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

NLG
MLG
Introduction
The ALLEGRA project

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

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

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].

Trinity College Dublin, The University of Dublin
Introduction
The ALLEGRA project

Pininfarina Wind Tunnel features:
- Jet section: 11 m² (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

ALLEGRA specifications:
- **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

NL3

NL2

NL1
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
## Microphones Arrays

<table>
<thead>
<tr>
<th>Array name</th>
<th>Characteristics</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Far Field Array</td>
<td>13 microphones 4.22m from model axis</td>
<td><img src="image1.jpg" alt="Picture" /></td>
</tr>
<tr>
<td>Side Array</td>
<td>3 meter diameter half-wheel array 66 microphones 4.22m from model axis</td>
<td><img src="image2.jpg" alt="Picture" /></td>
</tr>
<tr>
<td>Top Array</td>
<td>3 meter diameter wheel array 78 microphones 1.82m from the model</td>
<td><img src="image3.jpg" alt="Picture" /></td>
</tr>
<tr>
<td>Front Array</td>
<td>Spiral array 15 microphones upstream the landing gear plane at an angle of 10 degrees</td>
<td><img src="image4.jpg" alt="Picture" /></td>
</tr>
</tbody>
</table>
Introduction

Microphones Arrays

Diagram of linear far field array angles for the NLG

Diagram of linear far field array angles for the MLG
**Wind Tunnel Tests Matrix:**

<table>
<thead>
<tr>
<th>Yaw angle</th>
<th>Wind Tunnel Flow Speed</th>
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<tbody>
<tr>
<td></td>
<td>40m/s</td>
</tr>
<tr>
<td>-10°</td>
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</tr>
<tr>
<td>-5°</td>
<td>-5°</td>
</tr>
<tr>
<td>0°</td>
<td>0°</td>
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<tr>
<td>5°</td>
<td>5°</td>
</tr>
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<td>-10° to +10°</td>
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Angle of attack: 4°

Yaw Angle
## Wind Tunnel Tests Matrix:

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<td>-10° to +10°</td>
<td></td>
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</table>

**Angle of attack: 4°**

**Yaw Angle**
Nose Landing Gear Results
NLG Results

Directivity of the nose landing gear noise

$\Delta SPL$(dB) wrt baseline NLG as a function of frequency and directivity - Linear Far Field array

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

**Spectrograms**

- **Downstream**
  - $142^\circ$
  - 16$^{\text{th}}$ microphone

- **Upstream**
  - $41^\circ$
  - 4$^{\text{th}}$ microphone

Up to 15 dB

- 150 – 230 Hz
- 284 – 380 Hz

150 Hz – 1400 Hz

50m/s and $0^\circ$ yaw
ΔSPL (dB) as a function of frequency and directivity - Linear Far Field array

**NLG Results**

**Directivity of the nose landing gear components**

- 50 m/s and 0° yaw

**Wheels**

- (NLG-Dress)-(NLG-DressW)
  - 139°
  - Up to 7.5 dB
  - $f_{FF} = 636$ Hz
  - $f_{EE} = 968$ Hz

- 260 - 400 Hz
- 650 Hz
- 1kH

**Torque Link**

- (NLG-DressW)-(NLG-DressWT)
  - 139°
  - Up to 5.3 dB
  - 148 Hz

**(NLG)-(NF)**

- 37°

Reference:
- 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

Steering Pinion

(VNLG-DressWT)-(NLG-DressWTS)

139°

192 Hz
320 Hz

Up to 4.2dB

Doors

(VNLG-DressWTS)-(NLG-DressWTSD)

139°

120-1200 Hz

Up to 5.6dB

Vortex shedding frequency:

\[ f = \frac{US_t}{d} = 190 \text{ Hz} \]
$\Delta$SPL(dB) as a function of frequency and directivity - Linear Far Field array

\[ f = \frac{USt}{d} = 89, 105, 138, 173, 208 \text{ Hz} \]
ΔSPL(dB) as a function of frequency and directivity - Linear Far Field array

Bay only NB

\[ f_{HR} = 32 \text{ Hz} \]
\[ f_1 = 104 \text{ Hz} \]
\[ f_2 = 156 \text{ Hz} \]

NLG Results

Directivity of the nose landing gear components

Are these bay cavity modes radiating to the far field?

\( \Delta \text{SPL (dBA)} \) wrt baseline NLG as a function of frequency and directivity

Linear Far Field array

142°

(NLG-DressWTSD) - NF

Leg structure
124 – 250 Hz

Leg+Bay

0° yaw
50m/s

\( f_1 = 104 \text{ Hz} \)

\( f_{HR} = 32 \text{ Hz} \)
NLG Results
Directivity of the nose landing gear components

Are these bay cavity modes radiating to the far field?

\[ \Delta \text{SPL (dBA)} \text{ wrt baseline NLG as a function of frequency and directivity} \]

Linear Far Field array

- Leg structure 124 – 250 Hz
- Leg+Bay+DOORS
- Doors

\( f_1 = 104 \text{ Hz} \)
\( f_{HR} = 32 \text{ Hz} \)
50m/s and 0° yaw

\[ \Delta \text{SPL (dB)} \] as a function of frequency and directivity

- Linear Far Field array

**NL1-NLG:**

- Up to 10dB noise reduction

**139°**

**Steering Pinion**

- (NLG-DressWT)-(NLG-DressWTS)

**Leg structure**

- (NLG-DressWTD)-(NB)
NLG Results
Noise reduction technologies

NL2-NLG:
240Hz to 2000Hz
Up to 6dB noise reduction

NL3-NLG:
240Hz to 2000Hz
Up to 6dB noise reduction

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

50m/s and 0° yaw

Wheels
NLG Results
Noise reduction technologies

Above 7dB noise reduction broadened to both lower and higher frequencies

NL6-NLG: 100Hz to 2000Hz

50m/s and 0° yaw

Steering Pinion

Leg structure

Wheels

+ DOORS! (120-2000 Hz)
Main Landing Gear Results
MLG Results
Directivity of the main landing gear noise

\( \Delta \text{SPL}(\text{dB}) \) wrt baseline MLG as a function of frequency and directivity - Linear Far Field array

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

65 m/s and 0° yaw
Spectrograms

Downstream 139°
Up to 23 dB

Upstream 32°
60 – 250 Hz
60 Hz – 1200 Hz
MLG Results
Directivity of the main landing gear components

$\Delta$SPL (dB) as a function of frequency and directivity - Linear Far Field array

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Directivity</th>
<th>Top Doors</th>
<th>Side Doors</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>139°</td>
<td>Up to - 10dB</td>
<td>Up to + 20dB</td>
</tr>
<tr>
<td>132</td>
<td>139°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>37°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>37°</td>
<td>(MLG)-(MLG-TopDoors)</td>
<td>(MLG)-(MLG-SideDoors)</td>
</tr>
</tbody>
</table>

65 m/s and 0° yaw
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 Results**

**Beamforming – Top Array**

Functional Frequency Domain Beamforming

65 m/s, 0° yaw

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**Outer Wheels**

**Folding Stay**

**Attachment structures**
MLG Results

Noise reduction technologies

Upstream

1-5 kHz

42° - mic 2

64° - mic 4

91° - mic 6

Downstream

117° - mic 8

139° - mic 10

ML7 – Mesh Fairings

SPL(dB) narrow band frequency spectra

40 m/s and 0° yaw
MLG Results
Noise reduction technologies

Upstream 300-1500 Hz

- 42° - mic 2
- 117° - mic 8

Downstream

- 64° - mic 4
- 139° - mic 10

ML8 – Hub Caps + Axle Fairing

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

Noise reduction technologies

\[ \Delta \text{SPL(dB)} = \text{MLG} (f_{\text{OB}}) - \text{ML7} (f_{\text{OB}}) \]

Beamforming results

- 1dB

40m/s and 0° yaw

Time Domain Beamforming analysis
MLG Results

Noise reduction technologies

ΔSPL(dB) = MLG (f_{OB}) - ML8 (f_{OB})

Beamforming results

Hub Caps + Axle Fairing

40m/s and 0° yaw
**Landing Gear Noise:**

- Amplitude: Up to 15 dB
- Frequency Range: 150 Hz – 1400 Hz
- Particular contribution: 150 Hz – 230 Hz, 284 – 380 Hz

**Directivity NLG-NF**

- Microphone number
- Frequency (Hz)

**Broadband**

- 192 Hz
- 320 Hz

**Nose Landing Gear Results Conclusions**

- 260 - 400 Hz
- 650 Hz
- 1kH

- 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

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


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

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<thead>
<tr>
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<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tyres Noise</strong></td>
<td>Door-side tyres magnitude &lt; Sidebrace-side tyres magnitude (Yokokawa et al.)</td>
<td>Sidebrace-side tyres magnitude &lt; Door-side tyres magnitude (≈2 dB)</td>
</tr>
<tr>
<td></td>
<td>40% scaled two-wheel type aircraft LG (100-PAX class regional jet airliner)</td>
<td></td>
</tr>
<tr>
<td><strong>Folding Stay Noise</strong></td>
<td>100, 1600, 3000 Hz (Yokokawa et al.)</td>
<td>400 - 1250 Hz</td>
</tr>
<tr>
<td></td>
<td>40% scaled two-wheel type aircraft LG (100-PAX class regional jet airliner)</td>
<td></td>
</tr>
<tr>
<td><strong>Hub Caps + axle fairings</strong></td>
<td>-3 dB (500 - 1000 Hz) -2 dB (1000 - 2500 Hz) -1 dB (2500 - 5000 Hz) (Bouvy et al.)</td>
<td>-1 dB (500 Hz - 3000 Hz)</td>
</tr>
<tr>
<td></td>
<td>Two-wheels full scale LG</td>
<td></td>
</tr>
<tr>
<td><strong>Mesh Fairings</strong></td>
<td>- 2dB (Bouvy et al.)</td>
<td>-5 dB (4000 Hz)</td>
</tr>
<tr>
<td></td>
<td>Two-wheels full scale LG</td>
<td></td>
</tr>
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</table>

Thank you