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)

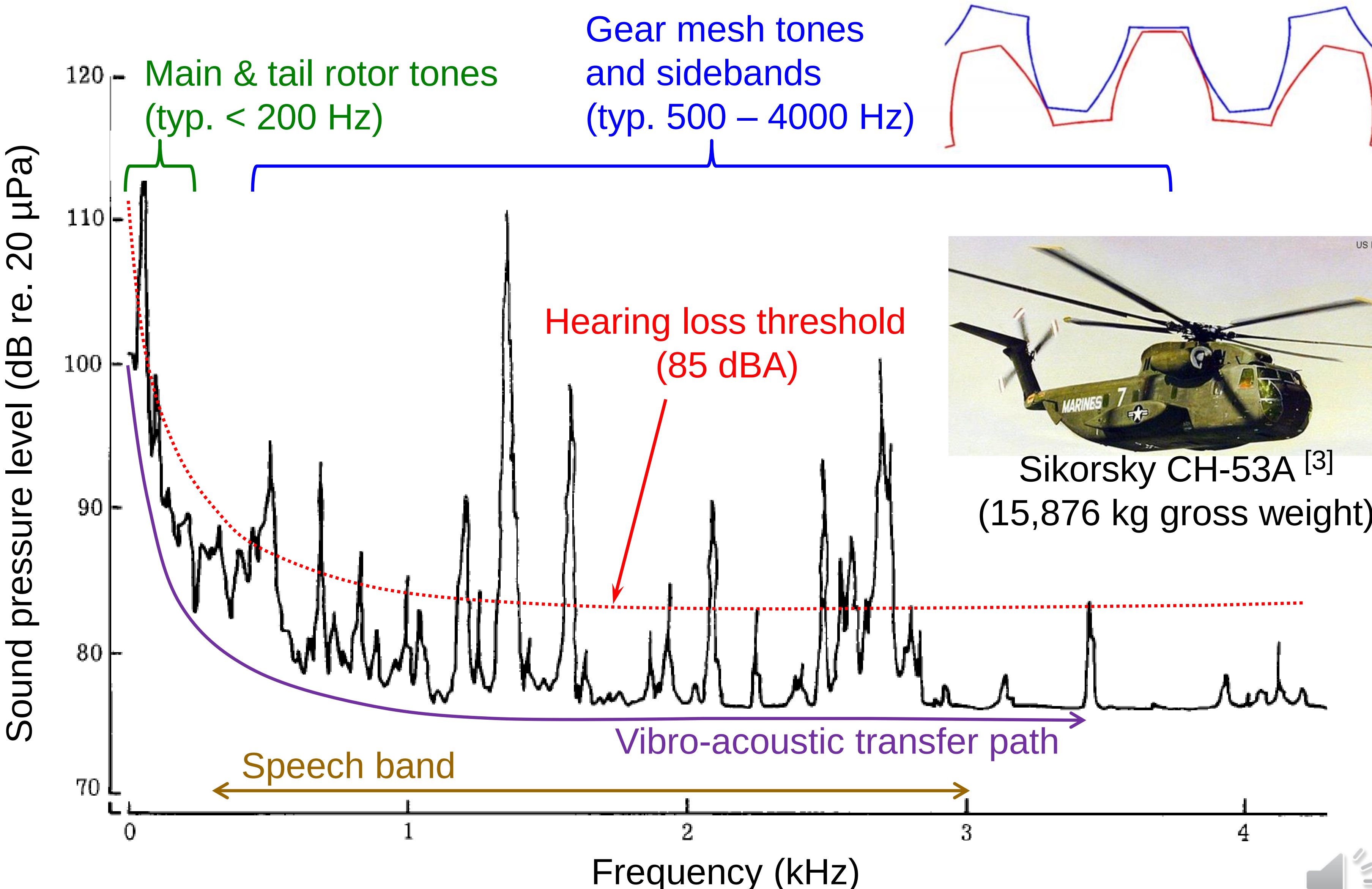
Noise and Vibration control technologies

- 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%
NASA's Rotary Wing Project goal [2]	reduce cabin noise below 77 dB

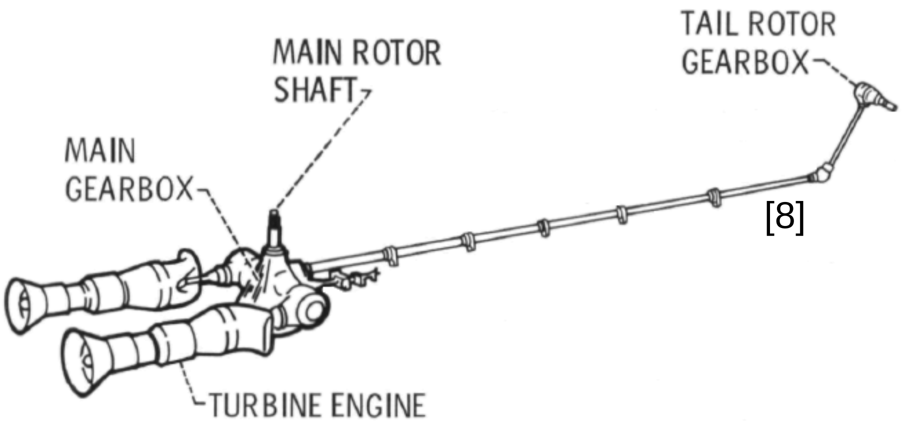
1. Security and Homeland Defense Goal #2, 2010 National Aeronautics R&D Plan
2. Subsonic Rotary Wing Project goals, 2011 ARMD Program and Project overview

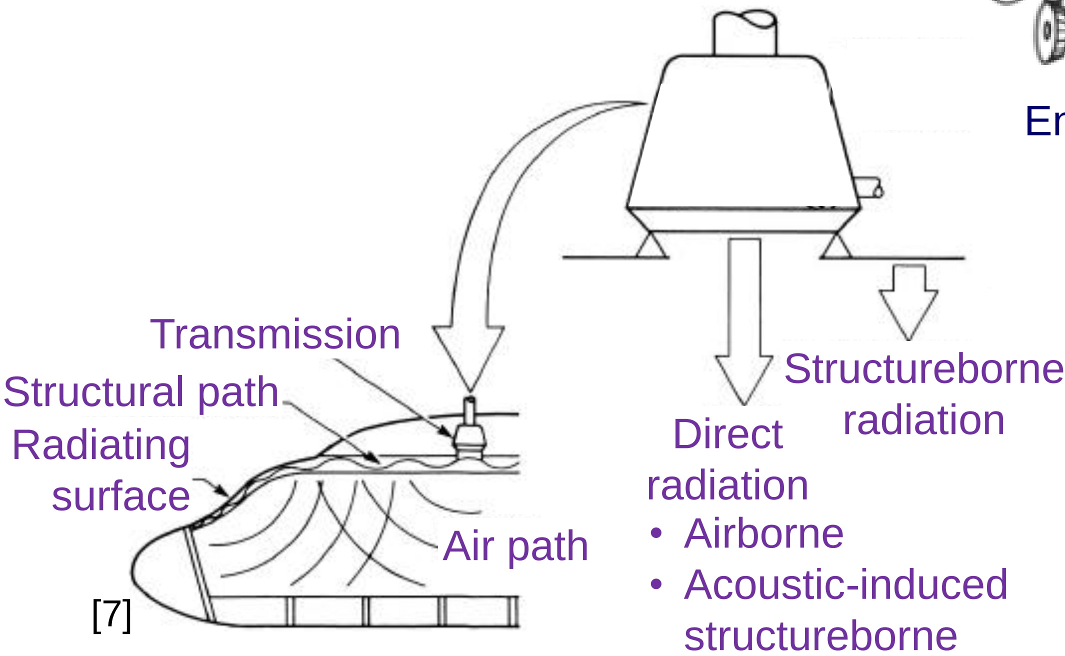
Typical Cabin Noise Spectrum



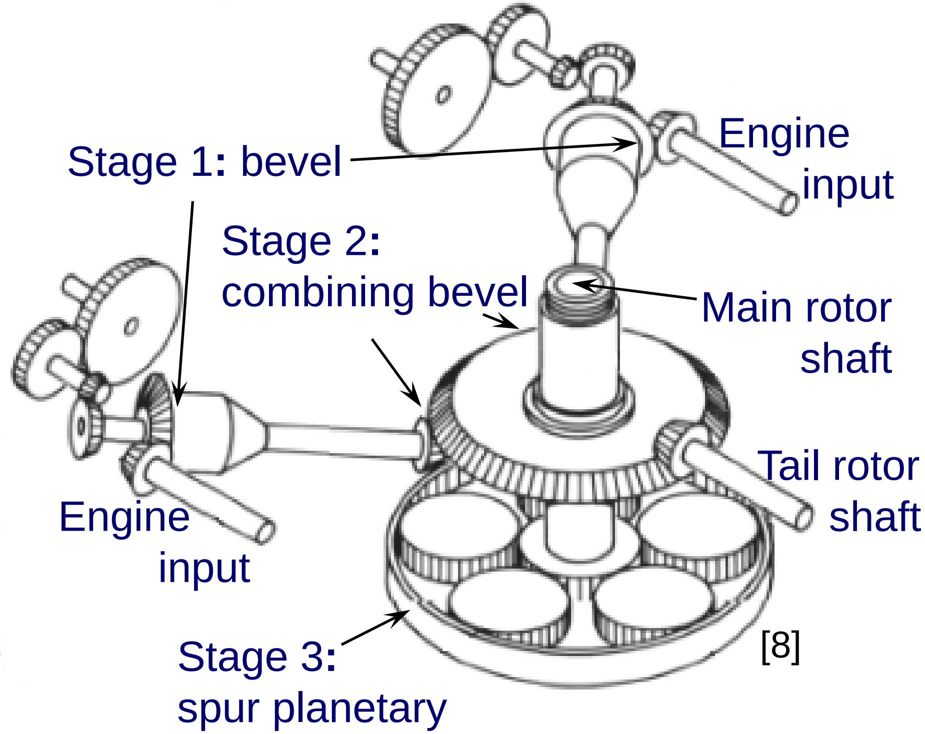
3. Howlett et al. 1977 NASA Report No. NASA-TN-D-8477.

Example Rotorcraft Driveline





UH-60 Blackhawk transmission



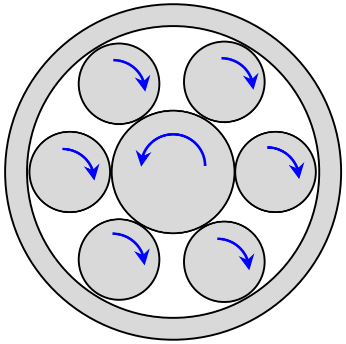
8. Weden et al. 1984 NASA Report No. NASA-TM-83726.

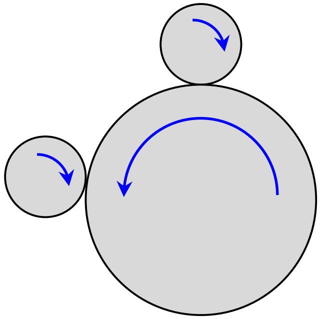
Cabin Noise Trends

- 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


Planetary gear


Bull gear

Scope and Organization

Scope

- Vibration control treatments close to the gear mesh source

Considered	Not considered
transmission	rotor blades and hub
strut/mount connection to fuselage	gas turbine engines
	fuselage

- Journal & conference papers, NASA & U.S. Army reports, U.S. patents

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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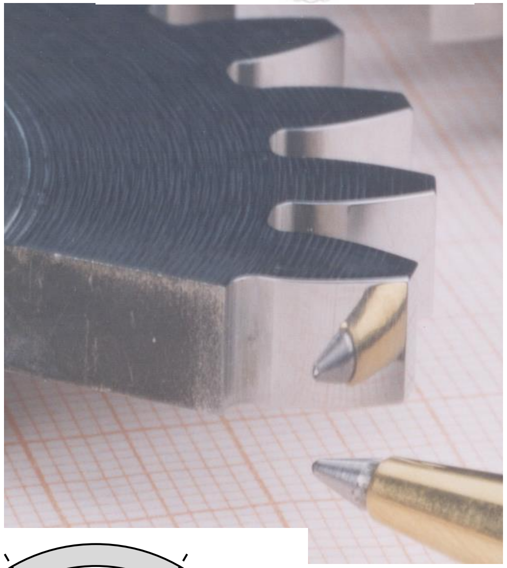
Mature Technologies: Source Control

- 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



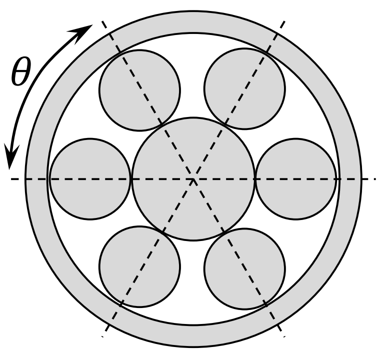
- Oswald et al. [11] measured noise due to gear type, profile, and CR – total CR is most important, helical 2-17 dB quieter than spur

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

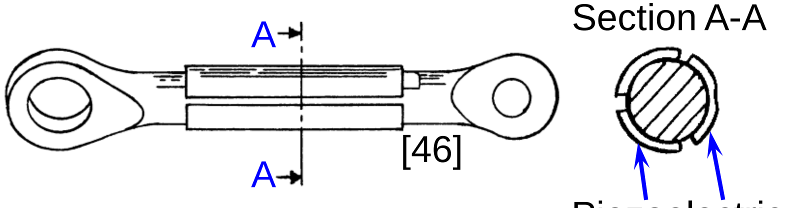


10. Litvin et al. 2002 Mech. Mach. Theory 37(5):441-459.
11. Oswald et al. 1998 Gear Technology 15(1):10-15.
12. Hansen et al. 2006 AGMA Tech. Paper 06FTM02.
13. Schlegel et al. 1967 Proc. ASME Design Eng. Conf. 67-DE-58.

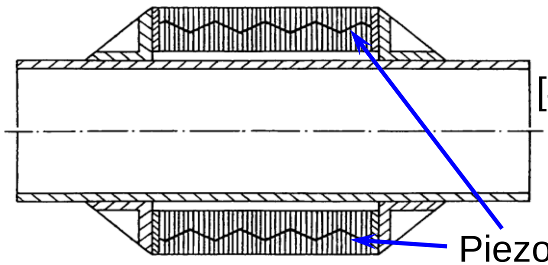
Mature Technologies: Path Control

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 1st harmonic, 4-8 dB at higher harmonics

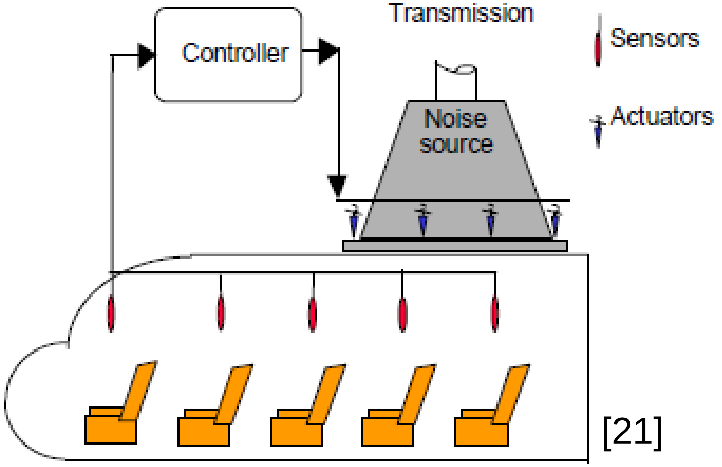


Strut cross-section



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



19. Maier et al. 2002 Proc. 8th AIAA/CEAS Aeroacoustics Conf.
20. Hoffmann et al. 2006 Proc. 12th AIAA/CEAS Aeroacoustics Conf.
21. Millott et al. 1998 Proc. AHS 54th Annual Forum.
46. Strehlow et al. 2002 U.S. Patent 6480609 B1.
47. Bebesel & Jaenker. 2008. U.S. Patent 7453185 B2.

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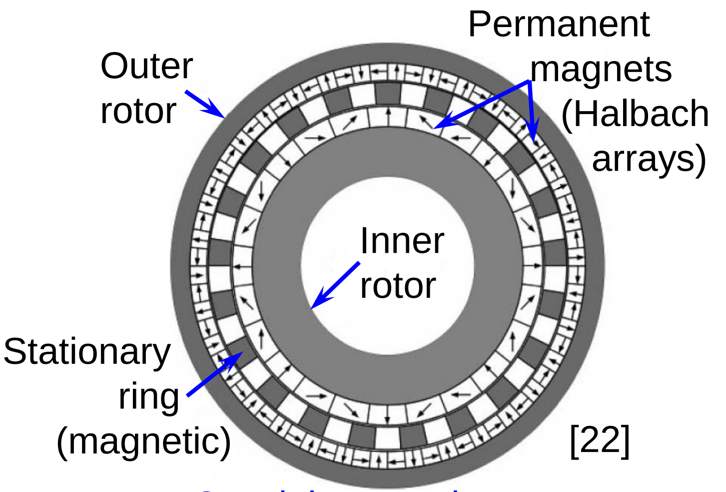
Emerging Technologies: Source Control

Magnetic gears

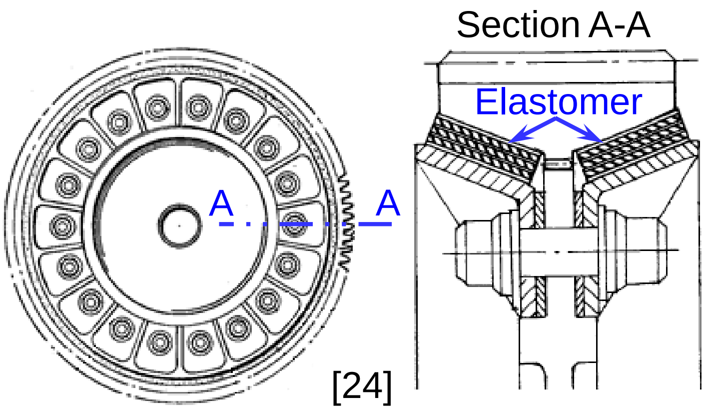
- Potential benefits: higher reliability, dramatically lower vibration, and improved loss of lubrication
- Paden [23] built 15 kW (20 hp) prototype with low mass (294% of optimized, non-magnetic version)
  - Prediction: 122% of non-magnetic when scaled up to 300 kW (402 hp)



Coaxial magnetic gear

On-the-gear passive and active control

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

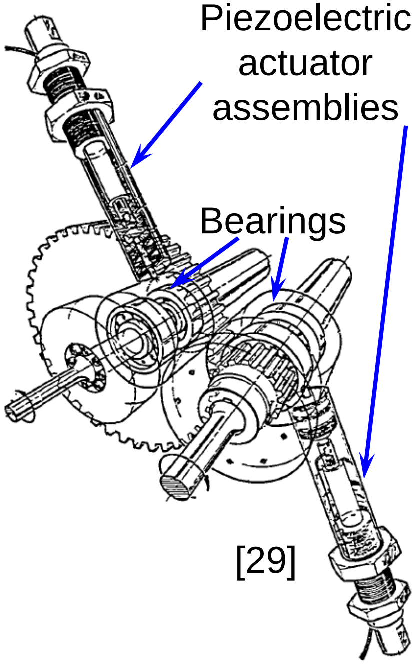


22. Jian et al. 2010 IEEE T. Energy Conver. 25(2):319-328.
23. Paden 2015 NASA Report No. A1.06-9338.
24. Kish 1993 NASA Report No. NASA-CR-191079.
25. Chen et al. 2000 Smart Mater. Struct. 9(3):342-350.
26. Guan et al. 2004 J. Sound Vib. 269(1-2):273:294.

Emerging Technologies: Source Control

Active transverse vibration control of shafts

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

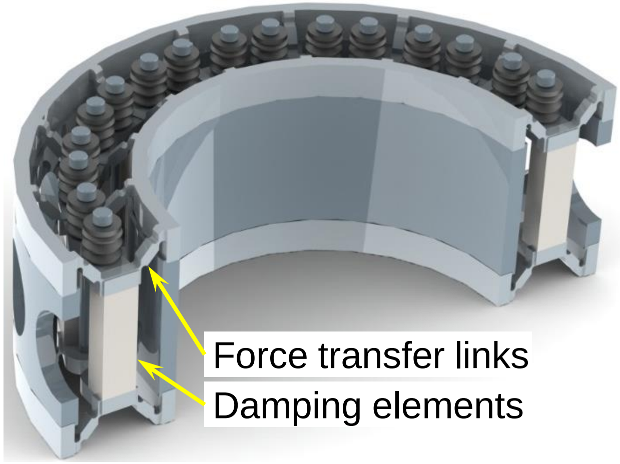


Piezoelectric bearings and shaft attachments

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

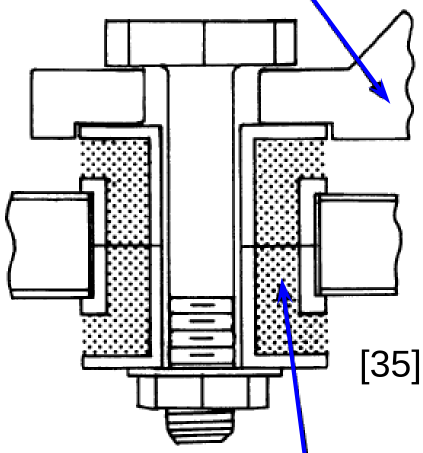
Periodic shafts

- 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



27. Rebbechi et al. 1999 Proc. Active Cont. Sound Vib. Conf.
28. Guan et al. 2005 J. Sound Vib. 282(3-5):713-733.
29. Montague et al. 1994 NASA Report No. NASA-TM-106366.
30. Atzrodt et al. 2009 Proc. 16th Intl. Cong. Sound Vib.
31. Pinte et al. 2010 J. Sound Vib. 329(9):1235-1253.
32. Asiri et al. 2005 J. Vib. Control 11:709-721.
33. Asiri et al. 2006 Smart Mater. Struct. 15:1707-1714.

Emerging Technologies: Path Control

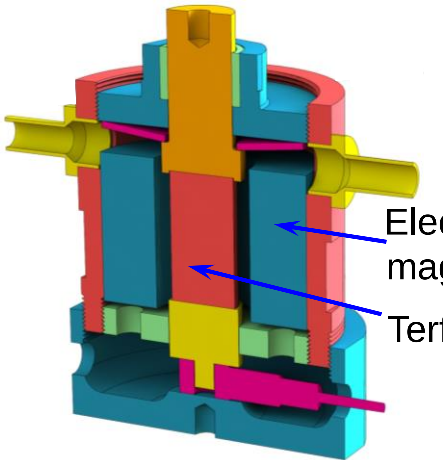


Elastomeric mounts for hard-mounted transmissions

- 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

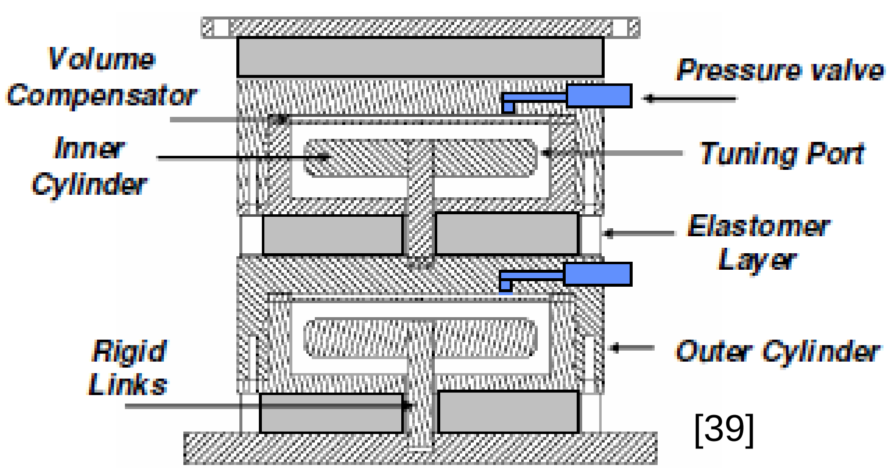
- Provide high static stiffness and low dynamic stiffness
- To date, implemented in very low frequency isolators
  - Suspending large aircraft in “free” BC during ground vibration testing [36]

34. Scheidler et al. 2016 Smart Mater. Struct. 25(3):035007.
35. Yoerkie et al. 1986 NASA Report No. NASA-CR-178172.
36. Woodard et al. 1991 J. Guid. Control Dynam. 14(1):84-89.

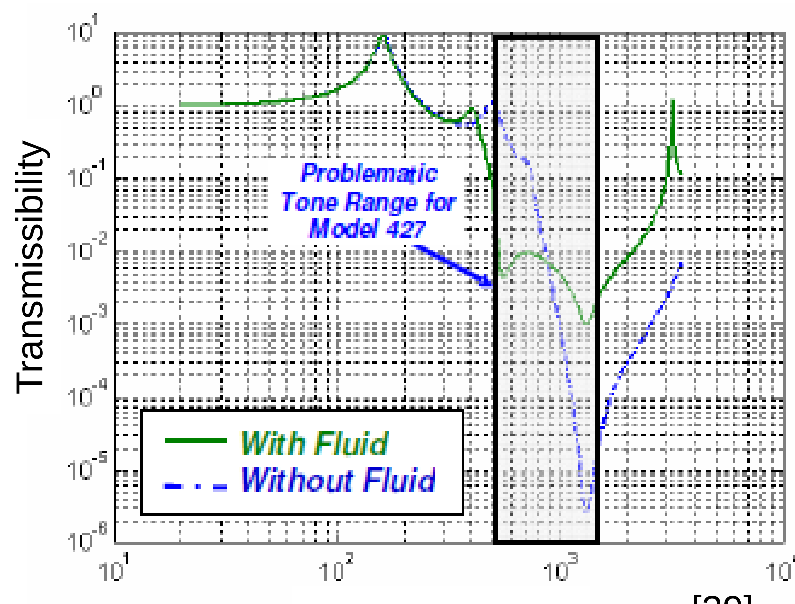
Emerging Technologies: Path Control

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)



[39]



[39]

37. Szefi et al. 2003 Proc. 44th Struct. Struct. Dyn. Mater. Conf.
38. Szefi et al. 2004 Proc. 45th Struct. Struct. Dyn. Mater. Conf.
39. Szefi et al. 2006 Proc. AHS 62nd Annual Forum
40. Le Hen et al. 2005 Proc. 46th Struct. Struct. Dyn. Mater. Conf.
41. Dylejko et al. 2014 J. Sound Vib. 333(10):2719-2734.

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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 1st 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

46. Asnani et al. 2005 Noise Control Eng. J. 53(5):165-175.

Conclusions

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

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

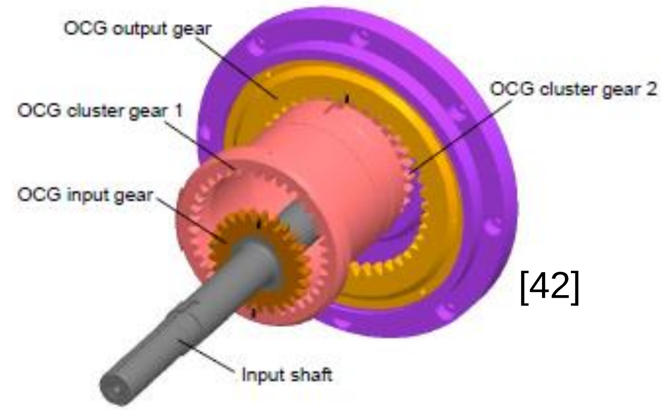
TRL: technology readiness level (NASA [48])

48. https://esto.nasa.gov/files/trl_definitions.pdf

Disruptive Trends in Rotorcraft Development

Multi-speed and variable speed transmissions

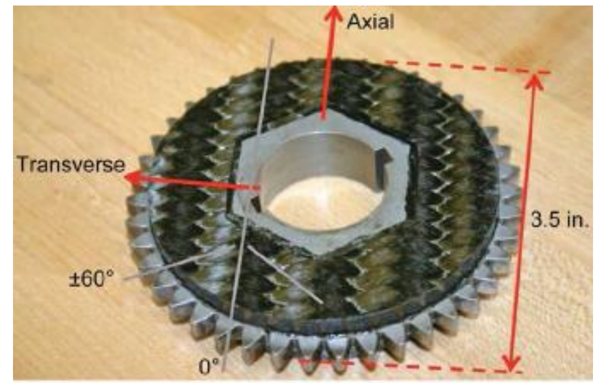
- Abrupt or smooth tonal shifts over wide band
- <u>Motivates:</u> maturation of variable frequency technologies



[42]

Composite gears and shafts

- Early goal**:** composite gear body and hub
- <u>Motivates:</u> higher performance vib. control, tailored anisotropy, embedded treatment



[43]

Electrification

- Significantly different powertrain configurations and source locations
- <u>Motivates:</u> understanding of the source

Sikorsky Firefly

[44]

DARPA VTOL X-Plane

[45]

42. Lewicki et al. 2015 NASA Report No. NASA/TM-2015-218816.
43. Handschuh et al. 2014 NASA Report No. NASA/TM-2014-216646.
44. Sikorsky Firefly www.sikorsky.com
45. DARPA VTOL X-Plane www.darpa.mil

NASA

Extra slides…..

Cabin Noise Measurements

Vehicle	Ref.		Max gross weight, kg	Peak, dB	Band/Tone, Hz	Comment
Bell OH-58C	1987 [7]	M	1,451	85	573	Single tone measurement
Agusta A-109	1980 [4]	C	2,559	90	1000	
Westland Lynx	1980 [4]	M	3,291	98	500	Common powertrain
Westland WG30		C	5,806	94		
Sikorsky S-76A	1986 [5]	U	4,587	105	1000	
Bell 212	1980 [4]	U	5,080	103	1000	
Aérospatiale Puma	1980 [4]	M	7,000	103	1000	
Sikorsky Sea King	1980 [4]	M	10,000	102	500	
Westland VIP Commando		C	9,707	89		Common platform
Sikorsky S-61N		C	8,620	86		
Sikorsky CH-53A	1977 [3,6]	M	15,876	110	1000	CHRA was a CH-53A w/ custom sealed cabin
NASA-Sikorsky CHRA		R	15,876	76		

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

4. Leverton et al. 1980 Proc. Symp. Internal Noise in Helicopters.
5. Yoerkie et al. 1986 NASA Report No. NASA-CR-172594.
6. Levine et al. 1977 NASA Report No. NASA-CR-145146.
7. Coy et al. 1987 U.S. Army Report No. USAAVSCOM-TR-87-C-2.

Rotorcraft Gear Mesh Frequencies

Vehicle	Mesh frequencies, Hz		Vehicle	Mesh frequencies, Hz	
Aérospatiale - Puma	Spur 2-pair	–	Sikorsky - Sea King - S-61N	Spur 2-pair:	13325
	Helical 2-pin/1-gear:	~4550		Helical 2-pair:	5968
	Bevel pair:	~1750		Spiral-bevel:	1369
	Planetary stage 1:	~1600	Westland - VIP Commando	Planetary:	**683**
	Planetary stage 2:	~550, ~**1100**			
Agusta - 109	Combining stage	–	Sikorsky - UH-60 Blackhawk [9]	Bevel 2-pair	–
	Bevel pair:	1850		Bevel 2-pin/1-gear:	**1628**
	Planetary:	**820**		Planetary:	**980**
Westland - Lynx - WG30	Combining stage	–	Sikorsky - CH-53A	Bevel pair:	2710
	Spiral-bevel 2-pair:	~2150		Planetary stage 1:	**1370**
	Conformal 2-pin/1-bull:	~**450**	NASA-Sikorsky - CHRA	Planetary stage 2:	527
Sikorsky - S-76A	Helical 2-pair	–	Bell - OH-58C	Spiral-bevel pair:	1919
	Spiral-bevel 2-pair:	1221		Planetary:	**573**
	2-Spur/1-bull:	**727.5**			

Peak cabin noise tone in bold

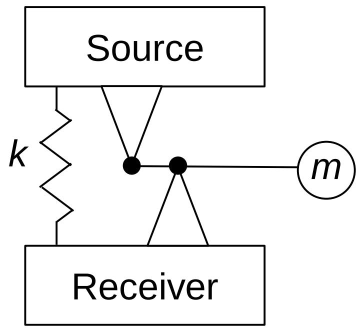
- Low-speed, final stage gearing has greatest impact on cabin noise
  - Peak noise in 7 out of 8 cases
  - Most harmonics in speech band

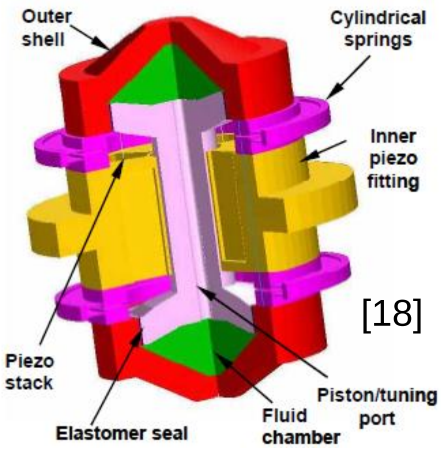
9. Yoerkie et al. 1985 U.S. Army Report No. USAAVRADCOM-TR-83-D-34.

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





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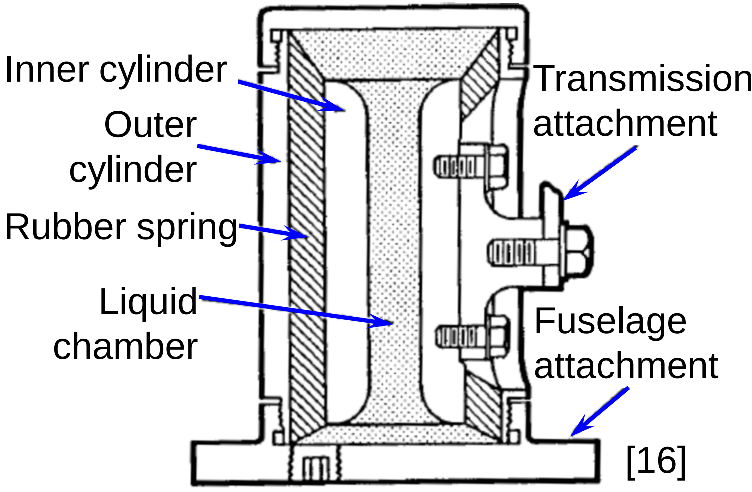

[16]

14. Flannelly 1967 U.S. Patent US3322379.
15. Hooper et al. 1976 SAE Tech. Paper 760893.
16. Halwes et al. 1980 Proc. AHS 36th Annual Forum.
17. Smith et al. 1999 Proc. AHS 55th Annual Forum.
18. Smith et al. 2002 Proc. AHS 58th Annual Forum.