Defining the Cockpit Noise Hazard, Aircrew Hearing Damage Risk and the Benefits Active Noise Reduction Headsets Can Provide

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Abstract

Over the years, cockpit noise levels in military aircraft have been steadily increasing, particularly in fast jets. As the noise levels increase, greater levels of personal hearing protection are required to keep aircrew noise dose within legislative levels and speech and non-speech signal communications intelligible during front line operations. If the predictions of noise levels in the next generation of fast jets are confirmed, then even more effective mitigation techniques will be needed.

This paper outlines the problem areas in the military cockpit including the contribution cockpit noise and electrical communications make to aircrew noise dose and the benefits offered by newer personal protection technologies such as Active Noise Reduction. Results of both experimental trials and in-service operational trials are presented.

1 Introduction

In recent years a number of surveys have been conducted in a variety of military aircraft. These have shown that even with the very best hearing protection some aircrew are still being exposed to a noise dose in excess of the current legislative criteria set out in the UK's Health & Safety Executive's (HSEs) Noise at Work regulations. This situation will be further exacerbated in February 2006 when new and more stringent noise legislation arising from the EU's Physical Agents Directive 2003/10/EC will become UK law.

The Ministry of Defence (MoD) considers personal protection (including hearing protection) a duty of care issue and aim to provide personal protective equipment (PPE) that is fit for purpose and that aligns with legislative criteria. The high noise levels that some aircrew are subjected to will, without adequate protection, cause permanent hearing damage which, in turn, will require aircrew to be downgraded from flying duties with the incumbent re-training costs for downgraded personnel and training costs for new/replacement aircrew. Additionally, since 1987 when section 10 of the Crown Proceedings Act was repealed, military personnel have gained the right to sue the MoD for disabilities incurred during the course of duty. Hence, MoD will not only have to meet the costs of disability pensions but there is the added burden of compensation and litigation costs. A similar situation is found in the US, where the military pay out some $270m a year in service disability pensions related solely to hearing loss and it would not be unreasonable to assume that the UK figures will soon be proportionate.

Up until about ten years ago the hearing protection devices (HPDs) used in the cockpit environment had essentially been optimised to provide maximum performance within the confines of the helmet/headset technology available at that time. Small benefits may have been achieved by using new materials in the earshell cushions or as an absorptive lining to the earshell, but if a major noise problem was monitored within the cockpit there was little scope to make radical enhancements to personal hearing protection. During the last 15 years however, Active Noise Reduction (ANR) techniques have become available to enhance the attenuation of HPDs. These could now be adopted in the military cockpit environment to help meet the current and future noise legislation.

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This paper aims to:

- present existing knowledge of the noise hazards in both current and future military aircraft and the major contributors to aircrew noise dose;
- provide an understanding of the effects of high noise at the ear;
- address the impact cockpit noise can make on operational capability;
- discuss the methods of alleviating noise problems and the benefits ANR can offer

2 Major contributors to aircrew noise dose

2.1 Internal cockpit and cabin noise

2.1.1 History

Cockpit noise is not a new problem. It is documented that in the biplanes era communications could be a problem and in post World War 1 commercial aviation, the constant noise exposure of pilots undertaking long haul flights in aircraft of the Handley Page type, further highlighted the issue of hearing loss and the 'Aviators Notch'. Figure 1 illustrates the levels of noise in a World War 2 USAAF aircraft and shows that even for these early cockpits, noise levels were reaching 120dB [1]. The introduction of the gas turbine engine in the late 1940's removed the propeller and exhaust noise and internal cockpit noise levels were noticeably reduced. As aircraft design progressed and the engine(s) gradually moved towards the rear of the aircraft or became buried in the fuselage, further reductions in internal cockpit noise were achieved.

The majority of the current problems associated with high levels of cockpit noise are generated, essentially, from the post 1960's need to fly operationally at high speed and low-level. These flight tactics were adopted in order to minimise detection by radar and exposure times to ground based weapon systems. Ingress to target is usually flown at speeds of around 420 to 480 knots at heights at, or below, 250 feet and egress is quite often lower and faster. At these speeds and heights noise levels in the fast jet aircraft cockpit have been increasing over the years, with one or two exceptions, and cockpit noise levels of 115dB to 120dB are now not unusual during high-speed, low-level flight.

High cockpit noise is not exclusive to fast jets. A similar upward trend in cockpit and cabin noise has been exhibited in the military helicopter fleet over the last 30 years. At some crew locations in the modern Chinook helicopter noise levels of 120dB are also now being generated.

2.1.2 Modern fast jet noise

In fast jets the internal cockpit noise spectrum is generally random in nature with high energy levels spread over a broad frequency band. The noise is generated from two predominant sources. One is the external airflow around the aircraft canopy and the front structure of the aircraft, and the other is internally generated noise from the air conditioning and cooling flows into the cockpit space.

Boundary layer flow noise

Generally the noise levels generated from the external airflow sources are dependent upon the dynamic pressures on the aircraft ($1/2\rho v^2$) and thus the speed and height. The levels of noise are generated from the turbulent flow around and across the canopy and from any protuberances around the cockpit area such as IR sensors, canards, refuelling probes etc.

Noise levels decrease with altitude as the dynamic pressures are reduced due to the decrease in air density at altitude. This is clearly demonstrated in Figure 2 that shows a comparison of the cockpit noise measured in a Harrier GR5 during high-speed, low-level flight and during flight at altitude. A difference in cockpit noise levels of some 10dB is exhibited across the frequency band. Another source of increase in internal noise levels is from aircraft manoeuvres that further alter the instability of the flow patterns around the canopy and aircraft front fuselage. In many cases there will be differences in noise levels between front and rear crew.

Cockpit conditioning noise
The other major source of internal noise is from the airflow from the cockpit conditioning and pressurisation systems. The noise is mainly generated through turbulent flow from the outlet sprays. The noise levels associated with the cabin conditioning/cooling flow are nominally constant with speed and height, although the cockpit noise spectrum will vary with conditioning mode. For example, Figure 3 compares the cockpit noise spectrum in an F-16A with the Environmental Conditioning System (ECS) on normal setting and with maximum defog switched on. The plot shows that with the ECS on there is a large increase in high frequency energy that increases the overall A-weighted Sound Pressure Level (SPL) by some 10dB and, if used for any length of time, will provide a significant contribution to the noise dose received by the pilot.

Combined effects of boundary flow and cockpit conditioning
Depending upon the design of the aircraft and its systems, the cockpit noise may be dominated by either the externally or internally generated noise or be a balance of both of these noise sources. Measurements made in a Jaguar GR1 showed it to be an example of where contributions from both sources are approximately equal, and the cockpit noise remains essentially constant irrespective of speed or height (Figure 4).

In some fast jet aircraft, however, there may be other contributing factors. Measurements in the Harrier GR5, for instance, showed a contribution from the engine compressor fan (Figure 5). This large fan is close to the cockpit and as a dominant source is seen as a discrete narrow band noise source around 2.5kHz. The absolute frequency will obviously be dependent upon engine speed.

2.1.3 Helicopter noise

Helicopters have a different mechanism of generating noise and the sources are both aerodynamic and mechanical. The cockpit or cabin noise is predominantly narrow band discrete tones with associated harmonics superimposed on a low-level, broadband background noise. Aerodynamically induced noise is generated from the main and tail rotors, including interactions between the rotors in a twin rotor design (e.g. Chinook) and interactions between the rotors and fuselage. The mechanical noise originates from revolving systems connected to the rotors in the form of gearboxes, transmission shafts, transfer gears, auxiliary systems, drive shafts etc. Figure 6 shows a narrow band analyses for a Lynx helicopter and the sources of the noise peaks. Due to each type of helicopter being mechanically and aerodynamically different (e.g. 2,3,4,5 or more rotor blades in the main rotor, or differing gearing ratios in the main gearbox), each helicopter will have a unique acoustic signature. Boundary layer noise is not present to any great extent due to the restricted forward speeds of helicopters, but turbulent airflow noise will be apparent when the helicopters are flown with doors, windows or ramps open. Some helicopters, such as Merlin, have a significant range of avionics systems equipment installed in the aircraft with cooling fans and this equipment may add significantly to the overall cockpit/cabin noise levels.

2.1.4 Transport and Surveillance aircraft noise

The cockpit and cabin noise in aircraft that fall between being helicopters or fast jets i.e. transport aircraft of the Hercules type (turbo-prop), C17 type (turbo-fan) or those that use the Tilt Rotor approach, can have a number of sources. Some noise will be generated from the propellers, rotors or wing mounted gas turbines, some from boundary layer flow and some from equipment cooling and cockpit conditioning systems. The overall cockpit and cabin noise levels are a differing combination of discrete and random noise.

Propeller driven
For propeller driven aircraft, the cockpit and cabin noise spectrum is normally dominated by the fundamental frequency of the propeller, generally in the 80Hz to 100Hz region, and this is exhibited as a discrete, narrow-band frequency peak superimposed on lower level, broadband background noise.

Figure 7 compares the cockpit noise environment for the 4-bladed propeller driven Hercules C130K [2] and the 6-bladed propeller driven C130J [3]. The plot shows how the fundamental blade passing frequency

(68Hz and 102Hz for the C130K and C130J respectively) dominates the whole cockpit noise spectrum. Similarly, passengers transported in the cargo compartment of this type of aircraft will also be exposed to high noise levels. In the C130J, noise levels of up to 118dB were measured in the forward cargo compartment during high-level route sorties with maximum levels occurring just forward of the propeller plane.

Gas Turbine driven
Aircraft that are essentially civil-based militarised aircraft e.g. Nimrod (surveillance/maritime patrol) and AWACS/JSTARS (Boeing 707) (Command & Control) generate higher amounts of boundary layer noise in the cockpit than the cabin. The predominant noise source in the operator's cabin is from the forced airflow into the aircraft to cool the avionics and crew.

2.1.5 Future aircraft noise problems

For the fast jets, it is probable that during forward flight cockpit noise levels will remain high, and be similar to those currently found in Harrier and EF Typhoon where levels are at their highest during low level operations. It is currently proposed that the Royal Navy (RN) will employ the short-takeoff/vertical-landing (STOVL) variant of the Joint Strike Fighter (JSF) F-35B. The takeoff and landing operation succeeds through technology known as the shaft-driven lift fan propulsion system. The counter rotating blades of the lift fan provide about 18,000 pounds of lifting power and, based on the minimal amount of F-35 cockpit noise data available, it is believed the overall internal cockpit noise levels during a vertical landing will be around 120dB. As the fan is situated immediately behind the cockpit, during this phase of flight the cockpit noise will be dominated by a strong tonal component, although there is currently little information available on what the exact spectral components will be.

2.2 Electrical communications

It is important to note that hearing damage occurs in the early stages of the hearing process, i.e. as damage to the hair cells in the cochlea of the inner ear. Interpretation of the signal is only performed in the high level processes of the brain that occur after the cochlea processing. Consequently, it doesn't matter what the signal is at the ear (speech, noise, music etc.) if it is presented at a high enough level for a long enough duration it will cause hearing damage. During flying duties in the cockpit/cabin environment the noise dose received by aircrew is a combination of both the cockpit/cabin noise transmitted through their HPD and the electrical communication signal that is delivered directly to the ear via the communications telephone mounted in the HPD.

Aircrews' speech communications are generally converted into electrical signals by a microphone built into the oronasal oxygen mask, by a 'noise-cancelling' boom microphone or by throat/bone conduction microphones. In the cockpit and cabin environment ambient noise is often introduced into the speech communications line through the microphone of the speaker and the transmitted signal is a combination of the intended signal (i.e. speech) and the unwanted noise. This combination signal is transmitted to the ear of the listener via radio or intercom and may be further contaminated with noise pick-up from the electronic systems or from radio interference. This contamination of the intended signal will reduce its intelligibility and clarity and the additional noise will add to the overall noise dose received by the listener. Hence, when considering the cockpit noise hazard it is important to address methods for reducing the levels of "unwanted" noise on the communications line.

3. Effects of high noise at the ear

3.1 Overview

High noise levels in the aircraft cockpit or cabin, and the consequent high noise levels at the aircrews' ear, can lead to a number of short and longer-term problems for aircrew. The types and levels of cockpit and cabin noise generated during flight operations will, without adequate protection, cause permanent hearing damage. High noise will also interfere with speech communications (reducing the clarity and intelligibility of the speech signal), with non-speech communication signals such as the detection of auditory warning alerts or, inhibit signal detection tasks such as listening for sonar returns. Hence, there are both flight safety and operational implications. Whilst these physiological effects are relatively easy to assess and quantify, high noise levels are also known to effect the cognitive, perceptual and psychomotor responses, although to date, little research has been conducted into the psychological effects of high noise or the operational implications.

This paper is only concerned with the cockpit noise hazard and the risk it poses to aircrews' hearing. Hence, only the direct effects of the two main contributors (cockpit noise and electrical communication signals) are considered here.

3.2 Hearing damage risk and current UK legislation

If the human ear is exposed to sound energy above a certain amplitude for a long enough period, some permanent hearing damage will result. The main difficulty in predicting hearing damage lies in determining the length of exposure and the levels that cause a defined amount of damage. The situation is confounded by many variables such as individual sensitivity, intermittence of exposure, whether noise is steady or impulsive and any noise exposure outside the working environment.

The risk of hearing damage is correlated with the amounts of ‘A’-weighted energy received by the ear. Energy is a function of level and time exposure, and the current UK legislation quotes an allowable daily noise dose for a nominal 8-hour working day of 85dB(A), or an equivalent continuous noise level (Leq). An Leq is the notional sound level which would, in the course of an 8 hour period, cause the same A-weighted energy to be received by the ear as that due to the actual fluctuating sound over the actual working period. Hence, energy levels may be offset against exposure duration to provide an equivalent continuous level. In the UK a 3dB(A)-conversion rate is used for a doubling of sound energy. If the noise level increases by 3dB(A) then to maintain the same risk of hearing damage the exposure duration must be halved to give an equivalent continuous noise level. Similarly, if the noise level is reduced by 3dB(A), the exposure time may be doubled to maintain the same Leq and risk of hearing damage.

3.3 Future legislation (Physical Agents Directive 2003/10/EC)

In 1993 the European Commission (EC) proposed the Physical Agents Directive which sought to establish a new framework for the regulation of physical agents at work applying initially to noise, vibration, optical radiation and non-optical electromagnetic fields. The proposed framework for noise regulation is more stringent than the 1986 directive aiming to reduce the first and second action levels to 80dB(A) and 85dB(A) respectively. There have been many years of negotiation and conciliation between the member states and the new directive was formally adopted by the EC in early December 2002 and appeared in the Official Journal of the European Communities on 15 February 2003. The UK now has three years from that date to bring in implementing legislation.

3.4 Physiological effects of direct high cockpit and cabin noise

Even with a protective helmet or headset, cockpit noise levels reaching the ear can alone be high enough to produce a risk of hearing damage. Over the years, there has been a number of reviews of hearing damage risk in UK Military aircraft starting in around 1974 [4] when some of the first personal noise dosimeters produced were used to provide risk figures for aircrew wearing the Mk2 and Mk3 flight helmets and early headsets. With the introduction of the Mk4 series helmets and the Racal Atlantic headsets, both with considerably improved acoustic attenuation characteristics, a continuing assessment has been made as new aircraft and aircraft types have entered service [5-13].

All forms of hearing protection have an acoustic attenuation characteristic that varies with frequency and will let through the structure of the device different levels of noise at different frequencies. Thus, while the helmet has a defined fixed attenuation characteristic (see Figure 8), using the helmet in different noise fields will result in different noise levels at the ear. For example, in a helicopter that is rich in low frequency sound, the limited low-frequency attenuation characteristics of a helmet or headset will let through almost all the low frequency noise. However, at the higher frequencies where the helicopter generates little noise and the helmet attenuation is at its maximum, the noise levels at the aircrews' ear will be low. For a fast jet, the cockpit noise is higher across a much broader frequency range and hence the noise spectrum at the ear will generally be higher than for a helicopter, with a higher hearing damage risk. Figure 9 shows typical noise levels at the ear for the fast jet, helicopter and Hercules cockpit environment.

To minimise hearing damage caused directly by the transmission of cockpit and cabin noise through the HPD, the cockpit noise levels can either be reduced at source or the noise attenuation characteristics of the HPD can be improved.

3.5 Effects of communications levels

On top of the risk generated from cockpit noise levels alone will come the risk associated with the additional contribution from the communications (comms) [14]. When considering the contribution the comms make to aircrew noise dose the preferred personal listening levels and aircraft type need to be considered.

In order to assess any trend in comms load with aircraft type the average comms contribution and the associated standard deviations were calculated for some aircraft that have been surveyed by QinetiQ. The results are shown in Table 3-1. Although the comms contribution to overall noise dose appears to be relatively small compared to that contributed by the ambient noise reaching the ear, it is important to remember that it is additional to the background noise, effectively riding on top of the background signal. If no comms were present throughout, for example, a Harrier flight, the aircrew could fly 10 times as long for the same risk of hearing damage, i.e. the comms is making a significant contribution.

Aircraft Category	Aircraft Type	mean comms dB(A)	Sdev comms dB(A)
Helicopters	Sea King Mk5	6.3	2.2
	Sea King Mk4	7.9	1.4
	Sea king Mk6	7.1	2.0
	Lynx Mk7 & Mk9	9.8	2.5
	Chinook HC1	8.6	2.6
Fast jets	Harrier GR5	10.0	4.3
	Jaguar GR1	9.9	4.2
	Tornado	10.4	2.9
	Hawk	9.1	3.2
	Sea Harrier	9.1	2.7
Training	Tucano	8.5	1.8
Transport	Hercules C1/C3	8.4	3.0
	HS125	10.6	4.8

Table 3-1 The overall mean communications contribution figure calculated for each aircraft type

4 Operational Issues and Impact

4.1 Cockpit Noise survey data

Over the last 12 years QinetiQ have conducted a series of comprehensive cockpit noise surveys in a range of helicopters, fast jets, transport, training and surveillance aircraft. All surveys have been carried out at operational squadrons, using operational aircraft and the normal range of operational sorties. Two types of measurements have normally been made. Firstly, noise dose measurements for comparison with the legislative criteria and secondly, audio recordings to allow analyses of the cockpit and “noise at ear" spectra.

Table 4-1 presents the mean measured noise dose and the associated standard deviations for all the aircraft that have been surveyed over the last 15 years. However, it is important to note that the mean noise dose calculated from the data only represents the exposure level experienced by 50% of the aircrew. To protect the majority of aircrew it is important that a representative noise dose figure is used in the hearing damage risk calculations so for the purpose of this paper, a mean noise dose value plus two standard deviations covering 98% of aircrew will be used (column 4, Table 4-1).

Aircraft	Position	Mean dose	Standard Deviation	Mean +2 Standard Deviations
Jetstream Tmk1	Left seat	80.8	3.6	88.0
	Right seat	80.4	3.5	87.4
Harrier GR5	Pilots	90.1	3.4	96.9
Jaguar GR1	Pilots	91.8	4.6	101.0
Chinook HC1	Pilots	87.0	2.5	92.0
	Air Load Master	88.6	2.7	94.0
Hercules C130K	left pilot	80.1	4.1	88.2
	right pilot	83.1	4.1	91.2
	Navigator	77.3	1.9	81.0
	Engineer	76.9	2.6	82.0
	Air Load Master	83.6	2.3	88.2
Sea King AEW2 (non-ANR)	Cockpit	89.0	2.4	93.8
	Cabin	90.0	2.1	94.2
Sea King HAS6	Pilots	83.8	3.5	90.8
	obs/a'man	87.0	2.7	92.4
Sea King HC4	Pilots	83.0	2.3	87.6
	a'man	85.5	2.7	90.9
Lynx AH7	Pilots	86.9	3.6	94.1
Lynx AH9	Pilots	86.3	3.5	93.3
HS/BAE 125	Right seat	84.0	3.0	90.0
	Left seat	85.3	3.9	93.1
Hawk	Front Seat	86.8	4.7	96.2
	Rear Seat	92.0	4.0	100.0
Hercules C130J (ANR)	Pilot (CMk4)	76.1	0.7	77.5
	Pilot (CMk5)	75.7	1.1	77.9
	Air Load Master (CMk4)	80.4	2.1	84.6
	Air Load Master (CMk4)	78.7	1.1	80.9
Sea Harrier	FA2	92.0	2.5	97.0
	T8 Front	91.5	3.3	98.1
	T8 Rear	95.3	4.4	104.1
Tucano	Combined front/rear seats	88.1	3.4	94.9

Table 4-1 Measured noise dose received by aircrew

4.2 Application of noise legislation criteria to aircrew noise dose

4.2.1 General methodology

In general terms the noise exposure legislation is geared for employees such as factory workers, who work in a constant noise field for 8-hours a day, 5 days a week. Typically, aircrew do not conform to this type of working pattern and are generally only exposed to the high cockpit/cabin noise for a small proportion of their daily working shift. The measured noise dose figures shown in Table 4-1 are the dose received during a single sortie and the majority of the 98% cover figures shown in column 4, exceed the current 85dB(A) criteria. For direct comparison with the legislation a correction could be made to normalise the sortie Leq to an 8-hour Leq, on the assumption that aircrew spend all their non-flying hours in a quiet environment and are not exposed to any other contributory noise. However, perhaps more importantly for aircrew is an understanding of the numbers of hours they may fly in their particular cockpit whilst staying within the noise exposure limits.

The 1989 directive specifies a maximum permissible exposure level at the ear of 85dB(A) for 8 hours. If, for example, a noise dose figure giving a 98% cover of 100dB(A) were measured, it would be some 15dB(A) above the allowable legislative level of 85dB(A). 15dB(A) represents a ratio of 32:1, and within a nominal 8-hour working day would represent an allowable flying time of just 15 minutes (480 minutes/ 32). However, if the new legislative level of 80dB(A) is adopted, the example noise dose figure of 100dB(A) will now be some 20dB(A) above the allowable limit and represents a ratio of 100:1. This reduces the allowable daily flying time to just under 5 minutes.

Table 4-2 presents the calculations of the allowable number of hours that aircrew may fly daily in their cockpit /cabin with the level of hearing protection they are currently provided with, for both the current and future legislative limits.

The table shows that the dose received by Harrier, Jaguar, Hawk and Sea Harrier crew would limit their daily flying time to less that 40 minutes if they are to stay within the current legislative guidelines of an 85dB(A) Leq (8hr). However, with the introduction of the more stringent guidelines the allowable flying duration will be prohibitive for the majority of aircraft. Hence, if an operationally viable number of flying hours are to be permitted whilst keeping aircrew noise dose within the strict daily criteria set out in the new legislation, the noise levels reaching the aircrews' ears will have to be significantly reduced.

4.3 Impact of legislation on hearing protection requirements

Hearing damage risk is based on a combination of the level and duration of the noise exposure. There is a clear understanding of the numbers of hours aircrew are required to fly operationally in a working year but averaging noise dose over annual working hours is not strictly accommodated in the legislation. Nevertheless, it is a useful way of providing an indication of the levels of improvement in hearing protection that are required if legislative criteria are to be met whilst allowing flight operations to continue unlimited.

Aircrew may fly anything between 150 and 420 hours per year depending on the aircraft type and crew position. If the current legislation is taken as an example, aircrew could fly 8 hours a day, every day of the year assuming their noise dose did not exceed 85dB(A). To calculate hearing damage risk over a working year an adjustment can be made to the allowable noise dose of 85dB(A) to account for the proportion of the working year that is actually spent flying. The adjustment is calculated using the following formula:

Exposure time correction factor = $10\log(n/1920)$

where n = number of hours flown
1920 = number of hours in a 40 hour week, 48 week year

If the number of annual flying hours equalled 1920 then no correction need be applied but if, for example, aircrew only flew 250 hours a year a correction factor of 8.9dB(A) is calculated and their exposure limit could theoretically be increased to 93.9dB(A).

Clearly the number of hours flown will effect the annual Leq calculated. But if the actual measured noise dose for a particular aircraft is compared to the adjusted allowable noise dose calculated for the number of annual hours that aircraft normally flies, then an indication of the reduction in noise exposure required to stay within the regulations will be provided. If, for example, a noise dose figure of 100dB(A) is used then for aircrew who typically fly 250 hours a year, it is clear that some steps need to be taken to reduce the noise exposure by 6.1 dB(A) to the 93.9dB(A) allowable figure. The pilot can either fly fewer hours per year (in this case reducing from 250 hours to less than 63 hours) or the noise exposure needs to be reduced.

Aircraft	Position	Allowable daily flying hours	Allowable daily flying minutes	Allowable daily flying hours	Allowable daily flying minutes
		85dB(A) limit		80dB(A) limit	
Jetstream Tmk1	Left seat	4.0	240.6	1.3	76.1
	Right seat	4.6	276.2	1.5	87.3
Harrier GR5	Pilots	0.5	31.0	0.2	9.8
Jaguar GR1	Pilots	0.2	12.1	0.1	3.8
Chinook HC1	Pilots	1.6	95.8	0.5	30.3
	Air Load Master	1.0	60.4	0.3	19.1
Hercules C130K	left pilot	3.8	228.7	1.2	72.3
	right pilot	1.9	115.1	0.6	36.4
	Navigator	20.1	1205.7	6.4	381.3
	Engineer	16.0	957.7	5.0	302.9
	Air Load Master	3.8	228.7	1.2	72.3
Sea King AEW2 (non-ANR)	Cockpit	1.1	63.3	0.3	20.0
	cabin	1.0	57.7	0.3	18.2
Sea King HAS6	pilots	2.1	126.3	0.7	39.9
	obs/a'man	1.5	87.3	0.5	27.6
Sea King HC4	pilots	4.4	263.8	1.4	83.4
	a'man	2.1	123.4	0.7	39.0
Lynx AH7	pilots	1.0	59.1	0.3	18.7
Lynx AH9	pilots	1.2	71.0	0.4	22.5
HS/BAE 125	Right seat	2.5	151.8	0.8	48.0
	Left seat	1.2	74.3	0.4	23.5
Hawk	Front Seat	0.6	36.4	0.2	11.5
	Rear Seat	0.3	15.2	0.1	4.8
Hercules C130J (ANR)	Pilot (CMk4)	45.0	2699.2	14.2	853.6
	Pilot (CMk5)	41.0	2461.7	13.0	778.5
	Air Load Master (CMk4)	8.8	526.3	2.8	166.4
	Air Load Master (CMk4)	20.6	1233.8	6.5	390.2
Sea Harrier	FA2	0.5	30.3	0.2	9.6
	T8 Front	0.4	23.5	0.1	7.4
	T8 Rear	0.1	5.9	0.0	1.9
Tucano	Combined front/rear seats	0.8	49.1	0.3	15.5

Table 4-2 Allowable flying duration in accordance with current and future legislation

Based on annual averaging Table 4-3 provides an indication of the reductions in noise dose (or enhancements to hearing protection) required to meet both the current and future noise legislation. Calculations have been made for the first action level criteria as it is the maximum exposure level employees can be exposed to without hearing protection and it is the noise dose value that protects about 97% of the population from hearing damage.

Aircraft	Position	Hours flown annually	Noise dose correction factor	Reduction in noise dose to meet 85dB(A) Leq	Reduction in noise dose to meet 80dB(A) Leq
			dB(A)	dB(A)	dB(A)
Jetstream Tmk1	Left seat	350.0	-7.4	0.0	0.6
	Right seat	350.0	-7.4	0.0	0.0
Harrier GR5	Pilots	260.0	-8.7	3.2	8.2
Jaguar GR1	Pilots	250.0	-8.9	7.1	12.1
Chinook HC1	Pilots	350.0	-7.4	0.0	4.6
	Air Load Master	350.0	-7.4	1.6	6.6
Hercules C130K	Left pilot	340.0	-7.5	0.0	0.7
	Right pilot	320.0	-7.8	0.0	3.4
	Navigator	320.0	-7.8	0.0	0.0
	Engineer	250.0	-8.9	0.0	0.0
	Air Load Master	420.0	-6.6	0.0	1.6
Sea King AEW2	Pilot	250.0	-8.9	0.0	4.9
	Observer	250.0	-8.9	0.3	5.3
Sea King HAS6	Pilots	250.0	-8.9	0.0	1.9
	obs/a'man	210.0	-9.6	0.0	2.8
Sea King HC4	Pilots	275.0	-8.4	0.0	0.0
	A'man	275.0	-8.4	0.0	2.5
Lynx AH7	Pilots	250.0	-8.9	0.2	5.2
Lynx AH9	Pilots	250.0	-8.9	0.0	4.4
HS/BAE 125	Right seat	250.0	-8.9	0.0	1.1
	Left seat	250.0	-8.9	0.0	4.2
Hawk	Front Seat	250.0	-8.9	2.3	7.3
	Rear Seat	250.0	-8.9	6.1	11.1
Hercules C130J	Pilot (CMk4)	340.0	-7.5	0.0	0.0
(with ANR)	Pilot (CMk5)	340.0	-7.5	0.0	0.0
	Air Load Master (CMk4)	420.0	-6.6	0.0	0.0
	Air Load Master (CMk4)	420.0	-6.6	0.0	0.0
Sea Harrier	FA2	150.0	-11.1	0.9	5.9
	T8 Front	150.0	-11.1	2.0	7.0
	T8 Rear	150.0	-11.1	8.0	13.0
Tucano	Combined front & rear	250.0	-8.9	1.0	6.0

Table 4-3 Hearing protection requirements to meet current and future legislation for annual flying hours flown

5 Methods of Alleviating Noise Problems

5.1 Introduction

In order to adhere to the new noise exposure criteria whilst still flying an operationally viable number of hours, the calculations presented in section 4 have shown that noise exposure must be reduced by as much 13dB(A) in some aircraft. Both the current and new directives require that noise be reduced at source as far as is reasonably possible and then hearing protection provided to bring the personal noise exposure within the set limits. For new aircraft, reducing noise at source is most effectively, and efficiently, carried out during the design stages. However, it is generally impractical, and certainly unlikely to be cost effective, to modify an existing in-service aircraft. However, the possibility of modification should be reviewed for individual aircraft, once the primary noise sources are identified.

The most cost-effective approach to reduce aircrew noise exposure for in-service aircraft would be to upgrade the hearing protection levels in existing aircrew flying helmets and headsets. Improving the passive attenuation of the headsets fitted to the UK's Mk4 or Mk10 series helmets, or the Racal Atlantic and other headset types currently being used by aircrew can achieve this. Alternatively, ANR techniques can be used in appropriate noise fields, and this technology is already fully cleared and flying in some UK aircraft. These approaches are discussed in more detail in the following sections.

5.2 Reducing noise by personal hearing protection

5.2.1 Flight Helmet/Headset approach

In most military cockpits, aircrew are required to wear a protective flight helmet, and this helmet can be made to provide a level of acoustic protection by incorporating hearing protection earmuffs into the helmet shell. Alternatively, headsets are used in larger transport or surveillance aircraft, but, in both cases, the earmuffs provide the overall hearing protection.

The level of protection provided by these types of devices varies with frequency and the passive circumaural protectors generally have three different mechanisms controlling the protection in the low, mid and high frequency bands. The overall effect of these mechanisms is to produce the attenuation characteristics shown in Figure 8. Whilst the absolute attenuation levels vary depending on the device type, the general attenuation characteristic is similar for all circumaural hearing protectors. As is the case for most engineering systems, some protectors are better than others, some companies understand the design process better than others and some sacrifice good design and performance for lower cost.

Changes can be made to the attenuation characteristic by using different materials for the earshell itself (in the mid-frequency range), different internal absorbent materials (at higher frequencies) or by the increase of shell volume (at low frequencies). Doubling the volume of the shell will provide a theoretical increase in low frequency attenuation of some 6dB and a further doubling will provide a further 6dB increase, and so on. However, practicality of use, particularly in the aircraft cockpit, precludes the use of the large physical sizes of helmet that would be necessary to house these large volume earshells. Although, as in the USA with the SPH4 helmet, larger volume earshells could be used in helicopters and transport aircraft.

5.3 Methods of improving the attenuation of hearing protectors

5.3.1 Active Control of Noise (Active Noise Reduction – ANR)

Because of the relatively poor attenuation of circumaural protectors at the lower frequencies, coupled with the high levels of cockpit noise at these frequencies, the noise levels at the pilots ear (Figure 9) are rich in low frequency content. Whilst improved passive methods are available, in terms of large volume earshells, they are generally impracticable for aircrew helmets and headsets. Hence, the approach started some 20 years ago, [15 & 16], was the use of active methods of cancelling the noise.

The principle of ANR is relatively simple and well documented but the practical application has proved more difficult. A number of systems exist in the UK, USA, France, Netherlands etc. and a typical active attenuation performance is shown in Figure 10. Within a flight helmet earshell, the working range is between 50Hz and 1000Hz with peak levels of active attenuation of between 20 to 23dB. When added (arithmetically) to the existing passive attenuation of the earshell significant improvements in overall attenuation is achieved, and in operational flight trials and laboratory trials, reductions of around 6-10dB(A) have been measured in both fixed and rotary wing aircraft noise.

The increased helmet attenuation that can be achieved from the integration of ANR into a flight helmet earshell is shown in Figure 11. If this attenuation characteristic is theoretically applied to the cockpit noise of a Harrier jet during high speed, low level flight (Figure 12), the overall A-weighted SPL reaching the ear is shown to reduce by some 10dB(A) when the ANR system is switched on. Measurements made during flight trials in both fast jets (Harrier and Sea Harrier) and helicopters (Sea King, Lynx, Gazelle, UH60, UH1, OH58D, AH64 and Apache) confirm the validity of these results. Figure 13 compares the time pressure histories for cockpit noise and noise at the ear for aircrew wearing a standard Mk4 flight helmet (top trace) and for aircrew wearing a Mk4 ANR flight helmet (bottom trace). The plots shows that although the fluctuations in level due to communications are similar, the actual levels experienced are some 10dB(A) lower for the ANR helmet. This reduces the total noise dose received during the sortie by 10dB(A) and means aircrew flying with an ANR helmet in this noise environment can fly 10 times as long for the same risk of hearing damage as those pilots flying with the standard helmet or, their hearing damage risk will be significantly reduced for the same number of flying hours.

5.3.2 Operational Effectiveness of ANR

Over the last 20 years a number of flight trials have measured the effectiveness of ANR during fully operational sorties [17], [18] and [19] and shown significant improvements in the reduction of hearing damage risk without compromising, in any way, the operational effectiveness of the participating squadrons. The QinetiQ/MoD ANR system has been put into production for the Royal Navy for use in it's Sea King squadrons, and is now a fully accepted in-service piece of kit [20].

An example of the effectiveness of the ability of ANR to reduce hearing damage risk in an operational scenario is shown in the results from the long-term Sea King AEW2 trial with the Royal Navy at RNAS Culdrose (Table 5-1). The measurements were made at the aircrews' ear (under the flight helmet) during operational flights with a dosimeter on the dates noted in the table. The figures show that as the crew acclimatise to the lower background noise levels they gradually reduce their comms level to maintain a constant Signal to Noise Ratio (SNR), and the full benefit of ANR is utilised. Improvements of 8-9dB(A) are achieved, resulting in a significant reduction in hearing damage risk as well as a more acceptable working environment.

Role	Std Helmet Feb 99	ANR Helmet Mar 99	ANR Helmet Apr 00
Pilot	89.3 (4.3)	85.6 (3.5)	80.9 (2.8)
Observer	90.4 (3.9)	83.8 (4.5)	80.7 (4.4)

Table 5-1 Mean noise dose (and associated standard deviations) measured in Sea King AEW2 for Standard and ANR Mk4 flight helmets

Similar in-flight measurements made in the Hercules C130K and the Sea Harrier jet showed the increase in attenuation afforded by the ANR flight helmet compared to the standard flight helmet to be some 9.7dB(A) and 7dB(A) respectively. Assuming the aircrew in these aircraft follow a similar trend to the Sea King crew and with experience gradually reduce their comms levels to maintain their preferred SNR, the noise dose will also reduce by similar amounts.

The trials in the Sea Harrier highlighted the effectiveness of ANR and anecdotal evidence from the aircrew suggested that as well as reducing their noise dose they were also able to balance their radios more effectively, resulting in improved clarity and intelligibility of speech communications. ANR is now a fleet wide fit for Sea Harrier.

Similarly in the C-130J, ANR is now in full service use and has significantly reduced noise exposure levels.

5.4 Future hearing protection development

5.4.1 Overview

The in-flight measured data suggests that the integration of ANR into the current generation of military flight helmets and headsets will provide a 6-10dB(A) reduction in aircrew noise dose in fast jet, helicopter and transport aircraft. Whilst the absolute benefit may vary slightly depending on the specific noise field characteristics, the current analogue ANR systems should bring noise levels at the aircrews' ear, in the majority of operational aircraft, down to a level where hearing damage risk is within the new European and UK legislative criteria. However, the fast jet cockpit is likely to remain a problem area where existing ANR systems will reduce noise dose but will not fully resolve the problem.

Comprehensive measurements made in the Sea Harrier jet suggest that once aircrew are fully acclimatised to the new noise environment a reduction in noise dose of 7dB(A) will be achieved. As other jets have similar cockpit noise spectra it may be assumed that current analogue ANR systems will provide, in these cockpits, the same level of benefit as exhibited for the Sea Harrier. Table 4-3 shows that to meet the noise dose criteria set out in the new legislation, improvements in hearing protection up to 13 dB(A) are needed if all fast jet crew are to be adequately protected. Hence, ANR as it stands today is not a panacea. Significant improvements in hearing protection are still required if current aircrew are to be sufficiently protected and, similarly for future jets. Whilst cockpit noise data for the F-35 is scant, calculations made on the limited data available suggest that the noise dose received by JSF aircrew will be similar to current worst-case jet aircraft.

5.4.2 Passive devices

Some new developments have shown that improvements in passive attenuation can be achieved through the use of different materials and construction techniques. The use of passive hearing protection provides the simplest, least expensive and most operationally effective method of providing hearing protection for aircrew. Where noise levels are high, the smaller levels of attenuation gained by improvements of passive attenuation are highly cost effective, especially compared to the relative expense of electronic control systems and aircraft installation costs.

The use of new earshell cushion technologies has been shown to improve the variance measured during acoustic attenuation trials. By reducing the variance in performance across subjects, the target attenuation figures in high attenuation devices become easier to meet due to lower variance in the measured attenuation figures and hence, a lower penalty is incurred when meeting the demands of the population spread (mean minus two standard deviations). There is also some preliminary evidence from the USA that personally tailored cushions (i.e. which fit correctly around the individual head and similar to those used in the early Mk3 series flight helmets) may provide increased levels of hearing protection. It is possible that anthropometric scanning techniques could offer some benefit in this advanced approach.

5.4.3 Active devices

Over the last 20 years a better understanding of the interaction between active and passive devices has been gained allowing the combination of these two differing protection techniques to provide greater levels of hearing protection.

Analogue ANR systems may be further enhanced by miniaturising the electronic circuitry such that the full earshell volume can be taken advantage of. Currently, some of the active performance is used to regain some of the loss in passive attenuation incurred due to the installation of circuit boards within the earshell cavity. The large circuit boards reduce the internal volume of the earshell and consequently reduce its passive attenuation characteristics. By removing or miniaturising the electronics the full benefits of both the passive and active attenuation should be achieved. The use of these miniaturised circuits could be usefully incorporated into newly designed higher passive attenuation earshells (for helmets or headsets). Here, a combination of good passive attenuation may be successfully combined with the active circuitry to provide a broader band of acoustic attenuation than can be currently achieved.

5.4.4 Future technologies

Current ANR systems are in analogue form, which reduces the flexibility of approach to the range of aircraft problems. The development of a digital controlling technique will allow not only a software control system to be able to potentially tailor the ANR performance to a specific requirement, but to hopefully provide control of the active attenuation to optimise hearing protection throughout flight operations.

Another advantage of digital control is the potential to concentrate the noise reduction in a narrower frequency band. For aircraft with high levels of discrete noise (helicopters, turbo-prop aircraft, JCA etc.) this should allow considerably higher levels of acoustic attenuation in those narrower bands and the subsequent reduction of hearing damage risk. There is also potential to allow tailoring of broader band active attenuation (perhaps one or more octaves) to specific aircraft needs.

6 Concluding discussion

Sections 4 and 5 of this report have shown that if aircrew of existing military aircraft are to fly safely within the new noise exposure criteria whilst maintaining their current annual flying hours, the current noise exposure levels will have to be reduced. The degree of noise reduction required is dependent on the aircraft type and crew position. As noted earlier, from a technical viewpoint, the most cost effective solution will be to provide aircrew with more effective hearing protection.

Comprehensive noise surveys in operational aircraft have shown that the current generations of analogue ANR systems provide reductions in aircrew noise dose of between 6 and 10dB(A). This level of extra protection will probably achieve the noise reduction required to keep the majority of military aircraft flying within the new legislative criteria. However, ANR in its current form will not solve the noise dose problems in the current fast jet cockpit or future cockpits such as the JSF. Aircrew who fly in these aircraft require hearing protection improvements of up to 13dB(A) compared to standard flight helmets.

It is clear that some hearing protection companies have significantly improved passive attenuation through the innovative use of new materials and structures. It is possible that in the timescales to February 2006 when the new noise dose criteria become law, this technology could be available for use in the Mk4 and Mk10 series of flight helmets. This would allow the use of existing helmets and require changes to only the headset, and could be implemented on a replacement basis. Further development of the existing analogue ANR system (through miniaturisation of the electronic circuitry) should provide perhaps up to 8 to 10dB(A) extra active attenuation and if integrated in the improved passive earshells will go a long way to meet the fast jet requirements. Further integration of digital ANR techniques should fully protect fast jet crew to the new noise dose criteria.

However, in the absence of updated technology the use of the existing ANR systems should, at least in the short term, be considered to minimise hearing damage risk in all aircraft falling short of the new legislative criteria.

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8 Figures

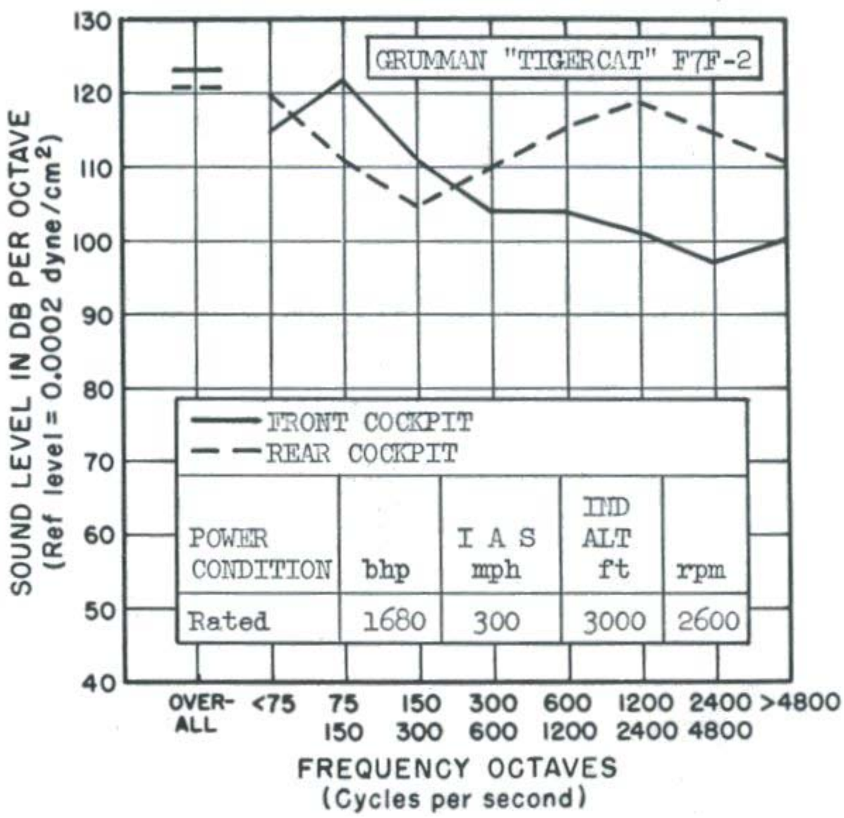

Figure 1 Cockpit noise in F7F-2

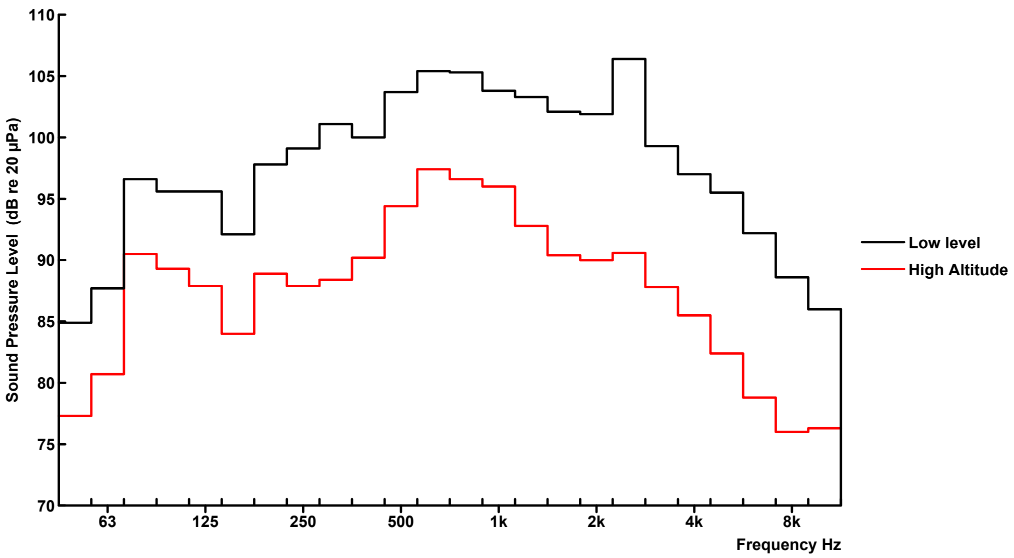

Figure 2 A comparison of cockpit noise in Harrier during high and low altitude flight

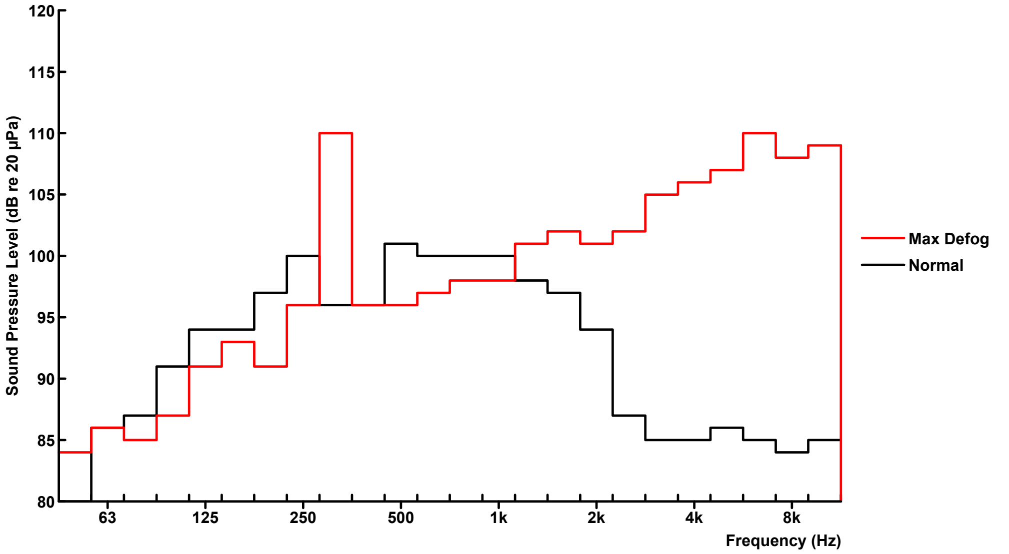

Figure 3 A comparison of cockpit noise in the F-16A with ECS switched on and off

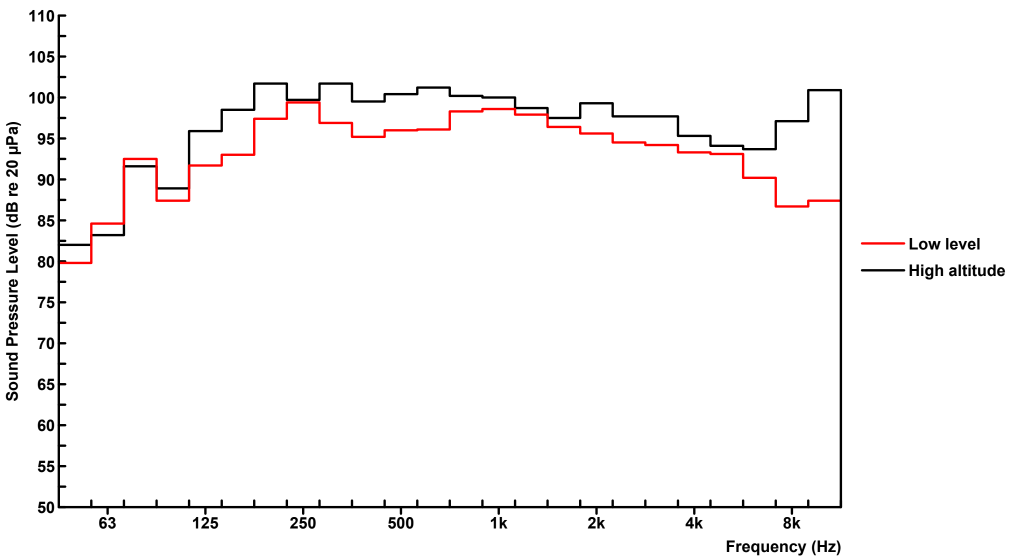

Figure 4 A comparison of cockpit noise in Jaguar during high and low altitude flight

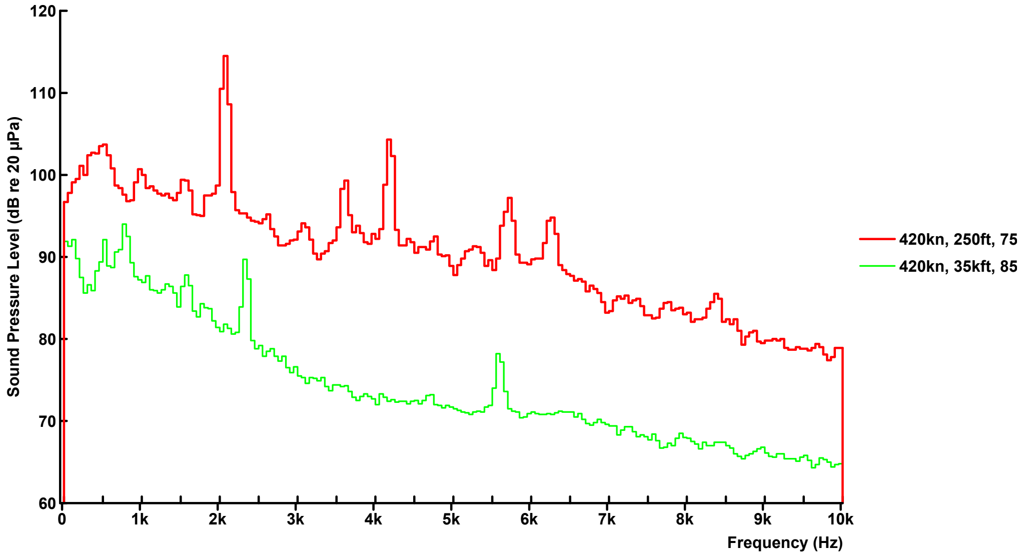

Figure 5 Cockpit noise in Harrier illustrating the compressor fan tone.

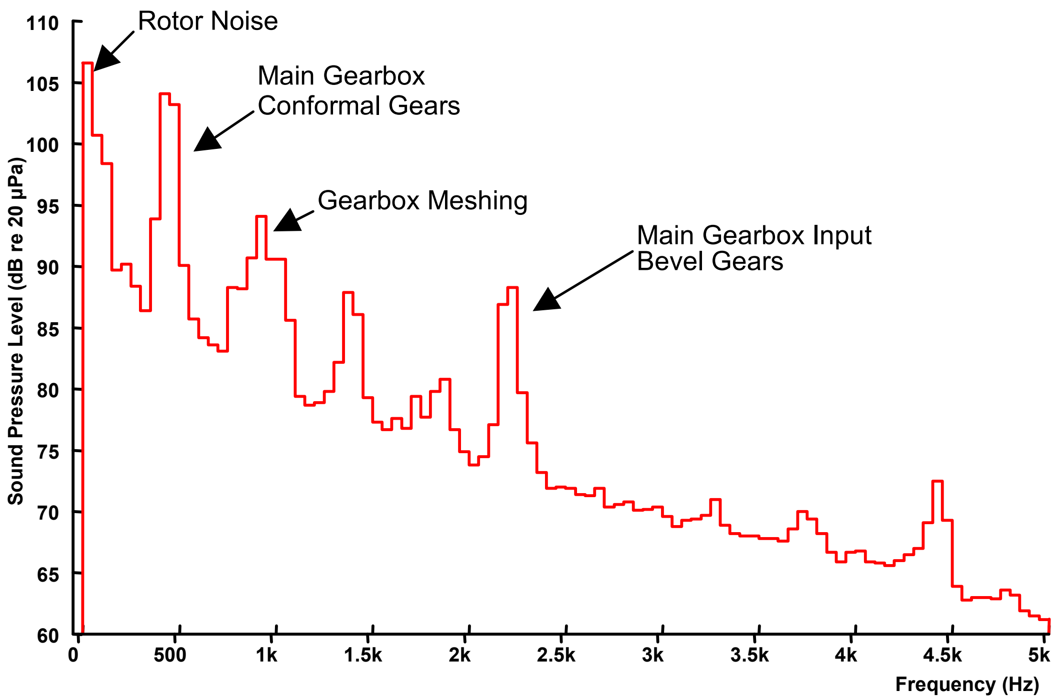

Figure 6 Narrowband analysis of cockpit noise in the Lynx helicopter (100 knots)

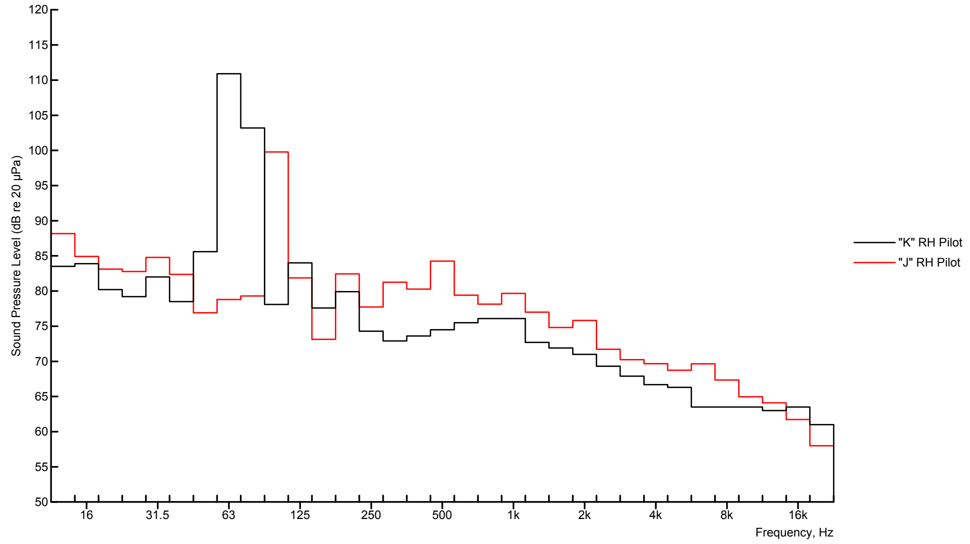

Figure 7 Cockpit noise in the C130K and C130J variants of the Hercules

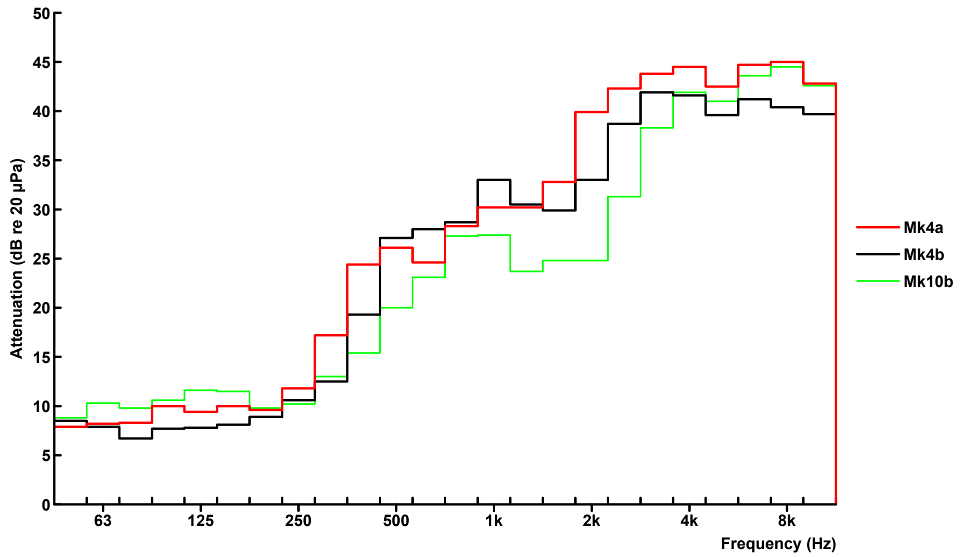

Figure 8 The attenuation characteristics of the Mk4 and Mk10 flight helmets

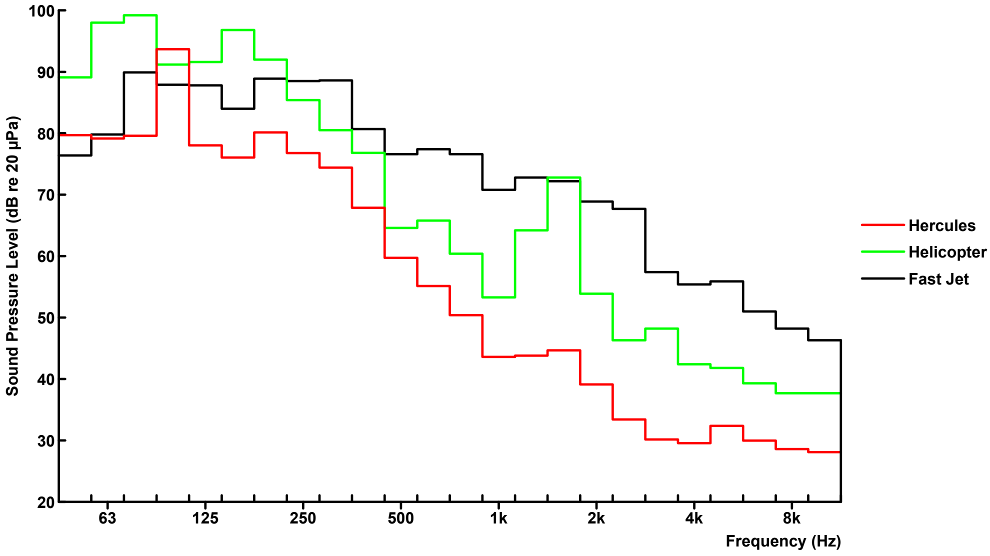

Figure 9 Typical noise levels at the ear experienced in fast jets, helicopters and Hercules

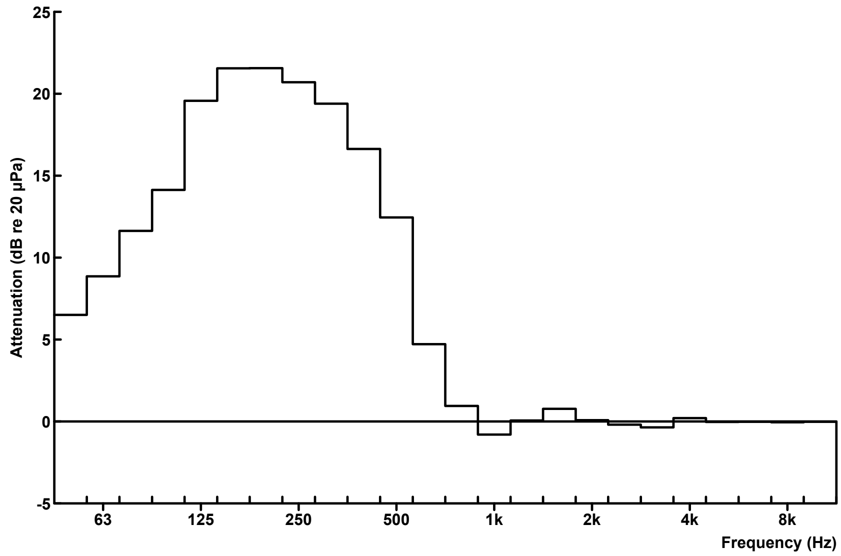

Figure 10 The active attenuation performance afforded by a helmet mounted ANR system

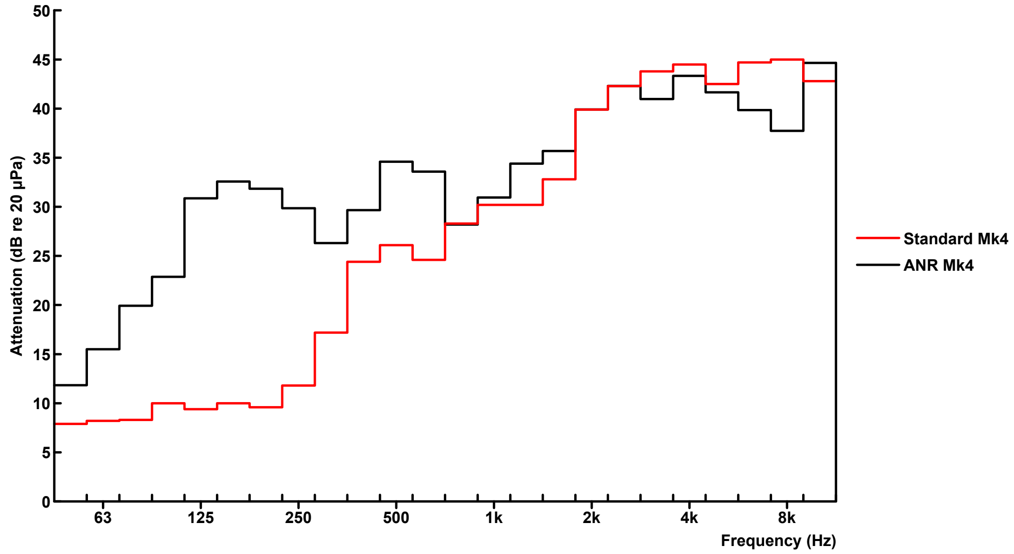

Figure 11 The passive plus active attenuation performance afforded by a helmet mounted ANR system

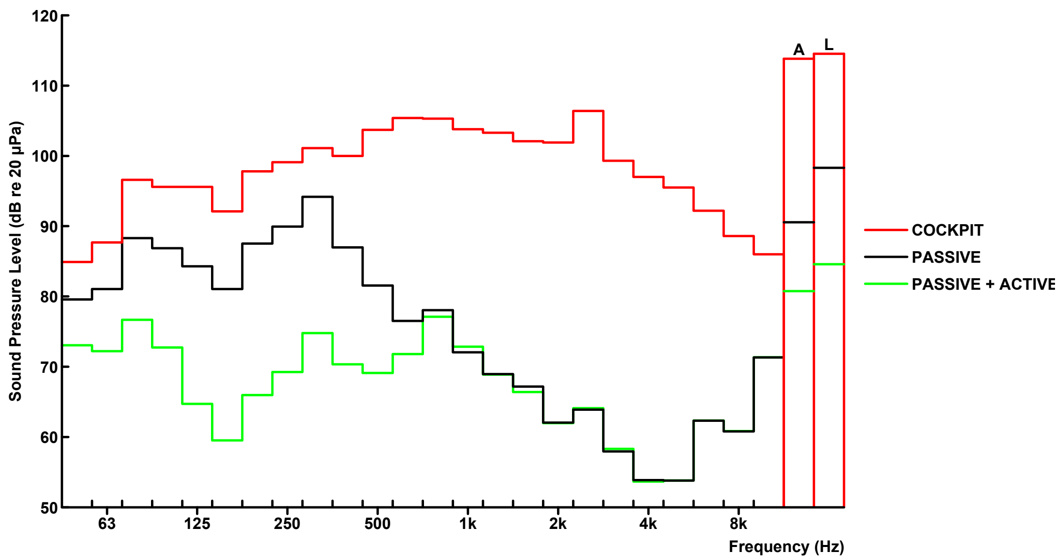

Figure 12 A comparison of noise levels at the ear in Harrier GR5 during high-speed low level flight for passive and passive plus active helmet attenuation.

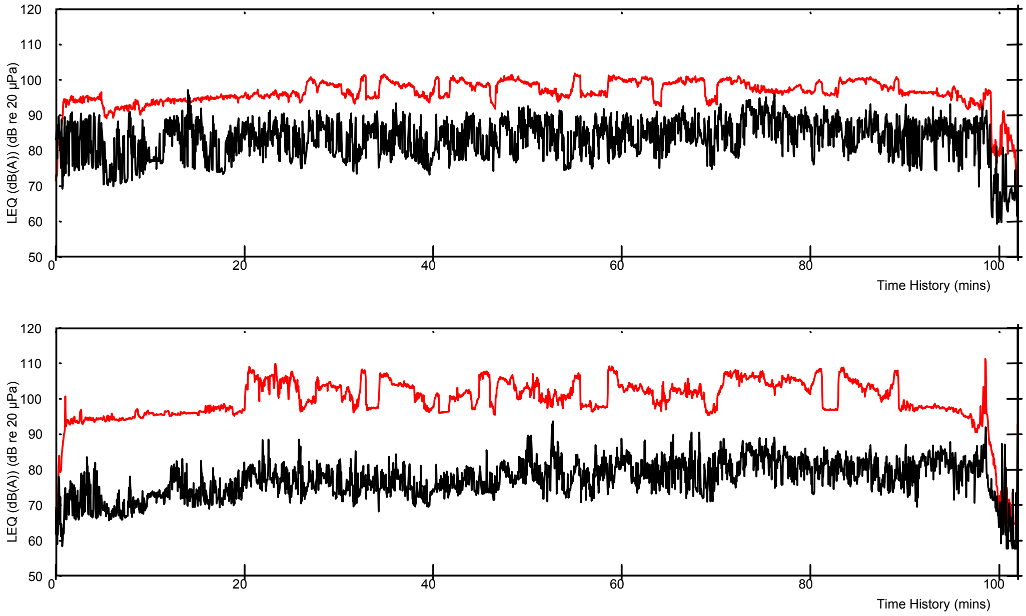

Figure 13 Comparison of time histories of overall noise dose in the cockpit and at the ear with passive (top trace) and passive plus active (bottom trace) helmet attenuation.