HELICOPTER NOISE - WHAT IS IMPORTANT FROM A COMMUNITY PROSPECTIVE?

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ABSTRACT

Helicopter operations are being inhibited or curtailed in North America, Europe and many other parts of the world by objections and concerns about noise. Such opposition is difficult to understand because most helicopters generate noise levels considerably below the internationally agreed noise certification standards and generally meet established community noise rating criteria and guidelines. As a result it is being suggested that noise criteria or limits associated with noise certification and community rating procedures should be lowered, i.e. made more stringent. Responding to this perceived requirement for lower noise, manufacturers are placing major effort at reducing the maximum noise levels in a belief that this will improve public acceptance. However, within the constraints imposed by economic considerations, current activity is only likely to achieve reductions in the order of 5 dB(A) relative to the quieter helicopters already in service . Moreover, it appears that small helicopters often give rise to the same or even greater number of complaints than larger helicopters that typically generate higher noise levels. In fact available evidence makes it clear that public acceptance of helicopters is not wholly reflected by either conventional community rating procedures or the noise certification requirements. This puts into question the view of many national authorities and some helicopter manufacturers that a reduction in the absolute noise level should be the main focus in finding a solution to the problem of making helicopters more acceptable to the general public.

This paper addresses what is different about helicopters and gives a clear indication of how the level of public acceptance can be improved. Design considerations and the implications of main rotor tip speed on public acceptance are also discussed.

This paper is based on papers published jointly by the authors (1, 2) in 1998 and 1999, plus addition research by the authors since that time.

INTRODUCTION

The development of helicopter operations around the world, and in particular in the United Sates and Europe, is being restricted by objections about noise. The commissioning of new heliports, and changes to services at existing facilities, tend to be controversial and are often rejected as a result of public opposition. Prime examples include operations at the Issy-les-Moülineaux heliport in Paris, the continuing debate about helicopter operations and heliport development in London (3), the use of heliports in New York (4) and helicopter sightseeing tours of the Grand Canyon (5). The issue of helicopter noise in connection with heliport operation and community response is continually being reported in the aviation and general press. The topic was also discussed in depth at the Public Acceptance Workshop held in Montreal, Canada in conjunction with the 1999 American Helicopter Society (AHS) Annual Forum and more recently at Fly Neighborly workshops and meetings held at the HAI's Heli-Expo in 2004, 2005 and 2006. This issue is also addressed in a report on non-military helicopter noise to the US Congress by the FAA, dated December 2004, made available in October 2006 (6).

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The situation is further complicated in practice because in many areas local communities experience noise from a combination of military, civil and law enforcement helicopters. Military helicopters and those used by law enforcement agencies are not subjected to the same constraints as those operated by the civil sector and may create disturbance by operating directly over communities by day and night. However, although there is some evidence that people are more tolerant of helicopters used by the police, annoyance is a combined effect so that all helicopters are placed in the same category. Some locations are also exposed to Helicopter Emergency Medical Service (HEMS/EMS) operations and while there is normally less resistance to such use, noise at hospital heliports is still a significant issue in the U.S. Indeed, at a Helicopter Association International (HAI) Heli-Expo meeting in 2006, it was reported that development of a hospital heliport in California had been abandoned as a result of objections to noise. In this context it is worth noting that although EMS operations involve life threatening conditions, the majority of such flights are hospital-to-hospital transfers, etc. which do not enjoy the same level of public acceptance.

Such opposition to helicopters and helicopter operations is difficult to understand because most helicopters generate noise levels considerably below the internationally agreed certification limits and comfortably satisfy established community noise rating criteria and guidelines. The inference is that even relatively sophisticated noise rating methods based on complex objective measurements fail to account for the disturbance caused by helicopters. As a result of concerted opposition to helicopter operations it has been suggested that the noise criteria or limits associated with the community rating procedures should be lowered. Although minor adjustments to the assessment criteria may be helpful, analysis of the issues indicate that such action will have little or no direct effect on the level of public acceptance. This point is significant because various national authorities and industry observers believe a reduction in absolute noise levels will make helicopters more acceptable. However, examination of the problem makes it clear that public acceptance of helicopter noise is not really reflected either in conventional community rating procedures or helicopter noise certification. This is surprising because the same rating methods are used successfully for controlling the environmental impact of large commercial aircraft and other forms of transportation.

The fundamental question addressed by this paper is why is the reaction to helicopters different to that of other forms of transport and what can be done to improve the level of public acceptance?

SOCIAL SURVEY RESULTS

A review of case histories, press reports and information collected by industry associations makes it clear that helicopters and heliports in many locations enjoy only a low level of public acceptance. This was put into perspective a number of years ago when the results from a number of studies connected with the operation of helicopters in the United Kingdom was reported in 1993 by the Civil Aviation Authority (CAA) (7). Figure 1, reproduced from the 1993 report, shows annoyance as a function of the noise levels expressed in terms of L_{eq} (16 hr) [1].

In the 1982 survey, data were obtained by the CAA along the route of the Gatwick-Heathrow *Airlink* service (no longer operating) and at Aberdeen, Scotland, the major base for offshore oil industry helicopter operations in the North Sea.

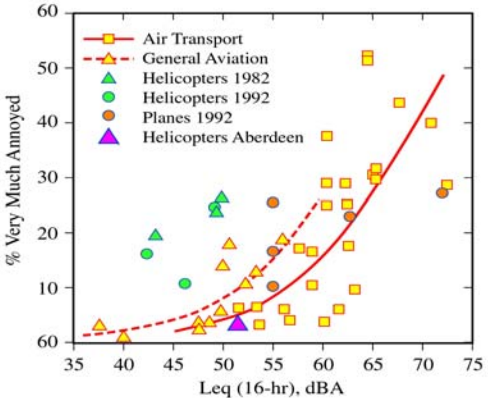

Figure 1: UK CAA Social Survey Results

Figure 1 reveals that, relative to air transport (fixed wing aircraft), helicopters operating in the London area are considered to be up to 15 dB(A) more annoying at the 10% and 20% *Very Much Annoyed Level*. The helicopter results contrast with those obtained in Aberdeen which shows no difference to fixed-wing aircraft. Ollerhead (7) suggested this disparity in reaction can be explained in socio-economic terms: "*better off people tend to be more annoyed*". Also the residents under the *Airlink* were less favorably disposed towards a helicopter shuttle service which was being used by first class passenger, whilst in the Aberdeen

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[1] The noise metric L_{Aeq} (16-hr) expresses time varying A-weighted noise levels occurring during an observation period as a single constant value having the same acoustic energy. The 16 hour period from 7:00 to 23:00 is used for planning purposes in the UK. This metric is similar to the Day-Night Average, $L_{DN,,}$ metric used in the United States.

area, North Sea oil operations contribute significantly to the local economy.

In drawing such conclusions it is important that the sources of annoyance should not be different from one another. The *Gatwick-Heathrow Airlink* used the Sikorsky S61 but a number of other helicopters used the same route. In the Aberdeen region operations also included large numbers of the Sikorsky S61, and Eurocopter Super Puma (about 65% of the operations), together with Sikorsky S76, Eurocopter AS365 Dauphins and other types. Thus in both cases the characteristics of the acoustic environment were influenced by large, acoustically non-impulsive helicopters.

In 1992 a small scale study was performed by the CAA in London at Fulham and Putney, and along the River Thames in the vicinity of Battersea and near one of the *London Helicopter Routes*[2]*:* these locations are affected to some extent by overflights of aircraft landing at Heathrow. These results were similar to those for the *Gatwick-Heathrow Airlink* evaluated 10 years earlier (see Figure 1). The *London flights* were dominated by the corporate market using light/medium helicopters including a large number of Bell Jet Rangers and Long Rangers plus Aerospatiale (now Eurocopter) Dauphins, Sikorsky S76s and a few larger helicopters. Studies carried out by the *Greater London Council* in the same time frame also confirmed an underlying concern of the residents about noise and safety of helicopters.

Comments similar to those made in London are common whenever helicopter complaints are examined. The conclusion from this evidence reached by many observers is that for a similar level of annoyance or acceptance helicopter noise levels need to be much lower than those of fixed wing aircraft and other forms of transportation. **This view contrasts with that of the authors who believe that certain noise sources, highly characteristic of helicopters, are one of the aspects responsible for the difference in attitude towards such operations. The proposition is that annoyance caused by main rotor blade/tip vortex interaction (BVI), main rotor thickness noise and impulsive noise resulting from shock waves etc., commonly referred to as high speed impulsive noise (HSI), main rotor wake/tail rotor interaction (TRI), and tail rotor noise (TR), is largely ignored by conventional rating procedures.** In fact, an underlying dislike of helicopters and the additional annoyance due to the transient characteristics of rotor noise are both important when assessing public acceptance as discussed in this paper.

Analysis of the social survey results also reveals a strong connection between noise and safety and that safety, or perceptions about safety, also play a significant part in public reaction towards helicopters which, of course, has a direct bearing on the level of acceptance.

Another common misconception is that helicopters generally fly in an uncontrolled manner and the national authorities have little or no power over the flight paths/heights used. This is not true, particularly in metropolitan environments in the US, Canada or Europe, but such misconceptions seem to be deeply routed. A1987 study for the AHS (8) reported that the *"perceived intrusion of the helicopter into one's living space as evident by low flying is a significant negative factor"*. Another important issue is that of the low flyover height used by many helicopters, particularly in the USA. In this context, a study made in Hawaii in 1994 as a result of the anti-tour helicopter lobby (9) stated that people in rural areas felt that *"their home's privacy was invaded by helicopter flyovers"*. From these and other statements there appears to be a strong commonality in the response to helicopter noise irrespective of location or county being considered. Such assessments also suggest that there is a strong relationship between the number of flights and the level of annoyance with an upper limit of just four or five flights per day before the annoyance becomes unacceptable (9).

RATING OF COMMUNITY RESPONSE

The external noise signature of helicopters is the result of several complex sources. Most of the acoustically dominant sources are aerodynamic in origin so that the relative strength of each and, therefore, the overall signature heard on the ground depends on a number of factors. Despite a high degree of variability, helicopter noise exhibits certain characteristics peculiar to this type of vehicle which make rotorcraft readily identifiable even at quite low sound levels. It is these peculiar characteristics that not only make helicopters potentially more annoying than vehicles with less distinctive signatures but also impose special demands on the techniques used to rate the level of annoyance. As far as the latter point is concerned it should be noted that any form of noise assessment must be based on units that reflect subjective response to the noise being controlled.

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[2] Routes established for helicopter flights in the greater London region.

Most community rating procedures are based on the use of A-weighted sound pressure level integrated over a relatively long period [3] to account for the noise level of individual events and the number of occurrences in a specified period. This type of analysis may be applicable to the large number of operations that occur at a major airport where sound levels are relatively constant. However, the effectiveness of methods based on long term averaging is questionable in those cases where the duration of the event is very much shorter than the evaluation period and the number of events in that period is such that noise levels are subject to large variations. The length of the integration period in relation to the duration of typical helicopter overflights means that the maximum A-weighted noise level of the helicopter during any single event can be nearly 20 dB(A) above ambient 64 times per day before any real public concern is forecast by the community rating methods. Even higher differences between maximum noise level and ambient would be rated as acceptable if the number of flights is lower.

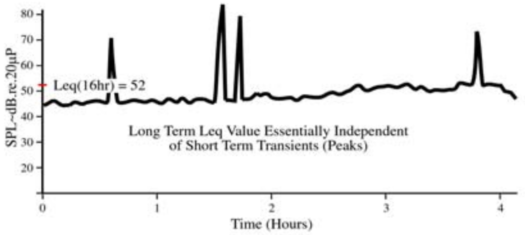

Figure 2: Community/Helicopter Noise Levels

Figure 2 shows a section of A-weighted time history with four helicopter flights over a 4-hour period. Expressed in terms of $L_{Aeq\ 16\ hour}$, the noise level is virtually independent of the short duration helicopter noise events even though individual occurrences would be noticeable and probably considered annoying. Therefore, in the opinion of the authors, current community rating methods are deficient in two respects. First, the subjective effect of the more intrusive helicopter noise sources is underrated. Second, evaluation over a period of several hours fails to properly account for the disturbance caused by relatively short duration events. Coupled together, these two deficiencies help to explain why helicopters attract special attention.

In the context of this discussion it is with noting that this issue is highlighted in a report recently issued by the FAA (6) which stated the following. "*Civil helicopter annoyance assessments utilize the same acoustic methodology adopted for airplanes with no distinction for a helicopter's unique noise character. As a result, the annoyance of unaccustomed 'impulsive' helicopter noise has not been fully substantiated by well-correlated metric.*" Even so the FAA makes an additional statement: "*… the FAA will continue to rely upon the widely accepted Day-Night Sound Level (DNL) as its primary descriptor for …. Heliport land use planning.*" This does appear logical but the FAA has little choice since there is no agreed noise rating methodology to fully take into account the unique impulsive character of helicopter noise.

PUBLIC ACCEPTANCE

Community noise rating procedures predict the impact of fixed-wing aircraft noise around airports and within local communities relatively well. This is not the case for helicopters and heliports, which appear to create a level of adverse reaction disproportionate to the measured and predicted noise levels. A partial explanation for the disparity between noise assessments and community reaction to helicopter operations has been identified by the authors of this paper as deficiencies in the rating methods. For a more complete analysis of the issues it is necessary to examine the way in which helicopters operations are perceived. Fixed-wing aircraft operations typically involve a large number of flights per day and, because the noise characteristics of most of the large jets are similar to one another, the noise climate is relatively uniform. Away from airports aircraft over fly at very high altitude and there is little general concern over aircraft safety. Helicopter operations are very different. In general, the number of operations per day, even near a busy heliport, is relatively low and very variable in nature. Flight paths, unlike those used by fixed-wing aircraft, vary widely and so at any one location the noise pattern is much less consistent. There is also a very large difference in both level and, more importantly, the character of noise created by different helicopters with some small helicopters *sounding noisier* than larger ones. Overflights are generally made at relatively low altitudes so that any concerns over safety are heightened.

Acoustic (Direct Noise) Stimulation

A generalized dB(A) sound pressure level time history of a helicopter flyover is illustrated in Figure 3. The figure shows the effect of high levels of thickness/high speed (main rotor) impulsive noise (HSI), tail rotor noise (TR), main rotor wake/tail rotor interaction noise (TRI) and main rotor blade/blade vortex interaction noise (BVI) on overall noise level.

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[3] 16 hours in the UK / 24 hours in the USA.

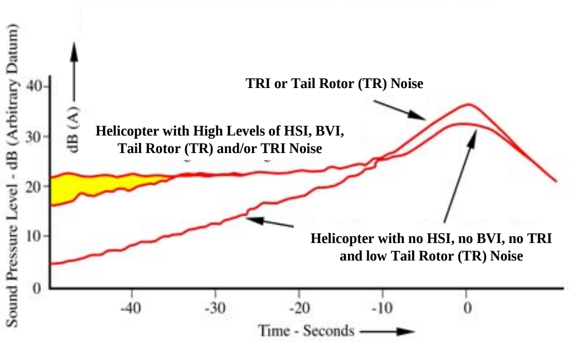

Figure 3: Generalized Flyover Time History

Measured in conventional subjective units, the form ofthe dB(A) time history will be similar to that indicated in Figure 3 whichever of the sources discussed above are predominant. Moreover, because all of the sources considered generate similar absolute noise levels, there will be little change in the time history even if one or two of the sources is pronounced at the same time. The directional characteristics of HSI and BVI are such that it has little influence on the maximum noise level that normally occurs close to the overhead position. TRI or high levels of tail rotor (TR) noise can affect the maximum level, but experience suggests the influence is no more than 5 dB(A) as shown in Figure 3. More importantly, it can be seen that the greatest effect of the intrusive sources occurs more than 10 dB(A) below the maximum value so they will have little or no influence on time integrated units such as Sound Exposure Level (SEL) and Effective Perceived Noise Level (EPNL). HSI, TRI and TR noise are most pronounced during flyover. BVI and to a lesser extent, TRI and TR noise are normally associated with descent. However intermitted BVI can also occur on some helicopters during flyover/cruise flight. This condition is apparent in the case of tandem helicopters where BVI can be present during the complete flyover and also during descent. Also whereas during descent the main BVI of interest is related to the main rotor advancing blade, in cruise flight BVI is associated with both the main rotor advancing blade and the main rotor retreating blade. The BVI associated with the advancing blade is the most pronounced and on some helicopters the retreating blade BVI is effectively non-existent. Figure 3 is also a fair representation of a helicopter where the level of tail rotor noise (TR) and/or TRI occurs during the complete flyover.

When the time history sound pressure level record of real helicopters are examined they will, however, often be different from the generalized trends illustrated in Figure 3. The upper trace represents the case where one or more of the sources are detected continuously at the observer location. On many helicopters, however, the sound pressure level time history is different in that instead of the sources being continuous in nature, they occur sporadically so that the time history shows exhibits a fairly rapid increases and decreases in level. This is particularly true on helicopters which are prone to BVI during level flight or shallow descents or those where the level of tail rotor noise (TR) and/or TRI is sensitive to minor inputs by the pilot to the tail rotor controls. This is particularly noticeable on helicopter designs which use high tip speed (above 755 ft/s~230m/s). From a subjective point of view the intermittent generation of the intrusive sources is equally or more annoying than if the sound occurred continuously and tends to draw immediate attention to the helicopter. This is important when considering annoyance.

Annoyance Stimuli

Assessments conducted in London and Los Angeles by authors for GKN Westland Helicopters (now AgustaWestland) together with information in the files of the HAI and general experience of the industry makes it clear that the subjective impression created by the impulsive noise sources are very important when considering public acceptance. Also, except in the case of tail rotor noise (TR), the *sources of interest* are mainly detected at levels well before the '– 10 dB down point'[4].

A study of the various factors involved shows the level of public acceptance can be considered to be a function of both acoustic (direct) noise and a non-acoustic element, termed *virtual noise*, as illustrated in Figure 4.

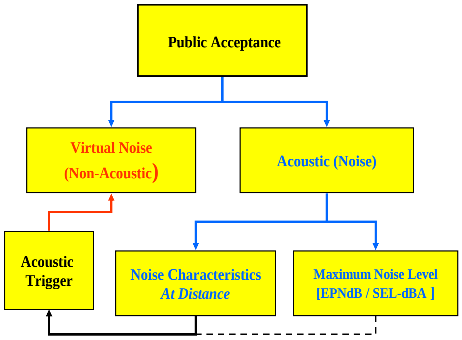

Figure 4: Elements of Public Acceptance

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[4] The 'position' on the sound pressure level time-history at which the level is 10 dB below the maximum or peak level.

The response to acoustic noise is a function of maximum noise level as defined by objective measurements and, more importantly in the context of public acceptance, the subjective characteristics of the noise as it first becomes audible. The magnitude of the non-acoustic component (*virtual noise*) is not related directly either to the absolute level or to the character of the noise generated by helicopters, but it is *triggered* by the direct acoustic signal. Even so the annoyance or level of public acceptance is usually quantified using measured noise levels as illustrated in Figure 1. Consequently the *virtual noise* element is treated, for all practical purposes, in the same way as the direct acoustic energy (noise) radiated by the helicopter. *Virtual noise* is dependent on a wide range of inputs but is *triggered* initially by any distinctive feature of the acoustic signature and, to a far lesser extent, the absolute noise level.

There are some situations in which resistance to operations occurs even though the relative levels of helicopter and ambient noise suggest the helicopter should not be audible. It would seem that in these situations the trigger for the *virtual noise* is visual. The surprise of suddenly seeing a helicopter has been commented upon a number of times by the general public and may offer a partial explanation for concerns about sight-seeing operations around the Grand Canyon and New York. The number of occurrences when the *visual trigger* is significant, however, appears to be extremely small so that the topic is not addressed further in this paper.

It cannot be stressed highly enough that whenever adverse reaction to helicopter operations results from *virtual noise*, attempts to address the problem by reducing *acoustic noise* at source will be largely ineffectual.

It is not simply that the level of sound, at long range as the helicopter approaches or flies towards the observer, are higher than on helicopter models with little or no noticeable HSI, tail rotor (TR), TRI, or BVI noise. Rather it is that the *tonal* and *impulsive* characteristics of these sources are in themselves more annoying and draw attention to the helicopter. Some rating criteria apply a +5 dB, or +10 dB, penalty to account for the extra disturbance if a tone or *whine* - similar to the sound generated by the tail rotor - is present in the acoustic (noise) signal. Many researchers argue that EPNL - and by implication the SEL, L_{DN} or L_{Aeq} metrics - give a realistic measure of both the source level and public response, implying that any increase in the sound associated with BVI, HSI, TRI and tail rotor noise is accounted for in full by metrics which take into account the duration.

The subjective rating of helicopter noise was investigated thoroughly in the late 1970s and early 1980s (10 to 15). One objective was to develop an impulsive correction that could be added to more conventional metrics to account for the subjective effect of BVI and tail rotor noise[5]. Despite the considerable effort expended, the results of these studies in combination were considered by many to be largely inconclusive. After an extensive review of all the issues, the International Civil Aviation Organization (ICAO) chose in 1983 to use EPNL for helicopter certification, with the proviso that manufacturers *strive to eliminate intrusive noise sources*.

The position of NASA was reconfirmed by Dr Powell who highlighted work conducted at NASA during 1978/1983 time frames and a more recent study conducted in 2001 in a presentation given at the 2003 AHS Annual Forum (16). Dr Powell said the NASA studies on subjective response to helicopter sounds showed that the addition of an *impulsive correction*, which some had suggested, did not improve the human response predictions. Whilst the case presented by NASA is valid, it is apparent that both the level and character of sound audible at distances greater than those involved in EPNL calculations play a major part in the rating or acceptance of helicopter noise by the general public. The tonal and impulsive quality of sound 15 to 25 dB(A) below the maximum noise level observed during any single event can influence the subjective response. It would appear that when the degree of blade vortex interaction (BVI), high speed impulsive/thickness noise (HSI), tail rotor interaction noise (TRI) and/or tail rotor tonal noise (TR) is pronounced these distinctive sources act as an audible cue, increasing the negative response to helicopter noise. These *low level triggers* are not accounted for in EPNL or SEL calculations which only accounts for acoustic energy within 10 dB of the maximum value.

Non-acoustic (*Virtual Noise*) Stimulation

The studies based on U.K. data, supplemented by information from other locations, including that associated with *Airspur* who operated in the Los Angeles, California area in the early 1980's, show that the *noise characteristics* and *virtual noise* are of equal or even greater importance than the maximum noise level observed during a particular flyover or flyby event. It is difficult to ascertain precise values for these

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[5] In the 1970s/early 1980s HSI was not really understood or considered: hence the subject impact of this source was not studied. Also all the studies, except those conducted by Westland Helicopters on tail rotor noise, were focused on the main rotor/BVI.

components because they are partly interrelated. For example, a helicopter generating BVI or HSI noise may cause annoyance directly, while at the same time acting as a *trigger* to highlight public opposition to some other aspect of the operation. The information available also suggests that sounds such as tail rotor *whine* and/or main rotor impulsive noise (BVI or HSI) also exacerbate concerns over the safety of the helicopter because the 'sound' may suggest (falsely) mechanical problems or conjure up an image of a helicopter crashing as often seen on television. Taking this argument to extremes, a helicopter generating low but perceivable levels of tonal or impulsive noise, flying over an area where the public have major concerns on helicopter safety could create the same negative response as one with high levels of tail rotor, TRI HSI or BVI operating over communities which are generally more tolerant of helicopters.

In the context of this evaluation it has been found that general aviation light propeller driven aircraft have a similar impact - at least in Europe. Research reported to ICAO (17) based on studies conducted at the University of Southampton, Institute of Sound and Vibration Research (ISVR) (18) has shown that a number of complaints attributed to the noise from general aviation aircraft are, in fact, related to other causes. This research attempted to classify complaints and to quantify the effect in terms of the equivalent A-weighted sound pressure level with the following results:

a) negative reaction to leisure flying	+ 5 dB(A)
b) poor community/airfield relations	+ 10 dB(A)
c) fear of crashes	+ 10 dB(A)
d) nobody acts on complaints	+ 20 dB(A)
e) aircraft are flying too low	+ 20 dB(A)

It should be noted that these equivalences are not reversible, so that, for example, reducing noise levels by 10 dB(A) will not remove the fear of crashes.

It is also interesting that while the ISVR study (18) was made at general aviation airfields dominated by light propeller driven aircraft, there was some helicopter traffic at one of the airfield sites studied. Examination of the results obtained indicates similar trends for both general aviation fixed-wing aircraft and helicopters, but it is difficult to be specific because the survey did not set out to highlight differences between helicopters and other forms of air traffic.

While it has not yet been possible to determine similar equivalence factors in such a precise manner, a review of other evidence suggests that the light airplane findings are generally applicable to helicopter operations. The main difference being that the first of the non-acoustical factors - negative reaction to *helicopter* flying - appears to be stronger than for general aviation aircraft and may be as high as 15 dB(A) at particularly sensitive locations. This is because the public at large often perceive helicopters to be engaged either in leisure flying or operating for no justifiable reason. As explained previously, however, if it is believed that helicopters provide a worthwhile service, as in the North Sea, the *virtual noise* factor can be very low or zero. Similarly, the concern over safety and fear of crashes in areas where flights are conducted over precise routes under air traffic control may be much less. Experience from Aberdeen, Scotland, where helicopters have become accepted much in the same manner as large fixed-wing transport aircraft, and in the Victoria/Vancouver area where *Helijet* operates a scheduled passenger helicopter service, supports this view.

Amongst the non-acoustic sources associated with airfield related disturbance, the work reported to ICAO (17) found that fear of crashes was the most significant factor. Low flying, changes in the noise signature of the engine, and previous crashes increased anxiety. At one airfield where an accident had occurred shortly before the survey, concern was almost three times greater.

'Startle' Effect

In order to further understand the aspects which influence *virtual noise*, some of the information in the *HAI Acoustic Committee* files for the period 1988/1998 related to US operations was re-examined by one of the authors. In addition information from three public hearings relating to a heliport application in Northern Virginia was studied. This highlighted an additional effect related to the sudden occurrence of the sound of the helicopter, which can be best described as a *startle effect*, when the helicopter flies over. This appears to not only increase the annoyance but raises concern to many on the safety of the operation. This was not apparent when a detailed review of complaints related to operations in the UK was conducted a number of years ago. This may be partly explained by the fact that in general the *flyover heights* used by helicopters are higher in the UK, than in the US and thus the occurrence sound of a helicopter is less sudden. In the UK, the regulations require overflights to be made at 2000 ft unless specific ATC considerations dictate lower heights. On the other hand although some operators in the US use such heights, many operate at much lower heights of 500 ft, and even lower heights in some cases are not uncommon. The duration and hence the 'sharpness' of rise and fall of the acoustic signal, *startle effect*, will be much greater with helicopters flying at lower altitudes. Conversely the higher the flyover height the lower the maximum noise level and the longer the duration of the signal heard on the ground and hence a decrease in the *startle effect.*

The lack of quantitative data makes it impossible to draw any specific conclusions. Nevertheless it is postulated that the *startle effect* is a significant contribution to the *virtual noise* component and to the perceived safety of helicopter operations in many operations where low (500 ft or less) flyover heights are involved. Somewhat ironically, this effect is likely to be more pronounced as noise levels are reduced and more especially with significant reductions in the long range cues such as HSI, BVI and TRI noise.

DESIGN CONSIDERATIONS

The helicopter, with the possible exception of those powered by piston engines, is unique amongst powered lift aircraft insofar as the primary lift and control surfaces – the main and tail rotors - are almost invariably the dominant sources of external noise *in all modes of flight.* Consequently, the noise characteristics of a given helicopter type are established almost completely once the main and tail rotor configurations and their position relative to one another has been decided. The realization of the quiet helicopter concept is, therefore, not one of post flight modifications to a noisy aircraft but a carefully planned compromise, made at the design stage, between several conflicting requirements. Unfortunately, simple physical considerations show that those design parameters most effective in reducing rotor noise also have the greatest influence on performance. Indeed, although purely acoustic considerations point towards low rotor blade tip speed, the aerodynamicist seeks the highest possible rotor speed commensurate with compressibility effects in order to save weight and to maximize rotor inertia in the event of autorotation. Genuine reductions in noise at source cannot, therefore, be achieved unless noise is treated as a design requirement and given the same priority as other attributes such as payload, range etc. all of which contribute to the overall effectiveness of the vehicle. Lower noise levels will come at the expense of either performance, operating costs or research activity (none of which may be palatable). Nevertheless penalties incurred in the pursuit of low noise should not be isolated for special attention. They are simply a legitimate part of the design process and must be accepted as such.

The close relationship between the various helicopter design parameters is illustrated in Figure 5. The rational behind the figures starts by assuming the main rotor tip speed has been reduced to lower the noise. To maintain performance, blade area has been increased to recover thrust capability, either by adding more blades of the same type or by changing the dimension of the blade, in either case further alterations to the helicopter will be necessary to accommodate the changes. Additional blades, for example, will require a more complex rotor hub while increasing the rotor radius may involve a longer tail boom to avoid interference with the tail rotor and so on. The way in which each parameter change necessitates others can be linked to an *explosion* radiating outwards from the initial modification as more factors come into play.

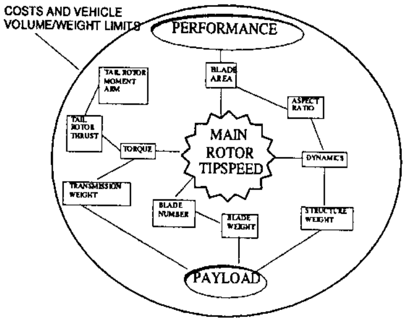

Figure 5: Effect of Design Changes.

For a completely *new* design the process of optimizing the balance between various attributes can continue until it is constrained either by technological boundaries or by cost and vehicle weight/volume limits. For *derived versions* of existing aircraft the freedom of choice before costs-to-change become prohibitive is more restricted. Inevitably this means that the level of noise reduction achievable without penalizing some of the other aircraft attributes is significantly smaller in the case of derived versions than that achievable by completely new designs.

Practical design improvements to reduce noise are currently directed towards BVI noise, principally during descent, and tail rotor noise. These sources (arguably) are the biggest cause of complaint about helicopter noise and also the main triggers for *virtual noise.* The problem of BVI noise is being addressed both by passive rotor blade tip planform modifications including the GKN Westland Vane Tip (19) and by active blade control systems such as active flaps, higher harmonic control (HHC) and individual blade control (IBC). All of these devices have been tested at model or full scale with varying degrees of success so, given sufficient development funds, it is possible to foresee improvements of perhaps 6 dB(A) in this area. In the light of these undoubted benefits it is, however, easy to overlook the fact that if an aircraft is not operating under BVI conditions, i.e. during noise abatement approaches or in level flight, little or no reduction in noise will actually occur. In cases when the approach technique avoids BVI, *operational* advantages may therefore be small. Perhaps a more effective use of active systems is to reduce or even eliminate the penalties traditionally associated with low rotor speed.

At this point it should be remembered that the noise certification approach flight condition (6 degree descent at the airspeed for best rate of climb, Vy) was adopted because it captures on most helicopters the maximum BVI noise levels. The approach test is, therefore, the most demanding of the certification flight conditions. Consequently, much of the research on passive palliatives, higher harmonic control and individual blade control will attempt to control noise at 6°, Vy. This combination of precisely controlled airspeed and fixed glide slope is at odds with the variable descent angle and decelerating airspeed employed in *normal* descents. Tests flights have shown that noise levels encountered during normal approach procedures can be as much as 10 dB(A) lower than those measured at 6°/Vy (20). Thus, although contemporary research will probably lead to lower *certification* levels, noise levels on the ground under normal operating conditions may show little or no significant improvement over the quieter helicopters of the present generation. The real benefit of technologies being developed comes in terms of expanding the area of the aircraft flight envelope in which noise levels are considered to be acceptable.

The importance of tail rotor noise, not only in terms of overall noise level but also as a function of subjective response, has been appreciated by some manufacturers for over 20 years. Westland Helicopters developed a quiet tail rotor (Q.T/R) for the Lynx and Westland 30 in the late 1970's. The basic design methodology is illustrated in Figure 6.

The concept of balancing the perceived *noisiness* of the main and tail rotors has been applied subsequently to the EH101 (20). The development by McDonnell Douglas of the NOTAR (NO Tail Rotor) series of helicopters was based on the desire of the U.S. Army to reduce the detectability of small helicopters. The solution was to remove the tail rotor source completely (21). This technique cannot be applied to large helicopters for a number of design and operational reasons. It should also be noted that with careful attention to detail the acoustic characteristics of a conventional quiet tail rotor can be just as acceptable as NOTAR (20). The *fenestron* fan-in-fin solution adopted by Eurocopter is also noteworthy in this context. Although early applications of this technology introduced a high frequency whine, recent modifications using unequal spacing of the rotor blades and non-radial stators have reduced this problem and under most flight conditions, it offers improvements comparable to NOTAR and Q.T/R (22). Again, however, structural, dynamic and aerodynamic limitations restrict fan-in-fin technology to low and medium weight helicopters.

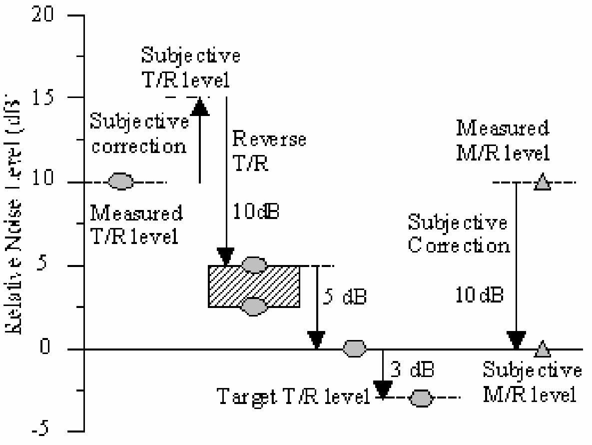

Figure 6: Balanced Noise Source Concept

It is interesting that the majority of papers dealing with noise reduction associated with the various NOTAR (21), Fenestron (22) and conventional low noise tail rotor solutions such as that applied to the Sikorsky S76 (23) concentrate on overhead noise levels and reductions expressed in EPNL and SEL metrics. In fact, the main acoustic advantage of these anti-torque systems is the change in the character of the sound as the aircraft flies towards an observer. This explains much of the perceived noise improvement achieved by NOTAR.

Effect of Mach number

An examination of data used in the study reported in this paper plus an in-depth review of test data for three helicopters by Dr. Leverton (one of the authors) [6] suggests that, in general terms when considering the public acceptance of helicopter noise, the advancing blade tip Mach number limits should be ideally not exceed 0.85. In addition this review suggested that the impulsive noise will normally be considered unacceptable if the advancing blade Mach number exceeds 0.875.

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[6] The authors wish to express his appreciation to Bell Helicopter Textron and in particular John Brieger, for allowing the results of the study conducted for Bell Helicopter Textron by Dr. Leverton to be quoted in this paper

There are, however, type-to-type variations between the impulsive characteristics of different helicopters due to the influence of blade tip shape, airfoil section, thickness, loading etc. (24) It follows that to ensure the character of flyover noise is acceptable; the tip Mach number of the advancing rotor blades ideally should be less than 0.85 and should not exceed 0.875 except in those cases where the use of advanced blade design delays the onset of transonic effects.

These limits apply to both the main rotor and tail rotor. However, on most helicopters, as discussed previously, the impulsive character of the main rotor is of greater importance when considering public acceptance, particularly if the helicopter is fitted with a *quiet tail rotor*.

The main rotor tip speeds of modern helicopters covers the range 680 ft/s (207.3 m/s) to 780 ft/s (237.7 m/s). Table 1 shows the corresponding advancing blade tip Mach number in hover and at 120 knots for a range of main rotor tip speeds at a temperature of ISA + 10° (25°C/77°F) - the reference temperature used in noise certification.

Tip Speed		Mach number ISA+10 (25ºC)	
(ft/s)	(m/s)	Hover	120 Kt
680	207.3	0.599	0.777
700	213.4	0.616	0.795
720	219.5	0.634	0.813
740	225.6	0.652	0.830
760	231.6	0.669	0.848
780	237.7	0.687	0.865

Table 1: Helicopter Main Rotor Advancing Blade Tip Mach number

Influence of Temperature

The speed of sound and, therefore, the advancing main rotor blade tip Mach number is dependent on the temperature of the air through which the blade is passing, i.e. the outside air temperature (OAT) measured on the aircraft. As the temperature decreases, the Mach number increases.

The effect of an increase in Mach number on the impulsive character of main rotor noise perceived by an observer as the aircraft approaches can be gauged from Figures 7 and 8 which the show the dramatic increase in both magnitude and impulsiveness of main rotor thickness noise close to the rotor disc plane (5 degree below the rotor disc plane) as temperature is reduced. These calculations were made using the monopole term of the Ffowcs-Williams Hawkings equation for a main rotor blade with a tip speed of 735 ft/s (224 m/s) flying at 143 knots.

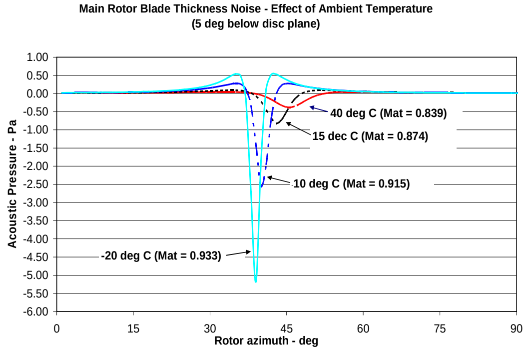

Figure 7: Effect of Temperature on magnitude and Impulsiveness of thickness noise

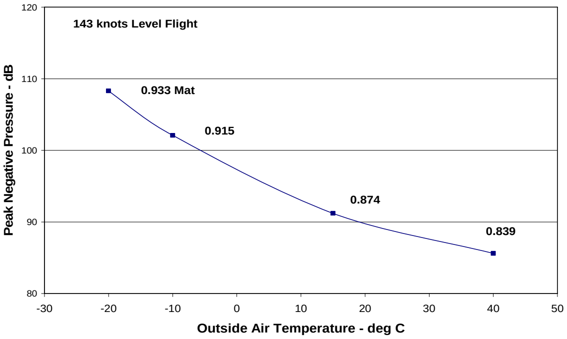

Figure 8: Impact of Temperature on magnitude of thickness noise

COMMUNITY ACCEPTANCE
EFFECT OF TEMPERATURE

It is common practice for manufacturers to issue noise data corrected to the noise certification reference temperature of ISA + 10ºC i.e. 25°C (77°F). Although this standardization allows the noise levels of different helicopters to be compared on an equitable basis, the potentially significant variation of noise level and subjective character with temperature described above is ignored. It also appears that in some cases the development of noise abatement or fly neighborly procedures has similarly failed to account for temperature effects. Such exclusion is, perhaps, excusable due to the extra complication involved, but is not realistic and will almost certainly result in noise levels and impulsive nature observed at distance at low temperature being higher than expected. The resulting 'errors' will be larger in the case of helicopters with high main rotor tip speeds and/or less sophisticated blade design which are inherently more sensitive to Mach number effects.

Clearly, in order to ensure the *public acceptance Mach number limits* are not exceeded, helicopters with high tip speed rotors will have to fly more slowly than those with lower tip speed rotors. This is illustrated in Figure 9 and 10. Figure 9 shows the advancing blade Mach number as function of airspeed for an OAT of 5°C (41°F) for three different tip speed of 680 ft/s (207.3 m/s), 730 ft/s (222.5 m/s) and 780 ft/s (237.7 m/s). Figure 10 shows the advancing blade Mach number as function of airspeed for five OATs ranging from -15°C (5°F) to +25°C (77°F) for a main rotor with a tip speed design of 730 ft/s (222.5 m/s).

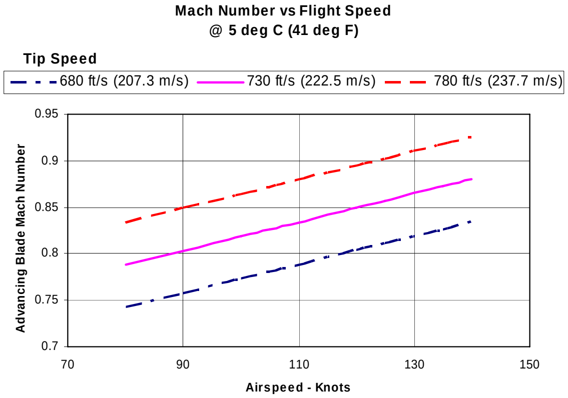

Figure 9: Mach Number vs. Flight Airspeed [Temperature 5°C (41°F)]

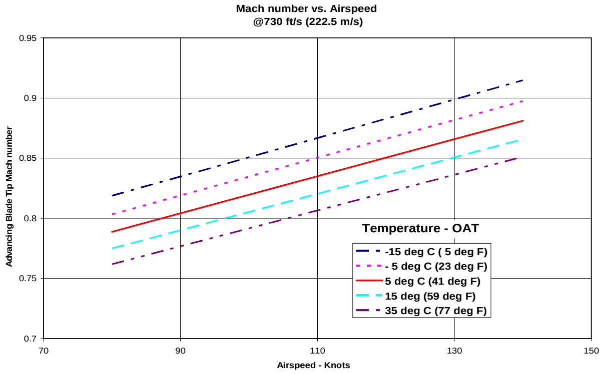

Figure 10: Mach Number vs. Flight Airspeed [Tip Speed 730 ft/s (222.5 m/s)]

It is worth noting that the outside air temperature (OAT) is relatively low in the early morning when many helicopter operations are conducted and typically decreases with increasing height above ground.

Although it is acknowledged that the majority of helicopter operations are conducted between 500 ft and 2000 ft AGL, the OAT can nevertheless be several degrees below that at ground level. The influence of temperature on noise level is similarly more pronounced on those aircraft with higher design tip speeds as illustrated in Figures 9 and 10

The effect of advancing blade tip Mach number on the character or impulsiveness of helicopter noise is illustrated in Figure 11 reproduced from reference 24 which shows measured acoustic data from a technologically advanced rotor. This figure shows the increase in the peak pressure as a function of advancing blade Mach number together with representative waveforms.

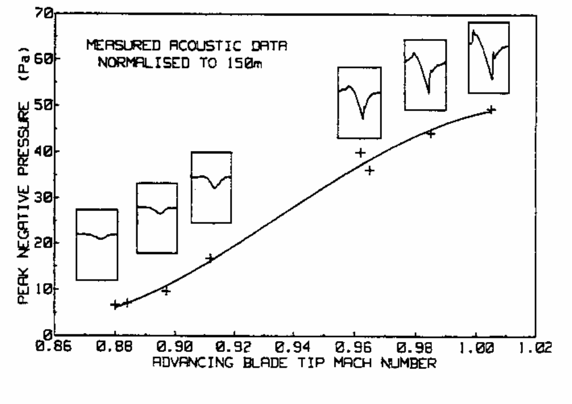

Figure 11: Measured Acoustic Data

It should be noted that the waveforms shown on Figure 11 were measured at considerable distance from the helicopter so that some of the high frequency content has been removed from the source waveforms by atmospheric absorption. This distortion of the waveforms which reduces the impulsiveness of the noise reaching an observer is a natural phenomenon, partially alleviating the effect of HSI noise under full-scale operational conditions. Figure 12 shows the 'source' waveforms estimated by removing the atmospheric absorption and the increase in impulsiveness can be seen clearly.

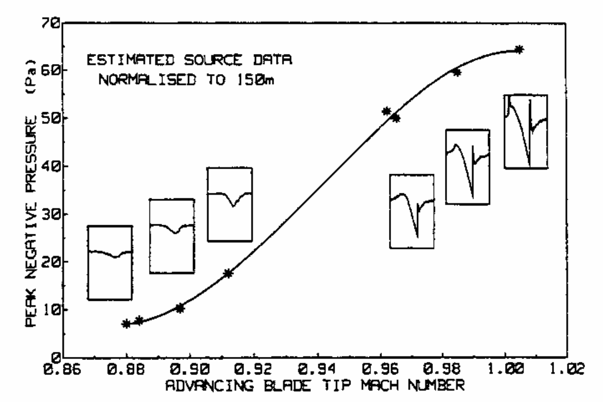

Figure 12: Estimated Acoustic Source Data.

Data is also presented in reference 24 which illustrates the variation in impulsiveness between helicopters with different main rotor designs.

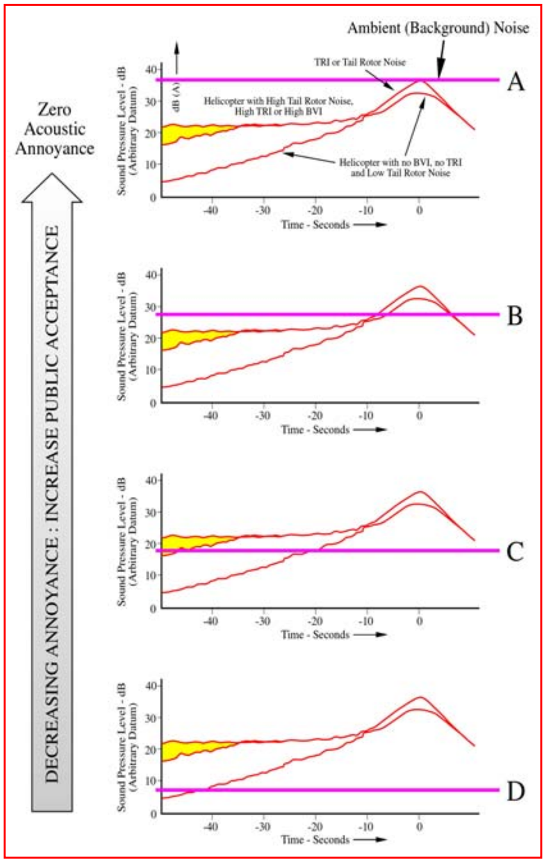

Figure 13: Influence of Ambient Noise

In the context of the above it is of interest to note that at the time of writing one manufacturer has already introduced recommended flyover speed limits which take temperature into account. Two other manufactures have also recently indicated that they too intend to introduce similar temperature dependent recommended 'fly neighborly' flyover speed.

It will also be noted from Figures 9 and 10 that in order to observe the Mach number limits discussed previously i.e. ideally < 0.85 with a maximum of 0.875, helicopters with high tip speed rotors will be restricted to very low forward speed.

In the case of the published data, some relief in the flyover speed reduction required at low temperature is allowed as the helicopter flyover height is increased, recognizing the attenuating effects of distance on the observed noise level. However such increases in height will not have a direct effect on the *impulsiveness* of the noise unless the *amplitude* is reduced to value below the ambient noise level. This is illustrated diagrammatical in Figure 13 in which the impulsive component is important when the ambient noise level relative to the helicopter noise is as shown in 'C' and 'D' which is typical of helicopter over flight. Only in the case of 'A' and 'B' will the impulsive component be unimportant and then only when the combination of flyover height and ambient noise is such that the 'signal to noise ratio' is low i.e. when either the flyover height or ambient noise level is high.

In this context the ambient noise, it should be noted it is that actual being experienced by the observer and not the value associated with the general locale which is of interest. If, for example, a residence is located in a busy urban area near a major road it is often assumed that the ambient noise levels will be relatively high. This may be the case at the part of the property facing the road, but as illustrated diagrammatically in Figure 14, the area facing away from the direct path of the traffic noise will be shielded and relatively low levels can exist. Consequently, many residential properties including those in urban and city areas experience low ambient noise levels and it is this localized environment that is relevant. Conversely, the acoustic signal from the helicopter is unshielded and radiates directly on to the property. This is particularly significant for low altitude level flyovers during which the impulsive thickness/HSI, BVI and tail rotor noise are all radiated forward and can be at a level such that for a significant period of time only these intrusive sounds are audible.

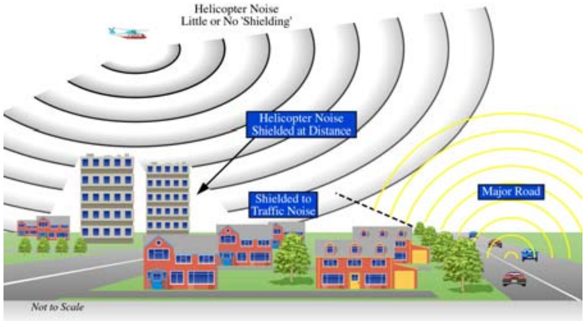

Figure 14: Helicopter noise Directivity and Effect of Shielding on Community Noise Exposure

SUBJECTIVE CONSIDERATIONS

The study reported in this paper shows that there is a need to consider the *character* as well as the absolute noise levels of sound heard by an observer. It is extremely difficult to quantify the effect on individuals of particular sounds in terms of a subjective weighting, but studies undertaken at Westland Helicopters (now part of AgustaWestland) in the period 1975 - 1985 suggested values of 4 to 6 dB(A) and 6 to 9 dB(A) should be added to measured levels to account for signals with high levels of tail rotor noise and high levels of impulsive (BVI) noise respectively (12,13). These values compare well with the quantitative results determined from the review reported in this paper.

When the information available was examined initially, a number of observations could not be explained. Further analysis showed that if an operation involves a mixture of helicopters with high levels of BVI, HSI, TRI and/or tail rotor noise and those without such sources, the least acceptable will tend to dictate the level of public acceptance. Thus a few *noisy* aircraft can create adverse response which will then affect the public response to all helicopters. If, however, the number of operations of noisy helicopters is very low this may not always be the case. In Aberdeen, Scotland one type of helicopter – Bell 212 - that generates high levels of impulsive noise (HSI and BVI) is known to provoke adverse public response. However, because of the small number of daily flights made by this aircraft and the careful selection of routes, it does not appear to detract from a generally acceptable level of public acceptance.
Also when addressing such operations it is important that the temperature and hence the advancing blade tip Mach number is also taken into consideration.

CONCLUDING REMARKS

The reaction to helicopters and heliports is dependent on several factors, some of which are completely unrelated to to the absolute level of the helicopter noise. These non-acoustic phenomena described collectively as *virtual noise* are usually triggered by acoustic noise although there is some evidence of a visual trigger. The non-acoustic component can dictate the level of public response to helicopters under certain circumstances. In addition it appears that the *startle effect* resulting from low level flyover also contributes to annoyance, and perceived safety, of helicopter operations in area where such flights are used and/or allowed.

The authorities, both internationally within ICAO and nationally, often argue that decreasing the absolute level of helicopter noise by lowering the noise certification limits or introducing operational noise limits, will dramatically improve the public acceptance of helicopters and solve most of today's objections to the level of noise generated by helicopters. The studies conducted by the authors reported in this paper do not support this view. The subjective character of the sound is equally or more important than the maximum noise level. The sound quality of the noise at levels 20 dB or more below the maximum level provides the initial audible cues that alert an individual to the presence of a helicopter i.e. provide the trigger for the *virtual noise* effect. It follows that improvements to the noise signature by reducing or eliminating the impulsive sources will result in greater public acceptance irrespective of the absolute noise level generated. This can be achieved by using main and tail rotors with low tip speeds, 705 ft/s (215 m/s) or less, and associated thin blade sections, low noise tip shapes, increased number of blades, etc. It also implies that many of today's small and medium size helicopters which have tip speeds well above that suggested will need to fly at 2000 ft to 4000 ft and that the use of noise abatement procedures for normal operations are essential. Also they will need to fly much slower than anticipated if impulsive noise is not to create a problem.

Ultimately however, there is certainly a need for more research into the subjective response to helicopter noise - the main activity in this area was over 20 years ago and there as been since little examination of these aspects. From the industry point of view (operators and manufacturers) it is essential to establish what *really* needs to be done to improve public acceptance and indeed, whether or not helicopter noise is a genuine problem, affecting a significant percentage of the population rather than just a vocal minority.

It follows that when designing a helicopter to have low noise characteristics the operating environment needs to be taken into account because of the impact of low temperature on the level of the total noise and more importantly the impulsive noise content. Thus, designs to achieve a high degree of public acceptance should not be based only on achieving compliance with the noise certification limits. It is also essential to take into account the sound pressure level and the subjective characteristics of noise throughout the period over which it is detectable i.e. well outside the 'maximum - 10 dB' range used to calculate EPNL and SEL. This is particularly important if high tip speeds are being considered for the main and/or tail rotor.

ACKNOWLEDGEMENTS

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