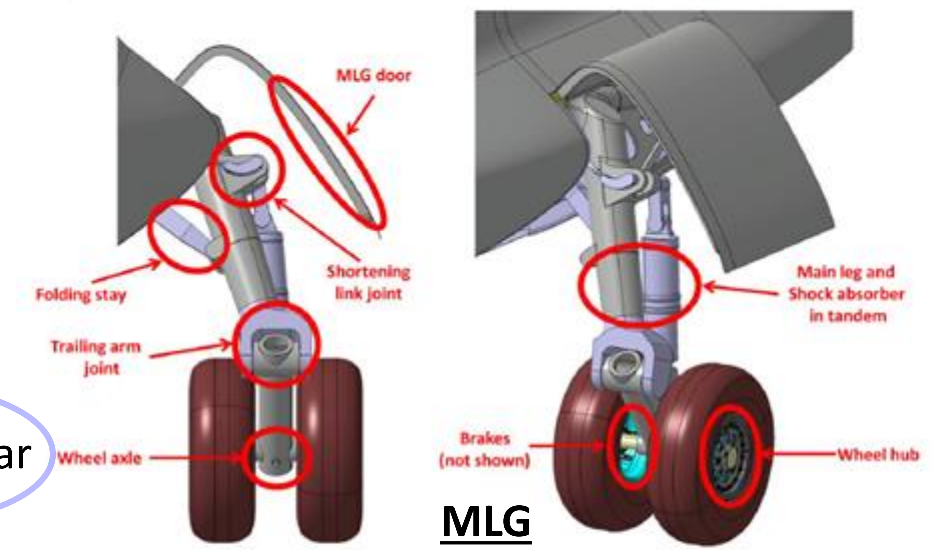
Engine noise

Airframe noise

High Lift devices
(flaps/slats)

Landing Gear





Introduction

The ALLEGRA project

ADVANCED LOW NOISE LANDING (MAIN AND NOSE) GEAR FOR REGIONAL AIRCRAFT

Clean Sky

ALLEGRA

Assess **low noise technologies** applied to a **full-scale nose landing gear** and **half-scale main landing gear** model of a regional aircraft

7 years research project

2.5 years research project

ITD:

LEONARDO

Trinity College Dublin (COORDINATOR)

KTH Sweden

Pininfarina SPA

Eurotech

Teknosud

Magnaghi Aeronautica

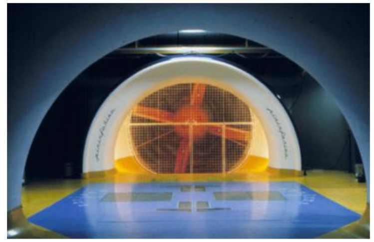
The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Clean Sky Joint Technology Initiative under grant agreement n° [308225].

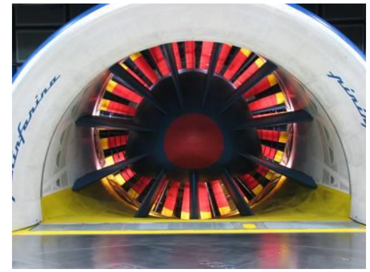
Introduction

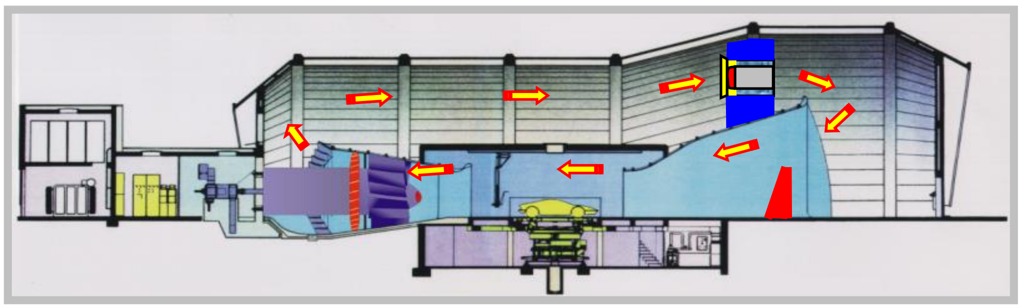
The ALLEGRA project

Pininfarina Wind Tunnel features:

- Jet section: 11 m^2 (semi-circular)
- Max speed: 260 km/h (empty test section)
- BNL: 68 dBA at V = 100 km/h
- Turbulence intensity: 0.3%
- Test Section: 8m x 9,6m x 4,2m







<u>ALLEGRA specifications</u>:

- **Full representation** of the landing gear detail and associated structures (e.g. bay cavity, bay doors, belly fuselage etc.) are included and addressed at a realistic scale.
- The Nose Landing Gear is designed at full scale and the Main Landing Gear at half scale.
- Implementation of low-noise technologies.

Introduction

NLG Baseline Configurations

NLG

Nose landing gear dressed: Baseline

NF

Closed Fuselage only

NB

BAY OPEN, No Landing gear, no doors

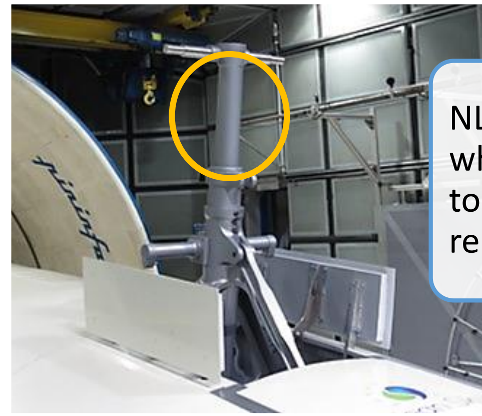
Introduction

Decomposition of NLG

NLG-DressW

NLU with wheels removed

NLG-DressWT



NLU with wheels and torque link removed

NLG-DressWTS

NLU with wheels, torque link and steering pinion removed

NLG-DressWTSD

NLU with wheels, torque link, steering pinion and doors removed

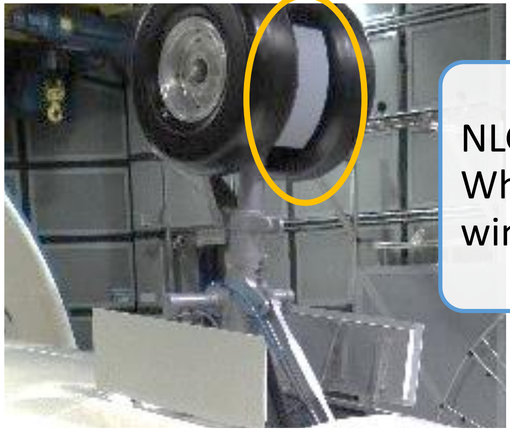
Introduction

Application of low noise technologies to the NLG

NL1

NLG + Ramp spoiler

NL2

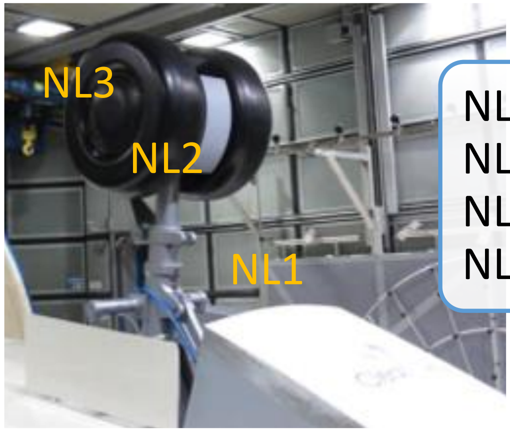


NLG + Wheel axle wind shield

NL3

NLG + Wheel hub caps

NL6



NLG + NL1 + NL2 + NL3

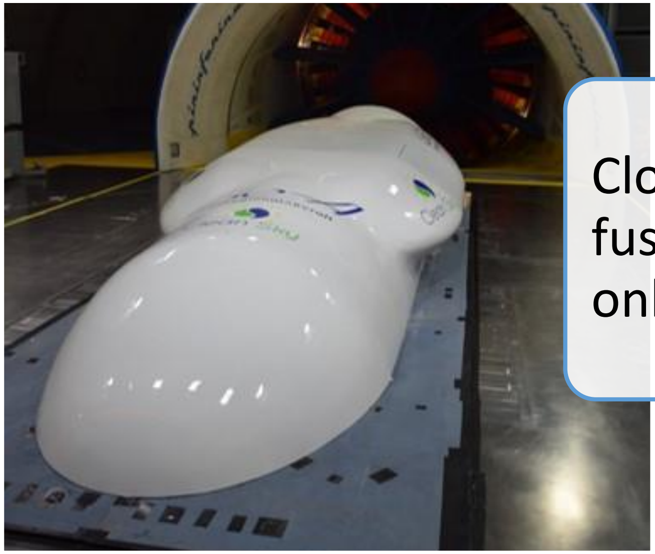
Introduction

MLG Baseline configurations

MLG

Main landing gear: Baseline

MF



Closed fuselage only

Introduction

Decomposition of the MLG

MLG-TopDoors

MLG with top doors removed

MLG-SideDoors

MLG with side doors removed

Introduction

Application of low noise technologies to the MLG

ML7

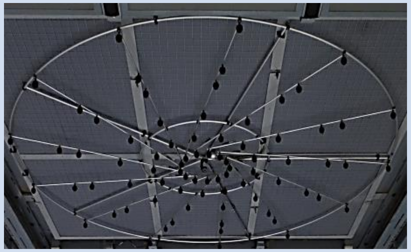
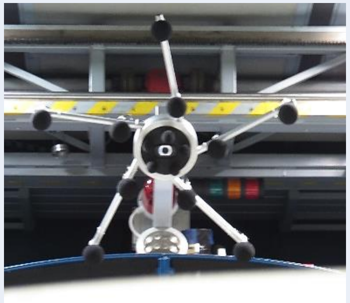
MLG +
Mesh
treatment

ML8

MLG +
Hubcaps +
Axle
perforated
fairing

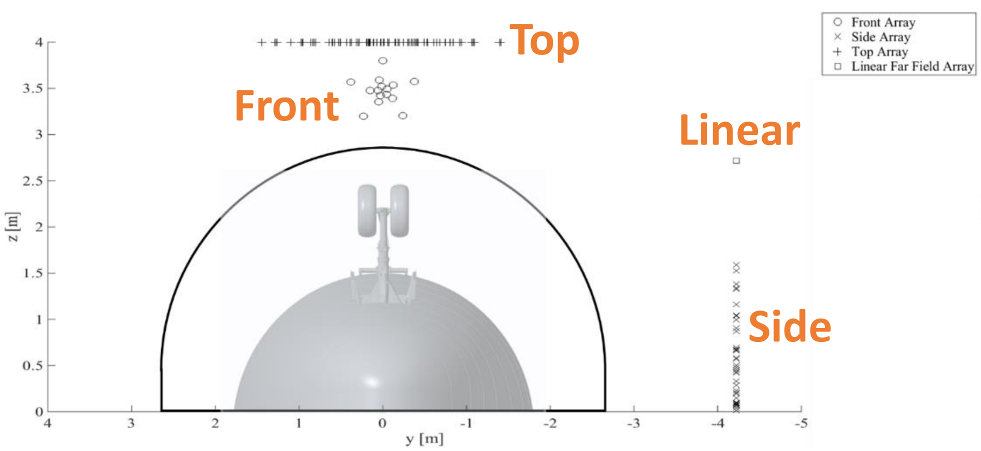
Introduction

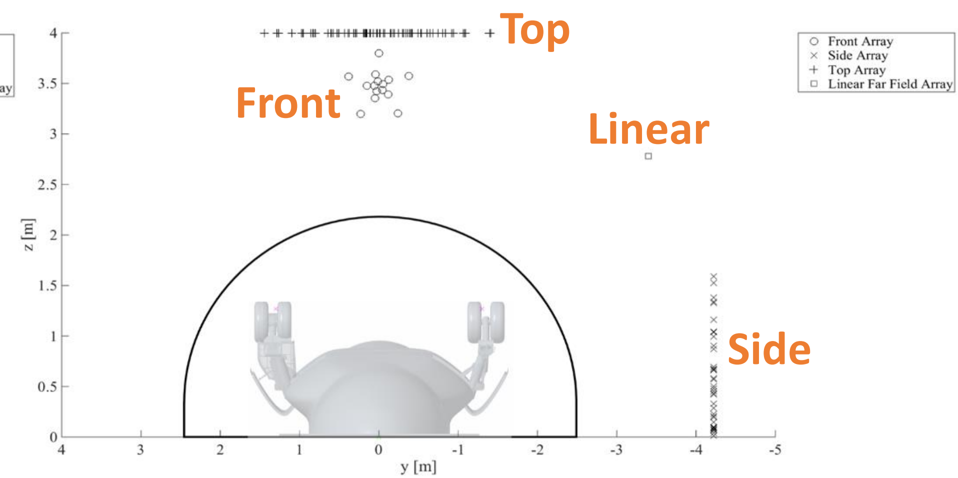
Microphones Arrays

Array name	Characteristics	Picture
Linear Far Field Array	13 microphones 4.22m from model axis	
Side Array	3 meter diameter half-wheel array 66 microphones 4.22m from model axis	
Top Array	3 meter diameter wheel array 78 microphones 1.82m from the model	
Front Array	Spiral array 15 microphones upstream the landing gear plane at an angle of 10 degrees	

Introduction

Microphones Arrays





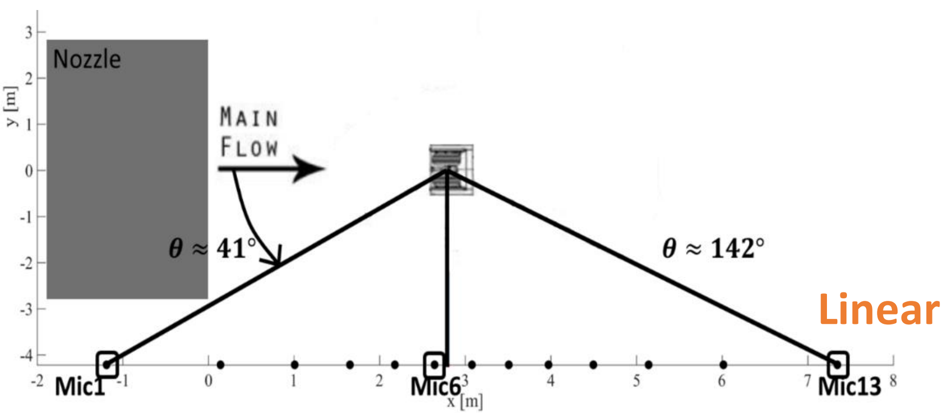


Diagram of linear far field array angles for the NLG

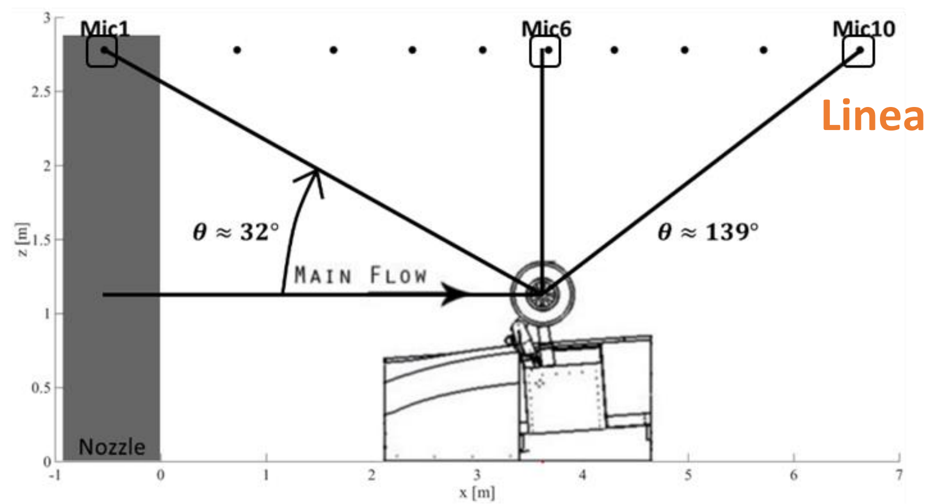


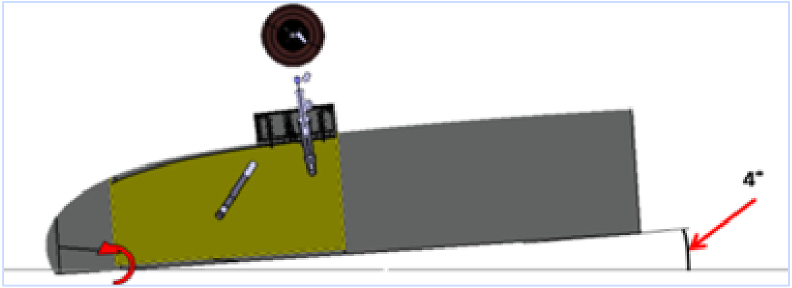
Diagram of linear far field array angles for the MLG

Introduction

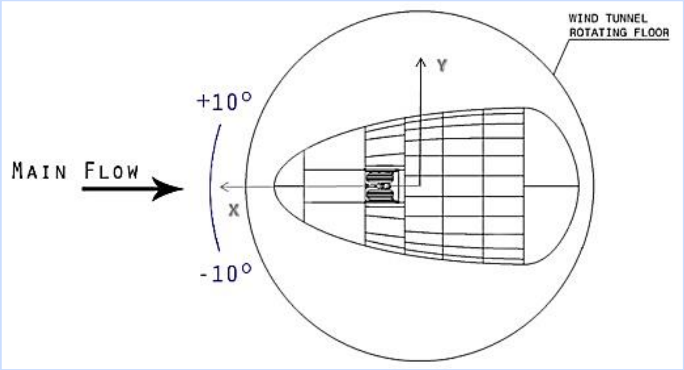
NLG Test Campaign

Wind Tunnel Tests Matrix:

	Wind Tunnel Flow Speed			
Yaw angle	40m/s	50m/s	60m/s	65m/s
	-10°	-10°	-10°	
	-5°	-5°	-5°	-5°
	0°	0°	0°	0°
	5°	5°	5°	5°
	10°	10°	10°	
	-10° to +10°			



Angle of attack: 4°



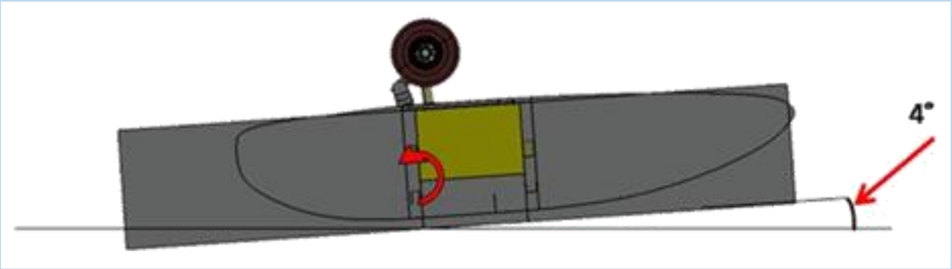
Yaw Angle

Introduction

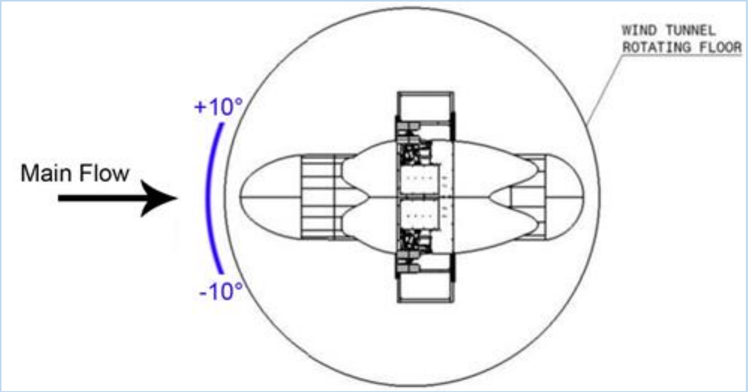
MLG Test Campaign

Wind Tunnel Tests Matrix:

	Wind Tunnel Flow Speed				
Yaw angle	40m/s	45m/s	50m/s	60m/s	65m/s
	-10°		-10°	-10°	
	-5°		-5°	-5°	-5°
	0°	0°	0°	0°	0°
	5°		5°	5°	5°
	10°		10°	10°	
	-10° to +10°				



Angle of attack: 4°



Yaw Angle

Nose Landing Gear Results

NLG Results

Directivity of the nose landing gear noise

ΔSPL(dB) wrt baseline NLG as a function of frequency and directivity - Linear Far Field array

50m/s and 0° yaw

Spectrograms

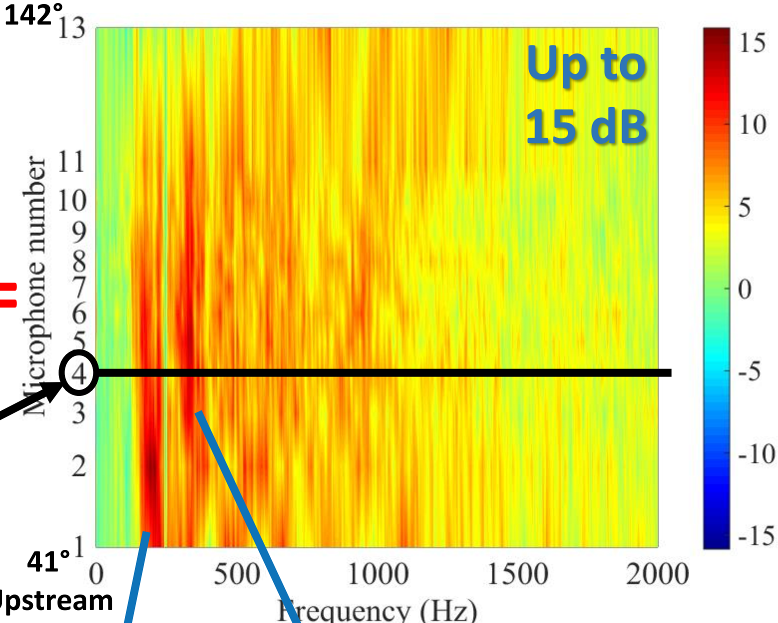
The **directivity** of the landing gear sources was found by subtracting the different configurations data

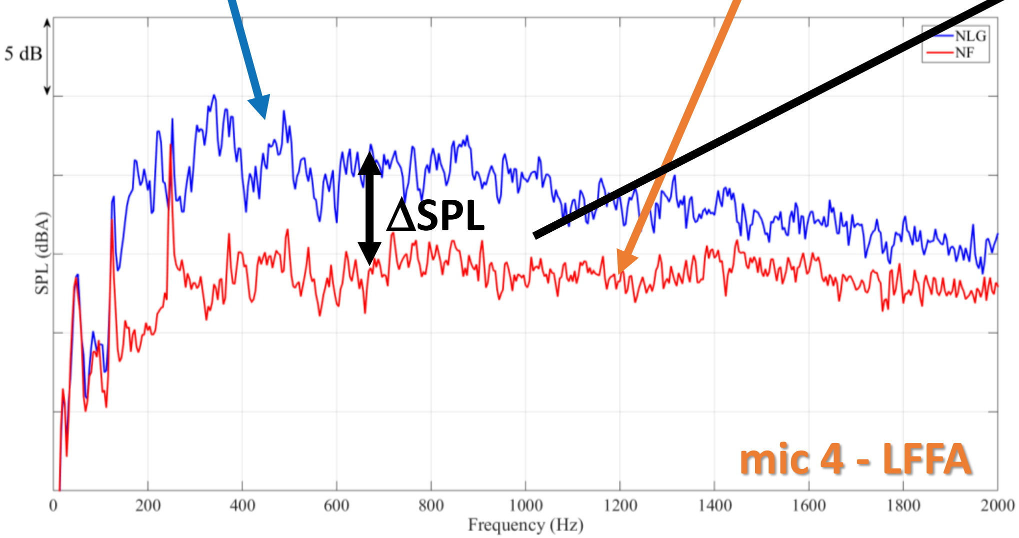
NLG

–

NF

=





150 – 230 Hz

284 – 380 Hz

150 Hz – 1400 Hz

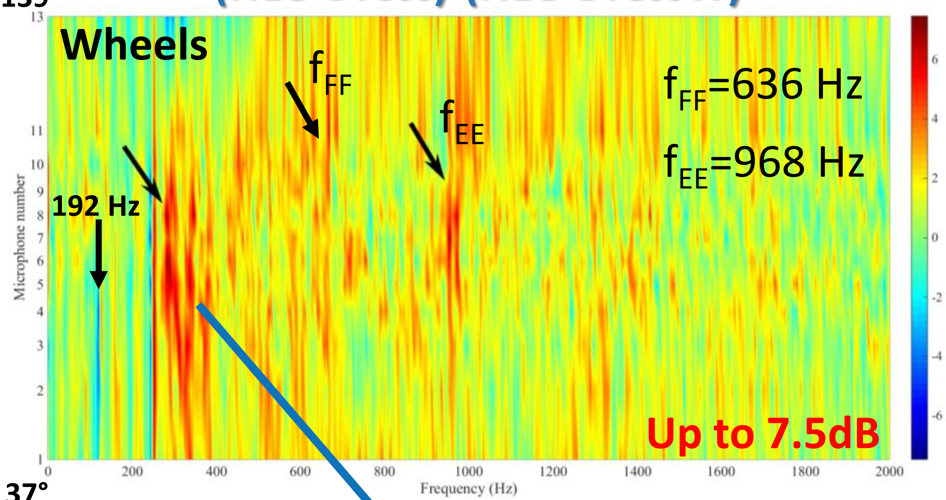
NLG Results

Directivity of the nose landing gear components

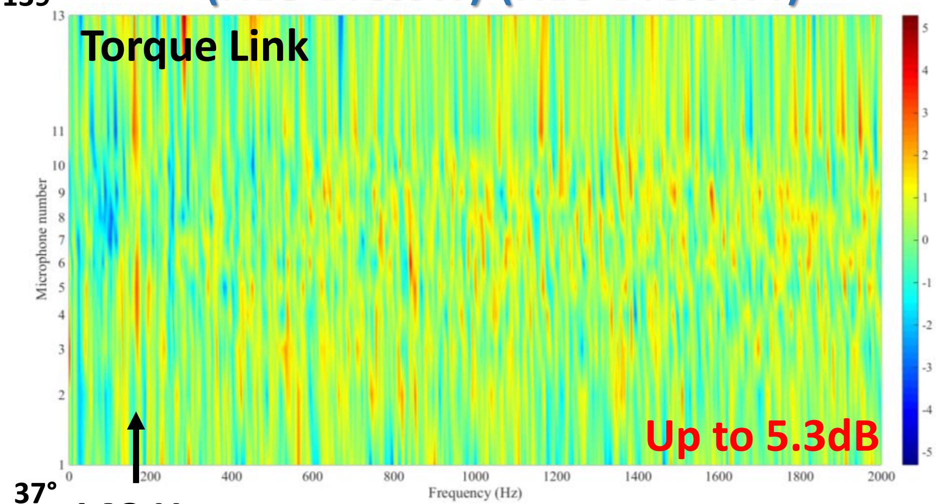
ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

50m/s and 0° yaw

(NLG-Dress)-(NLG-DressW)



(NLG-DressW)-(NLG-DressWT)



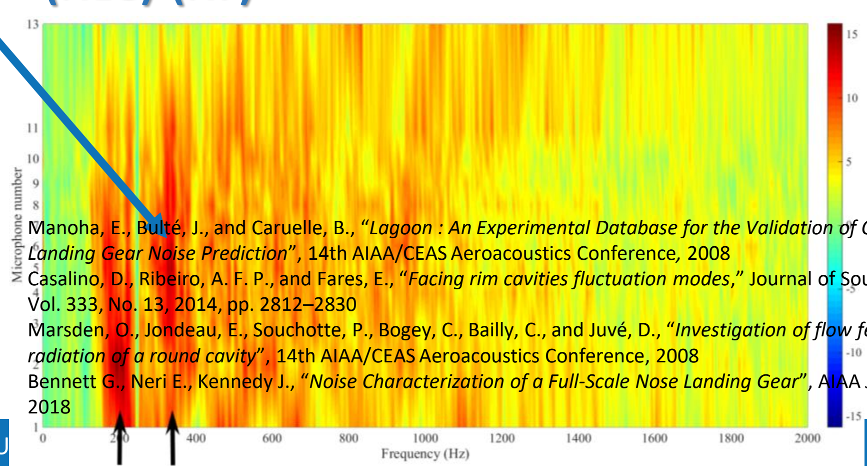
148 Hz

260 - 400 Hz

650 Hz

1kH

(NLG)-(NF)



- Manoha, E., Bulté, J., and Caruelle, B., "*Lagoon : An Experimental Database for the Validation of CFD/CAA Methods for Landing Gear Noise Prediction*", 14th AIAA/CEAS Aeroacoustics Conference, 2008
- Casalino, D., Ribeiro, A. F. P., and Fares, E., "*Facing rim cavities fluctuation modes*," Journal of Sound and Vibration, Vol. 333, No. 13, 2014, pp. 2812–2830
- Marsden, O., Jondeau, E., Souchotte, P., Bogey, C., Bailly, C., and Juvé, D., "*Investigation of flow features and acoustic radiation of a round cavity*", 14th AIAA/CEAS Aeroacoustics Conference, 2008
- Bennett G., Neri E., Kennedy J., "*Noise Characterization of a Full-Scale Nose Landing Gear*", AIAA Journal of Aircraft, 2018

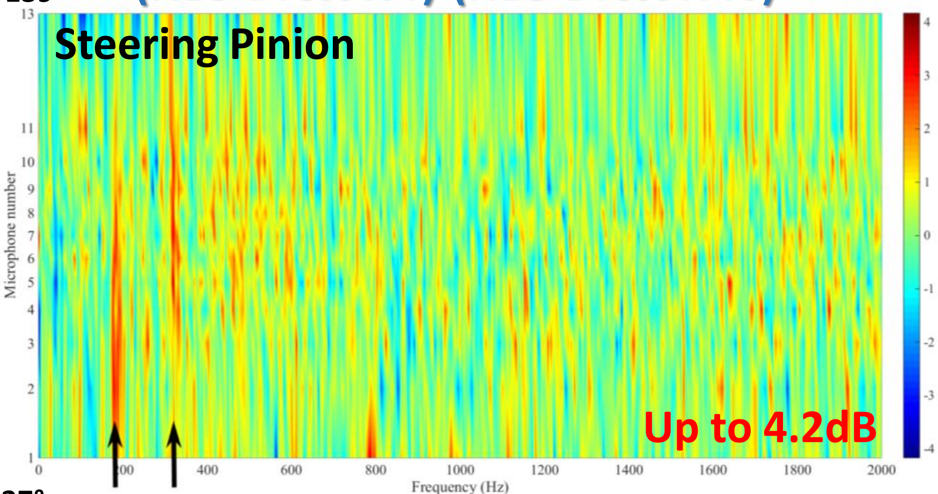
NLG Results

Directivity of the nose landing gear components

ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

50m/s and 0° yaw

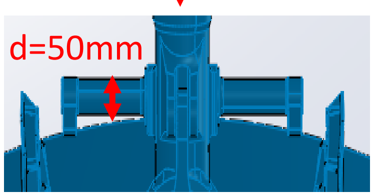
139° (NLG-DressWT)-(NLG-DressWTS)



37°

192 Hz

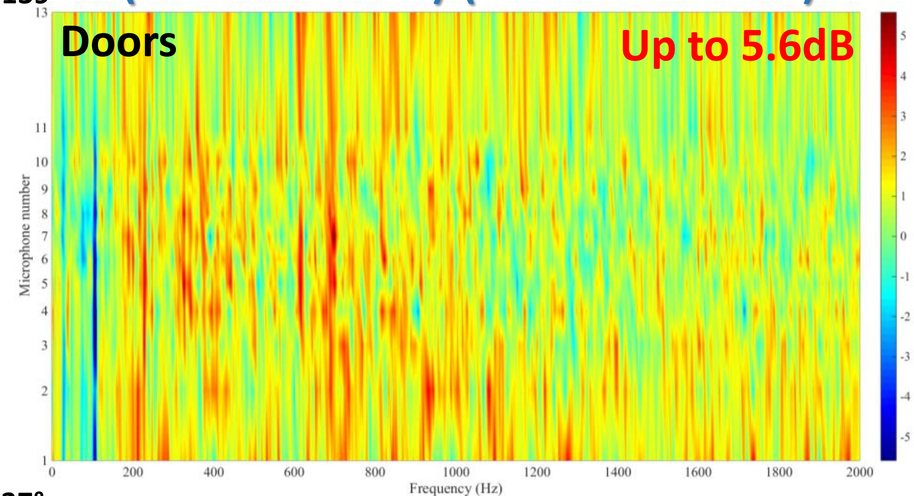
320 Hz



Vortex shedding frequency:

$$f = \frac{USt}{d} = 190\ Hz$$

139° (NLG-DressWTS)-(NLG-DressWTSD)



37°

120-1200 Hz

Directivity

NLG Results

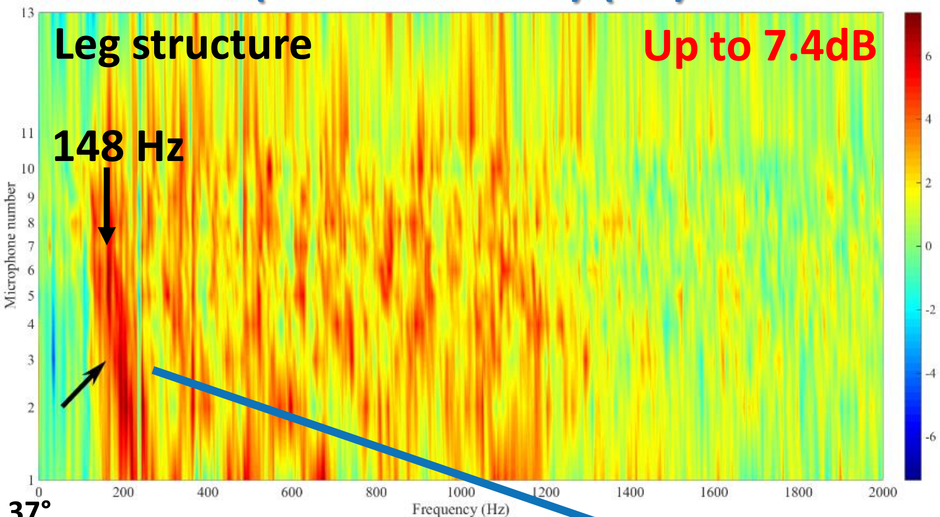
Directivity of the nose landing gear components

ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

50m/s and 0° yaw

(NLG-DressWTD)-(NB)

139°



37°

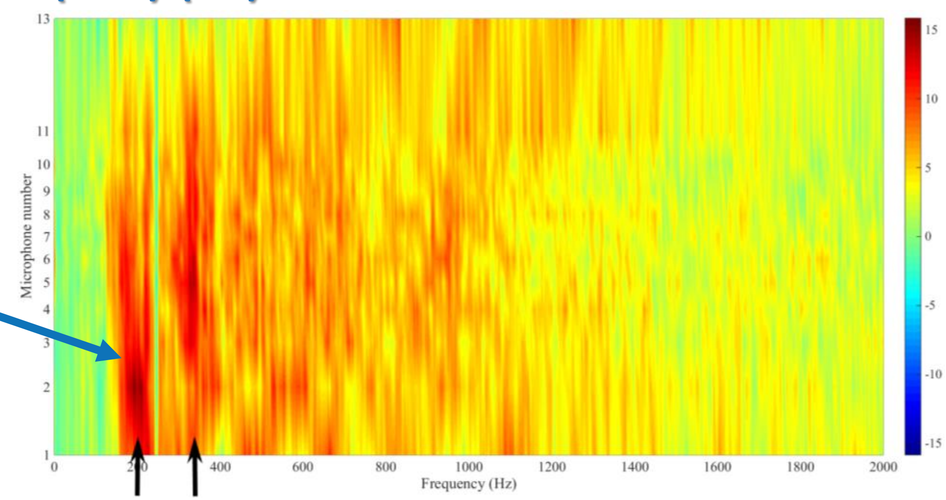
124 – 250 Hz

Vortex shedding frequency:

$$f = \frac{\boldsymbol{USt}}{\boldsymbol{d}} =$$

$$= \mathbf{89, 105, 138, 173, 208}\ \boldsymbol{Hz}$$

(NLG)-(NF)



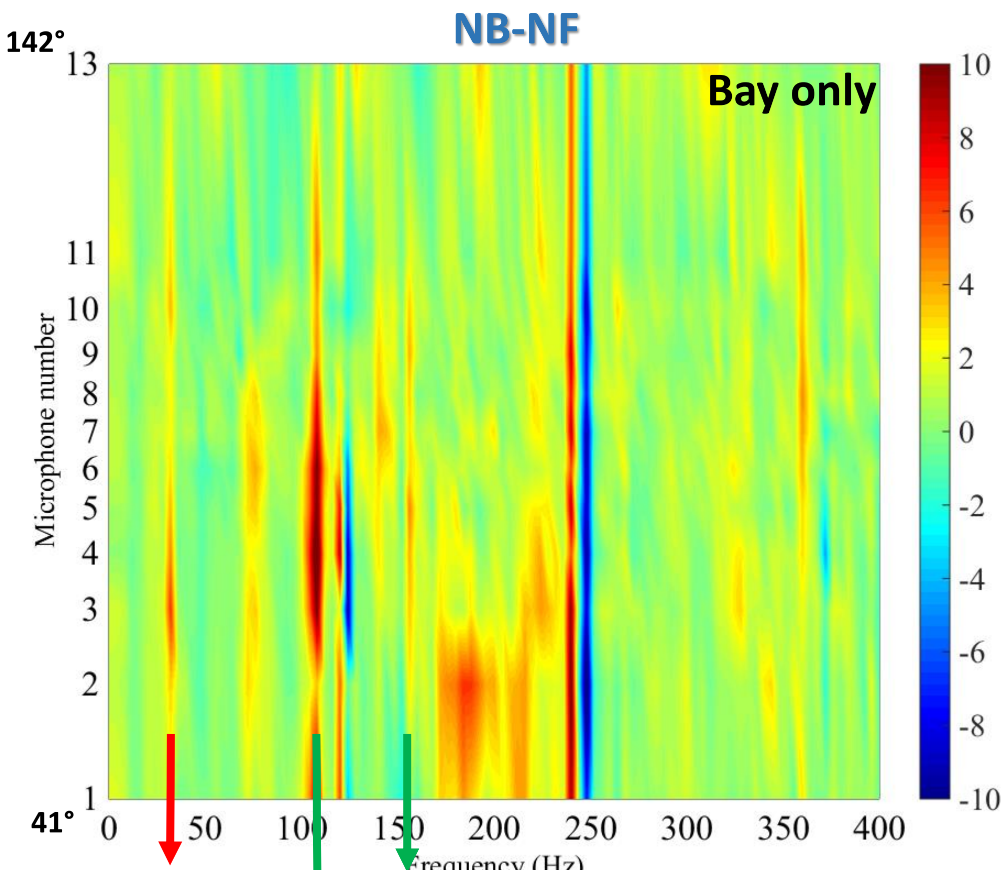
Directivity

NLG Results

Directivity of the nose landing gear components

ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

50m/s and 0° yaw



E. Neri. J. Kennedy, G. Bennett, "*Bay Cavity Noise for Full-Scale Nose Landing Gear: A comparison between experimental and numerical results*", Aerospace Science and Technology, 2017

<u>Bay only NB</u>

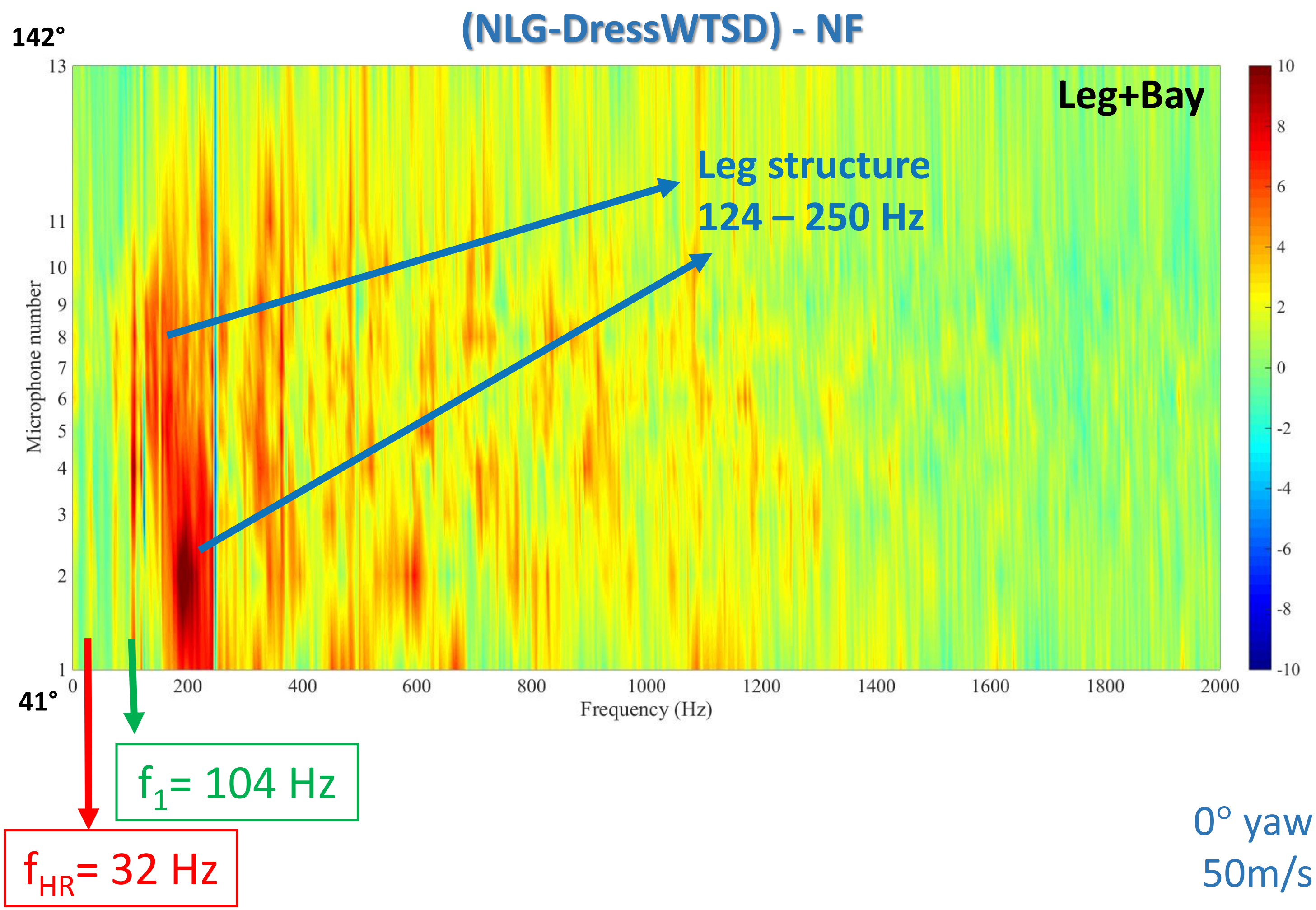
Directivity

NLG Results

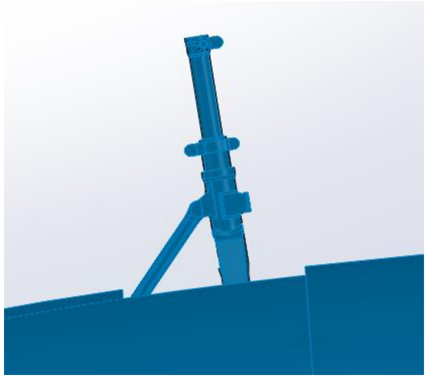
Directivity of the nose landing gear components

Are these bay cavity modes radiating to the far field?

ΔSPL(dBA) wrt baseline NLG as a function of frequency and directivity
Linear Far Field array



NLG-DressWTSD



0° yaw
50m/s

Directivity

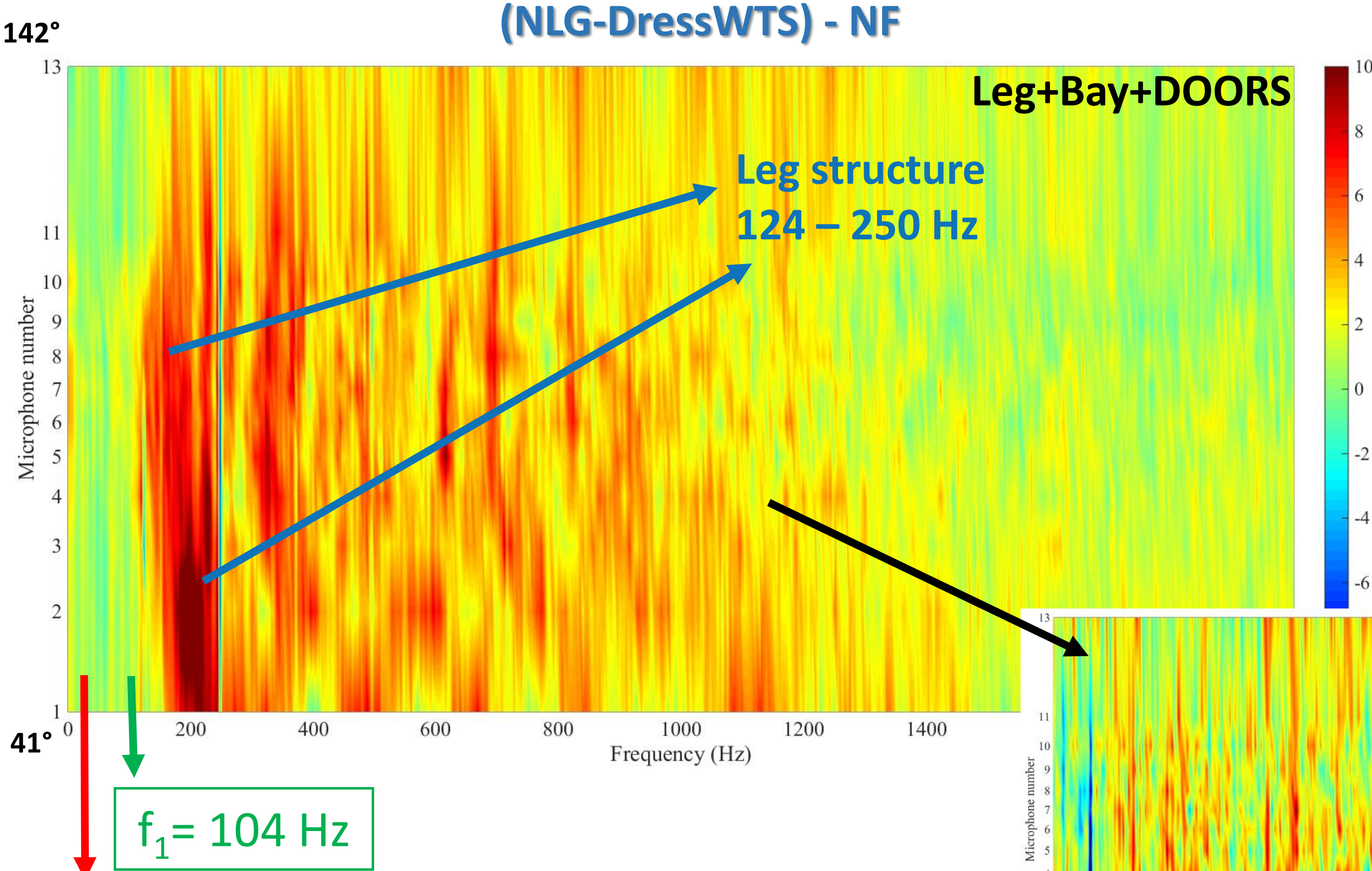
NLG Results

Directivity of the nose landing gear components

<u>Are these bay cavity modes radiating to the far field</u>?

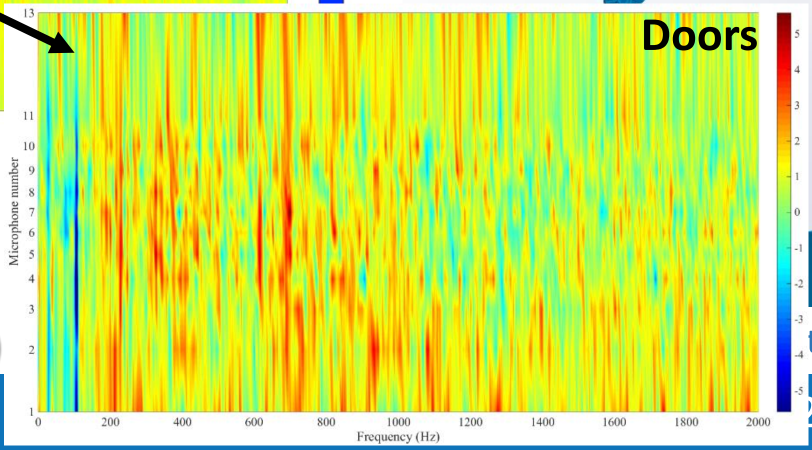
ΔSPL(dBA) wrt baseline NLG as a function of frequency and directivity
Linear Far Field array

(NLG-DressWTS) - NF



NLG-DressWTS

(NLG-DressWTS)-(NLG-DressWTSD)



NLG Results

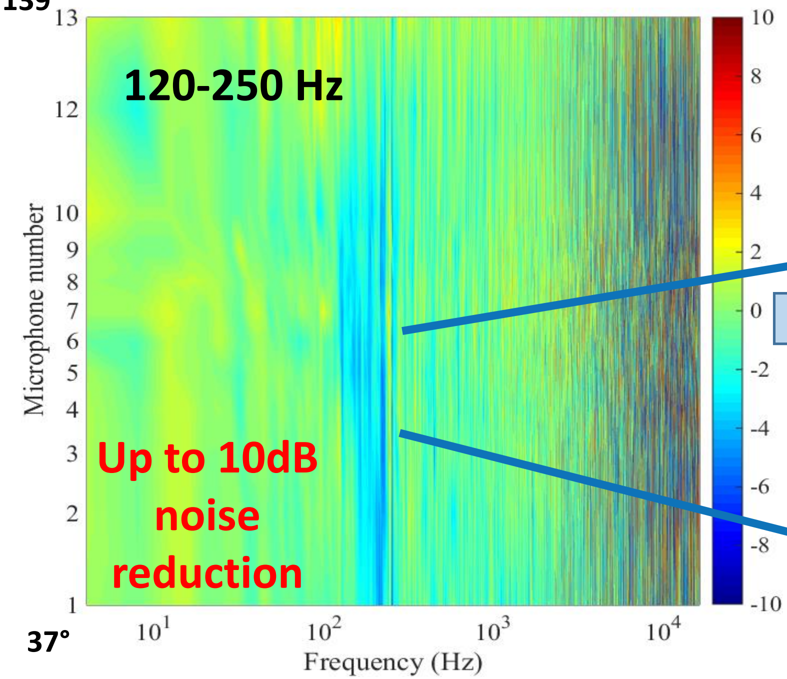
Noise reduction technologies

50m/s and 0° yaw

ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

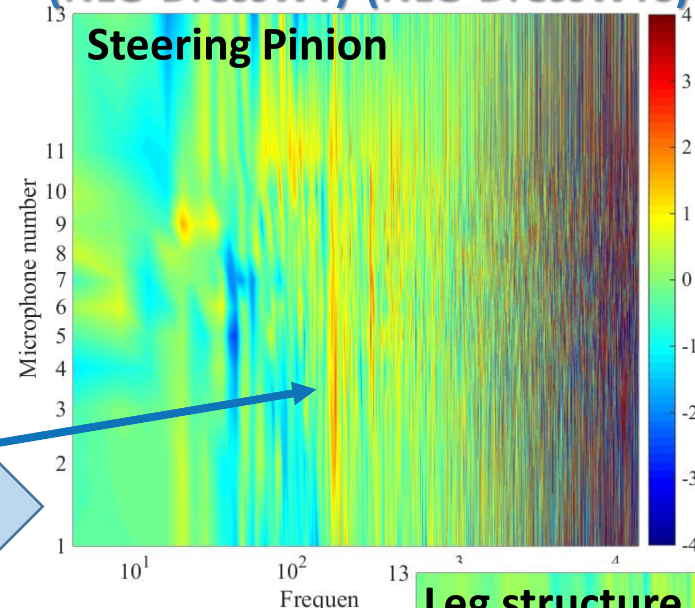
NL1-NLG:

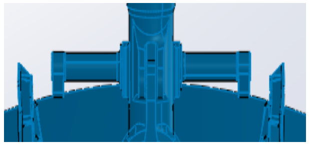
139°

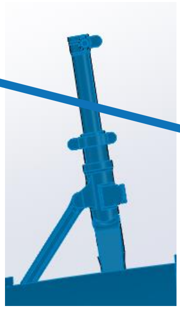


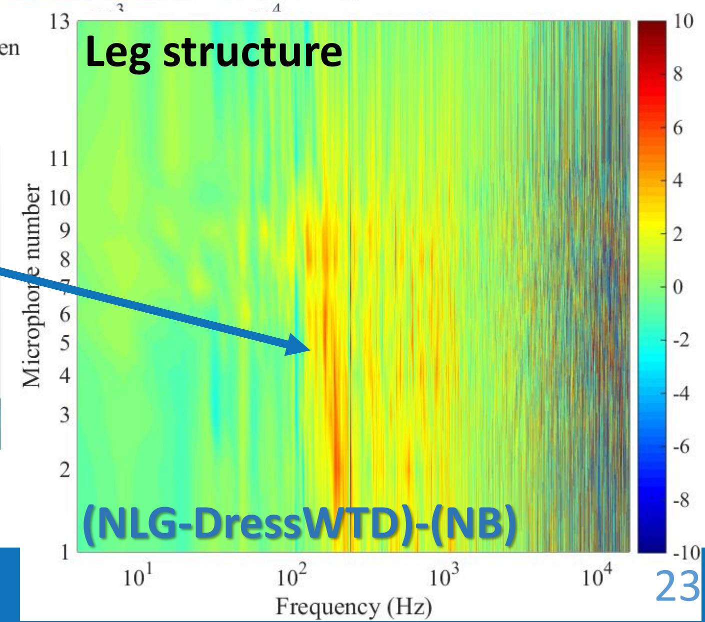
37°

(NLG-DressWT)-(NLG-DressWTS)





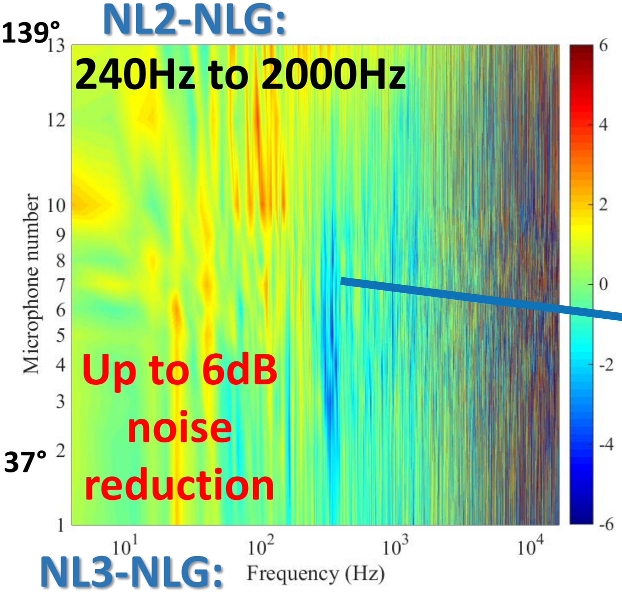


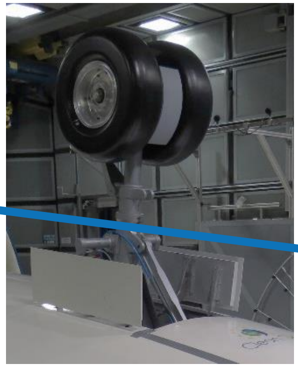


NLG Results

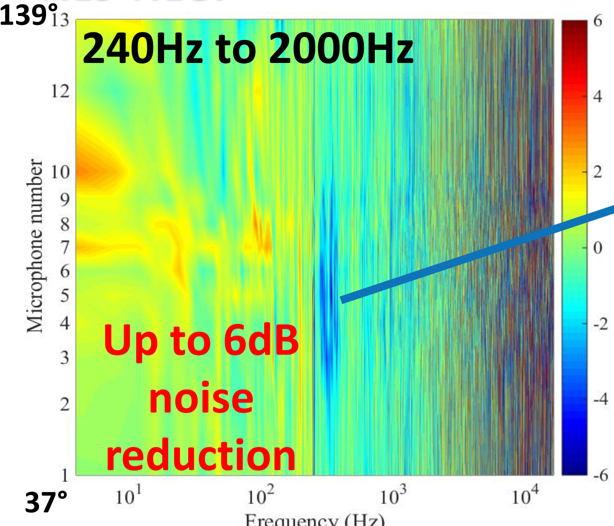
Noise reduction technologies

NL2-NLG:



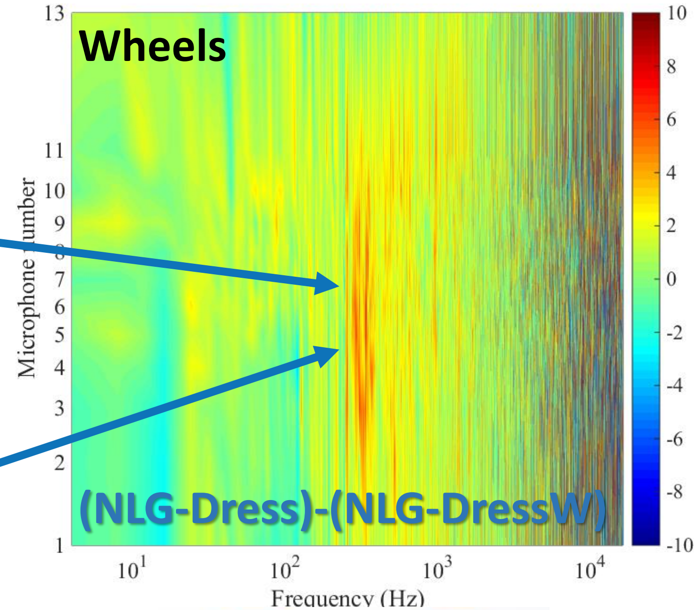


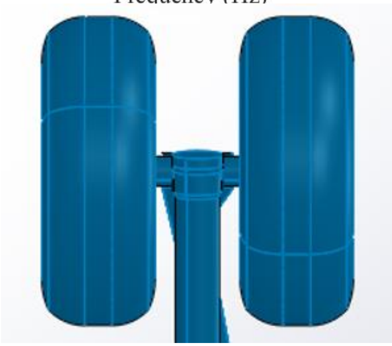
NL3-NLG:



50m/s and 0° yaw

ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

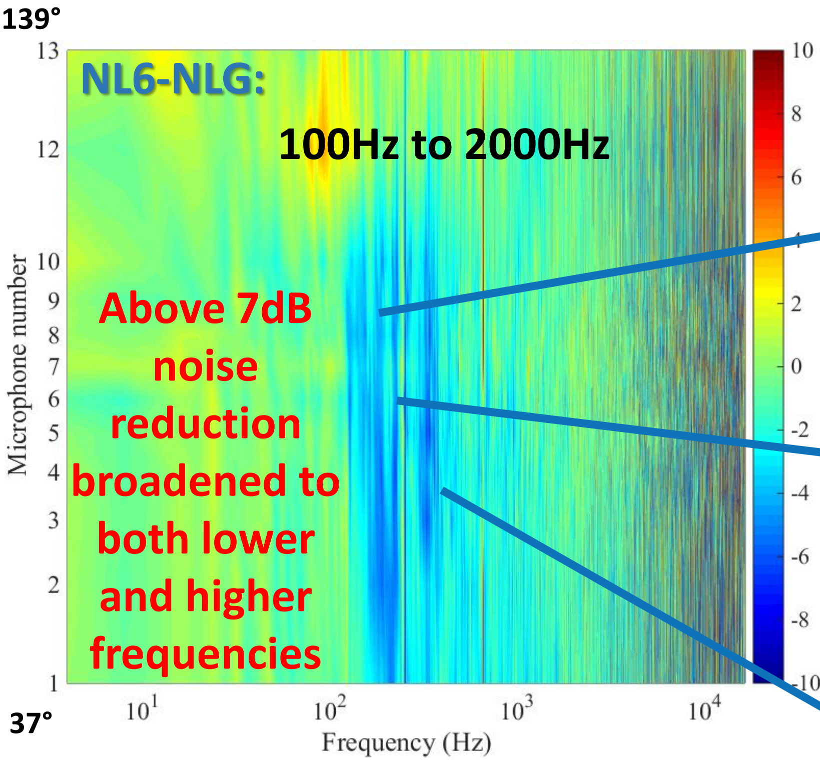


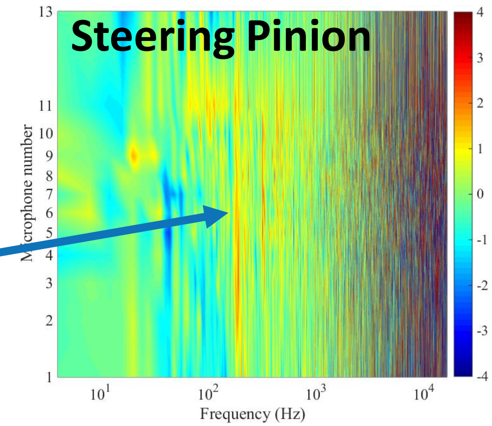


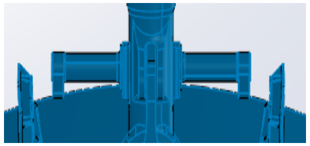
NLG Results

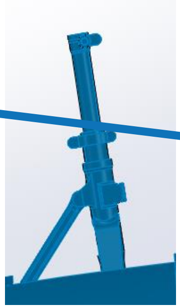
Noise reduction technologies

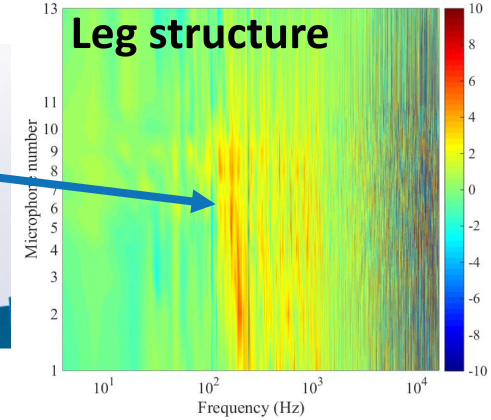
50m/s and 0° yaw

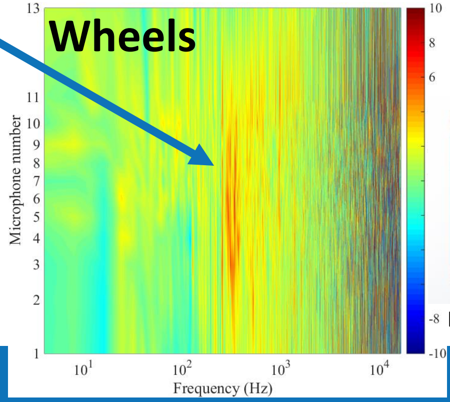












+ DOORS!
(120-2000 Hz)

ncy and directivity - Linear Far Field array

Main Landing Gear Results

MLG Results

Directivity of the main landing gear noise

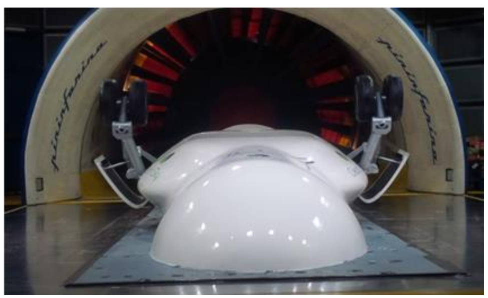
ΔSPL(dB) wrt baseline MLG as a function of frequency and directivity - Linear Far Field array

65 m/s and 0° yaw

Spectrograms

The **directivity** of the landing gear sources was found by subtracting the different configurations data

MLG



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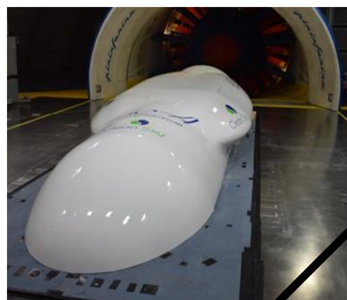
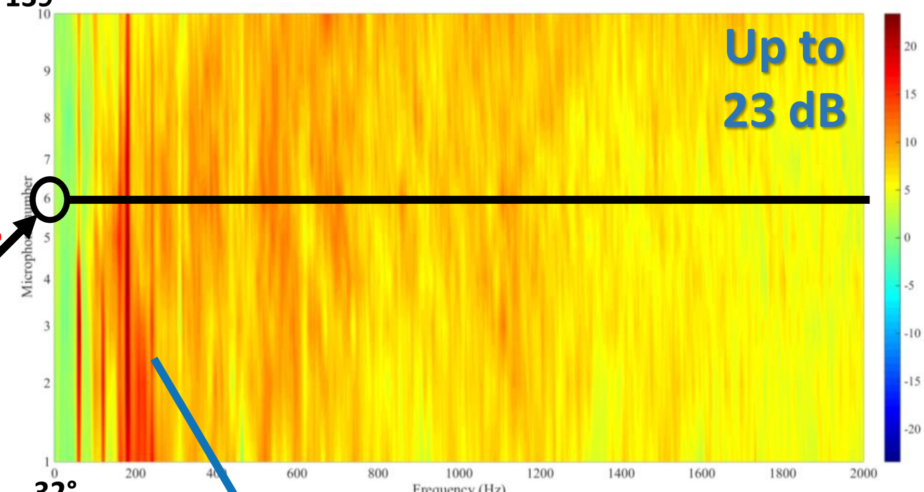
MF

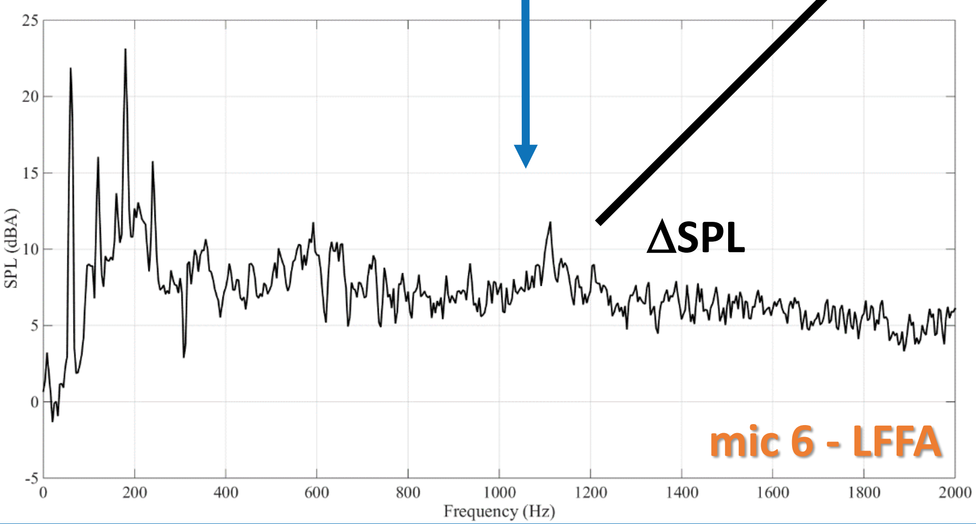


=

Downstream 139°



32° Upstream



ΔSPL

60 – 250 Hz

60 Hz – 1200 Hz

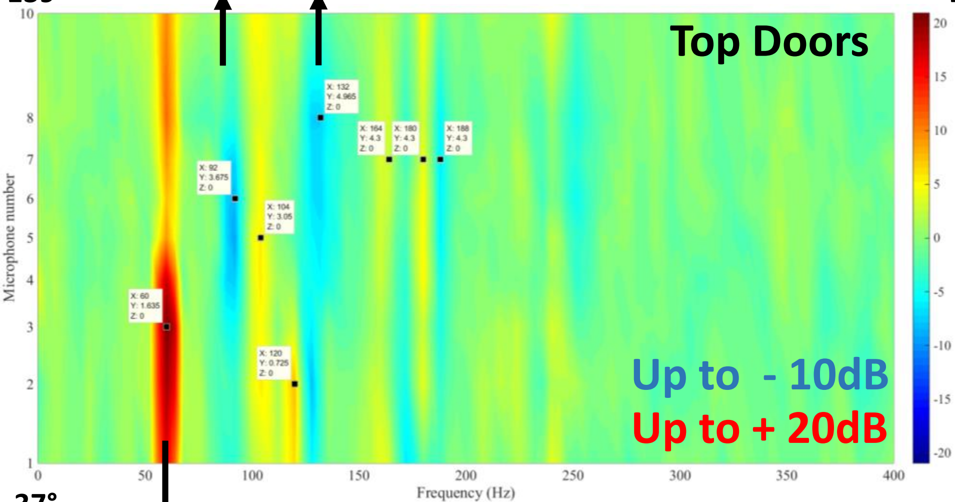
MLG Results

Directivity of the main landing gear components

ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

92 Hz 132 Hz

139°



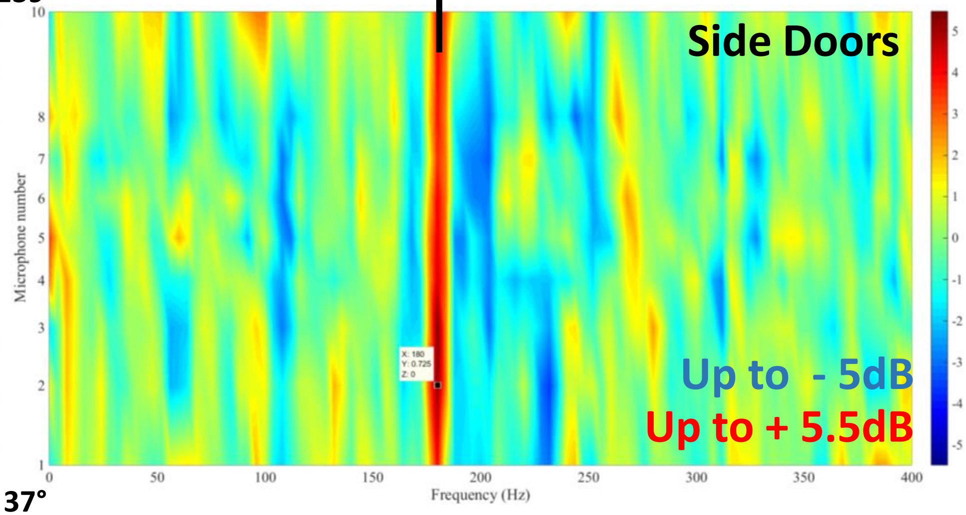
37°

60 Hz

(MLG)-(MLG-TopDoors)

180 Hz

139°



37°

(MLG)-(MLG-SideDoors)

–

=

–

=

65 m/s and 0° yaw

Directivity

MLG Results

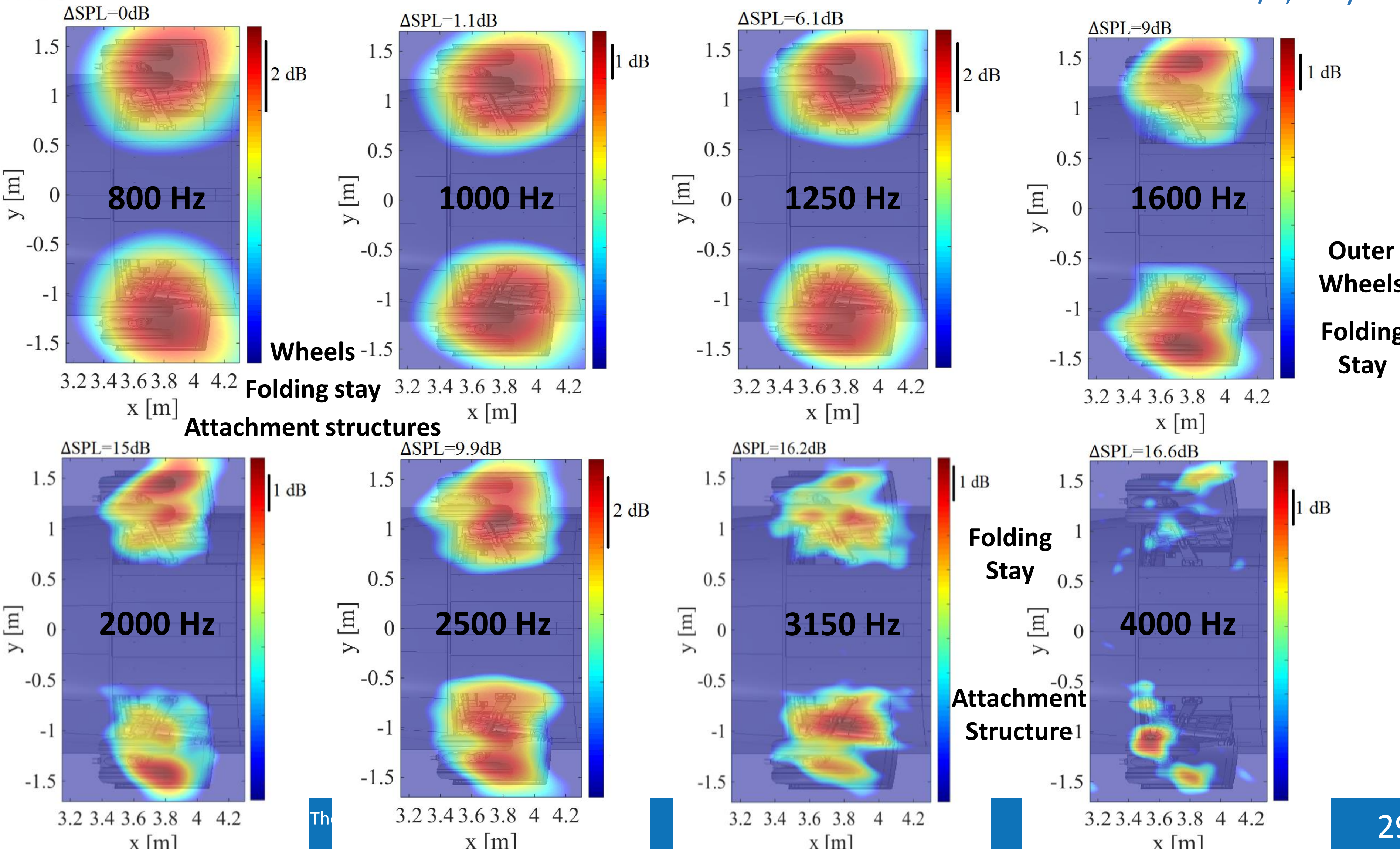
Beamforming – Top Array

The author acknowledges DLR, Institute of Aerodynamics and Flow Technology, Department of Experimental Methods for providing the SAGAS software used to generate these beamforming results

MLG

Functional Frequency Domain Beamforming

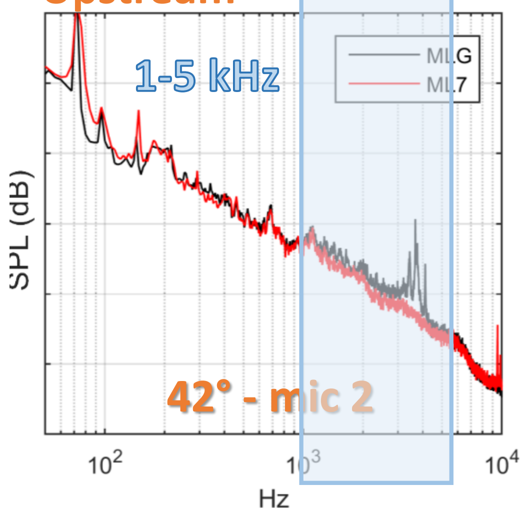
65 m/s, 0° yaw

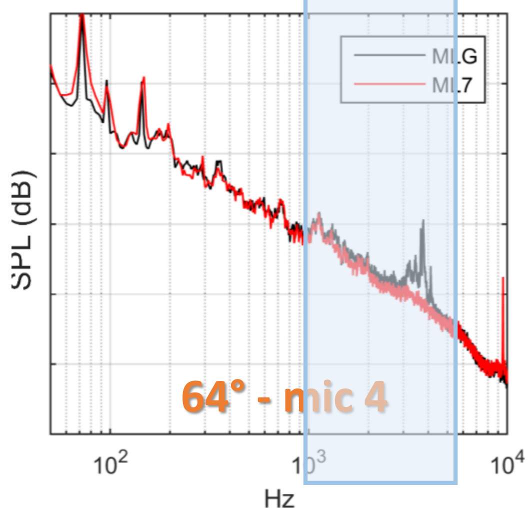


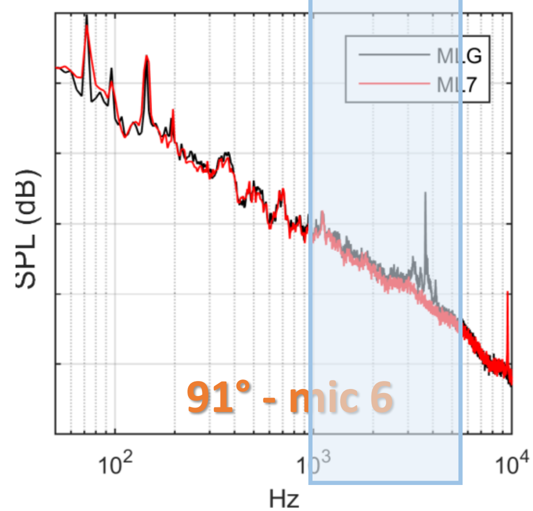
MLG Results

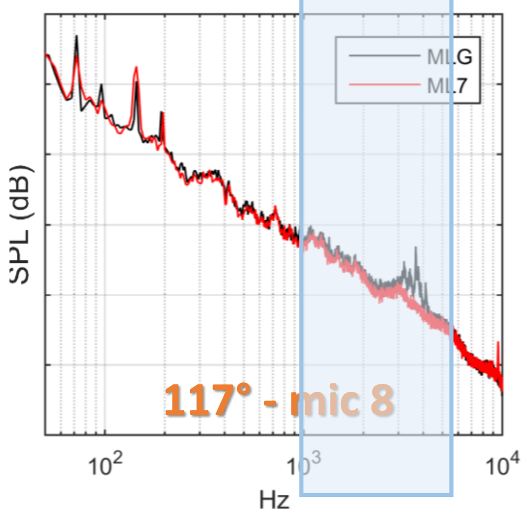
Noise reduction technologies

Upstream

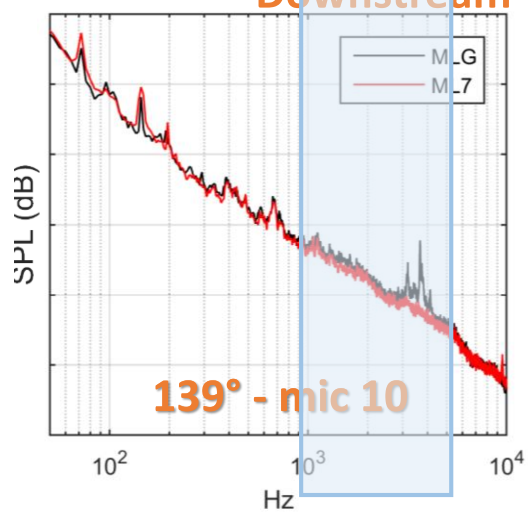








Downstream



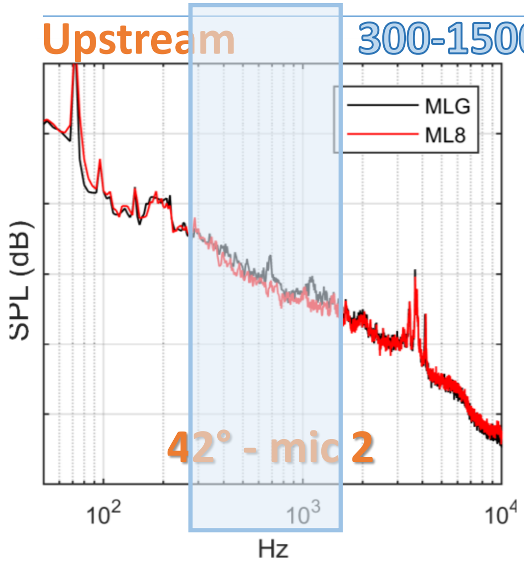
ML7 – Mesh Fairings

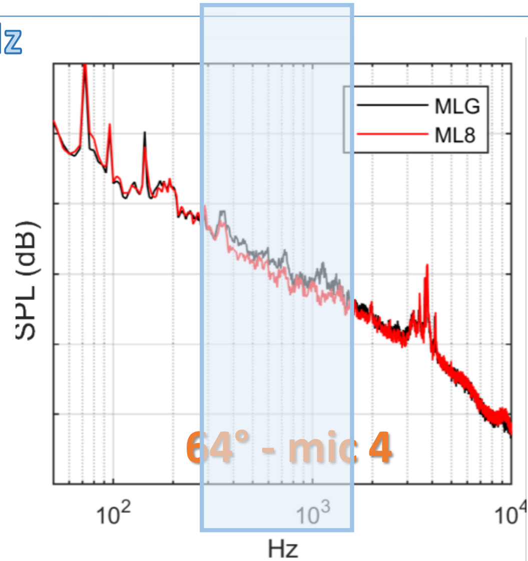
SPL(dB) narrow band frequency spectra

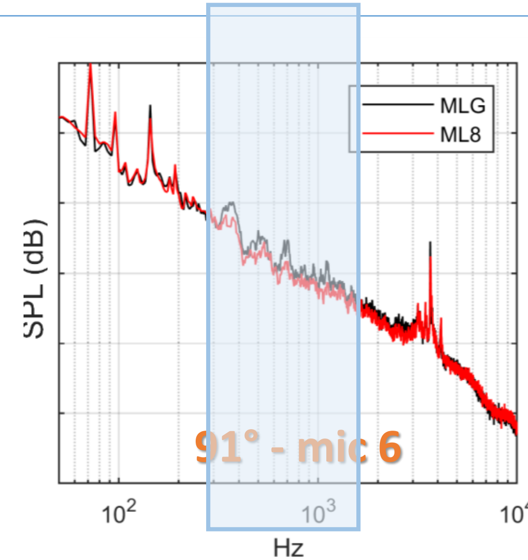
40 m/s and 0° yaw

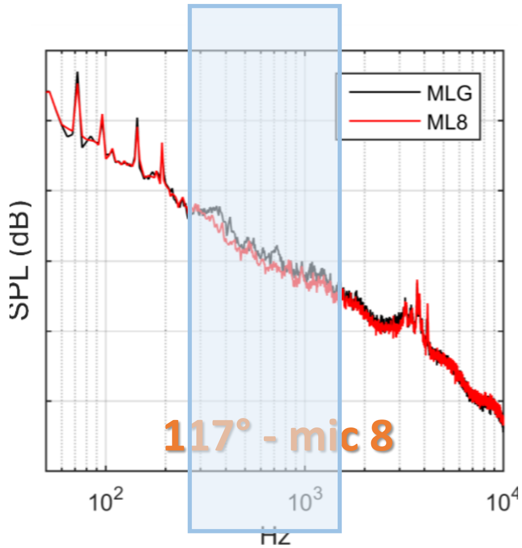
MLG Results

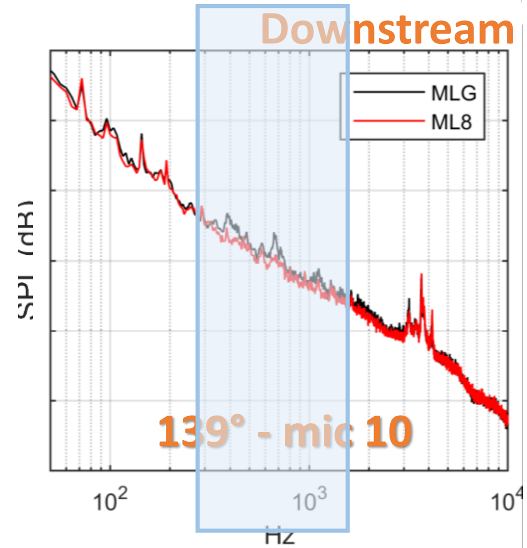
Noise reduction technologies











ML8 – Hub Caps + Axle Fairing

SPL(dB) narrow band frequency spectra
40m/s and 0° yaw

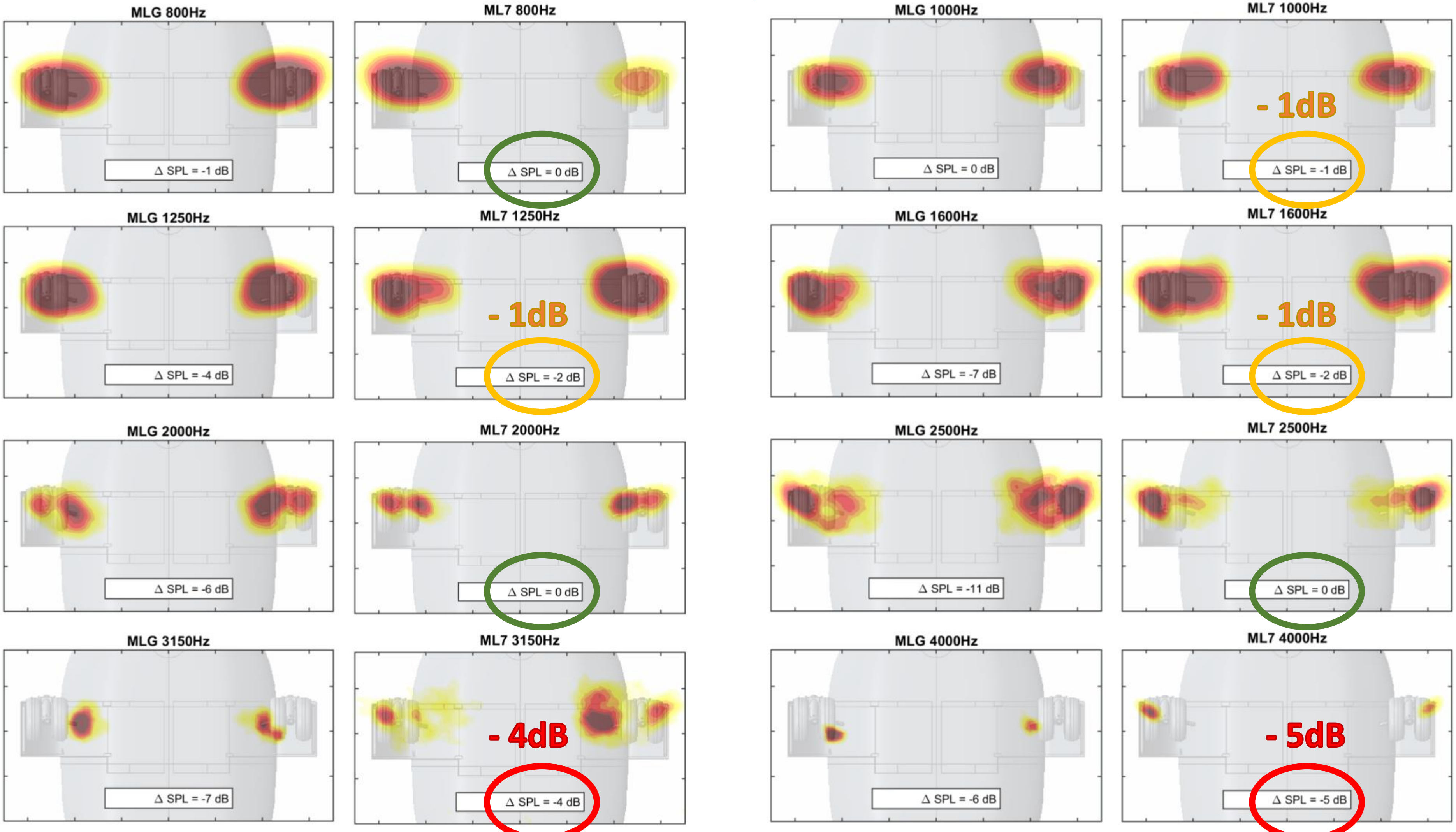
MLG Results

Noise reduction technologies

Mesh Fairings

$\Delta SPL(dB) = MLG\ (f_{OB}) - ML7\ (f_{OB})$

MLG ML7 Beamforming results MLG ML7



40m/s and 0° yaw

Time Domain Beamforming analysis

MLG Results

Noise reduction technologies

Hub Caps
+ Axle
Fairing

$\Delta SPL(dB) = MLG\ (f_{OB}) - ML8\ (f_{OB})$

MLG ML8 Beamforming results MLG ML8

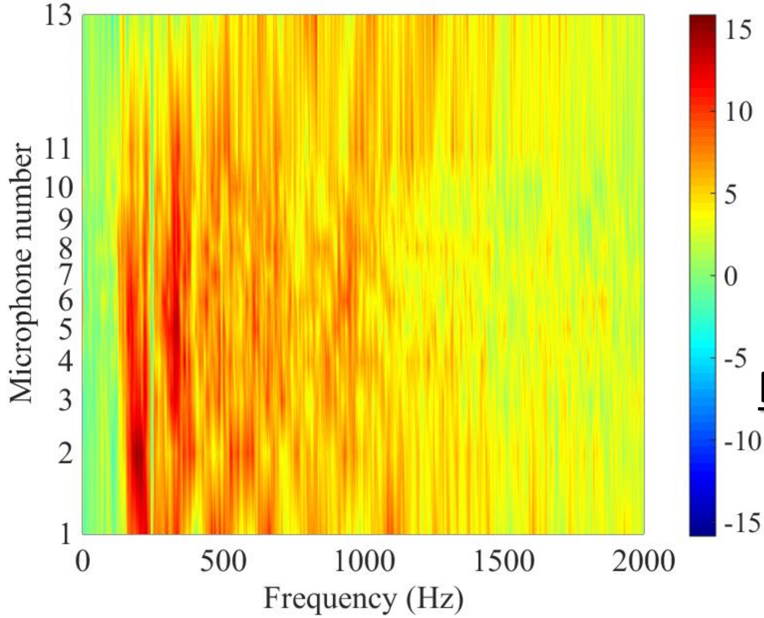
40m/s and 0° yaw

Nose Landing Gear Results Conclusions

Landing Gear Noise

Landing Gear Noise:

Directivity NLG-NF

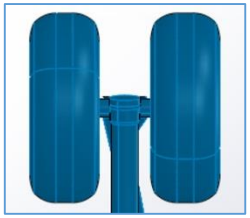


Amplitude:
Up to 15 dB

Frequency Range:
150 Hz – 1400 Hz

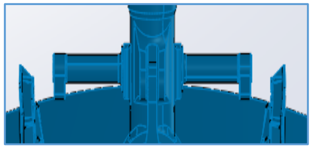
Particular contribution:
150 Hz – 230 Hz
284 – 380 Hz

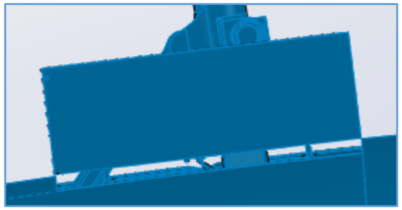
260 - 400 Hz
650 Hz
1kH



Broadband

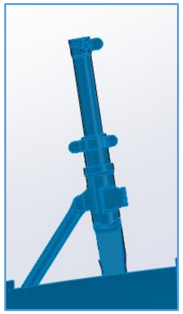
192 Hz
320 Hz

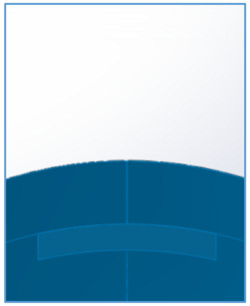




120 - 1200 Hz

124 - 250 Hz





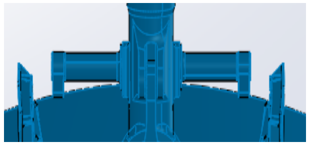
32 Hz
104 Hz
156 Hz

Nose Landing Gear Results Conclusions

Noise Reduction Technologies

120-250 Hz

-10dB



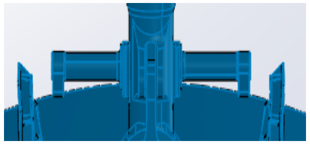
240Hz-2000Hz

-6dB

100Hz to 2000Hz

Suggested for the future!

-10dB



Nose Landing Gear Results Conclusions

Comparison with Literature

Case	Literature		This work
Landing Gear Noise above Fuselage	LAGOON 1:2,5 scaled simplified two-wheels LG	10 dB (*Manoha et al.*)	15 dB
Main Noise Sources	LAGOON 1:2,5 scaled two-wheels simplified LG	Axle, wheels, rim (*Azevedo et al.*)	Wheels, leg structure
Wheels Noise	33% scale isolated LG wheel	300 - 2000 Hz (*Zhang et al.*)	250 Hz - 2000 Hz
Torque Link Noise	30% scaled simplified two-wheels LG (Bombardier Global)	1980 Hz, over 3dB (*McCarthy and Ekmekci*)	Broadband, 2.5 - 5.3 dB
Ramp Spoiler	1/16th scale model of a typical large passenger aircraft LG	-7 dB (broadband) (*Dobrzynski et al.*)	-10 dB (120-250 Hz)
Hub Caps	33% scaled isolated LG wheel	- 6.1 dB (*Wang et al.*)	- 6 dB

E. Manoha, J. Bulte, V. Ciobaca, and B. Caruelle, "*LAGOON: Further analysis of aerodynamic experiments and early aeroacoustics results*," 15th AIAA/CEAS Aeroacoustics Conference, 2009

P. R. G. de Azevedo Junior and W. R. Wolf, "*Noise prediction of the lagoon landing gear using acoustic analogy and proper orthogonal decomposition*," 22nd AIAA/CEAS Aeroacoustics Conference, 2016

X. Zhang, Z. Ma, M. Smith, M. Sanderson, and P. Bissessur, "*Aerodynamic and acoustic measurements of a single landing gear wheel*," 19th AIAA/CEAS Aeroacoustics Conference, 2013

P. W. McCarthy and A. Ekmekci, "*The effect of strut geometry on the inter-wheel flow for a two-wheel landing gear*," 21st AIAA/CEAS Aeroacoustics Conference, 2015

W. Dobrzynski, B. Schöning, L.C. Chow, Ch. Wood, M. Smith, Ch. Seror, "*Design and testing of low noise landing gears*", AIAA/CEAS Paper 2005-3008, 2005

M. Wang, D. Angland, X. Zhang, and R. Fattah, "*High-order numerical simulations of an isolated landing gear wheel with a hub cavity*," 22nd AIAA/CEAS Aeroacoustics Conference, 2016.

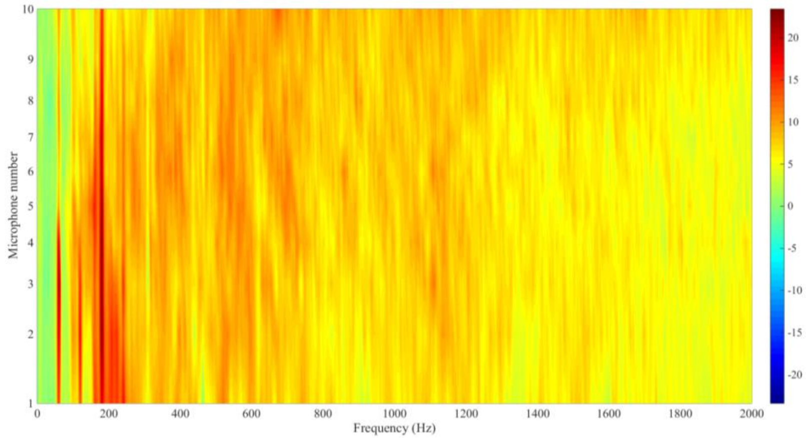
M. Wang, D. Angland, and X. Zhang, "*The noise generated by a landing gear with hub and rim cavities*," Journal of Sound and Vibration, vol. 392, pp. 127–141, 2017.

Main Landing Gear Results Conclusions

Langing Gear Noise

Landing Gear Noise:

Directivity MLG-MF



Amplitude:
Up to 23 dB

Frequency Range:
60 Hz – 1200 Hz

Particular contribution:
60 Hz – 250 Hz

ML7 – Mesh Fairings

-5dB

4000 Hz

ML8 – Hub Caps + Axle Fairing

-1dB

500Hz-3000Hz

Main Landing Gear Results Conclusions

Comparison with Literature

Case	Literature		This work	
Tyres Noise	40% scaled two-wheel type aircraft LG (100-PAX class regional jet airliner)	Door-side tyres magnitude < Sidebrace-side tyres magnitude (*Yokokawa et al.*)	Sidebrace-side tyres magnitude < Door-side tyres magnitude (≈2 dB)	Y. Yokokawa, T. Imamura, H. Ura, H. Uchida, K. Yamamoto, and H. Kobayashi, "*Experimental study on Noise Generation of a Two-Wheel Main Landing Gear*," 16th AIAA/CEAS Aeroacoustics Conference, 2010
Folding Stay Noise	40% scaled two-wheel type aircraft LG (100-PAX class regional jet airliner)	100, 1600, 3000 Hz (*Yokokawa et al.*)	400 - 1250 Hz	Y. Yokokawa, T. Imamura, H. Ura, H. Uchida, K. Yamamoto, and H. Kobayashi, "*Experimental study on Noise Generation of a Two-Wheel Main Landing Gear*," 16th AIAA/CEAS Aeroacoustics Conference, 2010
Hub Caps + axle fairings	Two-wheels full scale LG	-3 dB (500 - 1000 Hz) -2 dB (1000 - 2500 Hz) -1 dB (2500 - 5000 Hz) (*Bouvy et al.*)	-1 dB (500 Hz - 3000 Hz)	Q. Bouvy, T. Rougier, and P. Bertrand, "*Numerical approach for quieter landing gears*," X-Noise/CEAS Workshop, La Rochelle, France, 2015 Q. Bouvy, T. Rougier, A. Ghouali, D. Casalino, J. Appelbaum, and C. Kleinclaus, "*Design of quitter landing gear through Lattice-Boltzmann CFD simulations*," 21st AIAA/CEAS Aeroacoustics Conference, 2015
Mesh Fairings	Two-wheels full scale LG	- 2dB (*Bouvy et al.*)	-5 dB (4000 Hz)	Q. Bouvy, T. Rougier, A. Ghouali, A. Boillot, and B. Petot, "*Review of landing gear acoustic research at Messier-Bugatti-Dowty*," 22nd AIAA/CEAS Aeroacoustics Conference, 2016

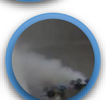
Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

Thank you

Flow Testing

Aeroacoustics Testing

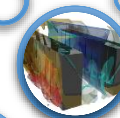
Wind Tunnel Tests



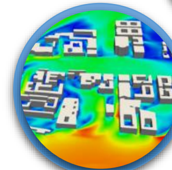
On Site Smoke Testing

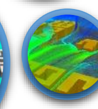
CFD and Multi-Physics Modelling

Urban and Buildings Aeroacoustics



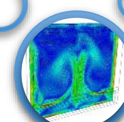
HVAC Analysis



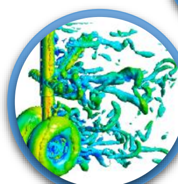


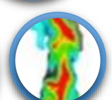
Wind Impact study

Aircraft and Wind Turbines Aerodynamic Noise



Façade Thermal Analysis





Fire and Smoke Modelling

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