Helicopter Noise Reduction Technology

Status Report

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Contents

1 Introduction

In the first Steering Group (SG) meeting of its tenth cycle (SG 2013-1, 3-7 November 2013 in Dubai) the ICAO Committee on Aviation Environmental Protection (CAEP) assigned the task N.08 entitled "Helicopter Noise" to Working Group 1 (WG1, Noise Technical) which included a specific remit to the WG1 Technology Task Group (TTG) to review advancements in helicopter noise technology.

The SG remit to WG1 and TTG for CAEP/10 Task N.08 *Helicopter Noise* is detailed in CAEP-SG/20131-SD/5 Annex C:

> *"WG1 Technology Task Group to review the noise technology advancements of helicopters including noise technology costs, and [SG] requested that WG1 assess the extent of the helicopter noise problem, in the context of the WG1 remit, and to inform CAEP SG2015 if there is a need for formal work in the CAEP/11 cycle regarding helicopter noise."*
>
> *Deliverable: Working Paper to Steering Group 2015*

In the first meeting of WG1 afterwards (WG1-03, 9-12 June 2014 in Tokyo) the task was somewhat refined and clarified as follows:

> Indeed the TTG task is limited to the compilation of a report on "*noise technology advancements of helicopters including noise technology costs"* while the second part of task N.08 is clearly considered a plenary task based on the findings of the report and additional information provided by CAEP members: "*assess the extent of the helicopter noise problem, in the context of the WG1 remit, and to inform CAEP SG2015 if there is a need for formal work in the CAEP/11 cycle regarding helicopter noise*".

Furthermore the contents and possible structure of the report were presented and approved by WG1. It was agreed that within the framework of the CAEP/10 assessment the term "noise technology costs" can only be treated in a qualitative manner by showing interdependencies and possible detrimental side effects related to noise reduction technologies.

The purpose of the present document is hence to answer to task N.08 by "*reviewing the noise technology advancements of helicopters including noise technology costs*". A "*Historic review of previous helicopter noise technology assessments"* is detailed in CAEP10_WG1_3_IP08 presented at the Tokyo WG1 Meeting in June 2014 and mentioned here as a reference to previous analyses specifically targeted to noise certification technology assessments. The Year 2000 is considered as the basis for the study to highlight the development since the last helicopter noise assessment report conducted in CAEP/5.

2 Helicopter noise sources and related noise generation mechanisms

2.1 Rotor noise

The general principles of rotor noise generation mechanisms are well summarized in the CAEP/5 HTTG4 HELO-2 Task Group *DATA REPORT to WG1 – Technology Status on Helicopter Noise Stringency* updated in 1999 and for simplicity summarized here.

The rotor generates different types of noise: Thickness noise is caused by the blade periodically displacing air during each revolution. This sound propagates in the plane of the rotor. Moreover a rotating blade at non-zero angle of attack imposes rotating forces onto the surrounding air, causing blade loading noise. This sound generally propagates in a direction perpendicular to the plane of the rotor. These two types of noise always occur, even in a hover condition.

In level flight the blade's rotational speed adds to the flight speed to result in higher speeds on the advancing side, with the blade angle of attack at a minimum. On the retreating side the blade tip speed subtracts from the flight speed to cause locally minimal flow speeds with angle of attack at a maximum, at times even resulting in local flow separation (dynamic stall). Maximum speeds on the advancing side may cause the periodic appearance of aerodynamic shocks on the blade surface, resulting in high speed impulsive noise (HSI). When these shocks delocalize from the rotor blade they exhibit the long propagation distances and very high annoyance levels typical of shock waves.

Each main rotor blade also sheds a strong tip vortex whose trajectory travels downstream from the rotor in an approximately epicyclical manner. In descent conditions and sometimes at moderate speeds in level flight, the vortex trail may intersect the paths of subsequent blades. This event causes a blade-vortex interaction (BVI) impulsive noise sometimes referred to as "blade slap".

Certain stochastic aerodynamic events on or near the blade also cause rotor broadband noise. They are a result of the blade encountering random inflows (e.g. aerodynamic turbulence or the aerodynamic wake from a previous blade) or of the shedding of a turbulent boundary from the blade's trailing edge.

2.2 Anti-torque noise

The noise mechanisms for the anti-torque system are basically identical to the rotor description in the paragraph above. However due to its position behind the main rotor, the anti-torque device can also be subject to non-uniform inflow caused by the main rotor wake. This leads to additional interaction noise phenomena. Alternative concepts like the NOTAR® or the Fenestron™ system feature ducted rotors that have a somewhat different noise characteristic due to the shielding effect of the duct in the rotor rotational plane. In the special case of the NOTAR® system the blower is located completely inside the tail boom. The air is guided from the blower through the tail boom and exits through slits in the tail boom thus generating the necessary anti-torque.

2.3 Engine noise

2.3.1 Turboshaft Engines

The noise emitted by turboshaft engines is basically composed of the mainly rotational noise produced by the radial and/or axial compressor(s) and turbine stages and broadband noise generated in the combustion chamber. The turboshaft engine compressor fan typically generates a high frequency tone emanating from the engine inlet and attenuates quickly through the atmosphere. Turboshaft engine exhaust noise has a broadband character and can become more prominent once the helicopter has passed overhead of the observer when rotor noise sources become less dominant.

2.3.2 Piston Engines

Piston engines are typically used on smaller helicopters and can be one of the prominent noise sources for those aircraft. Exhaust noise typically dominates piston engine noise emissions and, for helicopters, most piston engine noise reduction has been focused on use of upturned exhausts, mufflers and resonators. Unsilenced exhaust noise is broadband with the highest levels at low frequencies. The exhaust noise spectrum contains strong tones associated with the rate of cylinder firings. Engine exhaust noise can be controlled successfully by relatively advanced technology.

2.4 Contribution of noise sources depending on flight condition

The contributions of the individual noise sources to the global helicopter noise spectrum perceived on the ground differ considerably depending not only on the flight condition but also on the observer position. Even though each helicopter configuration might have particular characteristics some general trends can nevertheless be observed.

In the take-off case the main rotor is required to provide a maximum thrust level to gain altitude quickly. This results in high anti-torque and engine power requirements. For configurations with a main rotor and classical open tail rotor, in particular with small to intermediate size helicopters, the latter can be the dominant noise source in this flight condition due to the high thrust provided by the tail rotor. Also the engine noise emitted through the exhaust pipes can have a noticeable contribution in this flight state especially for an observer positioned behind the helicopter. For ducted fans the situation is shifted towards a higher engine noise contribution since the anti-torque noise is partially shielded by the duct, particularly for observers directly under the flight path.

In level cruise flight the situation is different. The power requirement is generally less than in take-off, and the anti-torque system is augmented by the vertical fin. The tail rotor thus needs to provide only relatively small thrust levels. Important in cruise condition is the high forward speed that adds to the rotational speed of the rotor, thus yielding high velocities on the advancing blade tips of the main rotor and tail rotor. This can even result in local transonic/supersonic effects and the so called high speed impulsive (HSI) noise emitted by the main rotor, typically encountered during cruise flight at low ambient temperatures. Most modern civil helicopters are therefore operating at lower rotational speeds and have included thin airfoils and special tip shapes to avoid this phenomenon. For these designs the noise emission of the classical open tail rotor that is operating in the disturbed inflow of the main rotor wake can be actually more pronounced than the main rotor noise. Tail rotor noise is typically the more predominant source in light helicopters than in heavy helicopters, and a quiet anti-torque solution has been shown to be effective at reducing overflight noise of light helicopters. With the exception of some smaller helicopters with more pronounced piston engine noise, engine noise plays a non-negligible but generally minor role.

The approach case is normally the loudest flight condition for a helicopter. Even though power requirements are very low compared to cruise flight or take-off, the special phenomenon called blade-vortex interaction (BVI) is responsible for the very characteristic “blade slap” noise emitted by the main rotor. Due to this effect the main rotor noise contribution is clearly dominant in approach flight. Some state-of-the-art helicopter technologies have greatly reduced the importance of this noise generation mechanism but cannot fully avoid it. Blade vortex interactions continue to be the most difficult source noise phenomenon to model accurately, and hence BVI noise remains the most difficult source noise to predict and/or mitigate in the helicopter design process, whether for a lower certification noise level or for lower operational noise levels.

The relative contributions of the various noise sources, dependent on both flight condition and noise source directionality, indicate that helicopter noise reduction is a complex issue. Although implementing a sophisticated noise reduction technology addressing one noise source may reduce the noise level at one flight condition, there may be, however, no change or in some cases increases in the noise levels at other flight conditions.

3 State-of-the-Art Helicopters

The present chapter provides an overview of design foci and key noise reduction technologies implemented in current production helicopter models. In order to serve this purpose, major helicopter manufacturers collaborated in the compilation of this report by providing noise-relevant information in a standardized format to allow a comparable representation of typical design tradeoffs.

In order to put advances in the field of noise reduction into perspective, current “State-of-the-Art” helicopters are compared to both out-of-production and in-production helicopter models, in particular to those models considered as candidates for future development either as derived versions or as representative of new type designs.

Not considered in this context are helicopters originally designed for military purpose and nowadays repurposed in the civil market. These helicopters typically have older technology and often are exclusively included in a restricted category and hence may not need a noise certificate. Examples of these restricted operations are fire-fighting or purely agricultural usage.

3.1 Selection logic for State-of-the-Art helicopter models

To facilitate an evaluation of the status of helicopter noise reduction technology, a number of recently certificated helicopters were selected as state-of-the-art helicopter designs along with one earlier model deemed representative of a state-of-the-art design. For the purposes of this selection process, state-of-the-art was defined in the broader sense of aircraft level design, but the selected state-of-the-art designs typically incorporate latest helicopter noise reduction technologies for one, two or all flight conditions and exhibit very good to the best individual and cumulative margins to the Chapter 8 or Chapter 11 noise limits in the Annex.

In defining state-of-the-art helicopter designs, existing helicopter designs were segregated into four categories, namely Out-of-Production, In-Production, Candidates for Future Development, and State-of-the-Art helicopter designs. All noise data for these helicopter designs were obtained from the EASA helicopter noise database, TCDSN Rotorcraft (Issue 19 of 03/12/2014), obtainable at:

http://www.easa.europa.eu/document-library/noise-type-certificates-approved-noise-levels

The Candidates for Future Development helicopters, detailed in Table A-1 of Attachment A, are considered by industry to be representative of future derived versions and/or new type designs for the purposes of this report. These Candidates for Future Development helicopters are also typically, but not necessarily required to be, In-Production models. The State-of-the-Art helicopter designs are a subset of the Candidates for Future Development helicopters and are discussed in further detail below. While the Candidates for Future Development helicopters included in Attachment A provide a broader picture of present day and near-to-intermediate future helicopter designs within typical system design tradeoffs and market-specific requirements, the State-of-the-Art helicopters provide a more focused picture of noise levels achievable with best acoustical and system design practices.

Summary of the four helicopter categories used henceforth in this report:

- **Out-of-Production helicopters**
- **In-Production helicopters**
- **Candidates for Future Development:** helicopters deemed representative of future new or derived versions with probable future market potential, typically In-Production helicopters
- **State-of-the-Art:** helicopters certificated in the last 5 years with design tradeoffs considered to meet current market demands

NOTE: “State-of-the-Art” in this report refers to the global system design rather than the pure noise aspect. State-of the-Art helicopters in this context are thus not necessarily the quietest helicopters.

Noise levels as functions of gross weight for the helicopter models included as Out-of-Production, In-Production, Candidates for Future Development, and State-of-the-Art Chapter 8 helicopter designs are shown vs. the 8.4.1 and 8.4.2 limits in Figures A-1 through A-3 in Attachment A. The comparable noise data for Chapter 11 helicopters vs. the 11.4.1 and 11.4.2 noise limits are shown in Figure A-4. Cumulative margins to Chapter 8, 8.4.1 and 8.4.2 noise limits for the helicopters included in Figures A-1 through A-3 are shown in Figure 1. This figure provides a good summary of the noise certification status of the State-of-the-Art Chapter 8 designs vs. the Out-of-Production, In-Production and Candidates for Future Development models.

One difficulty in evaluating the technology status of helicopters certificated to the Chapter 11 noise standard is that margins to the Chapter 11 standard do not directly compare to margins against the Chapter 8 standard. A method to predict cumulative Chapter 8, 8.4.1, margins using Chapter 11, 11.4.1, developed using noise data from helicopters models measured to both standards is presented in Attachment B. Based on the resulting linear correlation between cumulative Chapter 8 margins and Chapter 11 margins, cumulative Chapter 8 noise margins have been predicted for the Chapter 11 helicopters designated as State-of-the-Art helicopters as well as the Chapter 11 Out-of-Production, In-Production and Candidates for Future Development included in Attachment A. These predicted cumulative Chapter 8 noise margins are summarized in Figure 2 and overlaid on the Chapter 8 dataset in Figure 3. Note that the State-of-the-Art helicopter model Guimbal Cabri G2 is not included in Figure 2 as its gross weight puts it in the constant 82 dB limit range and hence its Chapter 8 cumulative margin cannot be predicted using the function developed in Attachment B. Also note that the R66 designated as a Chapter 8 State-of-the-Art design, was also certificated to 14 CFR Part 36 Appendix J (Chapter 11) and is included in the Candidates for Future Development database as a Chapter 11 helicopter. As can be seen in Figure 3, the predicted cumulative Chapter 8 margin for this helicopter model is essentially equivalent to the measured cumulative Chapter 8 margin.

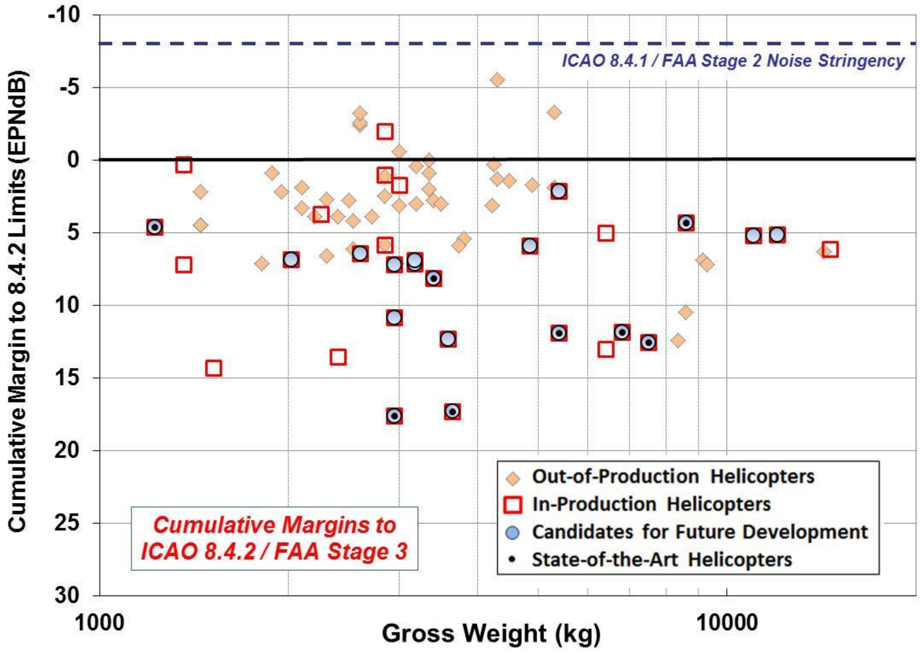


Figure 1. Cumulative Margins to 8.4.2 Noise Limits for Chapter 8 Helicopters
(Note that the ordinate values on this plot have been reversed for presentation purposes.)

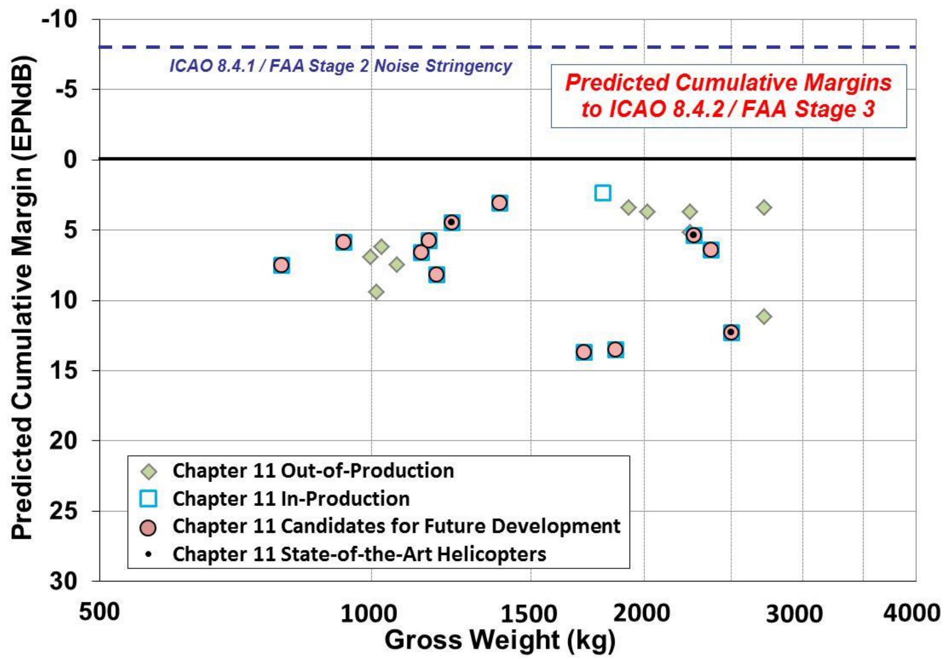


Figure 2. Predicted Cumulative Margins to 8.4.2 Noise Limits for Chapter 11 Helicopters
(Note that the ordinate values on this plot have been reversed for presentation purposes.)

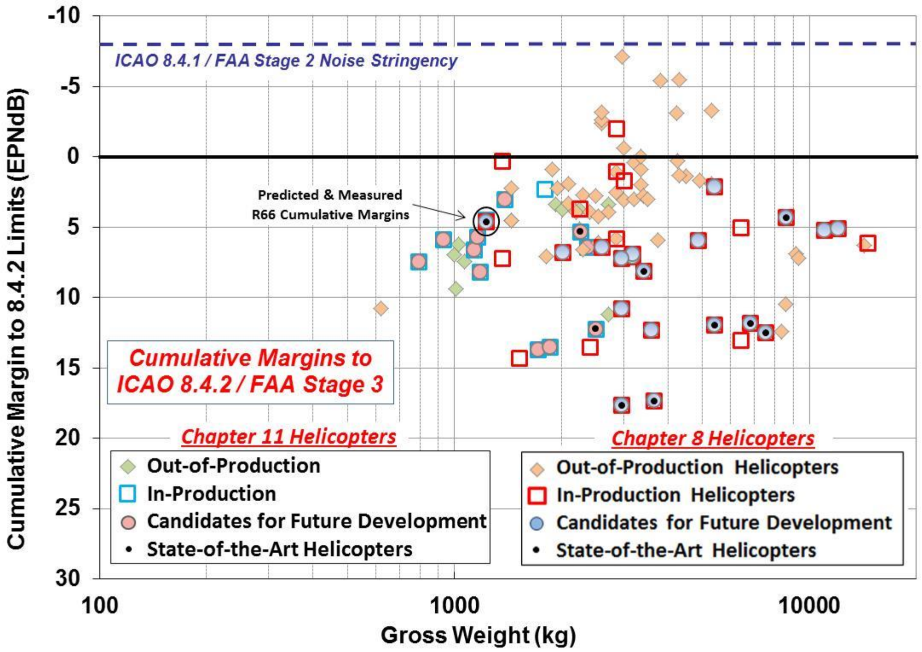


Figure 3. Overlay of Predicted Chapter 11 Cumulative Margins with Chapter 8 Cumulative Margins

(Note that the ordinate values on this plot have been reversed for presentation purposes.)

Ten State-of-the-Art helicopter models, certificated in the past five years, were selected because they are considered to adequately represent the best practices in helicopter design over a wide weight range starting from 700 kg and going up to 8600 kg. The MD900, though certificated in 1994, is additionally included as an eleventh State-of-the-Art helicopter due to its very specific design and the related low noise characteristics. Additional design details for these State-of-the-Art helicopter designs are provided in Attachment C.

The State-of-the-Art helicopters include seven new type designs (Guimbal Cabri G2, Robinson R66, MD Helicopters MD900, AgustaWestland AW139 and AW189, Bell 429, Airbus H175 (EC175B)) and four type designs derived from previous models (Bell 407GX, Airbus H130 (EC130T2) and H145 (EC145T2), Sikorsky S-76D). Seven of these helicopters were certificated according to the ICAO Annex 16 Chapter 8 standard while for three models – Cabri G2, 407GX and H130 (EC130T2) – the simplified procedure according to Chapter 11 was applied. One helicopter, the Robinson R66, was noise certificated to both the Chapter 8 standard and the Chapter 11 simplified procedure. Note that the new trade names recently designated by Airbus for its models are given with the previous trade names in parentheses.

3.2 Basic helicopter design parameter categories

Based on an ICCAIA review of historic and modern helicopter designs, some key design parameters affecting external noise have each been categorized into three different ratings (LOW / MODERATE / HIGH). These categorizations allow a fair comparison of helicopter designs without displaying proprietary manufacturer information for individual models.

Main rotor tip speed	**LOW**	**< 215 m/s <**	**MODERATE**	**< 230 m/s <**	**HIGH**
Tail rotor tip speed	**LOW**	**< 200 m/s <**	**MODERATE**	**< 215 m/s <**	**HIGH**
Climb rate	**LOW**	**< 1200 ft/min <**	**MODERATE**	**< 1800 ft/min <**	**HIGH**
Max. Cruise speed V_H	**LOW**	**< 130 kt <**	**MODERATE**	**< 150 kt <**	**HIGH**

These low, medium and high designations are used for all models throughout the individual helicopter descriptions presented in detail in Attachment C.

A purely acoustically optimized helicopter design would ideally incorporate low rotor tip speeds, a low to moderate cruise speed and a high climb rate.

3.3 State-of-the art in helicopter design

The presented helicopter data confirms that available mature noise reduction technologies are being implemented in both completely new designs as well as in newly derived models. These technologies include unequal blade spacing on ducted fans and classical tail rotors, new rotor designs and blade planforms as well as generally reduced or even automatically adapted rotor rotational speed laws.

As a consequence cumulative margins with respect to Chapter 8.4.2 certification limits of more than 17 EPNdB have been achieved for smaller twin-engine helicopters with alternative anti-torque concepts like the NOTAR® or the Fenestron™. On the H145 (EC145T2), the replacement of a high tip speed classical tail rotor by an acoustically shielded anti-torque system provided a cumulative noise benefit of 5 EPNdB for otherwise acoustically identical configurations. However, the use of a shielded anti-torque system to date has been limited to light to intermediate helicopters weighing less than 6000 kg due to an unfavorable scaling of system weight, efficiency and acoustic benefits.

The helicopters included in this study equipped with new main and classical tail rotor designs also verify the importance of anti-torque related noise by achieving significant cumulative margins of about 12 EPNdB towards Chapter 8.4.2 limits due to specific low-noise rotor designs operating at moderate or low blade tip speeds.

The four helicopters certificated according to Chapter 11 show – in comparison to Chapter 8 overflight levels – somewhat smaller margins towards the applicable limits. This suggests that the Chapter 11 margins are in fact not directly comparable to the Chapter 8 margins, although Chapter 11 margins can be used to predict cumulative margins as discussed above. Indeed this mirrors the philosophy that the simplified certification should be a strictly conservative approach, meaning that a Chapter 11 certificated helicopter shall always meet the Chapter 8 limits as well.

3.4 Constraints and challenges in helicopter low-noise design

All manufacturers represented in this study evidently strive with considerable effort towards lower noise emissions as a competitive advantage, especially for small to medium size helicopters that are particularly suited to fulfill a wide range of missions in densely populated areas.

Despite these general trends, safety or economic considerations for certain helicopter missions obviously can require somewhat different trade-offs leading to certification noise levels closer to the applicable limits according to Chapter 8 or Chapter 11. Though these helicopters incorporate most of the latest noise reduction features in terms of rotor blade design, the dimensioning of rotor tip speed and blade loading was optimized rather towards a maximum performance to weight ratio. A detailed description of typical design trade-offs and constraints associated with noise reduction technologies can be found in the dedicated chapter later in this report.

Low noise design capabilities are inherently impacted by technological feasibility and economical reasonableness issues which often correlate with weight class. For example, some low noise anti-torque technologies are technologically feasible for very small helicopters but may not be economically reasonable to implement in a given design. As gross weight increases, these anti-torque designs become more economically reasonable. As gross weight further increases, however, the technological feasibility disappears with unfavorable scaling of system weight and performance. Additionally, at medium to heavy gross weights, the higher main rotor blade loadings typically cause main rotor noise to be dominant, reducing the acoustic effectiveness of anti-torque noise reductions, and hence these anti-torque technologies have yet to be incorporated into medium to heavy weight helicopter designs. Similarly, technologies such as automated engine control, advanced 3D rotor blade designs and active rotor control increasingly become both technologically feasible and economically reasonable with increasing gross weight.

4 Overview of technology programs and research initiatives

The overall situation with respect to major noise technology research initiatives worldwide is summarized in Figure 4. It covers a 15-year period (2001-2015), providing an evolutionary perspective from the previous helicopter noise research survey performed before 2000 within Working Group 1. The major initiatives (e.g. USA, EU, and Japan) are represented and a summary of each of these research programs is provided in the following sections.

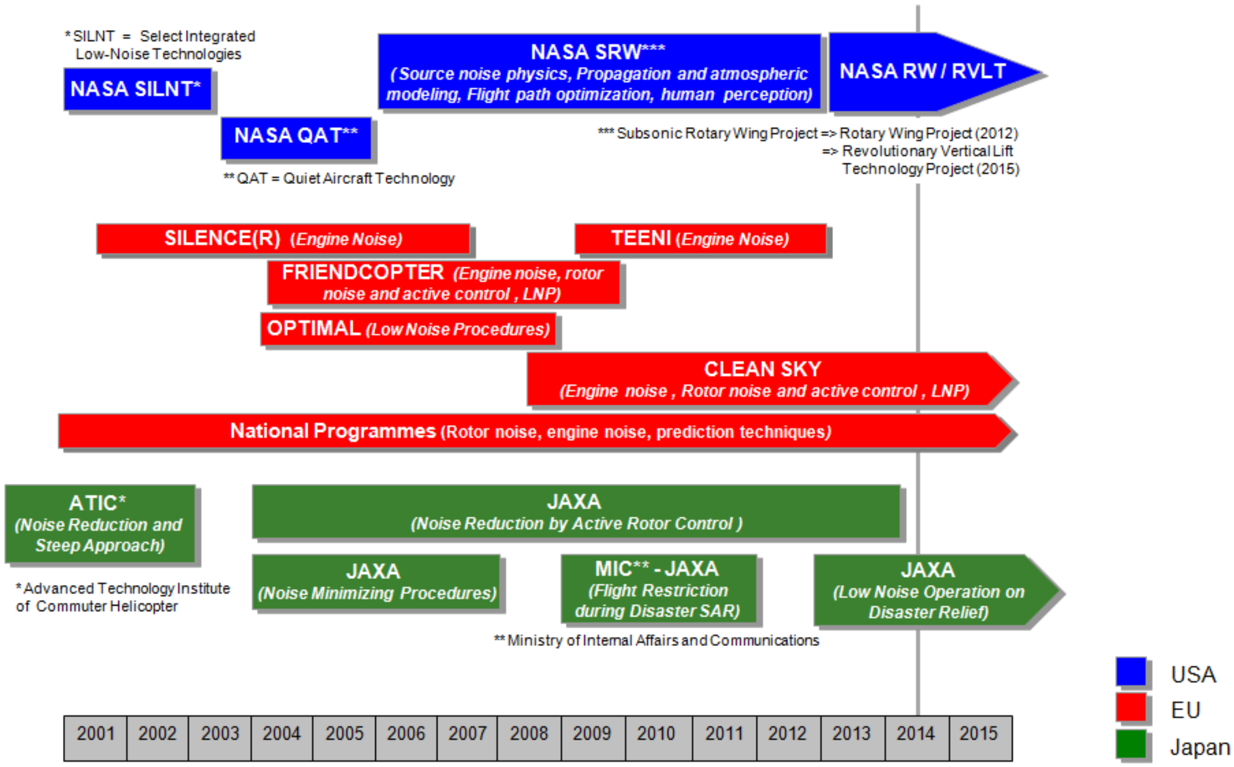


Figure 4. Major Initiatives in Helicopter Noise Research Since 2000

4.1 UNITED STATES

4.1.1 Scope of Research

Up until the 1990s, funding for NASA rotorcraft research was primarily basic research covering many rotorcraft technical areas at the NASA Ames, Glenn and Langley Research Centers. In the 1990s specific technologies for tilt-rotors were targeted in the Short-Haul Civil Tiltrotor (SHCT) project that was started in 1994 and continued for seven years. The SHCT project contained several elements: efficient, low-noise proprotor, low-noise terminal area approaches, contingency power, and technology integration. All of these elements focused on enabling a safe, quiet, and efficient civil tilt-rotor transport. The project consisted of major experimental efforts that included wind tunnel tests of a 0.25-scale V-22 isolated rotor, advanced tilt-rotor configurations developed by industry, and a full-scale XV-15 isolated rotor. Three acoustic flight tests using the XV-15 were executed to demonstrate low-noise flight trajectories. On the analysis side, the Tiltrotor Aeroacoustic Code (TRAC) was developed and validated using the data from wind tunnel and flight tests conducted under SHCT.

The SHCT project was followed by research that was captured under the theme of Runway Independent Aircraft, or RIA. In the early 2000s, the NASA rotorcraft effort sought to exploit the attributes of vertical take-off and landing (VTOL) by promoting an alternative to conventional fixed-wing use of runways and the national airspace. With renewed emphasis on airport and airspace congestion in the early 2000s, NASA sponsored industry studies and workshops that focused on the impact of RIA on reducing delays and increasing capacity. Between 2004 and 2005, rotorcraft research was executed within the Rotorcraft Sector of the Vehicle Systems Program. Primary goals of the Sector were to improve public mobility and access to air transportation. To this end, the Sector focused on technologies enabling a notional heavy-lift rotorcraft transport capable of carrying 120 passengers at a cruise speed of 350 knots at 30,000-ft altitude with a range of 1200 nm. Many of the vehicle technology goals (for example, noise) were based on the work from the RIA studies.

NASA Aeronautics research was refocused in late-2005 to concentrate more on foundational research and high-fidelity multi-disciplinary analysis rather than vehicle-centric technology goals. For rotorcraft research, reorganized under the auspices of the Subsonic Rotary Wing (SRW) Project of the Fundamental Aeronautics Program, emphasis was placed on first-principles tool development and validation. Milestones with quantitative metrics were developed for key activities in order to track progress in six technical disciplines with Acoustics research being a major component of the project.

In 2012, the Subsonic Rotary Wing Project reorganized and was renamed the Rotary Wing Project, continuing the emphasis on performance, efficiency and noise research. Noise research was addressed in the areas of:

- Cabin Noise
    - Structural / Acoustic Modeling for Interior Noise
    - Noise Mitigation and Design Concepts
- Human Response to Rotorcraft Noise
- Rotorcraft Aeroacoustics
    - Source Noise Physics
    - Flight Aeroacoustics
    - Rotorcraft Noise Mitigation Science

Experimental, analytical and modeling research was conducted in all areas, in keeping with the desire to develop and validate first-principles tools. RW was active from 2012-2014.

In 2015, the NASA Revolutionary Vertical Lift Technology (RVLT) Project was formed in a major re-structuring of the NASA Aeronautics Research Mission Directorate. RVLT develops and validates tools, technologies and concepts to overcome key barriers for rotary wing vehicles. RVLT research primarily focuses on vehicles that require mature technology solutions in the 2020-2030 timeframe. The scope of the noise research continues to encompass source noise physics, interior noise modeling, and flight aeroacoustics. Modeling and analysis validated with experimental data has been the emphasis of the research in all areas.

4.1.2 Assessment of Progress

The RVLT Project was just established at the start of 2015 and is in the process of establishing new work areas related to noise, so it is premature to report on progress of these efforts at this time. However, the NASA State-of-the-Art was documented in 2009 and RVLT progress will be measured relative to the 2009 SOA. ["A Status of NASA Rotorcraft Research," Editors: Gloria K. Yamauchi and Larry A. Young, NASA/TP–2009-215369, September 2009.]

NASA recently completed an assessment of active rotor concepts under the RW project and the major results can be summarized as:

- **Active Flap:** The test demonstrated on-blade smart material control of flaps on a full-scale rotor. The effectiveness of the active flap control on noise and vibration was conclusively demonstrated. Results showed reductions up to 6dB in blade-vortex interaction and in-plane noise, as well as reductions in vibratory hub loads up to 80%. Trailing edge flap deflections were controlled with less than 0.2 degrees error for commanded harmonic profiles of up to 3 degrees amplitude. The impact of the active flap on control power, rotor smoothing, and performance was also demonstrated. Finally, the reliability of the flap actuation system was successfully proven in more than 60 hours of wind tunnel testing. ["Wind Tunnel Test of the SMART Active Flap Rotor," F. Straub, V. Anand, T. Birchette, Boeing; B. Lau, NASA. 65th AHS Forum, Grapevine, May 27-29, 2009.]

- **Individual Blade Control:** The test demonstrated rotor power reductions (up to 5%), multi-parameter hub load reductions, multi-frequency pitch link load reductions, and in-plane noise reductions. Additional results indicate the benefits of IBC for in-flight tuning and show minimal coupling of IBC with rotor flight dynamics. ["Full-Scale Wind Tunnel Test of a UH-60 Individual Blade Control System for Performance Improvement and Vibration, Loads, and Noise Control," T. Norman, C. Theodore, NASA; P. Shinoda, US Army AFDD; D. Fuerst, U. Arnold, ZFL; S. Makinen, P. Lorber, J. O'Neill, Sikorsky. 65th AHS Forum, Grapevine, May 27-29, 2009.]

- **Active Twist:** The NASA/Army Active Twist Rotor (ATR-A) blade performed without failures in hover and benchtop testing, indicating that the design philosophy used by the Army is robust. Actuation was nominally what was predicted in the design process; however the magnitude of the actuation would not be sufficient for primary rotor controls. To evaluate active twist, the NASA rotor analysis capability was enhanced to predict the effect of individual blades, such as for a configuration with modulated blade spacing, etc. ["Coupled CFD/CSD Analysis of Rotor Blade Structural Loads with Experimental Validation," Massey, S., Kreshock, A., and Sekula, M., 31st AIAA Applied Aerodynamics Conference, San Diego, June 22-27, 2013. AIAA 2013-3158.]

The RVLT project will continue to focus on noise reduction and prediction as a primary research focus. Formulation of new goals and metrics are underway within the project.

4.2 EUROPEAN UNION

4.2.1 Scope of Research

In 2002, the newly created Advisory Council for Aeronautics Research in Europe (ACARE) issued its first Strategic Research Agenda (SRA). The ACARE SRA established a general framework for European aviation-related research, including the definition of quantified targets for 2020. The noise targets defined by the SRA-1 aimed at reducing noise emission of flying vehicles by half, which for rotorcraft was translated as follows in quantitative terms:

- **Reduction of noise footprint by 50%**, taking into account technology benefits (Rotorcraft of the Future contributor) as well as operational improvements (Noise Abatement Procedures contributor)

As part of the recommended strategy to address noise reduction, two main thrusts were identified as further described below in terms of associated technical and operational solutions:

- **Rotorcraft of the Future contributor associated solutions:** Low noise Main rotor, Anti-torque device, Engine / Aircraft integration-architecture / New VSTOL Concepts

- **Noise Abatement Procedures contributor associated solutions:** Improved Operating Practices with Current Concepts / Optimised Operations with New Technology / ATM-ATC Integration

The main noise research projects, including national efforts, contributing to the satisfaction of the ACARE target are represented in Figure 5

Figure 5: Roadmap of Rotorcraft Noise Projects in Europe.

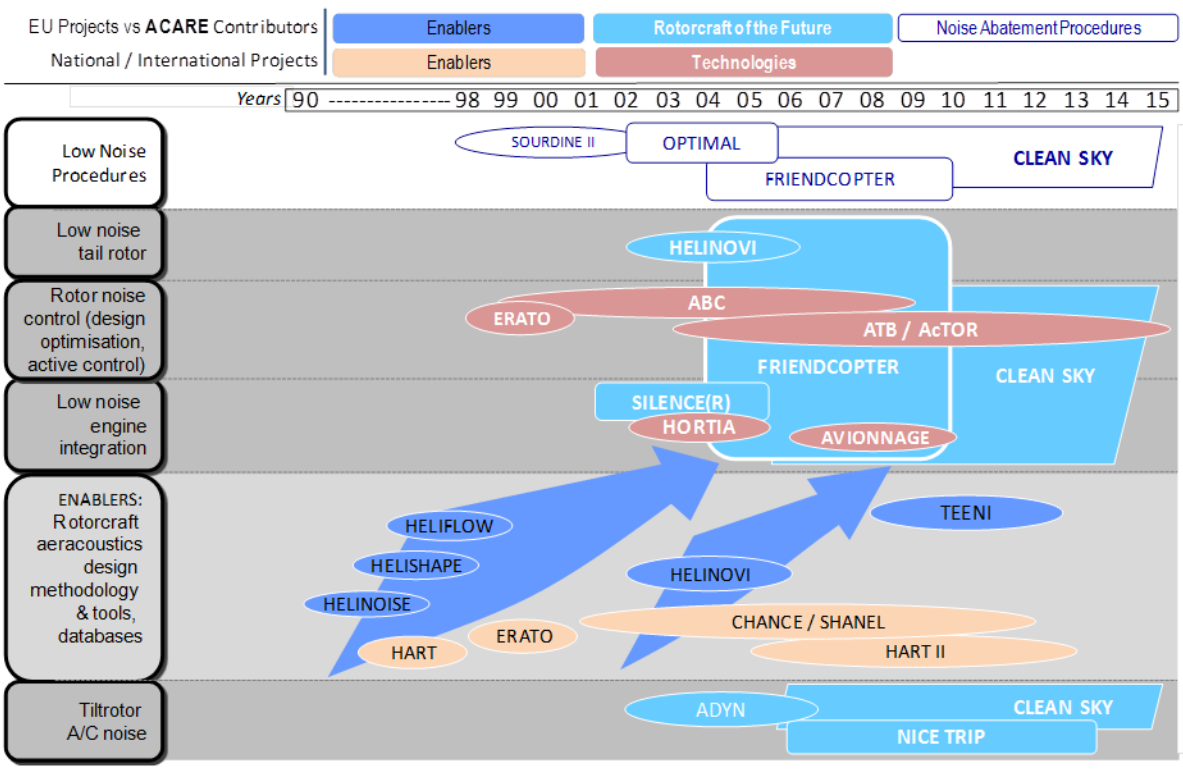


Figure 5: Roadmap of Rotorcraft Noise Projects in Europe

4.2.2 Key projects

- **HELINOVI** (Helicopter Noise and Vibration Reduction)

  The overall RTD objective was the performance enhancement of helicopters while at the same time increasing safety and ride comfort. The target was to reduce the blade-vortex interaction noise by 60%, which is more than 7 EPNdB, and to reduce rotor-induced vibrations by up to 90%.

  The goal of reducing noise by 60% was achieved by changing the tail rotor sense of rotation from "Advancing Side Down" to "Advancing Side Up". When comparing with tail rotor in "Advancing Side Down" mode, an average noise reduction of between 5 to 8 dB(A) has been measured depending on the flight condition. There was no performance penalty observed by the reversing tail rotor sense of rotation. As a result of tip speed reduction, an averaged noise reduction value of more than 2 dB(A) was observed for all flight conditions. The reduction of main rotor BVI noise, especially in the retreating side area, was even more than 3 dB(A).

  Figure: HELINOVI-Model in DNW-LLF wind tunnel

- **ADYN (**Advanced European tiltrotor dynamics and noise)

  The project was intended to enhance the EU knowledge on tilt rotor technologies by deeply analyzing the Whirl-Flutter, an aero elastic instability of the rotor/pylon system occurring at high inflow speeds typical of tilt rotors A second aspect was to optimize the rotor blade design for a low external noise level. The research is conducted by a comparison of analytical and experimental results. Tests were done in a high-speed wind tunnel facility using a half-span scaled model. The project provided final recommendations for the design of a full-scale tilt rotor flight demonstrator (ERICA).

  Figure: ADYN rotor in DNW-LLF wind tunnel

- **TEENI** (Turboshaft Engine Exhaust Noise Identification)

  The project dealt with experimental identification of engine modules' responsibilities on exhaust Broadband Noise emission. This noise component is the second dominant noise source of a Turboshaft engine, and installing acoustic liners on the exhaust can lead to significant noise benefit on the whole helicopter levels. Turboshaft exhaust noise is assumed to be a mix between combustion and turbine noise, with very little jet noise. It is representative of what is generally called core noise on aircraft engines.

The major deliverables of TEENI are:

- A comprehensive full-scale engine test database, the first of its kind, with extensive internal measurements and far field instrumentation.
- A noise breakdown realised out of a panel of original signal processing methods which have been developed during the project, using internal measurements to understand the origin of noise measured in the far field.

Figure: Engine experimental setup

- **FRIENDCOPTER** (Integration of technologies in support of a passenger and environmentally friendly helicopter)
  Main objectives of the research programme were:

  - Helicopter acoustic footprint areas reduced between 30% and 50% depending on the flight condition,
  - Fuel consumption reduction up to 6% for high speed flights,
  - Cabin noise levels near 75 dB(A) similar to airliner cabins for cruise flight,
  - Cabin vibrations below 0.05 g corresponding to jet smooth ride comfort for the same flight regime.

  The activities and achievements attained within the framework of FRIENDCOPTER are described in the following paragraphs.

<u>Noise Abatement Procedures</u>

In order to achieve low noise flight procedures in the annoyance-sensitive region near the ground, a semi-empirical tool (HELENA) to predict noise footprints of all relevant helicopters has been developed (see Fig. A1.1.12). It will support both quiet helicopter design and low noise manoeuvring and is based on data banks of acoustic flight test data. For three helicopter types, these data have been established during the programme.

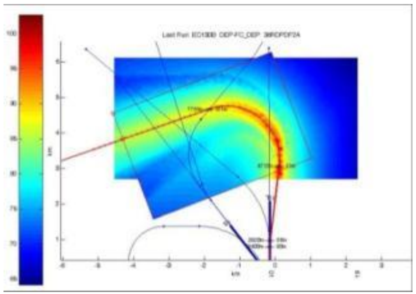
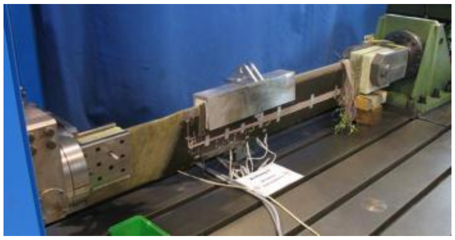


Figure: Noise footprint prediction of a turn, flown by an EC130

<u>Rotor Noise Control</u>

In order to suppress excessive blade slapping noise during approach, manoeuvre and high speed flight, to reduce dynamic rotor loads and cabin vibrations and to improve rotor performance by large steady blade twist modifications, active blade control has been realised enabling the blade to change its incidence angle – both quasi-steadily and in the form of high frequency oscillations. A full scale blade segment with active trailing edge has been developed and successfully tested on bending rig. In addition, a model rotor blade with active twist has been built and effectually tested on spin rig.



Figures: Hardware components of active blade control: Full scale ECD blade segment with active trailing edge during bending test (top), DLR Mach scaled model rotor blade with active twist in PZL manufacturing mould (bottom).

Engine Noise Reduction

In order to reduce performance losses of existing engine installations for rotorcraft with plenum chamber-type inlets, and at the same time the engine's acoustic radiation, a silenced lateral aperture to the compressor chamber has been installed in addition to the existing central one. The outlet noise has been diminished by an acoustic treatment of the engine nozzle's inner surface. Both have been successfully tested on ground rig and in flight.

Figures: Acoustically treated additional lateral air inlet to the compressor chamber (left) and treated ejector (right)

- **NICETRIP (Novel Innovative Competitive Effective Tilt-Rotor Integrated Project)**
  The main project objectives were to validate the European civil tilt-rotor concept, together with critical technologies and systems through the development, integration and testing of components of a tilt-rotor aircraft on full-scale dedicated rigs. The introduction of tilt-rotors in the European Air Traffic Management System was also evaluated.

  Concerning acoustics, concept validation included the capability of systems noise prediction to estimate the behaviour of the complete aircraft. The ATM related activity analysed the noise aspects of tilt-rotor operations.

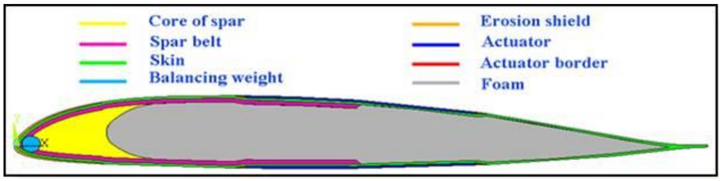
Figure: NICETRIP Tilt-Rotor model

- **CLEAN SKY Joint Technology Initiative**
  The Green RotorCraft ITD (GRC-ITD) gathers and structures all activities concerned specifically with the integration of technologies and demonstration on rotorcraft platforms (helicopters, tilt-rotor aircraft) which cannot be performed in platform-generic ITDs. In line with the ACARE environmental objectives for 2020 and the general Clean Sky objectives, the GRC top-level objectives are to:

• reduce CO_2 emission by 25 to 40% per mission (for rotorcraft powered respectively by turboshaft or diesel engines);
• reduce the noise perceived on ground by 10 EPNdB or halving the noise footprint area by 50%;
• ensure full compliance with the REACH directive which protects human health and environment from harmful chemical substances.

Noise reduction at source activities include:

- Blade stall alleviation, profile drag reduction (tailoring of blade design)
- Active blade devices
- Noise emission reduction of engine intake.



Figures: 3D blade profile tailoring (Right), active blade deformation, e.g. active twist (Left)

Operational aspects focus on noise abatement with optimized flight procedures in VFR & IFR including ATM constraints.

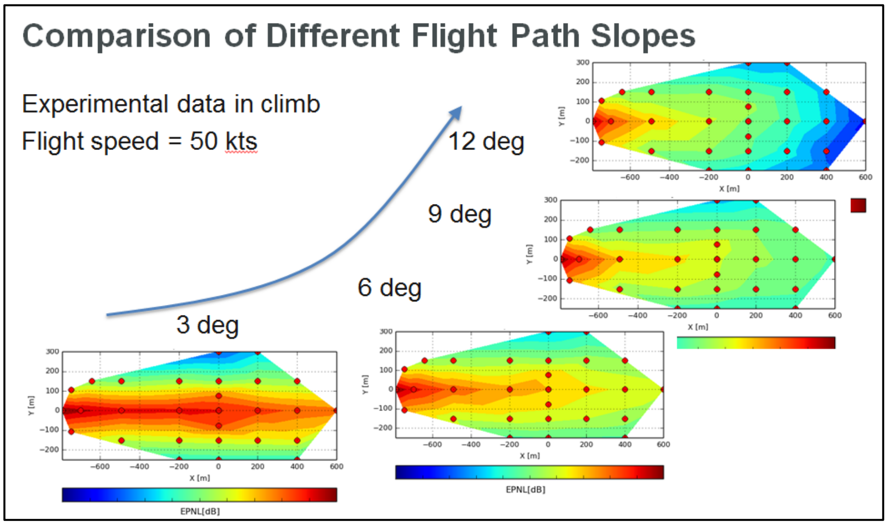


Figure: Comparison of Helicopter acoustic footprint at different climb slopes as measured in CleanSky

- **HART II** Test and international Workshop Higher Harmonic Control aeroacoustics rotor test)

  In 2001 the German Aerospace Center DLR performed a wind tunnel Test for a Helicopter Rotor with Higher Harmonic Control in order to validate the noise reduction potential. This data base was partly released to the public and in 2005 an international work shop has been established which finished in 2012. The objective of the HART II workshop was to validate numerical simulation tools for rotors including aerodynamics and aeroacoustics.

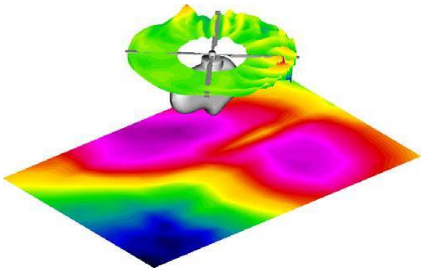


Figure: Load distribution on rotor and noise carpet below wind tunnel model.

- **CHANCE / SHANEL**

  The CHANCE project and its successor SHANEL have been conducted in cooperation between ONERA and DLR. In CHANCE, the Chimera techniques were developed and used for automatic mesh generation and adaptation in the *els*A solver. During SHANEL, thanks to the use of higher order schemes, matrix dissipation and efficient vorticity confinement techniques, it became possible for CFD to capture the BVI and, when coupled with a Ffowcs-Williams and Hawkings (FW-H) code, to provide a correct far field acoustic radiation compared to wind tunnel measurements. Nevertheless, these advanced CFD/FW-H methods are still too costly to be intensively used for rotor design or optimization.

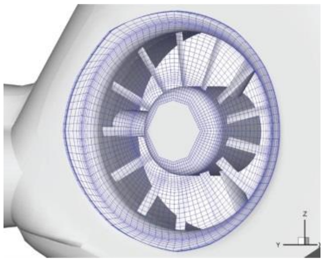
  

  Figure: Fenestron noise computation – Acoustic integration surfaces

- **ABC** (Active Blade Control)

  The ABC project concerned rotors equipped with trailing edge flaps. Following numerical optimization studies a model rotor was built and tested in the S1-Modane wind tunnel. The test proved a significant reduction of vibration and BVI noise. The research for the ABC rotor was a collaborative German French project by DLR and ONERA.

  Figure: active flap rotor in S1-Modane wind tunnel

- **ATB** (Active twist blade) / **AcTOR** (Active Twist optimized Rotor)

  The project is involved in the development of rotor blades with active twist. The active twist blades enable a Higher Harmonic Control in order to reduce BVI noise and vibrations. The blade twisting is achieved by gluing piezo ceramic actuators onto the blade skin, thus no moving mechanical parts are involved. After numerical studies several prototype blades in model scale have been manufactured and were tested on a whirl tower. Wind tunnel testing is planned for the future.

  Figure: rotor blade with piezo-ceramic actuators

- **AVIONNAGE**

  This French national project addressed among other issues the development of an engine treated lip demonstrator.

  Figure: engine intake treated lips

4.2.3 Assessment of Progress

Through the ACARE SRA1, two Contributors were associated to the "50% footprint reduction" noise target, namely the Rotorcraft of the Future and Noise Abatement Procedures. Since 2010, progress relative to ACARE targets across the board has performed through two successive exercises (AGAPE – 2010, OPTI - 2013). An examination of the overall projects roadmap showed clearly that the status of research progress concerning technology and operational solutions could be assessed concentrating on the results achieved by larger EU projects. As a general trend for noise related research, these tend to exploit the upstream research achievements of smaller projects carried out at EU or national level, bringing solutions to TRL 6 level.

The methodology established for the evaluation of progress relative to the rotorcraft noise subset of the SRA has been based on:

- the internationally recognized Technology Readiness Level scale, that allows tracking of the situation of individual technologies identified in the SRA1 as key elements of the ACARE technology oriented solutions for noise reduction. This tool is being used to measure the progress in term of strategy implementation considering the initial technology panel promoted in the ACARE SRA1
- a dedicated process, called Helena (**Hel**icopter **E**nvironmental **N**oise **A**nalysis), developed through the Friendcopter project and further upgraded and adapted to include operational aspects within the framework of the Clean Sky Technology Evaluator. This tool is being used to quantitatively establish the progress achieved at solution level as well as globally versus ACARE goals.

The qualitative (TRL) and quantitative assessment has then been carried out principally relying on the achievements reported by FRIENDCOPTER.

Certification figures for the rotorcraft types representative of main product categories have been used as the 2000 baseline in the quantitative evaluation performed through the HELENA analysis while for Operational Procedures, standard flight path as recommended by ICAO documentation have been considered for baseline. In parallel, a TRL position in 2000 has been established for the whole scope of individual noise reduction approaches.

A summary of key progress assessment findings is provided below:

Analysis of achievements and expected progress related to the two key Contributors to the Rotorcraft Noise target of 50% footprint reduction (Rotorcraft of the Future, Low Noise Procedures), led to the following recommendations in view of maximizing chances of meeting the target by 2020:

1) Maintain significant effort in support of all Noise Reduction at Source solutions, encompassing main rotor blade noise reduction through active and passive means as well as integrated quiet engine exhaust, in order to reach TRL6 as early as 2016
2) Maintain significant effort in support of the investigation and validation of environmentally friendly flight paths, as a highly significant contributor to the noise footprint reduction
3) Ensure effective exploitation of low noise operational procedures as successfully investigated in FRIENDCOPTER.

A new progress assessment exercise is planned for 2015 through the ACARE working group structure.

4.3 JAPAN

4.3.1 Scope of research and key projects

- **Research Program of ATIC**

ATIC (Advanced Technology Institute of Commuter-helicopter, Ltd.) was established in 1994 in order to research and develop the technologies to reduce the helicopter external noise for public acceptance and to enhance the flight safety in a 7-year research program. The final goal for the noise reduction area was to develop the technologies that can realize the helicopter external noise level at least 10 EPNdB less than the current ICAO noise limit.

Model Rotor Testing at DNW

Full Scale Rotor Testing

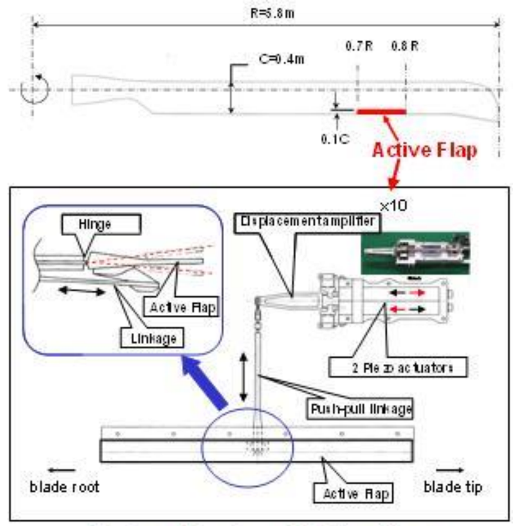
During 7-year ATIC activity term, the model rotor tests were carried out two times at DNW in order to evaluate the technologies which was developed by ATIC for noise reduction , and to get the validation data for the CFD and the rotor noise analysis codes. In these two tests, mainly performance and acoustic data of four types of model rotors were obtained on the level flight, descent and climb flight conditions.

ATIC also developed the full-scale rotor with the active flap in order to evaluate the actuation performance of the active flap and the aerodynamic performance of the tip shape by a whirl tower test. It is demonstrated by the test that the operability of the active flap system in the full-scale rotor is sufficient and AT2 with anhedral angle has the enhanced performance at the high thrust condition.

Model Rotor Testing at DNW

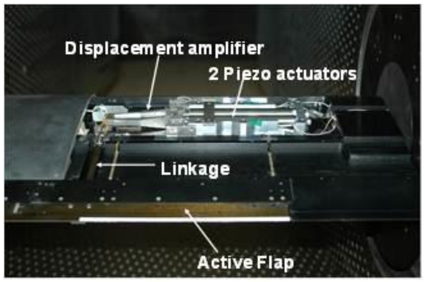
○ Noise Reduction by Active Rotor Control

JAXA started the research and development program of the full-scale active flap. As the first step, the conceptual study of the active flap system was carried out and the full-scale on-board active flap system was developed which demonstrated its operability by the bench test.



System Design of Active Flap

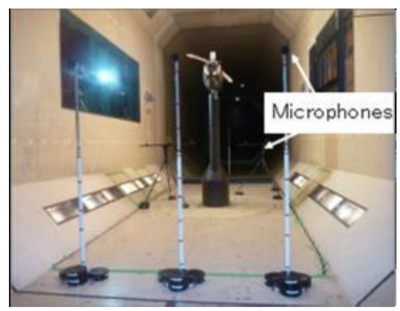
In the second step, a transonic wind tunnel test is performed on the condition to cover simulated several flight patterns such as landing/approach, hover, assumed maximum cruising speed of a helicopter in order to demonstrate the proper operability of the active flap system on more realistic environment.

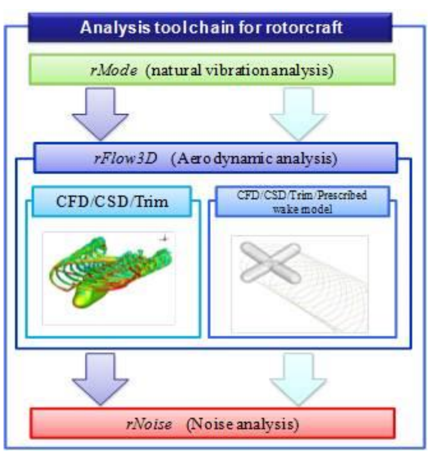


Wind Tunnel Test Model

It is shown by this test that the active flap system achieved the target value of a 6 degree amplitude on aerodynamically simulated BVI flight condition.

JAXA has built a 2-bladed model rotor with active flaps installed to evaluate the BVI noise feedback control in a wind tunnel. The feedback control of BVI is based on the pressure signals near the blade leading edge, where a strong correlation with the BVI noise level observed on ground can be established based on the numerical simulations and wind tunnel test.

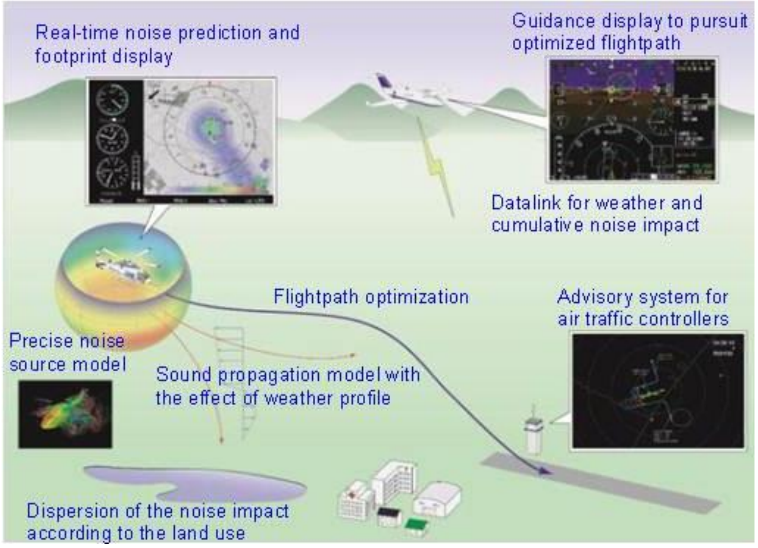




JAXA developed a CFD-based comprehensive analysis tool set (rFlow3D, rMode, and rNoise) to evaluate the aeroelastic behaviors of the rotor blade and to predict the rotor noise at an observation position, which has been used to evaluate the noise reduction capabilities of various active devices, including the HHC, active tab, active flap, and active twist.

- **Noise Minimizing Procedures**

  The scope and goals were to develop an onboard system to reduce noise impact on communities by optimizing flight conditions and paths with consideration to weather, land use, and cumulative noise by previous aircraft.

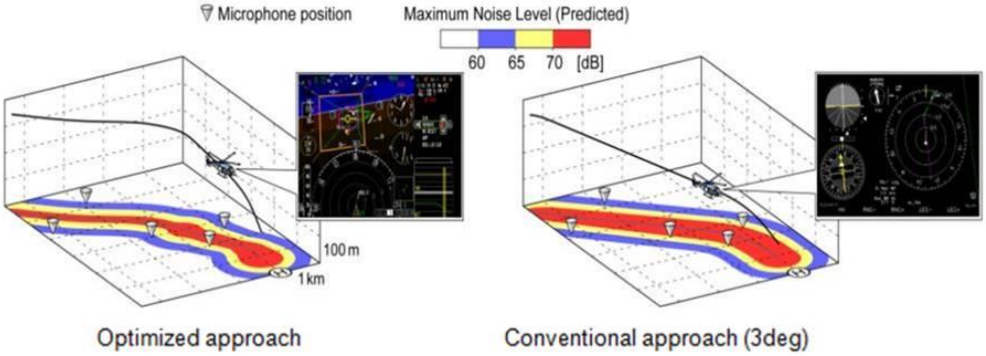


Concept of the system: the system will consist of:

- Noise prediction model.
- Database of land use and/or population.
- Real-time optimization algorithm.
- Guidance display.
- Datalink to provide atmospheric condition and noise levels accumulated by previous aircraft.

Principal results are listed below:

- Developed prototypes of subsystems.
  - Cockpit display to provide noise footprint predicted in real-time (2004).
  - Flight path optimization system and guidance display (2004-2007).
- Establishing noise prediction model
  - Measurement of the effect of propagation using cranes or balloons (2006-2007).
  - In-flight BVI noise measurement using an onboard, external microphone (2003-2007).
  - Comparison of BVI noise obtained by in-flight measurement and CFD computation (2007-).



4.4 Status of Noise Reduction Technologies

It is difficult to ascertain consistent technology readiness levels (TRLs) across multiple technologies and research efforts in multiple locations. The authors have endeavored, however, to identify the furthest progress achieved by category of technology. These observations are summarized below.

Automated Rotor Speed Reduction
Productionized/fielded.

Low Noise Anti-Torque Configurations
Productionized/fielded.

Advanced 3D Blade Design Technology
Productionized/fielded.

Active Rotor Control

- Active Flaps - has progressed to flight test demonstration. System integration, productionization and airworthiness certification all remain significant challenges.
- Active Twist – has progressed to wind tunnel demonstration.
- Individual Blade Control/Higher Harmonic Control - has progressed to flight test demonstration. System integration, productionization and airworthiness certification all remain significant challenges.

Noise Abatement Flight Procedures

- Pilot Controlled Procedures – in practice.
- Automated Procedures – flight test demonstrated. Some supporting infrastructure development remains.

Turbine Engine Noise Reduction Technologies

- Inlet/Exhaust Liners – has progressed to flight test demonstration.
- Core Noise – no activity at present.

Piston Engine Noise Reduction Technologies

- Upturned Exhaust – in certificated aircraft.
- Mufflers – in certificated aircraft.
- Resonators – flight test demonstrated.

5 Helicopter noise reduction technologies

The present chapter summarizes the available measures to reduce the noise emission from the dominant acoustic sources, namely main rotor, tail rotor and engines. In a first step the noise control measures are listed for each source. The implications of specific noise reduction technologies on other design requirements and constraints are then presented. The impact of different mission objectives and considerations on the design point of a helicopter are presented as well as the challenges in implementing noise reduction technologies in serial products.

It is important to note that a balanced acoustic design is needed to successfully field a low noise helicopter within the multiple design requirements of a modern helicopter. For example, rotor design features intended to reduce a source noise dominant in one flight regime (e.g., overflight) can inadvertently trigger increased noise levels in another flight regime (e.g., approach). Similarly, a balanced system design is also a requirement. For example, a large reduction in tail rotor speed can ultimately result in little to no acoustic benefits if the main rotor speed must be set at a high value for performance, handling qualities or safety reasons.

5.1 Source noise control

5.1.1 Main rotor noise control

Noise control on the main rotor can be realized in principal by the following design measures:

- Reductions in rotor rotational speed
- Increasing the number of rotor blades
- Advanced 3-D rotor blade design (radius, chord, twist, plan form, airfoil selection and distribution along radius, anhedral/dihedral, tip shape)
- Active technologies (Blue Pulse™, active twist, higher harmonic control at blade root)

The main lever for reducing the noise emission of a thrust generating rotor is reducing rotational speed. The effect is obvious in all flight conditions but also has adverse implications on almost any other discipline involved in both the main rotor design and the full aircraft design. Rotor speed reductions can also be implemented automatically to reduce noise throughout significant portions of the approved flight envelope including the noise certification flight conditions. Exemplarily typical effects of reducing the rotor rotational speed for a given helicopter design shall be described in some more detail below.

Decreasing the rotor speed means decreasing as well the kinetic energy stored in the rotor. In case of engine failure this energy is essentially needed to decelerate the helicopter in a flare thus allowing a safe autorotation landing. If the rotational speed is decreased, the inertia of the rotor thus has to be increased by adding additional blade mass. Furthermore helicopters are generally limited by gearbox torque especially in regions of high air density i.e. low altitudes. In these gearbox torque-limited regions a reduction of rotational speed thus means less power available for the rotor and therefore deteriorated helicopter performance. Adapting the gearbox torque limits would mean a re-design of the complete transmission system and additional weight which in most cases is not economically reasonable.

Another aspect to be considered is the functionality of passive vibration reduction devices that possibly need to be re-tuned or even re-designed in order to handle the different excitation frequencies caused by the change in rotational speed. Single frequency vibration reduction devices are inherently poor at addressing multiple rotational speeds, requiring use of a less effective broader frequency passive design, multiple passive vibration reduction devices, or implementation of an active vibration control (AVC) system capable of multi-frequency response. AVC systems can be effective but do introduce added weight, complexity and cost challenges.

Finally, helicopter handling qualities is another attribute that may be adversely impacted by rotor speed reductions, for example during high speed turns, where a reduced rotor speed increases unfavorable aerodynamic effects.

Nevertheless some modern helicopter designs take advantage of the low noise emission potential by automatically reducing the rotor speed only in certain regions of the flight envelope. For example a reduction at low altitudes and moderate flight speeds has no negative effect on the safety level of the helicopter which of course can never be a compromise. Decreasing the rotor speed at moderate airspeeds can also have positive side effects like reduced fuel consumption and thus increased maximum endurance of the helicopter. Managing a large bandwidth in rotational speed in the complete flight envelope of a helicopter however requires considerable knowledge and efforts in the design of particularly auto-pilot system, engine control, blade dynamics and anti-vibration devices.

A low rotor rotational speed is therefore not an easily integrated retrofit but rather an important and challenging task during a comprehensive design evaluation.

In comparison to the rotational speed the other main rotor design parameters influence the noise to a lesser extent and are oftentimes only effective against a specific physical phenomenon appearing only in specific flight conditions. In particular, a rotor blade design to minimizing noise in one flight regime can adversely impact noise levels in other flight regimes, and a rotor blade design that universally reduces noise emissions can be elusive.

Active rotor concepts try to reduce some inherently contradictive design tradeoffs between flight conditions by allowing an adaptation to the flight condition. Nevertheless the simultaneous reduction of external noise and cabin vibration levels by, for example, higher harmonic rotor blade control remains a challenging task. Furthermore the integration of an active rotor system adds a lot of complexity to the design and considerably increases the costs, both for acquisition and direct operating costs. Beside the fact that the systems investigated in research programs are not yet reliable enough for product integration, and economical reasonability needs to be addressed as well.

5.1.2 Anti-torque noise control

The noise control on a tail rotor follows quite similar rules as on a main rotor with some additional possibilities due to the specific task of the anti-torque generation:

- Rotor rotational speed
- Number of rotor blades
- 3-D rotor blade design (radius, chord, twist, plan form, airfoil selection and distribution along radius, anhedral/dihedral, tip shape)
- Conceptual variants:
    - Classical tail rotor
    - Ducted fan (e.g. Fenestron™)

  - Tail boom blower (e.g. NOTAR™)
- Sense of rotation and position with respect to the main rotor wake
- Aerodynamic surfaces providing anti-torque (modifying the thrust requirement for the tail rotor)
- Shrouded rotor specifics:
  - 3-D rotor/stator design
  - Leaned/swept blades,
  - Unequal blade spacing
  - Duct design

The discussion above on main rotor noise control applies largely to anti-torque noise control, particularly for classical tail rotor designs, although some of the issues encountered in main rotor speed reduction are not applicable or less problematic for anti-torque designs. In addition, the sense of rotation and position of a classical tail rotor are important in minimizing main rotor-tail rotor interaction noise. For shrouded tail rotors, the increased intensity/discernibility of emitted noise at descent conditions which minimize main rotor BVI noise emissions can become a consideration.

The anti-torque concept and the respective rotational speed are the main parameters for noise reduction. When introducing modifications in the anti-torque system, however, considerations include helicopter performance especially in hover, handling qualities, and, in particular, the impact on the center of gravity.

5.1.3 Turboshaft engine noise control

The noise reduction means for a turboshaft engine are in principal quite similar to those on turbofan engines. However the application of acoustic liners – as commonly applied in fixed-wing designs – is physically limited due to the short duct length in the radial compressor design of most helicopter engines.

Advances in engine noise reduction therefore strongly depend on measures introduced by engine manufacturers.

- Combustion noise optimization
- Frequency placement of compressor and turbine tones
- 3-D rotor/stator design
- Leaned/swept blades
- Number of blades
- Cut-off design for acoustic modes in axial rotor/stator stages
- Intake/exhaust design and acoustic liners

Most of the potential in engine noise reduction is related to the core engine design or engine exhaust design. On an aircraft level, modifications in the engine installation mainly impact weight, aerodynamic efficiency, installation losses and possibly icing behavior and icing protection requirements.

5.1.4 Piston engine noise control

As noted previously, piston engine noise is typically dominated by exhaust noise and most piston engine noise reduction efforts have focused on methods to minimize exhaust noise impacts to the ground observer.

- Upturned exhaust configurations

- Resonators
- Mufflers

5.2 Noise reduction outside the noise certification scope

It is important to note is that source noise reduction measures do not necessarily influence certification noise levels, since only the most relevant conditions for helicopter-related public annoyance are considered in the noise certification procedure. More details on the related advances in the past years are thus summarized in the dedicated research chapter of this report.

Pilot-selectable features like for example a switch to reduce rotor rotational speed can be an efficient mean of operational noise reduction. However these pilot-selectable measures are not considered in noise certification because the basic intention of the current certification scheme is to measure the worst case condition. This limitation has hindered the wider use of low rotor speeds in production aircraft.

Another example of noise reduction means not considered in noise certification are technologies that show a benefit in flight conditions other than those specified for certification (sea level, 25°C). This could be for example hovering flight, approaches at different glide slopes and different speeds, and operations in hot or cold conditions or at higher altitudes.

Any investigation based solely on certification noise levels therefore neglects the operational noise reduction potential offered by application of noise abatement procedures or pilot-selectable technologies. An issue naturally raised in this context is the level of correlation between certification and operational noise levels.

The certification flyover is considered representative of operational level flight at or near best range cruise speed. The same is true for the certification takeoff at best rate of climb which is fairly representative of standard operational practice. The certification approach at V_Y and 6 degree glide slope is intended to characterize the worst case condition with respect to the particularly annoying blade vortex interaction noise emissions, not to necessarily represent operational approach noise levels. This condition might therefore be less representative for true operational noise. On the other hand it seems impossible to define an operational standard approach for helicopters since the pilot under visual flight rules is free to operate in a broad range of conditions.

An objective to cover all possible approach flight operating conditions or even to determine the true worst case for a given helicopter model can be an elusive if not impossible challenge in designing for low helicopter noise. Helicopter manufacturers address this situation by developing robust rotor designs that show good acoustic characteristics in a broad operating range including the noise certification conditions. Many manufacturers further determine the acoustic behavior of their helicopters in non-certification approach conditions and provide guidance on low-noise operations to the operator, typically in the non-approved section of the rotorcraft flight manual. The theoretical danger of “tuning” a rotor design only to the certification conditions is deemed completely unrealistic due to the limited predictability and the high sensitivity of blade vortex interaction noise to operational conditions in approach.

Hover is a typical operational flight condition presumably not well captured by the current certification scheme but obviously a non-negligible source of annoyance for certain operations. Difficulties in the measurement of hover noise, however, make it poorly suited for certification purposes, in particular due to the high sensitivity to wind conditions leading to limited repeatability of test results. Individual experience shows that repeated hover measurements in stable weather conditions show discrepancies of up to 7 dB, with higher variations possible with changing test conditions. The ability of single and some twin engine helicopters to safely acquire hover noise data can be limited due to the avoid section at zero to low airspeeds and low altitudes of the H-V diagram (height-velocity diagram). Furthermore the typically long duration of hover is an issue. On the other hand hover conditions might be reasonably correlated with certification takeoff, due to the fact that both conditions are characterized by high main rotor thrust and anti-torque requirements.

5.3 Design tradeoffs and constraints

Unlike most fixed-wing aircraft, helicopters are designed for multi-purpose usage. The wide range of mission objectives leads to the challenging fact that the typical rotorcraft design does not require one but rather a number of design points / missions. Designs therefore have to be evaluated for a large flight envelope (including forward airspeeds from hover to 180 kt, sideward and rearward flight up to 35 kt) and different atmospheric conditions (covering a large range of altitudes, temperatures, and possible icing conditions). The respective trade-offs in the design depend heavily on the class (size) of aircraft and the anticipated mission priorities envisaged for this type of helicopter.

Typical civil helicopter missions are for example:

- News gathering or police surveillance, search and rescue
    - Long hover and low speed flight phases at low altitude
    - Hover at high altitudes and/or high cross-wind conditions
- Emergency medical services
    - Frequent take-offs from and landing at mostly urban helipads
    - Often under demanding weather and mission requirements
    - Hover and ground operations near very sensitive areas (patients in hospitals)
- Passenger transport
    - Frequent cruise flights along similar routes
    - Low speed loitering around tourist sites
- Oil & Gas
    - Long distance fast cruise over hostile environment
    - Take-off and landing in often extreme weather conditions
    - Take-off and landing on helipad close to inhabited areas.

A good acoustic design thus needs to incorporate reasonable compromises for the noise impact as part of the specific mission requirements. For many but not all missions a quieter helicopter design can be considered as a competitive advantage.

In order to include noise reduction technologies in new helicopter designs, several steps have to be passed successfully before a specific noise mitigation mean can find its way into serial production. The following list describes those phases in a certainly rather condensed and thus simplified format:

- Physical understanding of the noise generation mechanisms
- Mitigation concepts

- Demonstration of robust noise reduction for the respective condition
- Reliable quantification of
    - Noise benefits
    - Weight
    - Costs
    - Required integration and certification efforts
- Assessment of impact on other core design disciplines in the whole flight envelope
- Further affected areas: Supplier, manufacturing, maintenance, etc…

Even this non-exhaustive enumeration shows that the demonstration of acoustic effectiveness within a research activity is just an early step towards the serial application of noise control technologies.

Quantification of acoustic benefits is usually done, but determining the associated cost and weight for a potential future serial design is a far from trivial task.

The following assessment of potential impact on other core disciplines in the whole flight envelope is no less demanding given the still evident technical challenges in numerically predicting effects on for example aero-elastic loads, vibrations or ice accretion.

5.4 Affected disciplines assessment

An example of core disciplines typically affected by the introduction of noise reduction technologies is given hereafter:

- Rotor speed recovery after loss of engine
- Autorotation and landing flair capability – including one engine inoperative (OEI) for twin engine helicopters
- Aerodynamic efficiency and thus fuel consumption and basic helicopter performance including payload and range capabilities
- Handling qualities and flight mechanics
- Auto-pilot system behavior
- Rotor stability (ground/air resonance)
- Vibrations
- Loads on rotor blades and controls
- Anti-torque requirement
- Transmission system limitations – lower speed rotors require heavier, higher torque transmissions
- Centre of gravity
- Engine control
- Engine installation losses
- Behavior in icing conditions
- …

The detailed assessment of possibly negative effects in all these areas represents a major challenge with associated technical and monetary risks for a new design. Especially for an upgrade of an existing helicopter, the need for unmodified usage of existing components like the main gear box can introduce severe constraints for the introduction of new technologies. A forced introduction of noise technologies under these constraints can lead to technically feasible but economically unreasonable designs without adequate sales potential in the rotorcraft market.

Also for completely new helicopter designs the possibly positive effect of a noise reduction technology has to be evaluated in detail based on a comprehensive design assessment. The new technology might for example trigger the need for additional safety provisions or simply add weight at an unfavorable position that has to be compensated by putting additional mass somewhere else to counterbalance the effect on the center of gravity. So it might well happen that the originally estimated noise benefit for a modified component is largely decreased by the additional weight in a comprehensive helicopter design evaluation.

Unfortunately some of the most efficient noise control technologies like globally reducing the rotor rotational speed are generally in contrast to other design requirements such as light-weight design of the rotor and transmission systems, acceptable handling qualities and vibration levels, component lifetimes and autorotation capabilities. Since especially the latter directly concerns safe operation of the helicopter there can be no compromise. However a careful consideration of all the dimensioning flight conditions can highlight particular areas in the flight envelope where a reduced rotational speed can actually turn out to be beneficial for some other disciplines as well without a negative impact on flight safety. The resulting logic of a thus optimized automatic rotational speed law greatly increases the system complexity and therefore requires significant interdisciplinary expertise to handle the challenges in – among many others – the dynamic blade design, the auto-pilot system and the engine control.

The abovementioned interdependencies need to be carefully evaluated for each specific helicopter design and mission requirement in order to classify the introduction of noise reduction technologies in a serial product as technically feasible and economically reasonable.

5.5 Technology Goals

The noise certification database represented by the data in Figures A-1 to A-3 can be used to evaluate the noise benefits of design, technology and operational changes for current state-of-the-art helicopter designs [Ref. 1]. Because design optimization for a single flight condition, e.g., Approach or Overflight, can incur trade-offs with noise levels for the other flight conditions, the margins to the ICAO and FAA noise limits for these helicopters can provide a first cut look at the potential for future best practice cumulative margins to the noise limits.

The data in Figure A-1 to A-3 are reproduced in Figures 6 to 8 to provide illustrative examples of the noise benefits of rotor speed reduction and low noise anti-torque configurations. In each figure, the EC145 with classical tail rotor is highlighted in comparison to the H145 (EC145T2), the latter featuring a Fenestron™ anti-torque system. Otherwise both models are identical in terms of noise reduction technologies [Ref. 1]. Each figure also identifies the empirically derived noise reductions obtained for the S-76D™ helicopter noise levels with a main and tail rotor speed reduction of 5 % [Ref. 2]. Each of these example cases gives a cumulative margin benefit of ~5 EPNdB, indicating the potential benefits if applied to other comparable designs in the figures.

The Approach Noise Level plot in Figure 7 also includes an estimate of a “No Blade-Vortex Interaction” (“No BVI”) noise reduction threshold for 6^{o} certification Approaches based on noise abatement flight procedure development several years ago that demonstrated elimination of BVI noise both audibly and by test data analyses for the S-76C+™ [Ref. 3]. As BVI source noise can only be eliminated once, the S-

76C+ helicopter noise abatement EPNL shown in Figure 7 provides an indication of the potential Approach certification and operational noise levels that would be attainable with elimination of blade-vortex interactions within current state-of-the art rotor design capabilities. This is a conjecture, however, when applied to the entire helicopter fleet. Some of the results provided for the other BVI noise reduction technologies in development suggest potential Approach EPNL values as much as 2 EPNdB below this line, but it is not yet clear that such levels will be achieved. Hence the "No BVI" noise level line is approximate and not exact but, as postulated above, does provide a first cut estimate of current state-of-the art helicopter designs with no or minimal BVI source noise.

Combining all of the best-in-fleet noise margins in Figures 6 through 8 gives a total margin to the ICAO 8.4.2/FAA Stage 3 noise limits approaching 18 EPNdB. Given typical design constraints and the aforementioned trade-offs that often occur between flight conditions, simultaneously achieving best-in-fleet margins for all three Chapter 8 flight conditions appears possible, with the H145 (EC145T2), MD900 (MD Explorer) and S-76D at reduced rotor speed (research variant) coming close. In general, however, achieving cumulative margins of 4 to 17 EPNdB to the 8.4.2/Stage 3 limits (12 to 25 EPNdB to the 8.4.1/Stage 2 limits) remains a challenging goal for the near to intermediate term for the majority of future helicopter designs. In this context it needs to be considered as well that some advanced noise reduction features like unequal blade spacing or new main rotor blade designs are protected intellectual property and thus not available to all manufacturers.

Noting that the "No BVI" line in Figure 7 indicates up to a 2 EPNdB reduction by further BVI source noise reductions, a cumulative 8.4.2/Stage 3 margin of 20 EPNdB seems potentially achievable with improvements to current state-of-the-art designs. Getting to a cumulative margin to the ICAO 8.4.2 / FAA Stage 3 noise limits of at least 22 EPNdB (i.e., 30 EPNdB to the 8.4.1/Stage 2 limits) is a logical objective in the context of current total margins for the state-of-the-art helicopter designs. It is not clear, however, that this is achievable with current state-of the-art noise reduction capabilities including the use of advanced, high performance rotor blades. A step change in the state-of-the art will likely be needed to break the 22 EPNdB barrier for cumulative 8.4.2/Stage 3 margin (30 EPNdB barrier for cumulative 8.4.1/Stage 2 margin).

References

1. Gareton, V., Gervais, M., Heger, R., "Acoustic Design and Testing of the Eurocopter EC145T2 and EC175B – a harmonized Franco-German Approach," Proceedings of the 39th European Rotorcraft Forum, Moscow, Russia, 3-6 September 2013.
2. Jacobs, E.W. and Pollack, M.J., "High Performance and Low Noise Characteristics of the Sikorsky S-76D™ Helicopter," Proceedings of the 69th Annual Forum of AHS International, Phoenix, Arizona, 21-23 May 2013.
3. Jacobs, E.W., Prillwitz, R.D., Chen, R.T.N., Hindson, W.S. and Santa Maria, O.L., "The Development and Flight Demonstration of Noise Abatement Approach Procedures for the Sikorsky S-76," Proceedings of the AHS Technical Specialists Meeting for Rotorcraft Acoustics and Aerodynamics, Williamsburg, Virginia, 28-30 October 1997.

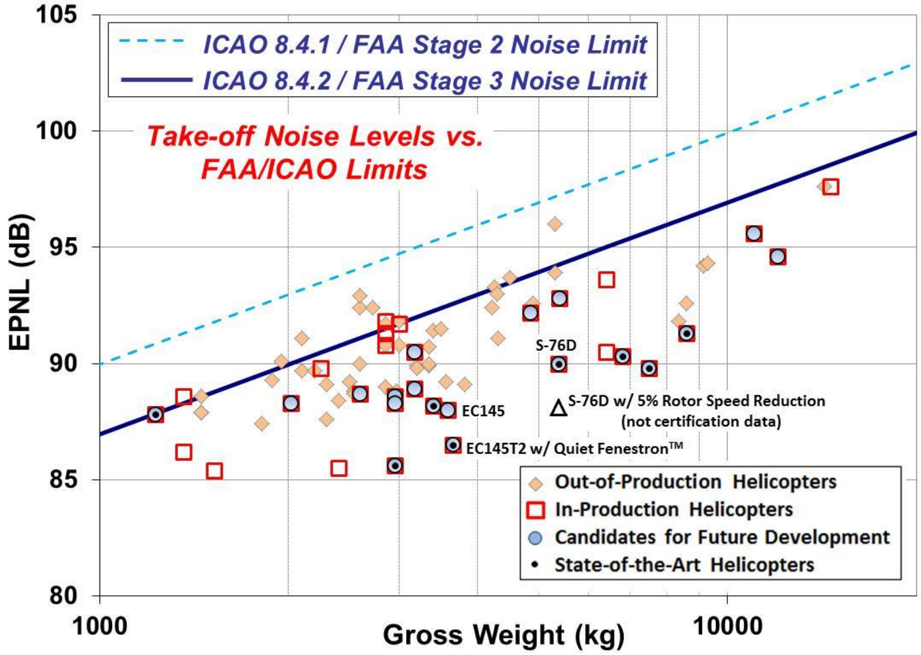


Figure 6. Chapter 8 Take-off Noise Levels vs. Gross Weight Showing Current Best-in-Fleet Margin to 8.4.1 and 8.4.2 Limits and Example Case of N_R Reduction

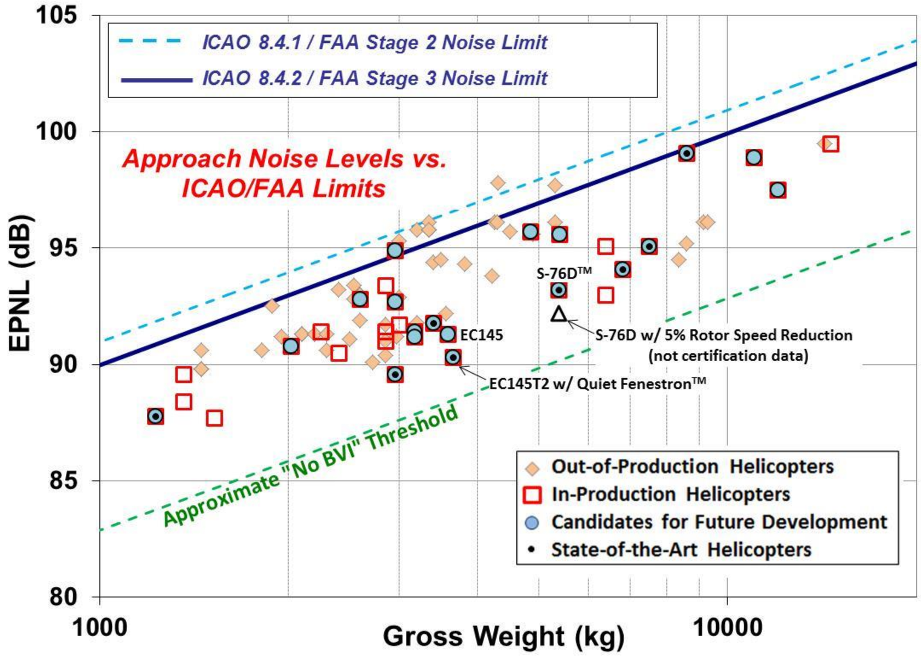


Figure 7. Chapter 8 Approach Noise Levels vs. Gross Weight Showing Current Best-in-Fleet Margin to 8.4.1 and 8.4.2 Limits, Example Case of N_R Reduction, and Approximate "No BVI" Margin Threshold

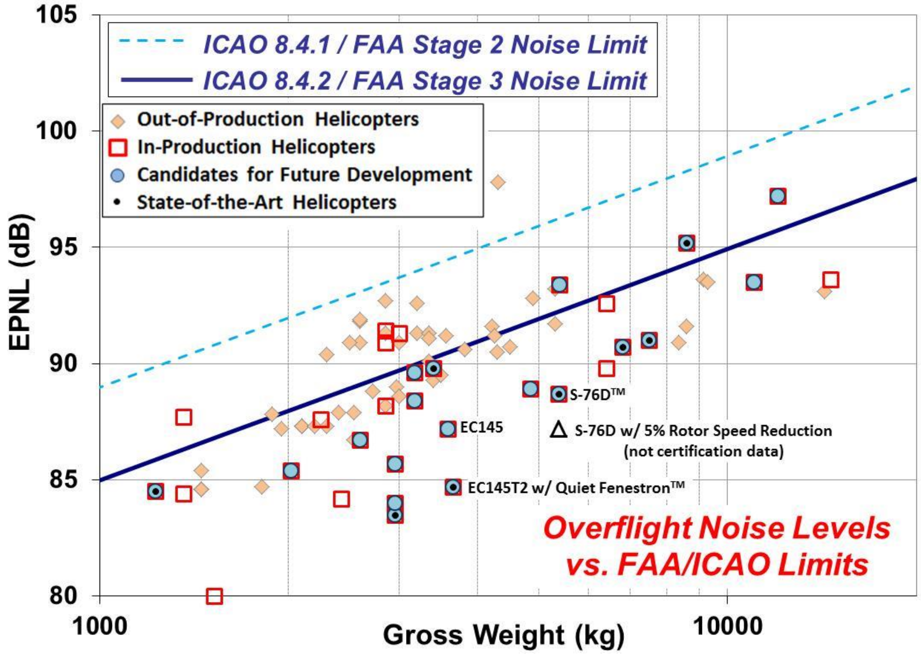


Figure 8. Chapter 8 Overflight Noise Levels vs. Gross Weight Showing Current Best-in-Fleet Margin to 8.4.1 and 8.4.2 Limits and Example Case of N_R Reduction

5.6 Helicopter low noise operations

Beyond the scope of noise certification regulations a lot of research has been dedicated to investigate operational noise reduction potential by following noise abatement procedures. The related outcomes are briefly summarized here to provide a larger picture with respect to helicopter noise reduction potential.

The Helicopter Association International (HAI) has published comprehensive guidance material on low noise helicopter operations, as well as on the implementation and monitoring of progress in the scope of its “fly neighborly” programme: http://www.rotor.com/Operations/FlyNeighborly.aspx

Beyond these generic recommendations, many manufacturers are providing more detailed, helicopter specific noise abatement recommendations on the HAI website and in some cases also in the non-approved sections of the rotorcraft flight manual.

Advanced accurate satellite based guidance systems will further enable to tailor also more complex procedures to specific helipad constraints, thus promising full exploitation of the operational noise benefit potential.

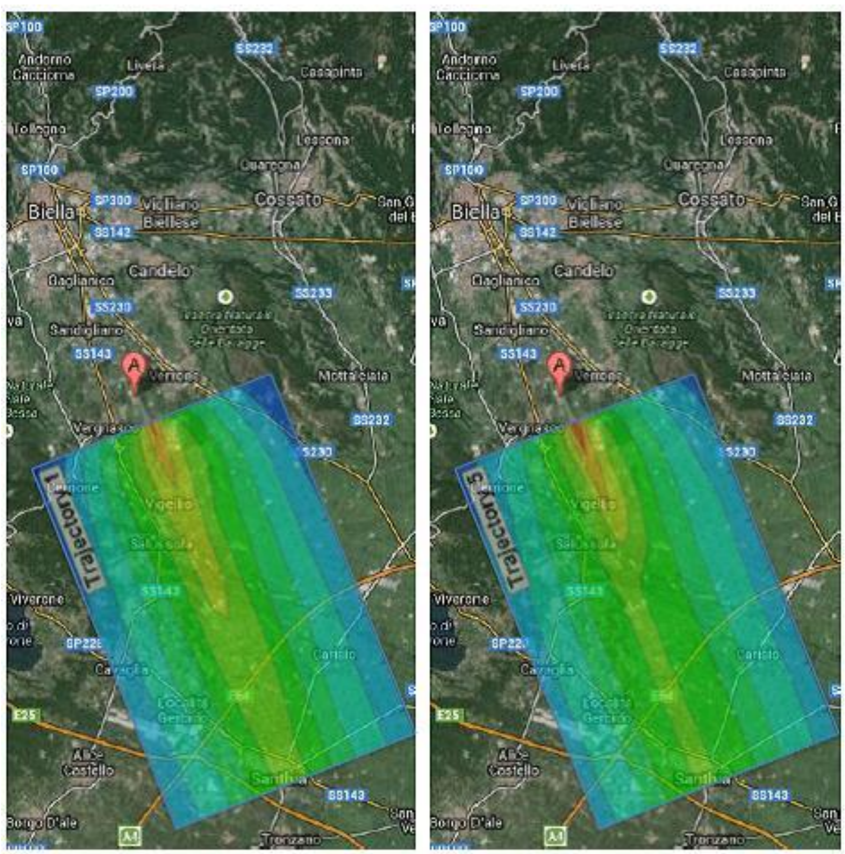


Figure 9. Helicopter acoustic footprint for baseline (left) and steep (right) approach procedures located over the Biella airport (Italy), showing noise footprint reduction (green areas).

6 Conclusions and Perspectives

The data presented in this report highlights that significant progress in the reduction of helicopter noise at the source has been achieved in the last 15 years for both, new type designs and derived versions of existing helicopter models.

Considerable funding has been dedicated to low noise helicopter research particularly in the United States, the European Union and Japan. The activities focused on the exploration of active and passive rotor technologies, the development and operational verification of noise abatement procedures and – to a smaller extent – engine noise reduction concepts and the improvement of numerical acoustic prediction capabilities.

Noise abatement procedures have especially proven to offer noticeable potential to reduce the noise impact on the ground. The implementation of noise optimized procedures is facilitated by comprehensive guidance material published by HAI as well as by new developments in pilot guidance concepts that promise to reduce the associated pilot workload.

While new technologies are continued to be explored, mature noise reduction technologies are regularly integrated in the designs of all major manufacturers. State-of-the-art helicopter designs achieve cumulative margins of 4 to 17 EPNdB to Chapter 8.4.2 limits.

High margins are achievable for small- and intermediate-sized helicopters partly due to low noise anti-torque concepts and typical mission related design tradeoffs for these weight classes. For certain missions, safety, performance, and economic design tradeoffs may lead to smaller noise certification margins. Special missions that require hybrid helicopter configurations (for high range and high speed) might face problems to comply with the applicable noise limits as specified for conventional helicopter configurations.

Noise reduction techniques necessitate extensive interdisciplinary design evaluations. Consequently integration into serial product lines often requires considerable time and expense. Some advanced noise reduction features are protected as intellectual property.

Reduced public annoyance with respect to helicopter noise is really a combination of low noise design and aircraft operations.

Attachment A – Candidates for Future Development Database

To provide context for the helicopters designated as state-of-the-art helicopters for this report, a database of all of the helicopters deemed representative of potential future designs, whether new type designs or derived versions, has been derived from the EASA noise certification database available online at http://www.easa.europa.eu/document-library/noise-type-certificates-approved-noise-levels. These helicopters have been designated as Candidates for Future Development and include the models designated as state-of-the-art designs. These Candidates for Future Development are generally, but not limited to, helicopter designs in current production.

				Helicopter Certification Noise Levels Chapter 8 / H			Noise Limits and Margins Chapter 8.4.1 = Stage 2						Noise Limits and Margins Chapter 8.4.2 = Stage 3					
	MTOW	Engine Type & Number	Engine	Take-Off	Flyover	Approach	Take-Off	Margin	Flyover	Margin	Approach	Margin	Take-Off	Margin	Flyover	Margin	Approach	Margin
	[kg]			[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]	[EPNdB]
AgustaWestland																		
A109 S	3175	T-2	Pratt & Whitney PW 207 C	90.5	88.4	91.2	95.0	4.5	94.0	5.6	96.0	4.8	92.0	1.5	90.0	1.6	95.0	3.8
AW139	6800	T-2	Pratt & Whitney PT6C-67C	90.3	90.7	94.1	98.3	8.0	97.3	6.6	99.3	5.2	95.3	5.0	93.3	2.6	98.3	4.2
AW189	8600	T-2	General Electric CT7-2E1	91.3	95.2	99.1	99.3	8.0	98.3	3.1	100.3	1.2	96.3	5.0	94.3	-0.9	99.3	0.2
AW169	4600	T-2	Pratt & Whitney PW210A															
Airbus Helicopters Deutschland																		
EC135P2+	2950	T-2	Pratt & Whitney PW206B2	88.6	84.0	92.7	94.7	6.1	93.7	9.7	95.7	3.0	91.7	3.1	89.7	5.7	94.7	2.0
EC135T2+	2950	T-2	Turbomeca Arrius 2B2	88.3	85.7	94.9	94.7	6.4	93.7	8.0	95.7	0.8	91.7	3.4	89.7	4.0	94.7	-0.2
BK117C2 (EC145)	3585	T-2	Turbomeca Ariel 1E2	88.0	87.2	91.3	95.6	7.6	94.6	7.4	96.6	5.3	92.6	4.6	90.6	3.4	95.6	4.3
BK117D2 (EC145T2)	3650	T-2	Turbomeca Arriel E2	86.5	84.7	90.3	95.6	9.1	94.6	9.9	96.6	6.3	92.6	6.1	90.6	5.9	95.6	5.3
Airbus Helicopters France																		
EC225LP	11000.0	T-2	Makila 2A1	95.6	93.5	98.9	100.4	4.8	99.4	5.9	101.4	2.5	97.4	1.8	95.4	1.9	100.4	1.5
AS 355 NP	2600.0	T-2	Turbomecca Arrius 1A1	88.7	86.7	92.8	94.2	5.5	93.2	6.5	95.2	2.4	91.2	2.5	89.2	2.5	94.2	1.4
EC 155 B1	4920.0	T-2	ARRIEL 2C2	92.2	88.9	95.7	96.9	4.7	95.9	7.0	97.9	2.2	93.9	1.7	91.9	3.0	96.9	1.2
EC175B	7500.0	T-2	Pratt&Whitney PT6C-67E	89.8	91.0	95.1	98.8	9.0	97.8	6.8	99.8	4.7	95.8	6.0	93.8	2.8	98.8	3.7
Bell Helicopter Textron																		
Bell 206L-4	2018	T-1	Allison 250-C30P	88.3	85.4	90.8	93.1	4.8	92.1	6.7	94.1	3.3	90.1	1.8	88.1	2.7	93.1	2.3
Bell 429	3175	T-2	Pratt & Whitney PW207D1	88.9	89.6	91.4	95.0	6.1	94.0	4.4	96.0	4.6	92.0	3.1	90.0	0.4	95.0	3.6
Bell 429	3402	T-2	Pratt & Whitney PW207D1	88.2	89.8	91.8	95.3	7.1	94.3	4.5	96.3	4.5	92.3	4.1	90.3	0.5	95.3	3.5
Bell 412EP	5398	T-2	Pratt & Whitney PT6T-9	92.8	93.4	95.6	97.3	4.5	96.3	2.9	98.3	2.7	94.3	1.5	92.3	-1.1	97.3	1.7
Enstrom Helicopters																		
Enstrom 280FX	1179	P-1	Lycoming HIO-360-F1AD	89.0	81.0	91.0	90.7	1.7	89.7	8.7	91.7	-0.7	87.7	-1.3	85.7	4.7	90.7	-0.3
Enstrom F-28F	1179	P-1	Lycoming HIO-360-F1AD	91.0	83.0	93.0	90.7	-0.3	89.7	6.7	91.7	1.3	87.7	-3.3	85.7	2.7	90.7	-2.3
MD Helicopters																		
500 N (520 N)	1520	T-1	Allison 250-C20R/2	85.4	80.0	87.7	91.8	6.4	90.8	10.8	92.8	-5.1	88.8	3.4	86.8	6.8	91.8	4.1
MD-902	2948	T-2	Pratt & Whitney PW 207E	85.4	83.5	89.6	94.7	9.3	93.7	10.2	95.7	-6.1	91.7	6.3	89.7	6.2	94.7	5.1
Robinson Helicopters																		
R22 Beta	621	P-1	Lycoming O-360_J2A	80.2	81.3	86.7	89.0	8.8	88.0	6.7	90.0	-3.3	86.0	5.8	84.0	2.7	89.0	2.3
R22 Mariner	621	P-1	Lycoming O-320_J2A	84.2	81.4	86.7	89.0	4.8	88.0	6.6	90.0	-3.3	86.0	1.8	84.0	2.6	89.0	2.3
R-66	1225	T-1	Rolls-Royce 250-C300/A1	87.8	84.5	87.8	90.9	3.1	89.9	5.4	91.9	-4.1	87.9	0.1	85.9	1.4	90.9	3.1
Sikorsky Aircraft																		
Sikorsky S-76D	5386	T-2	Pratt & Whitney 210S	90.0	88.7	93.3	97.3	7.3	96.3	7.6	98.3	-5.0	94.3	4.3	92.3	3.6	97.3	4.0
Sikorsky S-92A	12020	T-2	General Electric CT7-8A	94.6	97.2	97.5	100.8	-6.2	99.8	2.6	101.8	-4.3	97.8	3.2	95.8	-1.4	100.8	3.3

				Helicopter Certific	Noise Limits and Margins Chapter 11.4.1 =		Noise Limits and Margins Chapter 11.4.2 =	
	MTOW	Engine Type & Number	Engine	Flyover	Flyover	Margin	Flyover	Margin
Airbus Helicopters France								
AS350B3	2370	T-1	Turbomeca ARRIEL 2D	84.2	86.8	2.6	84.2	0.0
EC130T2	2500	T-1	Turbomeca ARRIEL 2D	81.1	87.0	5.9	84.5	3.4
EC120 B	1715	T-1	ARRIUS 2F	78.7	85.4	6.7	82.8	4.1
Bell Helicopter Textron								
Bell 407	2268	T-1	Allison-250-C47B	84.6	86.6	2.0	84.0	-0.6
Enstrom Helicopters								
Enstrom 280FX / F28F	1179	P-1	Lycoming HIO-360-F1AD	79.0	83.7	4.7	82.0	3.0
Enstrom 280FX / F28F	1179	P-1	Lycoming HIO-360-F1AD	80.1	83.7	3.6	82.0	1.9
Enstrom 480B	1383	T-1	Allison 250-C20W	83.7	84.4	0.7	82.0	-1.7
Hélicoptères Guimbal								
Cabri G2	700	P-1	Lycoming O360-J2A	75.7	82.0	6.3	82.0	6.3
MD Helicopters								
MD 600N	1860	T-1	Allison 250-C47M	79.1	85.7	6.6	83.2	4.1
Robinson Helicopters								
R22 Beta II	621	P-1	Lycoming O-320_J2A	78.9	82.0	3.1	82.0	3.1
R22 Beta	621	P-1	Lycoming O-320_J2A	78.2	82.0	3.8	82.0	3.8
R-44 II	1134	P-1	Lycoming IO-540-AE1A5	80.9	83.6	2.7	82.0	1.1
R-66	1225	T-1	Rolls-Royce 250-C300/A1	82.4	83.9	1.5	82.0	-0.4
Sikorsky Aircraft								
S-300CBi (269C-1)	794	P-1	Lycoming HIO-360-G1A	78.8	82.0	3.2	82.0	3.2
S-300C (269C)	930	P-1	Lycoming HIO-360-D1A	80.4	82.7	2.3	82.0	1.6
S-333 (269D)	1157	T-1	Allison 250-C20W	81.5	83.7	2.2	82.0	0.5

Figures A-1 through A-4 graphically show comparisons of the certification noise levels for the state-of-the-art and future design surrogate helicopters with non-surrogate in-production and out-of-production models. These plots provide further context for the technology status of the helicopter designs selected as state-of-the-art designs and/or future design surrogates.

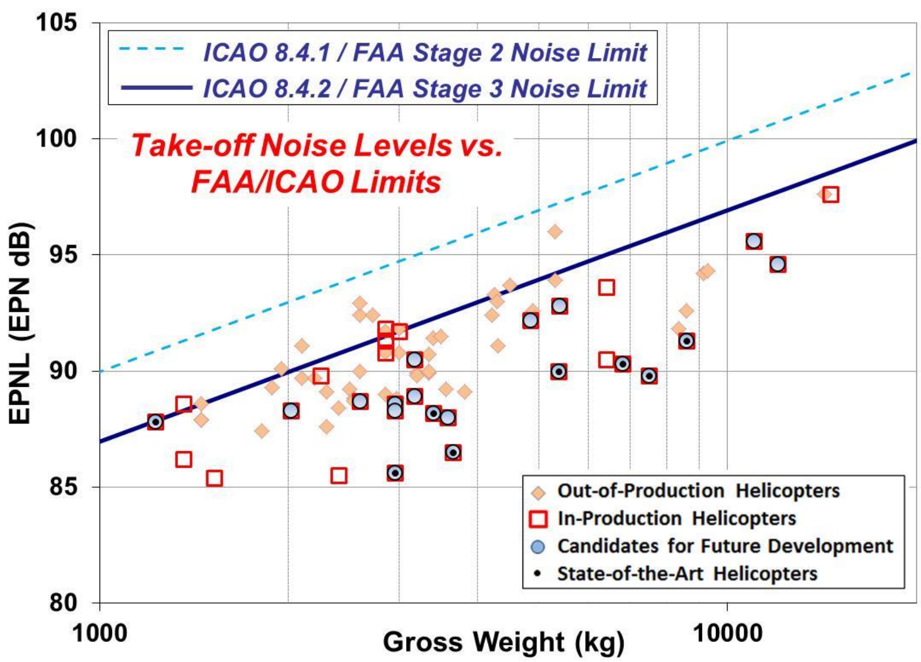


Figure A-1. Chapter 8 Take-off Certification Noise Levels vs. 8.4.1 and 8.4.2 Noise Limits

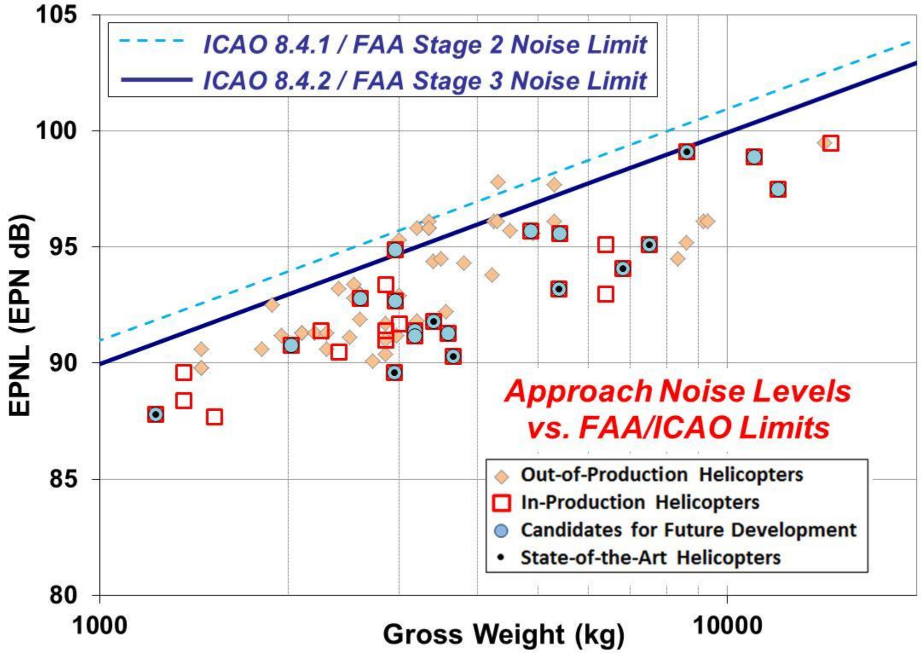


Figure A-2. Chapter 8 Approach Certification Noise Levels vs. 8.4.1 and 8.4.2 Noise Limits

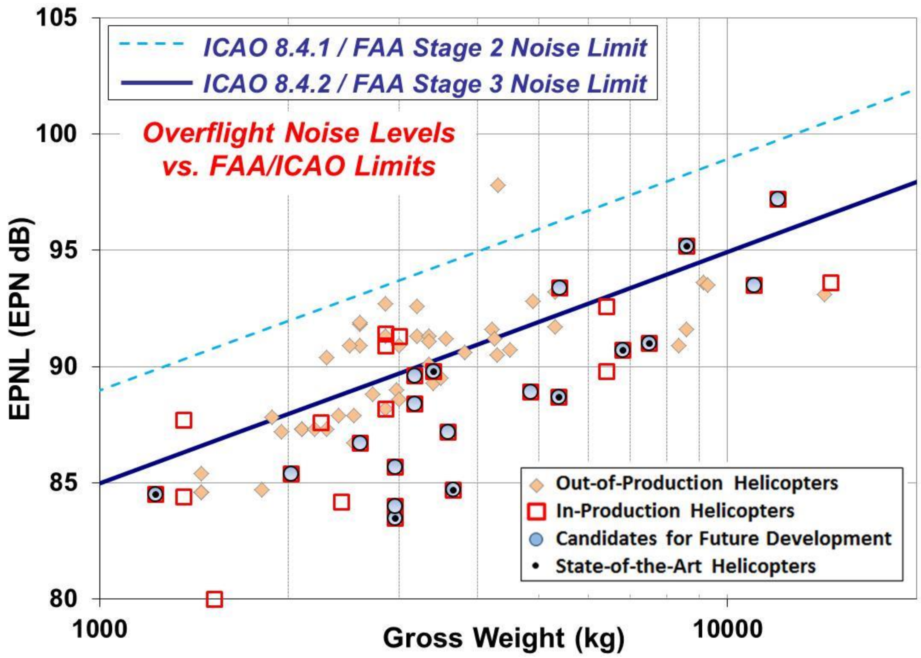


Figure A-3. Chapter 8 Overflight Certification Noise Levels vs. 8.4.1 and 8.4.2 Noise Limits

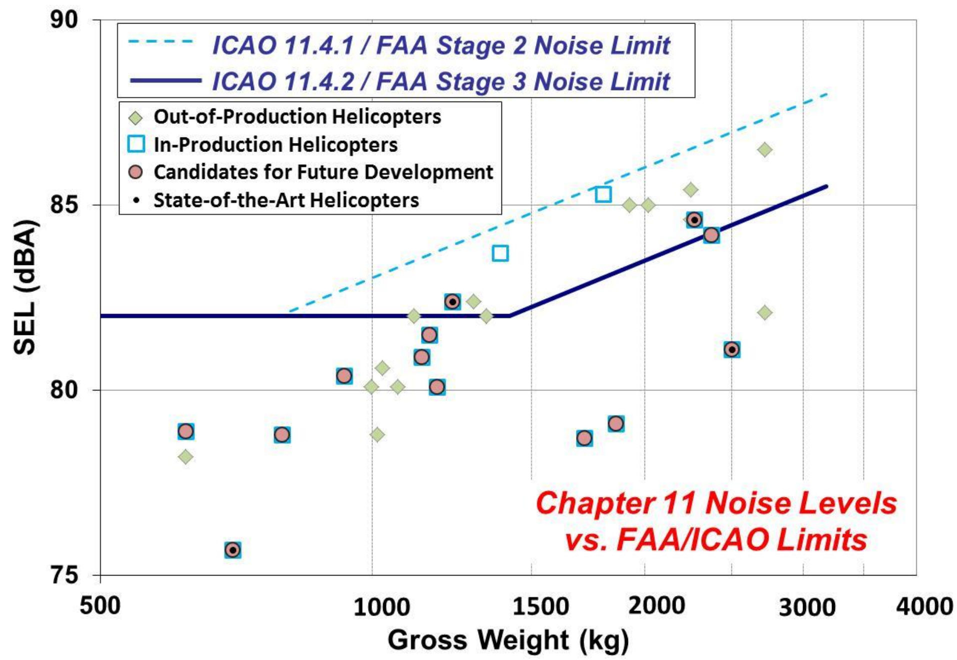


Figure A-4. Chapter 11 Certification Noise Levels vs. 11.4.1 and 11.4.2 Noise Limits

Attachment B - Correlation of Chapter 11 margins with Chapter 8 margins

One difficulty in evaluating the technology status of helicopters certificated to the Chapter 8 and Chapter 11 noise standards is that margins relative to the Chapter 11 standard do not directly compare to margins relative to the Chapter 8 standard. Chapter 11 was implemented for small helicopters (3,175 kg or less) as a lower cost “screening” Standard with sufficient stringency such that compliance with Chapter 11 noise limits ensures a type design would comply with the Chapter 8 noise limits. The Chapter 11 test is a single microphone measurement providing an SEL value for the Overflight condition only while the Chapter 8 test is a three microphone measurement providing an EPNL value for Overflight, Take-off and Approach conditions, with the latter two flight conditions more weakly correlated to the Chapter 11 Overflight SEL.

Rather than try to predict individual flight condition EPNL margins from Chapter 11 SEL margins, the analysis presented in this attachment examines cumulative margins to Chapter 8, 8.4.1, noise limits vs. margins to Chapter 11, 11.4.1, noise limits using data for helicopters which have been measured to both standards. The data base for this analysis utilizes both the dataset used in establishing the Chapter 11 noise standard (CAEP/2 WP/47, “Proposed Simplified Noise Certification for Light Helicopters,” CAEP/2, Montreal, 2-13 December 1991) supplemented by more recent data provided by both helicopter manufacturers and the EASA noise certification database available online at http://www.easa.europa.eu/document-library/noise-type-certificates-approved-noise-levels.

The WP/47 and certification/manufacturer datasets are shown in Table C-1 and linear correlations of the WP/47, certification/manufacturer and full datasets are shown in Figure C-1. As can be seen in Figure C-1, the WP/47 data correlation and the certification/manufacturer data correlation are in good agreement, indicating long term consistency in Chapter 8 cumulative vs. Chapter 11 Overflight margins to the respective noise limits. Given this consistency, the full dataset correlation shown in Figure C-1,

Cumulative Chapter 8 8.4.1 Margin = 1.77 (Chapter 11 11.4.1 Overflight Margin) + 9.8,

was used to define a relationship between Chapter 11 and Chapter 8 margins. Note that any helicopter model that is subject to the constant 82 dB limit below 788 kg cannot be used for this correlation as the Chapter 11 margin is not a function of weight as shown in Figure A-4. This includes the State-of-the-Art helicopter model Guimbal Cabri G2.

To provide the corresponding predicted margins to the Chapter 8, 8.4.2 noise limits, this correlation needs to be adjusted by a constant of -8 dB, i.e.,:

Cumulative Chapter 8 8.4.2 Margin = 1.77 (Chapter 11 11.4.1 Overflight Margin) + 9.8 – 8,

which has been used to provide the predictions shown in Figure 2 of this report of cumulative margins to Chapter 8, 8.4.2 noise limits for Chapter 11 certificated helicopters. These predictions allow the Chapter 11 certificated helicopters to be directly compared with Chapter 8 certificated helicopters as shown in Figure 3 of this report.

	Gross Weight (kg)	Chapter 11 Flyover Margin	Chapter 8 Cumulative Margin
WP47 Data			
Twinstar	2540	2.0	13.0
Astar	2250	1.8	15.0
MD500 (4TR)	1360	5.0	18.0
MD500 (2TR)	1360	0.8	9.3
Bell 206L	1814	2.0	14.5
MD520N	1520	5.7	21.9
280FX	1179	2.9	15.0
TH28	1293	2.1	12.2
330 (2TR)	1025	2.0	12.7
330 (4TR)	1025	6.5	21.9
300(b)	930	2.6	12.6
300(c)	930	2.5	12.6
Certification/Manufacturer Data			
EC135P1	2835	6.2	18.2
EC130B4	2400	5.0	21.2
Bell206L4	2018	1.1	14.8
Bell 407	2268	1.5	14.2
Bell 427	2948	0.4	10.5
Bell 429	3175	2.9	15.2
A109C	2720	0.6	11.8
A109LUH	3000	3.5	11.0
A109S	3175	2.9	15.1
280FX/F28F	1179	3.6	11.1
369ER	1406	-0.3	9.9
MD900	2720	5.3	24.7
R66	1225	1.5	12.6
BO105	2300	0.4	11.4
AS350B2	2250	1.1	11.7
AS350B3	2250	1.9	12.2
AS355N	2540	2.4	14.1

Table B-1. Margins to Noise Limits for Helicopters Measured to Both Chapter 11 and Chapter 8 Standards (11.4.1/Stage 2 Overflight Noise Margins vs. Cumulative 8.4.1/Stage 2 Margins)

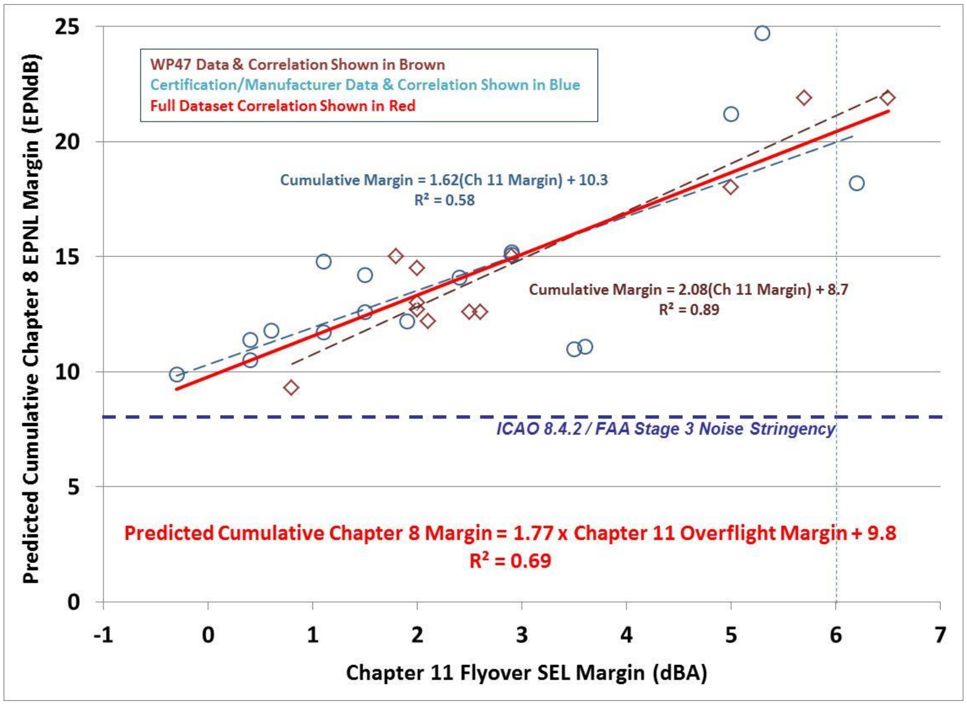


Figure B-1. Correlation of Cumulative Margins to Chapter 8 Noise Limits vs. Margins to Chapter 11 Overflight Noise Limit (Cumulative 8.4.1/Stage 2 Margins vs. 11.4.1/Stage 2 Overflight Noise Margins)

Attachment C – Datasheets for State-of-the-Art Helicopters

Classification table for acoustically dominant design parameters

Main rotor tip speed	**LOW**	**< 215 m/s <**	**MODERATE**	**< 230 m/s <**	**HIGH**
Tail rotor tip speed	**LOW**	**< 200 m/s <**	**MODERATE**	**< 215 m/s <**	**HIGH**
Climb rate	**LOW**	**< 1200 ft/min <**	**MODERATE**	**< 1800 ft/min <**	**HIGH**
Max. Cruise speed V_H	**LOW**	**< 130 kt <**	**MODERATE**	**< 150 kt <**	**HIGH**

Chapter 11 certificated helicopters

Guimbal Cabri G2

General Description: The Cabri G2 is a single piston-engine powered light helicopter with a maximum take-off weight of 700 kg.

Noise Design Overview: Due to the low take-off weight, the Cabri G2 has an inherently lower cruise speed and climb rate in comparison to the mostly considerably heavier helicopters in this report.

Main rotor	• 3-bladed main rotor • Rectangular planform • Low tip speed
Anti-torque system	• 7-bladed shrouded tail rotor • Low tip speed • Equal blade spacing
Rotational speed	• Fixed rotor speed
Performance	• Low cruise speed • Low climb rate
Engines	• 1 x Lycoming O-360 J2A • Front air intake
Certification year	• 2007

Certification margins		**Overflight**		
ICAO §11.4.1 [dB SEL]		6.3		
ICAO §11.4.2 [dB SEL]		6.3		

Bell 407GX

General Description: The 407GX is a single-engine, multi-purpose helicopter with a maximum take-off weight of 2268 kg.

Noise Design Overview: The 407GX and its predecessor, the 407, were designed for high performance and low cost. The two aircraft are acoustically identical. The 407 series design is based on the 206L series helicopter, and replaces the 206L's 2-blade main rotor with a new design 4-blade main rotor with lower main and tail rotor speeds to minimize the acoustic impact of the higher airspeed capability.

Main rotor	• 4-blade main rotor • Tapered planform • High tip speed
Anti-torque system	• 2-blade tail rotor • High tip speed
Rotational speed	• Fixed main rotor and tail rotor rotational speeds
Performance	• Low cruise speed • High climb rate
Engines	• 1 x Rolls Royce 250-C47B • Front air intake
Certification year	• 2011

Certification margins		**Overflight**		
ICAO §11.4.1 [dB SEL]		2.0		
ICAO §11.4.2 [dB SEL]		-0.6		

Supplemental Information: The 407GX is available with an optional Quiet Cruise Mode kit. The kit adds a pilot-selectable two-position switch on the collective that reduces main and tail rotor speed from 100% N_R to 92% N_R when operating in level flight cruise. The 407GX would be classified as having both low main and tail rotor tip speeds when Quiet Cruise Mode is selected. The 407GX Quiet Cruise kit is 3.8 dB SEL quieter than the baseline 407GX.

Airbus H130 (EC130T2)

General Description: The H130 (EC130T2) is a single-engine, multi-purpose helicopter with a maximum take-off weight of 2500 kg.

Noise Design Overview: The H130 (EC130T2) features a low noise Fenestron™ equipped with unequally-spaced blades in order to reduce the annoyance of the anti-torque system noise. The resulting acoustic design places the H130 (EC130T2) among the quieter aircraft of the Airbus Helicopters fleet.

Main rotor	• 3-bladed • Moderate tip speed
Anti-torque system	• 10 bladed Fenestron™ • Acoustic shielding by ducted fan concept • Low tip speed design • Unequal blade spacing • Stator blades leaned and swept with aerodynamic airfoils
Rotational speed	• Variable rotor speed law depending on air density and airspeed
Performance	• Low cruise speed
Engines	• 1 x Turbomeca ARRIEL 2D • Upper cowling air intake
Certification year	• 2011

Certification margins		**Overflight**		
ICAO §11.4.1 [dB SEL]		5.9		
ICAO §11.4.2 [dB SEL]		3.4		

Supplemental Information: An H130 (EC130T2) with six or seven passenger seats can obtain the FAA Grand Canyon National Park Quiet Aircraft Technology Designation (QATD) per Appendix A of Subpart U to 14 CFR 93 using the Overflight certification noise level.

Chapter 8 certificated helicopters

Robinson R66

General Description: The R66 is a single-engine helicopter with a maximum take-off weight of 1225 kg.

Noise Design Overview: Due to the low take-off weight, the R-66 has an inherently lower cruise speed and climb rate in comparison to the mostly considerably heavier helicopters in this report.

Main rotor	• 2-bladed • Rectangular planform • Low to moderate tip speed
Anti-torque system	• 2-bladed tail rotor • Rectangular planform • Low tip speed
Rotational speed	• Fixed rotor speed
Performance	• Low cruise speed • Low climb rate
Engines	• 1 x Rolls-Royce RR300 • Front air intake
Certification year	• 2014 (EASA)

Certification margins	Take-off	Overflight	Approach	Total
ICAO §8.4.1 [EPNdB]	3.1	5.4	4.1	**12.6**
ICAO §8.4.2 [EPNdB]	0.1	1.4	3.1	**4.6**
ICAO §11.4.1 [dB SEL]		1.5		
ICAO §11.4.2 [dB SEL]		-0.4		

MD Helicopters MD900

General Description: The MD900 is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 2948 kg.

Noise Design Overview: A low external noise signature was an explicit focus in the MD900 development. The resulting acoustic design features in particular a unique anti-torque system that combines a circulation control tail boom, a direct jet thruster and movable vertical tail surfaces.

Main rotor	• 5-bladed • Parabolic blade tips • Low tip speed
Anti-torque system	• NOTAR® Anti-Torque System • 13 bladed blower installed inside tail boom • Low tip speed
Rotational speed	• Fixed main rotor and tail rotor rotational speeds
Performance	• Moderate cruise speed • High climb rate
Engines	• 2 x Pratt &Whitney Canada (P&WC) 207E • Front NACA inlet
Certification year	• 1994

Certification margins	Take-off	Overflight	Approach	Total
ICAO §8.4.1 [EPNdB]	9.1	10.4	6.1	**25.6**
ICAO §8.4.2 [EPNdB]	6.1	6.4	5.1	**17.6**

Bell 429

General Description: The 429 is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 3402 kg.

Noise Design Overview: The design challenge in the 429 development was to improve helicopter performance, increase payload, and maintain high safety margins while incorporating new noise reduction features into the design and reducing rotor tip speeds below that of its predecessor the 427. The 429 was the first helicopter required to meet the Annex 16 Section 8.4.2 limits adopted in 2002.

Main rotor	• 4-bladed • Tapered planform • Thin airfoil at blade tips • Moderate tip speed
Anti-torque system	• 4-bladed tail rotor • Low tip speed • Unequal blade spacing
Rotational speed	• Fixed rotor speed
Performance	• Moderate cruise speed • High climb rate
Engines	• 2 x Pratt & Whitney Canada PW207D1 • Lateral air intake
Certification year	• 2011

Certification margins	**Take-off**	**Overflight**	**Approach**	**Total**
ICAO §8.4.1 [EPNdB]	7.1	4.7	4.5	**16.3**
ICAO §8.4.2 [EPNdB]	4.1	0.7	3.5	**8.3**

Supplemental Information: None

Airbus H145 (EC145T2)

General Description: The H145 (EC145T2) is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 3650 kg.

Noise Design Overview: The design challenge in the H145 (EC145T2) development was to improve helicopter performance and increase take-off weight while maintaining the low-noise levels of its predecessor the EC145. The resulting acoustic design comprises all the mature low noise features of the Airbus Helicopters fleet.

Main rotor	• 4-bladed • Double tapered planform • Thin airfoil at blade tips • Low tip speed
Anti-torque system	• 10 bladed Fenestron™ • Acoustic shielding by ducted fan concept • Low tip speed design • Unequal blade spacing • Stator blades leaned and swept with aerodynamic airfoils • Aerodynamic airfoil on drive shaft fairing
Rotational speed	• Variable rotor speed law depending on air density and airspeed
Performance	• Moderate cruise speed • Moderate climb rate
Engines	• 2 x Turbomeca Arriel 2E • Front air intake
Certification year	• 2014

Certification margins	**Take-off**	**Overflight**	**Approach**	**Total**
ICAO §8.4.1 [EPNdB]	9.1	9.9	6.3	**25.4**
ICAO §8.4.2 [EPNdB]	6.1	5.9	5.3	**17.4**

Supplemental Information: An H145 (EC145T2) with six or more passenger seats can obtain the FAA Grand Canyon National Park Quiet Aircraft Technology Designation (QATD) per Appendix A of Subpart U to 14 CFR 93 using the Overflight certification noise level.

Sikorsky S-76D™

General Description: The S-76D™ is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 5386 kg.

Noise Design Overview: The design challenge during the S-76D™ helicopter development was to improve hover, cruise and mission performance capabilities while simultaneously achieving 3 EPNdB noise reductions in all noise certification flight conditions versus its predecessor model, the S-76C++™. The resulting acoustic design comprises much of the low noise design capabilities of Sikorsky Aircraft for conventional rotorcraft.

Main rotor	• 4-bladed • New design, all-composite blades • Swept blade tips • Moderate tip speed
Anti-torque system	• 4-bladed tail rotor • Sikorsky Quiet Tail Rotor (QTR) blades • Moderate tip speed (reduced from the S-76C++™) • Tapered blade tip
Rotational speed	• Fixed main rotor and tail rotor rotational speeds
Performance	• High cruise speed • High climb rate
Engines	• 2 x Pratt &Whitney Canada (P&WC) 210S • Front air intake
Certification year	• 2013

Certification margins	**Take-off**	**Overflight**	**Approach**	**Total**
ICAO §8.4.1 [EPNdB]	7.3	7.6	5.1	**20.0**
ICAO §8.4.2 [EPNdB]	4.3	3.6	4.1	**12.0**

Supplemental Information: The S-76D™ was certificated at fixed main and tail rotor rotational speeds. The S-76D™ main rotor speed was unchanged from the predecessor S-76C++™. Automatic, FADEC-controlled dual rotor speed operation for reduced noise was evaluated on early prototype S-76D™ aircraft, however, and remains an option for future reduction of S-76D™ noise levels.

AgustaWestland AW139

General Description: The AW139 is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 6800 kg.

Noise Design Overview: The AW139 incorporates advanced noise reduction strategies compatible with the high performance requirements particularly for widely unlimited Category A operations. This includes low rotational speeds in combination with a carefully adapted blade shape design featuring low blade loading and minimized blade-vortex interactions.

Main rotor	• 5-bladed • Parabolic tip shape • Thin airfoil at blade tips • Low tip speed
Anti-torque system	• 4-bladed tail rotor • Moderate tip speed design • Parabolic tip shape
Rotational speed	• Fixed rotor speed
Performance	• High cruise speed • High climb rate
Engines	• 2 x Pratt & Whitney PT6C-67C • Lateral air intake
Certification year	• 2009

Certification margins	Take-off	Overflight	Approach	Total
ICAO §8.4.1 [EPNdB]	8.0	6.1	5.2	**19.3**
ICAO §8.4.2 [EPNdB]	5.0	2.1	4.2	**11.3**

Supplemental Information: None.

Airbus H175 (EC175B)

General Description: The H175 (EC175B) is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 7500 kg.

Noise Design Overview: The H175 (EC175B) principally features a main rotor RPM designed specifically to reduce the noise levels perceived on the ground while maintaining the highest safety standards and performance levels. This RPM schedule is mainly triggered by the proximity of the aircraft to the ground (and therefore to population). The resulting acoustic design places the H175 (EC175B) among the quieter aircraft of the Airbus Helicopters fleet.

Main rotor	• 5-bladed • Parabolic blade tip • Thin airfoil at blade tips • Low tip speed
Anti-torque system	• 3-bladed • Canted classical tail rotor • Moderate tip speed
Rotational speed	• Variable rotor speed law • Automatic variable rotor speed law triggered in part by proximity to the ground
Performance	• Moderate cruise speed • High climb rate
Engines	• 2 x Pratt & Whitney PT6C-67E • Front air intake
Certification year	• 2014

Certification margins	Take-off	Overflight	Approach	Total
ICAO §8.4.1 [EPNdB]	9.0	6.8	4.7	**20.5**
ICAO §8.4.2 [EPNdB]	6.0	2.8	3.7	**12.5**

Supplemental Information: None

AgustaWestland AW189

General Description: The AW189 is a twin-engine, multi-purpose helicopter with a maximum take-off weight of 8600 kg.

Noise Design Overview: The AW189 has high performance design requirements particularly optimised for the long range, deep water missions typical of current offshore operations.

Main rotor	• 5-bladed • Parabolic anhedral tip shape • Thin airfoil at blade tips • Moderate tip speed
Anti-torque system	• 4-bladed tail rotor • Moderate tip speed design • Parabolic tip shape
Rotational speed	• Fixed rotor speed
Performance	• High cruise speed • High climb rate
Engines	• 2 x General Electric GE CT7-2E1 • Lateral air intake
Certification year	• 2014

Certification margins	Take-off	Overflight	Approach	Total
ICAO §8.4.1 [EPNdB]	8.0	3.1	1.2	**12.3**
ICAO §8.4.2 [EPNdB]	5.0	-0.9	0.2	**4.3**

Supplemental Information: None.