A review of noise and vibration control technologies for rotorcraft transmissions

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Acknowledgements:
• NASA Revolutionary Vertical Lift Technology (RVLT) Project
Outline

• Introduction

• Noise and vibration control technologies
  • Mature technologies
  • Emerging technologies

• Observations, recommendations, and conclusions

• Disruptive trends in rotorcraft development
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Introduction

Rotorcraft have the potential to...

• Improve accessibility of routine air travel
• Reduce airport congestion

Current limitations

• Range, speed, and payload capacity
• Safety / reliability
• Extreme cabin noise levels (>110 dB)

Noise and Vibration control technologies

• Improved passenger and environmental acceptance
• Increased service life

National aeronautics security goals [1]

• Reduce main rotor gearbox noise by 20 dB
• Reduce vibratory loads by 30%
• Reduce cabin noise below 77 dB

NASA’s Rotary Wing Project goal [2]

2. Subsonic Rotary Wing Project goals, 2011 ARMD Program and Project overview
Typical Cabin Noise Spectrum

- **Main & tail rotor tones**
  - (typ. < 200 Hz)

- **Gear mesh tones and sidebands**
  - (typ. 500 – 4000 Hz)

- **Hearing loss threshold (85 dBA)**

- **Speech band**

- **Vibro-acoustic transfer path**

Example Rotorcraft Driveline

UH-60 Blackhawk transmission

Stage 1: bevel
Stage 2: combining bevel
Stage 3: spur planetary

Transmission
Structural path
Radiating surface
Air path

Direct radiation
- Airborne
- Acoustic-induced structureborne

Engine input
Main rotor shaft
Tail rotor shaft

Cabin Noise Trends

• Maximum noise within 500 or 1000 Hz octave bands

• Military, utility (85-110 dB) louder than civil (86-94 dB)

• As gross weight increases…
  Military get louder    civil get quieter

• Low-speed, final stage gearing has greatest impact on cabin noise
  • Peak noise in 7 out of 8 cases
  • Most harmonics in speech band


**Scope and Organization**

**Scope**

- Vibration control treatments close to the gear mesh source
  - **Considered**
    - transmission
    - strut/mount connection to fuselage
  - **Not considered**
    - rotor blades and hub
    - gas turbine engines
    - fuselage


**Organization**

Mature technologies

- **Source control**
- **Path control**

Emerging technologies

- **Source control**
- **Path control**

**Source:** gears, shafts, bearings, housing  
**Path:** mounts, struts
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Mature Technologies: Source Control

- **Primary gear vibration sources**: static transmission error (STE), mesh stiffness variation, friction, and planet location changes

**Gear tooth profile optimization**
- STE minimized using involute spur / helical and Litvin’s \[^{[10]}\] bevel / spiral-bevel tooth profiles

**High contact ratio (CR) and helical gears**
- Oswald et al. \(^{[11]}\) measured noise due to gear type, profile, and CR – total CR is most important, helical 2-17 dB quieter than spur

**Isotropically-superfinished (IS) gear teeth**
- Hansen et al. \(^{[12]}\) installed IS gears in S-76C+, full-scale lab testing showed 3.7-7 dB decrease in bull and spiral-bevel stages

**Planet phasing**
- Schlegel et al. \(^{[13]}\) demonstrated 11 dB noise reduction in spur planetary

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Mature Technologies: Path Control

Active gearbox struts

- Maier et al. [19] flight tested a set of active struts: 11 dB lower cabin noise at primary gear tone, insufficient authority for multi-tonal control

- Flight testing by Hoffmann et al. [20]: 19.5 dB at 1\textsuperscript{st} harmonic, 4-8 dB at higher harmonics

Active noise control via actuation of fuselage at transmission mounts

- Millott et al. [21] flight testing on S-76: primary gear tone avg. reduction: 18 dB (steady flight), 8-14 dB (maneuvers)

- Implemented in Sikorsky S-92 Helibus
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Emerging Technologies: Source Control

Magnetic gears

- **Potential benefits**: higher reliability, dramatically lower vibration, and improved loss of lubrication
- Paden [23] built 15 kW (20 hp) prototype with low mass (294% of optimized, non-magnetic version)
  - Prediction: 122% of non-magnetic when scaled up to 300 kW (402 hp)

On-the-gear passive and active control

- Kish [24] introduced gear with elastomeric band for torsional isolation
  - 3-7 dB reduction at 1\textsuperscript{st}, 2\textsuperscript{nd} harmonics
- Guan et al. [26] modeled gearbox actuation concepts
  - On-gear challenging – slip rings, high force
  - Shaft control promising – lower force, simpler

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Emerging Technologies: Source Control

Active transverse vibration control of shafts

- Rebbechi et al. [27] – 2 magneto actuators along LOA, lab testing: 1\textsuperscript{st} (20-28 dB), 2\textsuperscript{nd} (5-13 dB), and 3\textsuperscript{rd} (0-2 dB) harmonics reduced
- Guan et al. [28] – 1 piezo actuator along LOA, lab testing: 18 dB (1\textsuperscript{st} harmonic), 2-6 dB (1\textsuperscript{st} + 2\textsuperscript{nd} harmonics)

Piezoelectric bearings and shaft attachments

- Atzrodt et al. [30] – bearing with 4 shunt-damped piezos, 17.5 dB lower transmissibility (1\textsuperscript{st} harmonic)
- Pinte et al. [31] – active bearing, 2 piezo actuators, transmitted force lowered 5-45 dB over 400-900 Hz

Periodic shafts

- Asiri et al. [32] – geometric or material periodicity, 0-40 dB lower transmissibility when isolating small gearbox
- Asiri et al. [33] – active piezo / metal periodicity, 10-30 dB better than passive periodic in stop bands

Emerging Technologies: Path Control

Elastomeric mounts for hard-mounted transmissions
- Yoerkie et al. [35] lab testing in very stiff rig: 0-60 dB over 0-5.5 kHz
  - Flight certification issues, difficult to retrofit

Variable stiffness mounts
- Scheidler et al. [34] developed mount with real-time stiffness control, testing: modulus tuned up to 22 GPa and 500 Hz

Nonlinear concepts and negative stiffness mechanisms
- Provide high static stiffness and low dynamic stiffness
- To date, implemented in very low frequency isolators
  - Suspending large aircraft in “free” BC during ground vibration testing [36]

Emerging Technologies: Path Control

Periodic elastomeric isolation mounts

- Szefi et al. [37-39] developed elastomer/metal periodic mounts with embedded anti-resonant isolators
  - Design for Bell Model 427: −40 dB transmissibility over 500-2000 Hz
- Le Hen et al. [40] included piezo actuator to add notches in spectrum
  - 30-41 dB extra reduction (70-81 dB passive + active)
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Select Observations & Recommendations

- Low-speed gear tones efficiently produce cabin noise (cabin treatment has low pass effect)

- Mature gear technologies are available, but not always used

- Considerable amount of work on active control recently
  - Full-scale testing needed to assess actuator requirements
  - FXLMS control algorithm is less effective than adaptive noise equalizer (ANE) control \[^46\] for modulated tonal disturbances

- Nonlinear or negative stiffness concepts have not been explored

- Technologies should 1\textsuperscript{st} integrate into military designs or be capable of retrofit

- Technologies exist to effectively attenuate rotor-induced tones
  - Gear noise concepts shouldn’t amplify rotor tones or displace effective rotor noise concepts

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## Conclusions

**IL**: insertion loss, reduction in metric due to integration of a technology

**TRL**: technology readiness level (NASA [48])

<table>
<thead>
<tr>
<th>Technology</th>
<th>Approx. freq., Hz</th>
<th>IL, dB</th>
<th>TRL</th>
<th>Mass/Size</th>
<th>Retrofit</th>
<th>Vary freq.</th>
<th>Key challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Broad-band</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive gear isolation</td>
<td>&gt;500</td>
<td>3-7</td>
<td>3-6</td>
<td></td>
<td></td>
<td></td>
<td>temperature limits</td>
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<tr>
<td>Bearing shunt damper</td>
<td>&gt;100</td>
<td>7-18</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>design integration</td>
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<tr>
<td>Periodic shaft</td>
<td>500-4k</td>
<td>0-40</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>shaft length</td>
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<tr>
<td>Elastomeric hard mount</td>
<td>&gt;250</td>
<td>0-60</td>
<td>4-7</td>
<td></td>
<td></td>
<td></td>
<td>reliability</td>
</tr>
<tr>
<td>Periodic fluid mount</td>
<td>500-3k</td>
<td>30-81</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>system-level data</td>
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<tr>
<td><strong>Narrow-band</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High CR spur gear</td>
<td>500-4k</td>
<td>2</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>Superfinished gear</td>
<td>500-4k</td>
<td>4-7</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>Helical gear</td>
<td>500-4k</td>
<td>2-17</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>added thrust load</td>
</tr>
<tr>
<td>Magnetic gear</td>
<td>500-1.6k</td>
<td>?</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>specific torque</td>
</tr>
<tr>
<td>Active gear</td>
<td>&lt;1k</td>
<td>7.5</td>
<td>3-4</td>
<td></td>
<td></td>
<td></td>
<td>complex, force required</td>
</tr>
<tr>
<td>Active transverse shaft</td>
<td>&lt;4k</td>
<td>2-28</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>size, force required</td>
</tr>
<tr>
<td>Active bearing</td>
<td>&lt;1k</td>
<td>0-45</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>size, force required</td>
</tr>
<tr>
<td>Active strut</td>
<td>200-2.5k</td>
<td>11-20</td>
<td>7-?</td>
<td></td>
<td></td>
<td></td>
<td>reliability</td>
</tr>
<tr>
<td>Active at mounting points</td>
<td>200-1.5k</td>
<td>8-18</td>
<td>7-?</td>
<td></td>
<td></td>
<td></td>
<td>force required</td>
</tr>
<tr>
<td>Variable stiffness mount</td>
<td>&lt;1k</td>
<td>?</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>unproven performance</td>
</tr>
</tbody>
</table>

Disruptive Trends in Rotorcraft Development

Multi-speed and variable speed transmissions
- Abrupt or smooth tonal shifts over wide band
- **Motivates:** maturation of variable frequency technologies

Composite gears and shafts
- Early goal: composite gear body and hub
- **Motivates:** higher performance vib. control, tailored anisotropy, embedded treatment

Electrification
- Significantly different powertrain configurations and source locations
- **Motivates:** understanding of the source

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44. Sikorsky Firefly www.sikorsky.com
45. DARPA VTOL X-Plane www.darpa.mil
Extra slides.....
# Cabin Noise Measurements

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Ref.</th>
<th>Max gross weight, kg</th>
<th>Peak, dB</th>
<th>Band/Tone, Hz</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell OH-58C</td>
<td>1987</td>
<td>M 1,451</td>
<td>85</td>
<td>573</td>
<td>Single tone measurement</td>
</tr>
<tr>
<td>Agusta A-109</td>
<td>1980</td>
<td>C 2,559</td>
<td>90</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Westland Lynx</td>
<td>1980</td>
<td>M 3,291</td>
<td>98</td>
<td>500</td>
<td>Common powertrain</td>
</tr>
<tr>
<td>Westland WG30</td>
<td></td>
<td>C 5,806</td>
<td>94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sikorsky S-76A</td>
<td>1986</td>
<td>U 4,587</td>
<td>105</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Bell 212</td>
<td>1980</td>
<td>U 5,080</td>
<td>103</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Aérospatiale Puma</td>
<td>1980</td>
<td>M 7,000</td>
<td>103</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Sikorsky Sea King</td>
<td>1980</td>
<td>M 10,000</td>
<td>102</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Westland VIP Commando</td>
<td></td>
<td>C 9,707</td>
<td>89</td>
<td></td>
<td>Common platform</td>
</tr>
<tr>
<td>Sikorsky S-61N</td>
<td></td>
<td>C 8,620</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sikorsky CH-53A</td>
<td>1977</td>
<td>M 15,876</td>
<td>110</td>
<td>1000</td>
<td>CHRA was a CH-53A w/ custom sealed cabin</td>
</tr>
<tr>
<td>NASA-Sikorsky CHRA</td>
<td></td>
<td>R 15,876</td>
<td>76</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

M: military, U: civil-utility, C: civil, R: civil-research

- Maximum noise within 500 or 1000 Hz octave bands
- Military, utility (85-110 dB) louder than civil (86-94 dB)
- As gross weight increases…
  
  Military get **louder**  civil get **quieter**

### Rotorcraft Gear Mesh Frequencies

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mesh frequencies, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aérospatiale</strong></td>
<td></td>
</tr>
<tr>
<td>- Puma</td>
<td>Spur 2-pair</td>
</tr>
<tr>
<td></td>
<td>Helical 2-pin/1-gear: ~4550</td>
</tr>
<tr>
<td></td>
<td>Bevel pair: ~1750</td>
</tr>
<tr>
<td></td>
<td>Planetary pair 1: ~1600</td>
</tr>
<tr>
<td></td>
<td>Planetary pair 2: ~550, ~1100</td>
</tr>
<tr>
<td><strong>Agusta</strong></td>
<td></td>
</tr>
<tr>
<td>- 109</td>
<td>Combining stage</td>
</tr>
<tr>
<td></td>
<td>Bevel pair: 1850</td>
</tr>
<tr>
<td></td>
<td>Planetary: 820</td>
</tr>
<tr>
<td><strong>Westland</strong></td>
<td></td>
</tr>
<tr>
<td>- Lynx</td>
<td>Combining stage</td>
</tr>
<tr>
<td></td>
<td>Spiral-bevel 2-pair: ~2150</td>
</tr>
<tr>
<td>- WG30</td>
<td>Conformal 2-pin/1-bull: ~450</td>
</tr>
<tr>
<td><strong>Sikorsky</strong></td>
<td></td>
</tr>
<tr>
<td>- S-76A</td>
<td>Helical 2-pair</td>
</tr>
<tr>
<td></td>
<td>Spiral-bevel 2-pair: 1221</td>
</tr>
<tr>
<td></td>
<td>2-Spur/1-bull: 727.5</td>
</tr>
<tr>
<td><strong>Sikorsky</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spur 2-pair:</td>
</tr>
<tr>
<td></td>
<td>- Sea King: 5968</td>
</tr>
<tr>
<td></td>
<td>- S-61N: 1369</td>
</tr>
<tr>
<td><strong>Westland</strong></td>
<td>Planetary: 683</td>
</tr>
<tr>
<td>- VIP Commando</td>
<td></td>
</tr>
</tbody>
</table>

**Peak cabin noise tone in bold**

- Low-speed, final stage gearing has greatest impact on cabin noise
- Peak noise in 7 out of 8 cases
- Most harmonics in speech band

Mature Technologies: Path Control

Anti-resonant isolators (rotor tones)

- Flannelly’s [14] DAVI – antiresonance using mechanically-amplified inertial force
  - Low mass, high static stiffness but low dynamic stiffness
- Many variants developed: Boeing’s IRIS, MBB’s ARIS, Eurocopter’s SARIB, Lord’s CBI
- Flight testing by Hooper et al. [15]: isolation of 40 dB at N/rev, >26 dB over N/rev ± 5%
- Halwes et al. [16] introduced the LIVE – hydraulic amplification (2x-10x higher) for compactness, lower mass
- Flight testing of 3.9 kg LIVE by Smith et al. [17]: 24 dB at N/rev, effective in transition
- Multiple adaptive and active LIVE variants
  - Smith et al.’s [18] “rigid” Smart Link