6-2016

Revisiting Applegate and Croker’s 1976 NCEJ paper: Reducing the Noise of a Rotary Lawn Mower Blade

Daniel J. Carr

Purdue University, djcarr@purdue.edu

Follow this and additional works at: https://docs.lib.purdue.edu/herrick


https://docs.lib.purdue.edu/herrick/191

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Classic Papers Presentation: Reducing the Noise of a Rotary Lawn Mower Blade
(S. L. Applegate & M. J. Crocker)

Daniel Carr
Ray W. Herrick Laboratories
Purdue University

Introduction

• Noise from lawn care equipment has been a frequent subject of citizen complaints in America
• 2000 EU standard specifying permissible sound power level from lawn mower based on cut width
• How to reduce noise without overly compromising cutting efficiency?

Example of lawnmower sound (not the tractor shown)
Overview of Presentation

• Summary of Applegate and Crocker’s paper
• Impact of work published
• Model parameter variation study
• Concluding comments
Paper Summary: Introduction

• Increasing public awareness of noise from equipment like lawnmowers (1976)

• Previous noise-control work on rotary lawnmowers
  – Focused on engine noise
    This noise is largely reduced by improved mufflers and/or use of electric engines
  – Blade noise and vibration-generated noise now important
Paper Summary: Vibration Noise

• Experiment: lawnmower assembly placed on artificial turf and driven by an external electric motor

• Sound power measured
  – Removing mower blades does not produce significant decrease in noise

• Velocity of mower housing measured
  – Significant amplitudes detected; vibration reduction methods should be examined

Figure 2– Mower assembly testing apparatus
Paper Summary: Vibration Noise

Damping/Stiffening

- Stiffening, damping of the housing: relatively ineffective (Figure 3)
- Isolating the blade drive shafts from the housing: most effective, feasible; blade noise is now the primary source (cf. Figure 4)

Vibration Isolation

Applegate & Crocker, Figure 3 (mower driven at 3300 rpm)

Applegate & Crocker, Figure 4 (mower driven at 3300 rpm)
Paper Summary: Blade Noise (Tonal & Broadband)

• Single blade operating in free space
• Blade driven by an electric motor mounted on a rig with a scale and a force transducer
• Lift thrust ($T$), drag torque ($Q$) measured
• Four blade designs tested

Sharp trailing edge       High-lift       Low-lift       Standard

Applegate and Crocker, Figure 7
Paper Summary: Blade Noise (Tonal & Broadband)

• Noise analyzed by using narrowband sound pressure analysis

• Noise contains both distinct pure tones and broadband components
  – Pure tones occur at multiples of the blade passing frequency (BPF)

• Conclusion: existing theory for fans and propellers might be applicable here
Paper Summary: Pure Tone Blade Noise

3300 RPM → 110 Hz BPF
Motor-driven blade assembly, with standard blade

Figure 6— Lift/drag measurement apparatus for blade-noise experiment

Figure 5—Narrowband mower blade spectrum. Standard blade, inside housing, 3300 RPM (110 Hz BPF)
Paper Summary: Pure Tone Blade Noise

- Gutin’s theory for pure-tone aircraft propeller noise
- Simplified equation for sound power of fundamental tone:

\[ W = \left[ \left( \frac{\omega_1}{2\pi c} \right) \left( \frac{1}{8} \right) \left( k^2 R_a^2 \right) \right] \left( \frac{\pi}{\rho c} \right) \left[ T^2 \left( \frac{16}{105} \right) + \left( \frac{2cQ}{\omega_1 R_a^2} \right)^2 \left( \frac{16}{15} \right) \right] \]

- \( W \): acoustic power
- \( \omega_1 \): circular frequency of fundamental tone (number of blades times the speed of rotation)
- \( c \): speed of sound
- \( k \): wavenumber
- \( R_a \): effective blade radius
- \( \rho \): density of air
- \( T \): lift thrust
- \( Q \): drag torque

Items in red are measured experimentally
**Paper Summary: Pure Tone Blade Noise**

<table>
<thead>
<tr>
<th>Blade type</th>
<th>Sound Power Level, dB (arbitrary reference)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fundamental tone</td>
<td>2nd harmonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rpm</td>
<td>BPF (Hz)</td>
<td>Actual</td>
<td>Computed</td>
<td>Actual</td>
</tr>
<tr>
<td>Standard</td>
<td>3300</td>
<td>110</td>
<td>85</td>
<td>83.7</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>2550</td>
<td>85</td>
<td>74</td>
<td>74.6</td>
<td>71</td>
</tr>
<tr>
<td>Low-lift</td>
<td>3300</td>
<td>110</td>
<td>77</td>
<td>74.8</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>2550</td>
<td>85</td>
<td>68</td>
<td>66.1</td>
<td>61</td>
</tr>
<tr>
<td>High-lift</td>
<td>3300</td>
<td>110</td>
<td>87</td>
<td>84.1</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>2550</td>
<td>85</td>
<td>81</td>
<td>76.9</td>
<td>71</td>
</tr>
<tr>
<td>Sharp</td>
<td>3300</td>
<td>110</td>
<td>82</td>
<td>79.1</td>
<td>73</td>
</tr>
<tr>
<td>trailing</td>
<td>2550</td>
<td>85</td>
<td>73</td>
<td>70.6</td>
<td>67</td>
</tr>
</tbody>
</table>

- Calculated and experimental sound power level values agree well ($\leq 4.1$ dB difference) for the fundamental tone (highest sound power level).
- Calculated levels of higher harmonics are underestimated ($\geq 40.6$ dB) Generally lower in sound power level and less important than fundamental tone.
Paper Summary: Pure Tone Blade Noise

• The effects of lift, drag, and speed on pure-tone noise can be predicted theoretically with a small amount of testing (first harmonic, not $2^{nd}$)

• Speed effects not as easy to account for as lift/drag effects (because speed changes lift and drag)
  – Blade speed generally set by grass cutting-efficiency requirements, but should be kept at a minimum for noise reasons
Paper Summary: Broadband Blade Noise

• Analyzed using vortex-shedding theory
• Relationship proposed by Applegate in his Master’s Thesis:

\[ W = k (Re)^{-0.4} A \rho \left( \frac{U_T^6}{c^3} \right) 2\pi \left( \frac{2}{3} \right) \]

- \( W \): sound power
- \( k \): blade factor (determined experimentally)
- \( U_T \): blade tip speed
- \( Re \): Reynolds number (based on \( U_T \) and blade mean chord)
- \( A \): blade area
- \( \rho \): density of air
- \( c \): speed of sound
Paper Summary: Broadband Blade Noise

- \( k \) selected to make measured and calculated sound powers agree at 3300 rpm
- Using this value of \( k \), the calculated sound powers agree reasonably well with measurements at the two other speeds

<table>
<thead>
<tr>
<th>Blade Type</th>
<th>Sound Power Level, dB (linear weighting, arbitrary reference)</th>
<th>Measured</th>
<th>Computed</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3300</td>
<td></td>
<td>93.1</td>
<td>93.1</td>
<td>0</td>
</tr>
<tr>
<td>2550</td>
<td></td>
<td>86.4</td>
<td>86.9</td>
<td>-0.5</td>
</tr>
<tr>
<td>1890</td>
<td></td>
<td>78.1</td>
<td>79.6</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

\[ k = 4.5 \times 10^{-5} \]

<table>
<thead>
<tr>
<th>Blade Width</th>
<th>0.0635 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Length</td>
<td>0.4572 m</td>
</tr>
<tr>
<td>( \rho )</td>
<td>1.21 kg/m³</td>
</tr>
<tr>
<td>( c )</td>
<td>343 m/s</td>
</tr>
</tbody>
</table>
**Paper Summary: Broadband Blade Noise**

**Rotation Speed**

- Higher sound power levels for low-lift blade may be due to lower bending stiffness of blade.

**Blade Geometry**

- Increasing RPM

Figure 8—Sound power level of standard blade, *housing removed*, varying RPM

Figure 9—Sound power level of different blades, *inside* housing, 3300 RPM

- Higher sound power levels for low-lift blade may be due to lower bending stiffness of blade.
Paper Summary: Broadband Blade Noise

• Ways to reduce vortex noise:
  – Reduce speed
  – Reduce $k$ (generally done by streamlining)

• In terms of perceived loudness, broadband vortex noise was more important than pure tones for the four blades used
  – This conclusion was reached on the basis of both A-weighted sound level and Zwicker Loudness calculations

Applegate and Crocker, Figure 7

Streamlined (sharp trailing edge)
Paper Summary: Conclusions

• Two types of noise from mower assembly considered

• Noise from vibration of the housing is most important
  – Can be effectively reduced by vibration isolating the blade-shaft bearings from the housing proper

• Aerodynamic blade noise becomes important after vibration noise is reduced
  – Can be reasonably predicted by equations based on propeller theory and vortex-shedding theory
Impact

• Applegate and Crocker’s paper is cited in four later publications
  – *Noise Control Engineering Journal* article: D. Tauro and J. A. Mann III
  – *Applied Acoustics* article: D. A. Guenther, M. J. Moran, and L. L. Faulkner. This article cited by:
    • *Journal of Mechanical Engineering* article: T. Gokool, F. Ali, B. V. Chowdary, and K. Kanchan
    • *Agricultural Mechanization and Research* article: authors unknown, published in Chinese
  – EPA publication: Tree, D. R. Lawn Tractor Noise Reduction. *EPA 550/9, 77(300), 3*
# Model Parameter Variation Study

<table>
<thead>
<tr>
<th>k</th>
<th>width (mean chord, in)</th>
<th>Length (in)</th>
<th>RPM</th>
<th>L_w (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>93.2</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>2550</td>
<td>86.9</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>1890</td>
<td>79.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>k</th>
<th>width (mean chord, in)</th>
<th>Length (in)</th>
<th>RPM</th>
<th>L_w (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50E-05</td>
<td>2.25</td>
<td>18</td>
<td>3300</td>
<td>92.9</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.38</td>
<td>18</td>
<td>3300</td>
<td>93.0</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>93.2</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.75</td>
<td>18</td>
<td>3300</td>
<td>93.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>k</th>
<th>width (mean chord, in)</th>
<th>Length (in)</th>
<th>RPM</th>
<th>L_w (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>15</td>
<td>3300</td>
<td>87.9</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>17</td>
<td>3300</td>
<td>91.5</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>93.2</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>20</td>
<td>3300</td>
<td>96.2</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>21</td>
<td>3300</td>
<td>97.6</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>24</td>
<td>3300</td>
<td>101.4</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>38</td>
<td>3300</td>
<td>114.6</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>42</td>
<td>3300</td>
<td>117.4</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>46</td>
<td>3300</td>
<td>120.0</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>48</td>
<td>3300</td>
<td>121.3</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>50</td>
<td>3300</td>
<td>122.4</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>54</td>
<td>3300</td>
<td>124.6</td>
</tr>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>60</td>
<td>3300</td>
<td>127.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>k</th>
<th>width (mean chord, in)</th>
<th>Length (in)</th>
<th>RPM</th>
<th>L_w (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>92.1</td>
</tr>
<tr>
<td>3.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>90.6</td>
</tr>
<tr>
<td>2.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>93.0</td>
</tr>
<tr>
<td>1.50E-05</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>88.4</td>
</tr>
<tr>
<td>5.00E-06</td>
<td>2.5</td>
<td>18</td>
<td>3300</td>
<td>83.6</td>
</tr>
</tbody>
</table>
Model Parameter Variation Study

![Graphs showing relationships between sound power level and various parameters like blade width, blade length, RPM, and k factor.](image)

Standard blade marked in red

- Sound Power Level (dB) vs. RPM
  - $w = 2.5$ in
  - $L = 18$ in
  - $k = 4.5 \times 10^{-5}$

- Sound Power Level (dB) vs. Blade Width (in)
  - $L = 18$ in
  - RPM = 3300
  - $k = 4.5 \times 10^{-5}$

- Sound Power Level (dB) vs. Blade Length (in)
  - $w = 2.5$ in
  - RPM = 3300
  - $k = 4.5 \times 10^{-5}$

- Sound Power Level (dB) vs. k factor
  - $w = 2.5$ in
  - L = 18 in
  - RPM = 3300
Concluding comments

• Tonal noise predictions for upper harmonics could be improved

• Broadband noise predictions are accurate

• Design questions: how do noise-reduction measures affect grass-cutting efficiency?
  – Dosage issues: short-duration exposure to louder sounds or long-duration exposure to quieter sounds
  – Reducing the blade length by a quarter (all other variables constant) requires the mower to be used 6.8 times as long to produce equivalent dosage of broadband noise

• While mowing the lawn, wear hearing protection!
References

Primary sources

Sources of predictive theories
References

Sources citing Applegate and Crocker, and their citing sources


• Tree, D. R. Lawn Tractor Noise Reduction. *EPA 550/9, 77*(300), 3.
