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Should Helicopter Noise Be Measured Differently From Other Aircraft Noise? - A Review of the Psychoacoustic Literature

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FOREWORD

This review of the psychoacoustic listerature on the human response to helicopter impulsive noise is a companion to, and carried out on the same NASA contract as, a report prepared for Wyle Laboratories by John Ollerhead, University of Technology, Loughborough, England (see Reference 24). The latter report presents the results of the most comprehensive study to date on noise metrics suitable for helicopters. The conclusions reached on this independent review of the literature are in general agreement with the experimental findings of the companion study.

1.0 INTRODUCTORY SUMMARY

The regulation of aircraft noise has been a concern of many nations for over 20 years. Methods for measuring the noise from conventional takeoff and landing (CTOL) aircraft have been elaborated so as to take into account the human response to this noise. The noise from helicopters, also known as vertical takeoff and landing (VTOL) aircraft, is distinctly different from the noise produced by CTOL vehicles. The question arises as to whether or not the methods commonly used to measure the noise from CTOL aircraft are adequate for use with VTOL aircraft. More specifically, can these CTOL methods handle the unique phenomenon of helicopter blade slap?

Helicopter or VTOL noise differs in many ways from that generated by CTOL aircraft. The main components of helicopter noise are the steady and impulsive parts of the rotor noise, engine noise, and gearbox noise. Since helicopters have vastly different structural and functional properties from CTOL aircraft, the acoustic characteristics of the two differ considerably in both the time and frequency domains. Furthermore, among helicopters considerable differences exist due to the particular type of craft and its operating mode.

The question of whether present measurement procedures for the noisiness or annoyance caused by aircraft can adequately account for the perception of helicopter blade slap is basically a psychoacoustic problem. The present report reviews 34 controlled psychoacoustic experiments related to this issue. These experiments employ different methods to present acoustic stimuli to listeners. Some present helicopter sounds live in the field, while others present reproduced examples of helicopter sounds, either in a free or a semi-reverberant acoustic field or over earphones. All of the reproduction methods share certain electroacoustic limitations, and some researchers have employed electronic simulation to overcome these and other restrictions encountered with using natural helicopter sounds.

Similarly various psychophysical methods have been used to measure the response of the listener in psychoacoustic tests. These have included comparison methods, adjustment methods, and rating scales. All these methods invoke verbal descriptors to restrict the response and statistical considerations to overcome variations among stimuli and individuals.

The outcome of the 34 psychoacoustic experiments reviewed in the present paper has been the development of a series of prediction methods and correction factors to account for the human response to helicopter blade slap. Several methods have been proposed, including those by South Africa, Westland Helicopters Limited, the National

Physical Laboratory, Aerospatiale, and the International Standardization Organization. There are additional methods based upon crest level, repetition rate, duty cycle, and a constant single-number adjustment. All of these yield different results.

A detailed review of the 34 studies indicated that several factors or variables might be important in providing a psychoacoustic foundation for measurements of helicopter noise. These are phase relations, tail rotor noise, repetition rate, generic differences between CTOL and VTOL aircraft, and crest level, in ascending order of possible importance. A careful analysis of the evidence for and against each factor reveals that, for the present state of scientific knowledge, none of these factors should be regarded as the basis for a significant impulse correction. The present method of measuring effective perceived noise level, L_{EPN}, for CTOL aircraft appears to be adequate for measuring helicopter noise as well. The inherent corrections for tonal components and exposure duration already incorporated in the L_{EPN} algorithm can account for people's reaction to helicopter blade slap. Thus the following conclusion is drawn from the often conflicting results of the 34 studies considered in the present review: there is apparently no need to measure helicopter noise any differently from other aircraft noise.

2.0 BACKGROUND

The regulation of aircraft noise has long been a concern in many nations. In the United States, the Federal Aviation Administration (FAA) was established in 1958 to regulate aircraft operations at a national level. By statutory authority given in the Federal Aviation Act of 1958,[1] which created the FAA, this agency is charged, among many other responsibilities, with the "protection of persons and property on the ground." This protection has been broadly interpreted to include protection against the adverse effects of aircraft noise. Other countries have evolved similar national policies.

2.1 CTOL Methods

One means of regulating aircraft noise is the specification of maximum permissible noise levels that an airplane can generate during qualification tests. In the United States, this is accomplished by Federal Aviation Regulations (FAR) Part 36, "Noise Standards: Aircraft Type and Airworthiness Certification".[2] This regulation prescribes noise standards for type certification of commercial transport aircraft and small planes of the conventional takeoff and landing type (CTOL). The noise levels for large jet aircraft are prescribed for three measurement locations and are specified for takeoff, approach, and sideline conditions (Appendix C). These levels vary for different gross weight categories of the aircraft, but the maximum effective perceived noise level (L_{EPN}) permitted at any location is 108 dB. Likewise, all propeller-driven small aircraft must meet a different noise standard (Appendix F). These airplanes are measured in level flyover at 300 m (1000 feet), with permissible levels again prescribed as a function of gross weight. The maximum level for all categories of small propeller planes is an A-weighted sound level (L_A) of 80 dB, as measured on the ground. Other nations have similar certification procedures for CTOL aircraft noise, and the International Civil Aeronautical Organization (ICAO) has issued recommendations on how this noise may be measured. ICAO has no regulatory authority, however. Thus each nation must adopt noise control regulations on its own, although many do follow ICAO recommendations. In the case of United States regulations, two separate measurement procedures and measurement units are prescribed: one for large, heavy jet and turboprop planes, and one for small, light propeller-driven planes.

2.2 VTOL Methods

The noise produced by helicopters, also known as vertical takeoff and landing (VTOL) aircraft, is quite different from that produced by CTOL vehicles. Helicopter noise differs from CTOL noise in frequency spectrum, level, and temporal flyby envelope. Furthermore, VTOL operations are vastly different from those of CTOL aircraft, yielding quite a different noise exposure pattern around a heliport than around a conventional airport. One salient distinguishing feature of helicopter noise is a periodic "slapping" or "banging" sound sometimes encountered during certain operations. Such helicopter "blade slap" is not always present, but certain kinds of helicopters tend to produce this distinct impulsive sound quite often, particularly on approach. It is generally considered that this periodic impulsive blade-slap sound is annoying to people.

The increased use of helicopters for convenient, fast, flexible transportation has raised the question in several countries of whether this type of aircraft needs to be regulated for its noise output. If certification as to noise is deemed necessary, this poses a further question of whether the present certification procedures for CTOL aircraft are satisfactory for use with VTOL vehicles. In particular, are the noise measurements currently specified adequate to account for the unique helicopter blade-slap phenomenon, or should certain impulsive noise corrections be added? This question is fundamentally a psychoacoustic one, involving how people respond to the impulsive noise produced by certain helicopter maneuvers.

3.0 PHYSICAL STIMULUS

Before any psychoacoustic information can be properly evaluated, the physical helicopter sound that forms the stimulus should be examined. The physical noise must be measured and analyzed as a first step in assessing the human response to this noise source.

3.1 Noise Source Mechanisms

Helicopter noise principally emanates from three major sources: (1) main rotor or main and tail rotors; (2) drive engine(s); and (3) gearbox(es). All of these sources produce a broadband random noise spectrum as well as discrete tonal frequency components. Under some conditions, the rotors may generate blade-slap impulsive noises. An excellent review of the physical source mechanisms of helicopter noise can be found in Magliozzi et al.[3] The following brief summary is based largely on their review.

3.1.1 Rotor Noise

Rotor noise contains discrete frequency components known as rotational noise harmonics, which occur at multiples of the blade passage frequency. These are produced by the loading of the rotor blade causing a rotating pressure field. By interaction with ingested turbulence or tip vortices, a considerable enhancement of this harmonic content can occur. Moreover, when the forward speed of the advancing blade exceeds some critical Mach number, an impulsive noise can be generated with sharp peaks in the acoustic waveform. Rotor noise also contains random broadband noise components, probably due to turbulence in the flow encountered by the passing blade. The frequency distribution of this broadband noise is principally determined by the velocity of the blade and the amount of the turbulence.

3.1.2 Impulse Noise

Impulsive rotor noise can be considered as a special case of rotational noise. In a narrowband analysis, many harmonics are revealed that decay slowly with harmonic order. A time-history analysis is characterized by sharp impulse waveforms occurring at the blade passage frequency. Interaction between tip vortices and the oncoming rotor blade is believed to be the primary physical mechanism of sound generation. Although analytical models of blade/vortex intersections have been developed, at present they can only produce qualitative predictions of measured waveforms. Many critical variables make estimation of the precise encounter of the blade with the vortex very difficult. For example, tip vortices follow very complicated and variable trajectories, so it is difficult to estimate where the vortex will be relative to the next blade pass. Further, the distribution of velocities within a vortex and the decay cycle of the vortex with time are difficult to assess. In addition, the aerodynamic operating point of the bending rotor blade is a function of many rapidly changing variables. Finally, tandem rotor helicopters can produce significant interaction between the passage of one blade and the downwash of another blade from a different rotor.

Impulsive noise observed during high-speed level flights of single-rotor helicopters is believed to be the result of compressible drag rise on the advancing rotor blade. Profile drag on the blades offers a source which is independent of the unsteady loading caused by vortex interactions. However, such drag is difficult to calculate accurately, especially near the blade tip. Torsional blade bending modes and lead-lag motions influence the angle of attack of the blade, and consequently its drag and noise. Thus, in summary, rotor impulsive noise is not a quantity that can be accurately predicted for any given new helicopter design. Nor, once it has been produced, can rotor impulsive noise be easily controlled by common noise containment and suppression mechanisms.

3.1.3 Engine Noise

Generally, helicopters are powered by internal combustion engines which provide power to the rotors and accessories. The vast majority of current helicopters use turboshaft engines. The noise from such engines has typically been partitioned into those noise sources that originate outside the engine and those that originate inside. The primary noise source coming from outside the engine is jet noise. This noise is produced by the momentum exchange between the higher velocity exhaust gases and the ambient air. Turbulent shear stresses caused by this momentum exchange result in pressure fluctuations and the generation of a radiated sound field, primarily downstream from the engine. Lighthill's[4] equation describes this source rather well; but typical helicopter engine exhaust velocities are so low (less than 100 m/sec, or 300 ft/sec) that jet noise is rarely a major component of the overall engine noise. Rather, internal noise sources – like combustion noise, strut noise, and turbine noise – are usually more prominent. However, these internal noises are often amenable to various forms of noise suppression.

3.1.4 Gearbox Noise

Gearbox noise is the result of imperfectly meshing gear teeth in the transmission of the helicopter. In addition to the intended constant force transmitted from the driving to the driven gear, these imperfections produce oscillating forces. The oscillating forces are transmitted as vibrations through the gears, bearings, and shafts, and finally radiate into the air from the gearbox housing or attached structures in the airframe. The noise is generally comprised of discrete frequency tones at the gear meshing frequency. If the tones are high enough in the frequency, classical vibration isolation and noise suppression should work well to attenuate them.

3.1.5 Generic Spectrum

The combination of these noise sources produce the characteristic sound readily recognized as helicopter noise. The generic noise spectrum of a typical helicopter is shown in Figure 1, compared with generic noise spectra for a CTOL jet and for turboprop or piston aircraft. The helicopter noise spectrum has considerably more energy at the low frequencies, and displays a more steady decrease in acoustic energy with increasing frequency. Thus the noise characteristics of helicopters are quite different from those of other aircraft.

3.2 Acoustic Characteristics

When one considers the wide variety of noise source mechanisms responsible for the generation of helicopter noise and the unique design, function, and operation of a helicopter, it is not surprising that helicopter noise should have acoustic characteristics that clearly distinguish it from CTOL noise.

3.2.1 Time Domain Analysis

At a microscopic level, with a time window of about 100 msec, the pressure waveform of helicopter noise can be examined as a function of time. When compared with CTOL jet takeoff noise, such a time-history analysis reveals the presence of somewhat more periodic or tonal energy in VTOL noise, even without any blade slap. Otherwise, the temporal waveforms look very similar, a mixture of periodic and random fluctuations. The presence of impulsive blade-slap noise changes the entire picture. Oscilloscope tracings of impulsive helicopter noise show distinct spikes at the blade passage frequency. These spikes can have rise times from less than 1 msec to about 5 msec, comparable decay times, and durations (for each pulse) of up to 20 msec. Actual examples vary greatly with helicopter type and operations, but the above values cover most of the range. The fundamental (blade passage) repetition rate or periodicity of the impulses also varies with different helicopters and operations, ranging from about 10 to about 60 Hz. Tail rotor noise has a higher fundamental frequency, ranging from about 60 to about 100 Hz, but usually exhibits a considerably lower pulse amplitude. The amplitude of the main rotor pulse may be extremely high relative to the other periodic

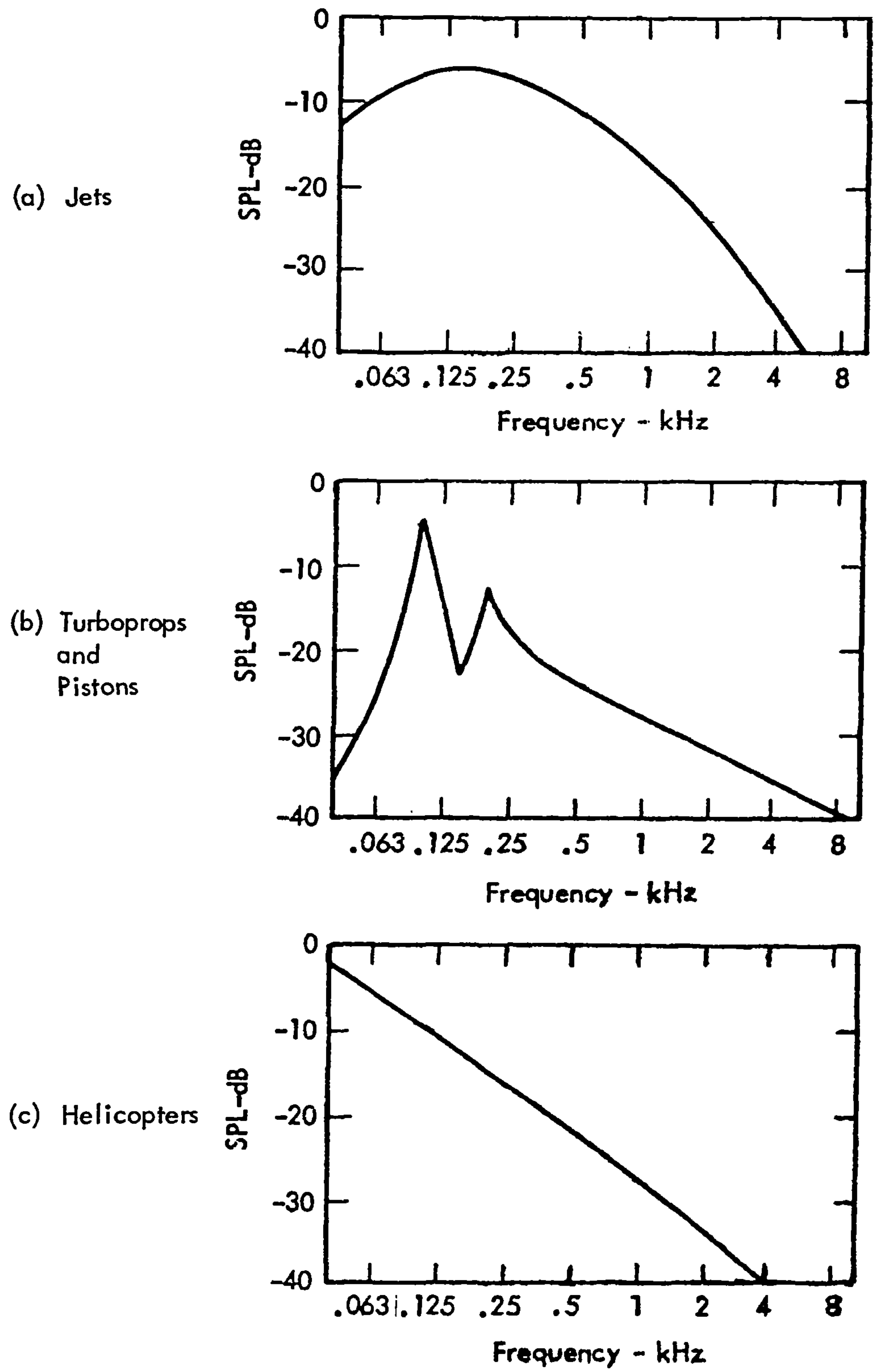


Figure I. Generic One-Third Octave Band Pressure Level Spectra for Different Aircraft, From Magliozzi.[3]

and random noise components, or it may be indistinguishable and buried among those other components. Thus crest levels may vary from a maximum of about 25 dB to a minimum of about 10 dB, which is the approximate crest level for a random white noise without any unusual impulses. Some typical short-term time histories of helicopter noise are shown in Figure 2, both with and without blade slap.

At a macroscopic level, with a time window of 20 to 30 seconds, one can examine the changes in sound pressure that occur during different stages of a helicopter flyby or other operation. The long-term time history of a helicopter flyby and that of a CTOL jet aircraft are somewhat different. The helicopter flyby is generally of longer duration, due to its lower airspeed. The envelope of a CTOL flyby is characterized by a rather steady rate of increase and decrease in noise level as the plane approaches and recedes from the measurement point. The helicopter envelope, on the other hand, grows gradually at first and then more rapidly as the overhead position is neared. The peak noise level occurs somewhat ahead of the actual overhead position, and is often accompanied by loud slapping and banging impulses. The decay of the helicopter envelope is like its rise, more severe near the overhead position, and more gradual as the craft moves farther away.

The transition that occurs just prior to and at the overhead position also contributes to the unusual sound of a helicopter flyby. The blade slap reaches a peak and disappears just as a Doppler shift is observed in the periodic frequency components. Thus the acoustic spectrum of a helicopter flyby is often drastically different on the approaching side than it is on the receding one. Such a severe transition is not encountered with most CTOL operations.

3.2.2 Frequency Domain Analysis

The detailed frequency spectrum of helicopter noise is far more complex than is indicated in the generic spectrum depicted in Figure 1. The spectrum of impulsive helicopter noise is characterized by considerable low-frequency energy at the blade passage frequency (10 to 60 Hz), representing the fundamental of the harmonic series comprising the periodic impulse waveforms. These harmonic multiples have decreasing amplitudes as the frequency increases, but significant amplitudes remain in a narrowband analysis at 1 kHz and above, as a result of the sharp rise times exhibited by the individual pulses. Thus the extreme low-frequency components are responsible for the deep thumping sounds of helicopter blade slap, while the relatively high-frequency components are responsible for the sharp cracking sounds. In addition, as mentioned earlier, the entire frequency spectrum changes radically during the course of a typical flyover. Figure 3 shows the short-term time history, one-third octave band spectrum, and the narrowband spectrum of simulated 40 Hz helicopter impulse noise alone, without the other random and

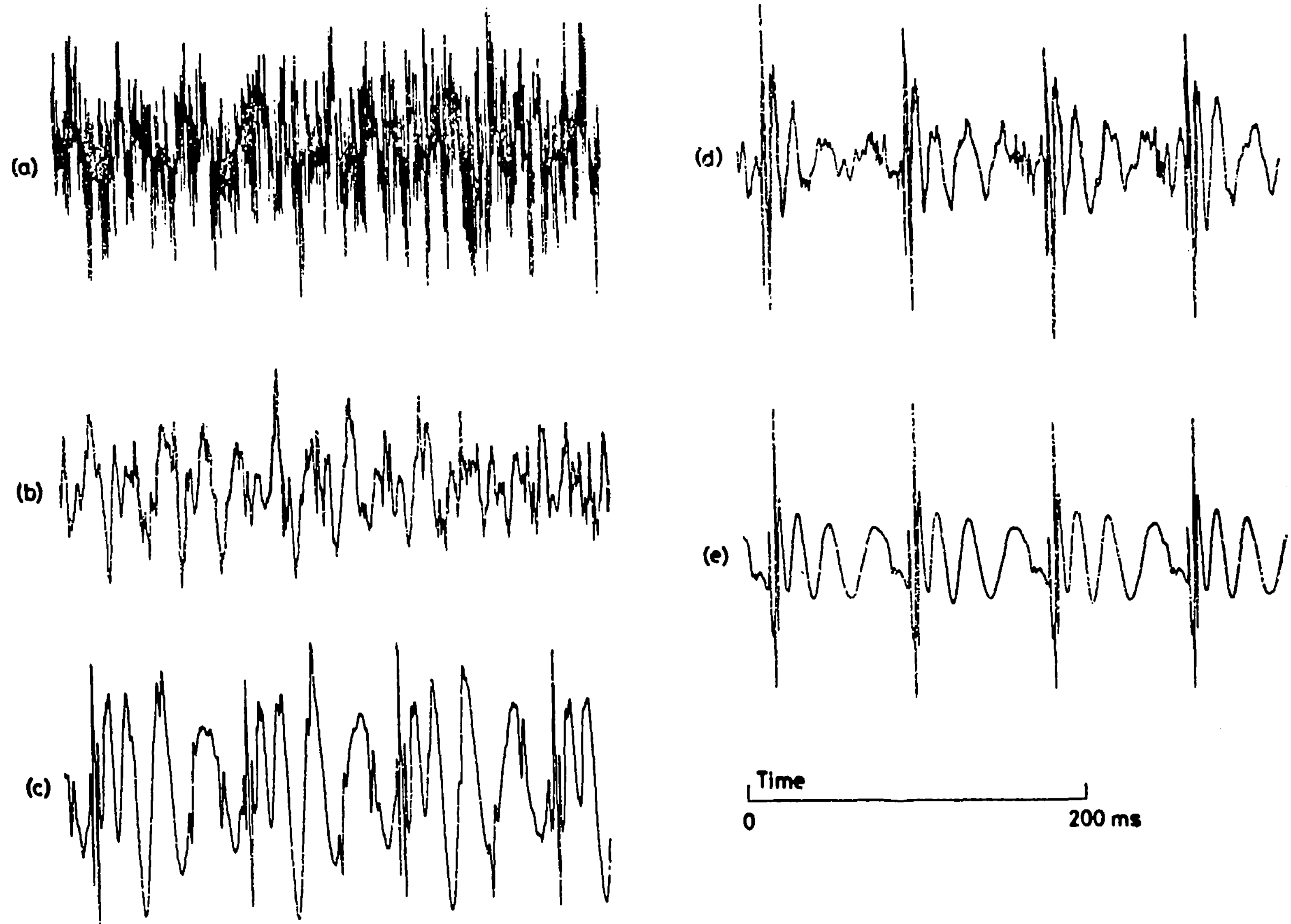
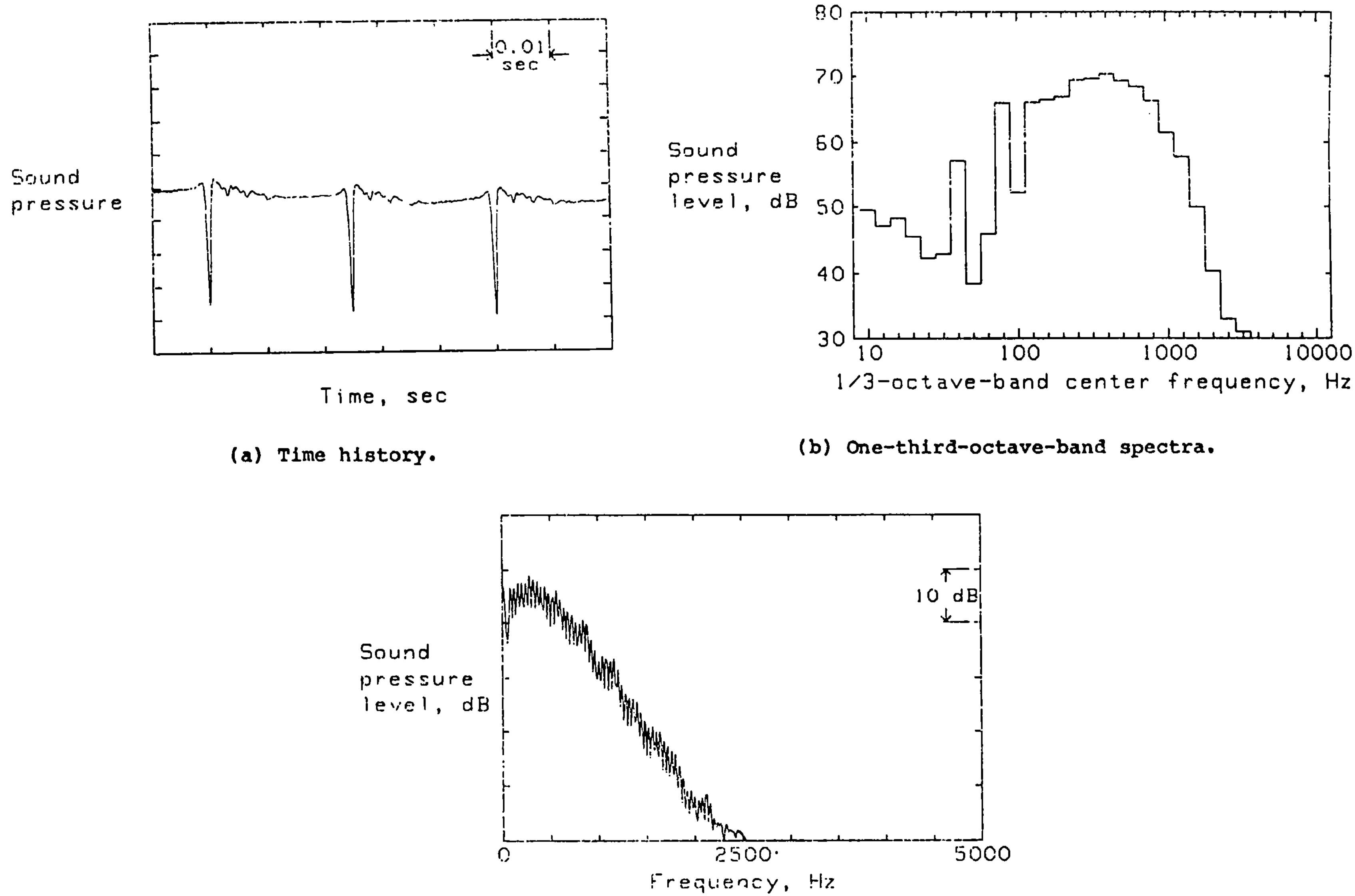


Figure 2. Time-History Noise Waveforms, From Berry et al.:[5]

(a) Wessex -- Hovering Without Blade Slap;
(b) V107 -- Hovering Without Blade Slap;
(c) UH1B -- Flyover at 90 knots;
(d) V107 -- Hovering With Blade Slap;
(e) UH1B -- Flyover at 120 knots With Blade Slap.



(a) Time history.

(b) One-third-octave-band spectra.

(c) Narrow-band spectra.

Figure 3. Characteristics of Simulated Helicopter Impulses With 40 Hz Repetition Rate, From Powell and McCurdy.[6]

periodic components always found in real samples. The figure shows the presence of a strong fundamental frequency component and many harmonics up to 2500 Hz. To obtain a more realistic picture of the entire sound, one should combine the generic spectrum shown in Figure 1 with the appropriate spectrum depicted in Figure 3.

3.3 Variations With Helicopter Type and Operations

Different types of helicopters produce different sounds, and the same helicopter can sound quite different during different operations or maneuvers.

3.3.1 Variations With Helicopter Type

Considerable variation in the noise characteristics of helicopters can be attributed to the specific type and design of the helicopter. The size of the helicopter will often determine the amount of noise that it produces, in particular the quality and degree of impulsive noise. If a helicopter is prone to be impulsive, a heavy helicopter will tend to produce more sustained or wider pulses. The blade passage frequency determines the repetition rate, so helicopters with more blades will have a higher frequency of repetition for the same rotor speed than those with fewer blades. Moreover, if there are two main rotors, the rotor noise can be rather complex, with two separate repetition rates having varying phase relations between them. When one considers the various noise source mechanisms enumerated under Section 3.1, and the multiplicity of combinations that different helicopter designs could conceivably produce, one can appreciate the vast degree to which the particular type and design of the helicopter can influence the characteristics of the noise emitted.

This same multiplicity of combinations also affords the engineer and the designer considerable opportunity to conceive of a relatively quiet helicopter from the outset. Given the technical specifications and tradeoffs required for a certain design, there are several things that can be done to reduce the probability of producing a noisy helicopter. Lower rotor speeds, and in particular tip velocities, are less likely to produce blade slap. If more lift is required, multiple blades could be added, as long as the rotor speed is sufficiently low. In addition, the blade cross-section and angle of attack can be modified to minimize blade/vortex interactions. These are just a few of many options available at the design stage for reducing possible noise problems, well before any noise suppression devices are considered.

3.3.2 Variations With Operations

Galloway[7] reported some of the variations that can exist in helicopter noise as a result of different modes of operation. This brief review of some of his work reveals several important variables.

For fixed-wing aircraft, the basic noise characteristics are controlled by the acoustical properties of the engines. Differences in both level and spectrum are associated with different power settings, as witnessed by the decidedly different takeoff and approach noises made by many commercial CTOL jet aircraft. Typically, a few important flight modes are characterized, and subsequent noise predictions are based upon this small subset. For each mode, at a fixed distance between the flight path and the observer, the duration of the acoustic event will be inversely proportional to the airspeed. Thus, for each of the primary operating modes, airspeed considerations may be directly incorporated into the duration correction in the L_{EPN} calculation scheme. Furthermore, for CTOL aircraft, there is often a close relationship between the power setting and the duration correction needed, thus simplifying the overall acoustic characterization.

The relationships between operating mode, engine power, and airspeed are not as restrictive in the case of helicopter noise. For fixed-wing aircraft in level flight, an increase in airspeed is generally proportional to an increase in power, or thrust. For helicopters, which can hover, rise, descend, fly forward, and sometimes even backward, the relationship is not as straightforward. Helicopters use a tradeoff in direct vertical lift and forward speed to operate over a wide speed range. At low airspeeds or during hover, the helicopter needs a higher power setting than at intermediate speeds. Likewise, at high airspeeds increased power is needed. Thus helicopters generally produce a minimum sound level at some intermediate airspeed, with higher sound levels at lower and higher airspeeds. This relationship may be seen in Figure 4, as well as some typical levels produced from 150m (500 feet).

For the same airspeed, helicopters often exhibit different sound spectra for approach versus level flight. During a landing approach, the helicopter is descending through its own main rotor downwash, resulting in a certain amount of blade slap, even in those helicopters which usually do not exhibit any blade slap in level flight. In the case of takeoff, this interaction does not occur, and most helicopter takeoff noise is, at least spectrally, rather similar to the level flight noise from that type of craft.

Hover operations with helicopters can be compared with stationary ground runup tests of the noise from fixed-wing aircraft. However, in the hover case the helicopter is actually supported above the ground by its rotor lift. Hover tests a short distance above the ground (1.5m) are generally characterized by rather large short-term temporal fluctuations of 5 to 10 dB. These are caused by basic operational instabilities involved in maintaining a hover over a single spot.

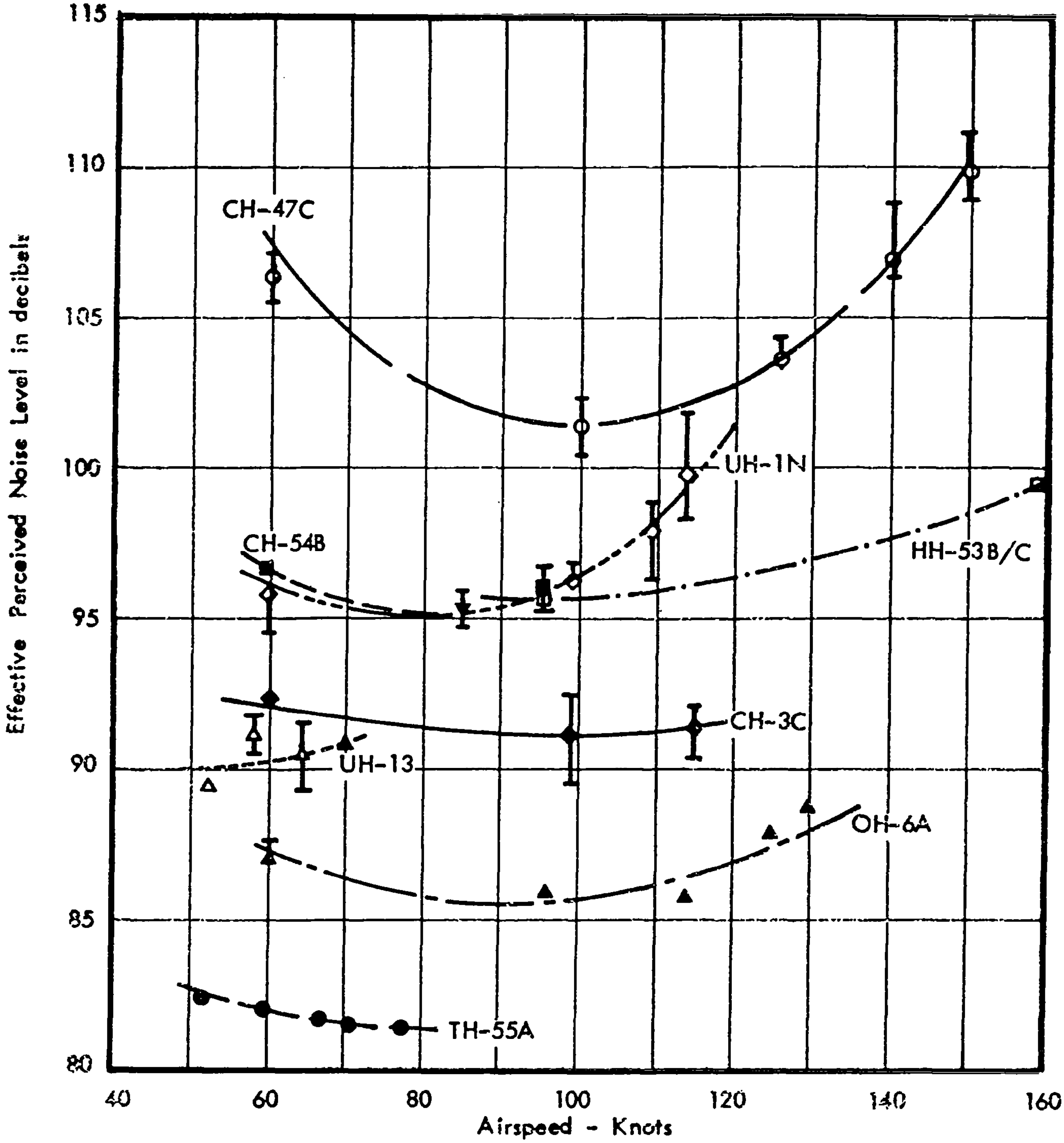


Figure 4. Variation of Effective Perceived Noise Level With Airspeed, 150m (500 ft) Flyover, From Galloway.[7]

4.0 HUMAN RESPONSE

There are two primary methods for determining the human response to noise stimuli. The first involves conducting rather carefully controlled psychoacoustic experiments, while the second involves making widespread community surveys of people's reactions in the field. The present paper will concentrate on 34 controlled psychoacoustic experiments (see Tables 1 to 4), because the experimental method typically can yield superior results for defining subtle corrections in the fine-structure of noise measurements.

4.1 Stimulus Presentation

Psychoacoustic experiments generally employ one of four methods to present acoustic stimuli to the participants in the experiment. These involve presenting the helicopter sounds: (1) live in the field, (2) reproduced in a free acoustic field, (3) reproduced in a semi-reverberant acoustic field, or (4) reproduced by means of earphones. Depending upon the means chosen, the subsequent results are often subject to interpretations and limitations based upon the unique advantages and disadvantages of the particular stimulus presentation method employed.

4.1.1 In The Field

Field experiments usually involve live stimulus presentation with one of two primary approaches. In the first approach, listeners are located outdoors, seated in areas near the operations of controlled helicopter flybys. Ideally, listeners should be located away from major reflecting surfaces – that is, either buildings or hard pavement surfaces – and away from unusual terrain conditions which could distort the path of the sound from the helicopter source. In the second approach, listeners are located inside a house or structure which is typical of the one they might occupy during actual exposure. In both cases, calibration is typically achieved by placing a microphone or an array of microphones at the approximate ear height and in the approximate location of the listener or listeners. The field conditions should be calibrated by checking for reflections with an impulsive test noise source, or by making measurements of spreading by the inverse square law.

The field method has several distinct advantages. It possess a high degree of face validity, because the people are receiving the stimulus in a live mode much as they would in the actual exposure condition. Thus the field method eliminates all of the problems inherent in electronic reproduction of the stimulus, and automatically incorporates, in a realistic way, all of the complex defraction patterns around the head and other phenomena in the immediate acoustic environment of the listener.

The primary disadvantages lie in stimulus specification and repeatability. Since the actual live helicopter flyovers must be conducted outdoors, there are many opportunities for perturbations in the presentation of the sound stimulus. For example, changes in wind, the temperature or humidity, refraction by temperature gradients, and many local climatic changes all affect the sound heard by the listener. In addition, the helicopter itself is difficult to control when attempting to create repeated exposures, as the pilot cannot fly the craft twice in exactly the same manner, especially as regards blade slap. Consequently, the experimenter faces certain limitations in insuring that his measurements accurately reflect the stimulus, and that repeated stimuli are as similar to one another as possible.

Of the 34 studies reviewed in the present paper, only two of them employed the field method using live stimuli from actual helicopters.

4.1.2 Free Acoustic Field

Many psychoacoustic experiments with helicopter noise have been conducted under free-field conditions. In this case, the listener or listeners are seated in a room which has been specially treated to eliminate acoustical reflections. To the extent that reflections have been reduced, and the inverse square law describes the spreading of sound in the room, such a facility presents a relatively unobstructed acoustic field for the presentation of impulsive noise stimuli by means of loudspeakers. The free field is typically calibrated by measuring the spreading and attenuation of sound with distance, or by investigating individual reflections by impulse or time-delay techniques. As in field experiments, a microphone is placed in the approximate location of the listener's head in order to make both calibrations and stimulus measurements.

The free-field method has one great advantage over many of the other reproduction methods. The elimination of reflections and reverberation make it much easier to control and specify an impulsive stimulus. If reflections were present, the impulse would become confused with its reflections.

There are some disadvantages to the free-field method, however. First, the exact position of the listener's head relative to the loudspeaker source is important in determining what is the actual stimulus delivered to the listener's ear. Defraction around the human head produces a sound shadow that can affect the acoustic waveform delivered to each ear. Second, this method assumes that the loudspeaker is a point source of sound, and that the listener is in the far acoustic field at all frequencies, something which is difficult to achieve in practice. Of course, the method does require electronic reproduction of the helicopter impulse sound, a non-trivial accomplishment at best. A further disadvantage is the unusual visual and acoustic atmosphere that such a free-field room often presents to the listener. Such a situation is hardly realistic from the point of view of psychologically simulating exposure conditions in the field.

Of the 34 studies reviewed, eight of them employed the free acoustic field method using loudspeaker reproduction.

4.1.3 Semi-Reverberant Acoustic Field

The semi-reverberant sound field is often employed as a more realistic alternative to the free-field as regards psychophysical simulation. With this method, rooms with typical furnishings or theaters or auditoriums with commonly encountered visual and acoustic properties eliminate some of the artificiality that can be present in the free-field method. Some sound absorption and deadening may be selectively applied in the room, but it is not the intent to eliminate as many reflections as possible, as in the case of the free field. Instead, the room has a reverberation time not unlike that of most office or home environments. Calibration is once again achieved by a microphone or microphones located in the vicinity of the listener. Typical calibration measurements involve determination of reverberation time and frequency response of the facility.

This method has the advantage of somewhat enhanced realism and is also easier to implement, since semi-reverberant rooms are readily available without serious modification. The face validity is fairly good, as considerable freedom is allowed for making the environment comfortable and realistic.

The main disadvantages concentrate around the nature of the sound field and the difficulty of reproducing impulses in a semi-reverberant field. Care must be taken as to loudspeaker placement and loudspeaker/room interactions. Certain vibrational modes in the room must be avoided, and no matter how carefully the room is calibrated, there will be considerable confusion and intermingling of the direct impulsive sound with its many echoes. This process of intermingling direct and reflective sound is basically a statistical one, adding considerable uncertainty to the stimulus.

Of the 34 studies reviewed, 13 of them employed a semi-reverberant acoustic field to present the helicopter stimuli.

4.1.4 Earphones

Many psychoacoustic experiments with helicopter noise have been conducted using earphones. This method is relatively inexpensive and, with proper controls, can reproduce impulsive stimuli with some degree of fidelity. There are several types of earphones in common use, but unfortunately many of the psychoacoustic studies on helicopter noise do not specify which type was employed. Supra-aural earphones are those having an electroacoustic driver pressing against the outer surface of the listener's pinna, with a shallow rubber pad or cushion between the driver and the ear. Circum-aural earphones have a cup that surrounds the entire pinna, producing a better seal than can be achieved with supra-aural earphones. Ear speakers represent a third type, where the driver is held some distance from the ear by a sponge-like acoustically permeable material, and the electroacoustic driver radiates into the ear canal from a short distance.

Depending upon the type of earphone employed, different calibration procedures may be required. These range from the use of hard-walled or soft-walled acoustic couplers, to employment of artificial ear models or the insertion of miniature microphones in the ear canal underneath the earphone. The latter method has the advantage that the miniature microphone can be used during actual stimulus presentation to monitor and measure the stimulus as well.

Earphone presentation has many advantages as regards cost and convenience. No elaborate rooms or structures are needed, with only minimal concern attending the acoustic environment in which the listener is located. As long as the ambient noise levels are sufficiently low, earphone presentation can be used practically anywhere. Furthermore, with special attention to details of calibration, earphones can reproduce an impulsive stimulus somewhat better than a loudspeaker.

The disadvantages of the earphone method concern the lack of psychological realism and the high degree of artificiality experienced by the listener wearing this atypical device on his head. Further problems are associated with maintaining a proper seal between the earphone and the ear to ensure adequate low-frequency reproduction, and maintaining sufficiently precise positioning of the earphone device to ensure adequate high-frequency reproduction.

Of the 34 studies reviewed, 11 of them employed earphones to present the acoustic stimuli to the participants.

4.1.5 Reproduction Problems

Irrespective of the method of stimulus presentation with the exception of the field method, certain common difficulties exist in electronically reproducing highly impulsive acoustic signals. The extreme crest factors often encountered with helicopter blade-slap noise are difficult to capture within the limited dynamic range of most tape recording devices. Even if a faithful magnetic tape of impulsive helicopter noise could be obtained, the electroacoustic transducer, be it a loudspeaker or an earphone, also has certain inherent limitations. The movement of the radiating diaphragm in the transducer device exhibits both inertia and momentum characteristics which make it difficult to follow the exact waveform of the helicopter impulse. Thus it is highly unlikely that any electronic reproduction system could be configured that would reproduce an impulsive helicopter sound with sufficient fidelity to be indistinguishable from the real sound presented in close temopral proximity to a jury of listeners. Nevertheless, only two of the 34 studies reviewed in the present paper employed the field method with live helicopter operations.

4.1.6 Simulated Helicopter Sounds

In order to overcome some of the tape recording and other electro-acoustic reproduction problems associated with presenting recordings of actual helicopter sounds over either loudspeakers or earphones, some investigators have chosen to employ electronically synthesized sounds that simulate various portions of real helicopter noise. Since the impulsive component is generally the most difficult part of the helicopter noise spectrum to reproduce, most of these experiments synthesize the individual helicopter pulses from a few cycles of a sine wave or from a square, triangular, or modulated waveform. Simulation by a synthetic waveform offers more control over the pulse parameters and more ability to overcome reproduction problems by choosing and modifying appropriate pulse signatures. Sometimes the continuous non-impulsive portion of the helicopter noise spectrum is also simulated, most often by means of a band of random noise shaped to have a frequency spectrum like that of a helicopter. In both instances, simulation offers improved uniformity and consistency in comparing the results of different experiments, since signal parameters can be accurately specified and repeated in different laboratories. The major drawback of the simulation approach, however, lies in a certain degree of artificiality in the subtle details of the acoustical stimulus. There are also some important methodological limitations involving possible stimulus sampling errors and psychological biases. These are explained in detail in Section 7.6. In the 34 studies reviewed in the present paper, there were 37 choices made between recording actual helicopter sounds and synthesizing them (some experiments used both). Nineteen studies employed recorded sounds; 18 employed synthetic ones.

4.2 Psychophysical Methods

Just as there is a variety of means to present the physical stimulus in psychoacoustic experiments, so there is a variety of psychophysical methods that can be employed to measure the response of a listener. As with stimulus presentation methods, the various psychophysical methods also exert an important influence on the interpretation of the psychoacoustic data obtained.

4.2.1 Comparison Method

One popular procedure for determining human response to helicopter noise employs the method of paired comparisons. In this method, two sounds are presented, one after another, with a brief response period to follow. The listener is asked to compare these two sounds on a certain psychological dimension. For example, sound A is followed by sound B, and the participant in the experiment indicates whether sound A is louder than sound B, or vice versa. The dimension upon which the sounds are judged can vary depending upon the verbal instructions given to the listeners.

The method of paired comparisons typically employs a standard stimulus which does not change in spectral characteristics, and a set of comparison stimuli which may vary both in spectrum and in level. In some experiments with helicopter noise, the standard stimulus is presented at a variety of levels and compared with each comparison stimulus. In other experiments, the standard stimulus remains fixed at a certain level, and the comparison stimulus is presented at a variety of levels to bracket the point of judged equality. In certain threshold experiments, a two-alternative forced choice (2AFC) variation is employed.

The method of paired comparisons has several advantages. First, it is a rather precise psychophysical method, typically producing standard deviations with acoustic stimuli of the order of 1 to 3 dB. The method also avoids complex conceptual scales and memorized standards, as the stimuli are presented in close temporal proximity and the judgments can be based on immediate sensory experience.

The method is not without its disadvantages, however. A paired comparison experiment usually takes a relatively long time to complete, since many different comparisons are necessary to obtain even a single psychophysical data point. Often such experiments employ relatively brief stimulus durations (several seconds), which are not very realistic when compared with typical exposure durations to helicopter noise. When the method is employed to compare complete helicopter flyovers (15 to 20 seconds), auditory memory must be invoked and the judgments become more difficult. There is also an inherent order bias which must be overcome. In addition, the method of paired comparisons is best suited for yielding information about relative sound levels, and can only be used indirectly to estimate absolute perceived levels.

Of the 34 studies reviewed, 11 employed some variation of the comparison method.

4.2.2 Method of Adjustment

Some psychoacoustic experiments on helicopter noise employ the method of adjustment. In this method, the listener has control over certain parameters of one stimulus and adjusts those parameters until a perceptual match is achieved with a standard stimulus. The two stimuli are typically alternated every few seconds so that the listener receives several samples of each sound during the adjustments. The listener usually indicates to the experimenter when the match has been achieved, and the experimenter records the final value of the parameter that had been under the listener's control, typically the sound level of one stimulus.

A variation of this method, or more precisely a hybrid between the paired comparison and adjustment methods, is called Parameter Estimation by Sequential Testing (PEST). In this case, depending upon the listener's previous judgments, predetermined statistical considerations modify the stimulus adjustments to be made on the next trial, instead of having the listener in direct control. In the PEST technique, the listener has limited indirect, rather than direct, control over the unfolding of the experimental protocol.

The method of adjustment is really a variant of the method of paired comparisons, but has one major advantage over the version employing constant, non-adjustable stimuli. The method of adjustment is usually quicker to execute. Large numbers of repetitions of each level of one of the sounds do not have to be presented in order to calculate a single perceptual match. The participant devises his own efficient strategy to make the match, eliminating the necessity of presenting extreme stimulus combinations, where judgments are practically obvious. Thus the observer can concentrate upon listening to sounds that are perceptually similar, and therefore of more importance in making a precise determination. In addition, since the sounds are generally continually alternated, some of the order bias associated with paired comparisons can be eliminated. The price for this increased efficiency is a somewhat more difficult statistical treatment of the data and a concomitant increase in variability. Otherwise the method of adjustment generally shares the same advantages and disadvantages as the method of paired comparisons from which it is derived.

Of the 34 studies reviewed, eight of them employed the method of adjustment.

4.2.3 Rating Scale

Another popular psychophysical method uses rating scales to generate responses that give an indication of absolute perceived levels for acoustic stimuli. There are two major types of rating scale methods, category scales and magnitude estimation scales. In the category scale method, the listeners are given a continuum that is partitioned into different categories defined by verbal descriptors. For example, an 11-point category scale may be represented by a line divided into ten spaces, with one end of the continuum being labeled "extremely noisy", and the other end "not noisy at all". After having heard the acoustic stimulus, the participant makes a mark on the scale as to where the particular stimulus lies. In some cases, the labels for the intervening intervals between the end points of the scale are left undefined. In other instances, a category scale may be divided into seven categories, each of which will have a verbal label indicating varying degrees along some psychological dimension.

In the method of magnitude estimation, the end points of the scale are not defined. Instead of using different verbal descriptors to lay out the measurement scale, the natural number system is employed. Typically, a standard or modulus stimulus is provided and arbitrarily assigned a certain value, say 100. The participants are instructed to judge other stimuli quantitatively in reference to that modulus stimuli. Thus, if the particular comparison stimulus is perceived to be twice as annoying as the modulus, then a mark is made on the scale at the point labeled "2". If, conversely, it is judged to be only half as annoying as the modulus, a mark is made at the point labeled "1/2". Of course, the numbers can be used without a linear scale representation, and the listeners can simply supply whatever numbers correspond to their judgments.

Category scales have the primary advantage that they are quick and easy to implement. Scaling methods do not necessitate the presentation of a large variety of stimulus levels in order to obtain a single data point. They are also more suitable for work in the field, where it may be difficult to produce a standard stimulus (the standard helicopter flyby) for each comparison being made. Even when a modulus stimulus is used, the modulus can be delivered infrequently during the experiment just to remind the participant of its characteristics, and auditory memory can be invoked for the majority of the judgments.

Of the 34 studies reviewed, 16 of them, or practically half, employed some sort of rating scale.

4.2.4 Verbal Descriptors

In a fundamental sense, all of the psychophysical methods enumerated above measure the ability of people to discriminate, i.e., to note differences between, distinguish, or differentiate features of their environments. Whether it be a comparison or a rating experiment, the various stimuli being judged usually vary in several dimensions at once. Verbal instructions to the observers must be employed to separate out or abstract those aspects of the stimulus that the observers should pay attention to, and those that should be ignored. For example, a helicopter noise with blade slap might be compared to one without. The listener is asked to adjust the two until they are "equally annoying", or to judge which is "more annoying", or which gets a higher score on an "annoyance" rating scale. Often the purpose of the latter two judgments is ultimately, through statistical means, to estimate at what levels the two sounds are "equally annoying". But, even at this point, the sounds are not equal in all respects, otherwise the judgment would be trivial. Rather, the observers have been instructed to judge the sounds according to their "annoyance", and ignore other aspects. At the point of perceptual equality with regards to "annoyance", the sounds could conceivably be quite different with regards to "loudness", "noisiness", "objectionability", "discomfort", etc. Certainly they would be different with regards to qualities such as "slapping", "thumping", "banging", etc.

Thus the selection of an appropriate verbal descriptor upon which to base the psychophysical judgment is an important consideration. Experimental evidence varies on the degree to which the commonly used descriptors like "loudness", "noisiness", and "annoyance" yield the same or different results. The subtle effects of using different verbal descriptors are not well understood for non-impulsive sounds, with different experiments pointing toward different conclusions. For impulsive-type sounds, even more uncertainty exists. Nevertheless, for non-impulsive stimuli, it may be surmised that "noisiness" and "annoyance" will yield similar results, but "loudness" may not, especially as regards the effects of duration. Since few psychoacoustic experiments with helicopter-type noises employ the "loudness" descriptor, the problem can largely be circumvented in the present review.

The 34 studies reviewed in the present paper offered 40 opportunities for a different verbal descriptor to be used in a psychoacoustic experiment (some studies employed multiple descriptors). Twenty-three studies employed "annoyance" (over half); six studies employed "noisiness"; three employed loudness"; and two each employed "disturbance", "intrusiveness", "acceptability", and "detectability".

4.2.5 Statistical Considerations

Psychoacoustic experiments on helicopter blade slap involve several important statistical concerns. First, the stimuli must be tested with sufficient controls and a sufficient number of times to accurately and reliably estimate the point of perceptual equality for each individual observer, and for the entire sample of observers participating in the experiment. In repeating the same physical stimulus on different occasions to the same listener, different judgments are often obtained. Many repetitions of the identical stimulus may be needed before a stable point of perceptual equality can be determined. Nevertheless, a statistical estimate of this perceptual match must be made, either directly or indirectly, in order to specify the amount by which a certain psychoacoustic measurement scale underestimates or overestimates helicopter noise samples that contain blade slap relative to those that do not. This is the primary means that has been used for determining whether an impulse correction is needed and, if so, how much.

In the case of reproduced helicopter noise stimuli, repeating the same stimulus at different times is not difficult. Magnetic tapes may be repeated with considerable consistency. Furthermore, if echoes and reflections are eliminated, helicopter noise stimuli may be reproduced by loudspeakers or earphones in much the same manner from trial to trial, although resemblance to the original helicopter noise signature may still be questioned. In the case of helicopter noises presented live in the field, as mentioned earlier, reproducibility may present more problems. In this instance, the variability encountered in repeated presentations of the same nominal stimulus would have to be added to that inherent in making a single psychophysical match.

Those statistical considerations mentioned above are primarily methodological and descriptive in nature. Most psychoacoustic experiments involve inferential statistical concerns as well. One wishes to generalize from the sample of helicopter sounds tested to the population of helicopters producing actual noise exposures. Likewise one wishes to generalize from the sample of listeners participating in the experiment to the population of listeners actually impacted by helicopter noise. In both cases, careful sampling procedures must be elaborated to ensure that representative and adequate samples of helicopter sounds and research participants have been selected so as to make quantitative distinctions in the data with a certain level of statistical confidence.

Thus, with some assumptions being made about the distributions and errors involved in both the physical and psychophysical measurements, one can specify the number of helicopters, listeners, and/or repetitions that might be needed for a given experimental design. The criterion for deciding these sample sizes and repetition numbers is the resolution on the dependent variable that one wishes to achieve. For hypotheses concerning impulse corrections in measuring helicopter noise, such a criterion might be the determination of a possible correction with a 95 percent confidence interval of ± 2 dB. Unfortunately, many of the psychoacoustic studies on helicopter noise do not reflect adequate sensitivity to important statistical considerations. The 34 studies reviewed in the present paper exhibit a wide variation in the number of different helicopter sounds sampled (range: 2 to 89) and the number of research participants sampled (range: 4 to 1,009). As a result, the conclusions presented in a particular study are often difficult to evaluate and reconcile with the findings of another study.

5.0 PREDICTION METHODS

Several prediction methods have been proposed to estimate the human response to helicopter imulsive noise from physical measurements without the need to conduct a separate psychoacoustic experiment in each instance. Several of these have been proposed at different times for incorporation into national and international standards.[8]

5.1 South African, Δ_{SA}

This method was proposed by the South African National Research Institute delegation to the Committee on Aircraft Noise (CAN) of the International Civil Aeronautical Organization (ICAO). As reviewed by Galloway,[9] it involves making two sound level meter (SLM) measurements. First, the time-integrated A-weighted sound level is measured with a precision SLM, set on "slow" averaging time. Simultaneously, the time-integrated A-weighted sound level is measured on a separate impulse SLM, set on "impulse" averaging time. The difference between the two, in decibels, is the Δ_{SA} impulse correction, which is added directly to any base measurement to account for the human response to the impulsive noise from helicopters.

5.2 Westland Helicopters Limited, Δ_{WHL}

This method was proposed by Westland Helicopters Limited in England. In this method, the noise is electronically processed through two separate channels and combined by visually analyzing a graph of the result. The first channel consists of an octave band centered at 250 Hz that feeds a peak detector with a 200 μsec rise time. The second channel consists of a precision SLM with an A-weighting frequency characteristic and a "slow" response integration time. The outputs of these channels are plotted graphically and a visual running average is determined. The Δ_{WHL} impulse correction is derived from the difference between these two graphic levels, expressed as a crest level in decibels. Δ_{WHL}, which can be added to any one of several commonly used noise measurement scales, is found by referring to the transfer function given by Leverton and Southwood.[10] In this version, there is a lower crest level cutoff of 11 dB, below which the impulse correction is defined as zero, but there is no upper limit. The 11 dB cutoff eliminates many fluctuating but non-impulsive noises, e.g., white noise has a crest level of about 10 dB. The function rises linearly from a 0 dB correction for an 11 dB graphic crest level to a 6 dB correction for a 20 dB graphic crest level.

5.3 National Physical Laboratory, Δ_{NPL}

This method was proposed by the National Physical Laboratory in England. In this method, the noise signal is passed through an A-weighted filter (without detection) and then digitized at a 20 kHz sampling rate through an anti-aliasing filter with a 10 kHz cutoff frequency. As presented by Berry et al.,[5] the measurement involves computing a quantity based upon processing these samples with two different integration times: a long time constant, T, and a short time constant, τ. The mean square sound pressure over the longer period T would then be defined as

$$S = \frac{1}{T} \int_0^T p^2 \, dt \ ,$$

and the running average of the mean square for each of the shorter periods τ, within T, would be defined as

$$f(j) = \frac{1}{\tau} \int_0^\tau p^2 \, dt \ ,$$

where $j = 1, 2, 3, \ldots n$.

The measure of impulsiveness is taken to be the extent of the deviations between the running values f(j) and the long-term mean square S. Similar to the variance statistic in descriptive statistics, a quantity $\bar{T}$ is defined as

$$\bar{T} = \sum_{j=1}^{n} \left[\frac{f(j) - S}{S}\right]^2 .$$

With a value for the short integration time τ of 10 msec, the series of quantities f(j) is calculated in real time from the sample values of the original signal amplitude V_i (proportional to sound pressure) according to

$$f(j) = \frac{1}{m} \sum_{i=1}^{m} V_i^2 \ ,$$

where m is the number of samples in the time τ seconds. Thus for a sample rate of 20 kHz and $\tau = 10$ msec, m = 200.

The longer integration time T is taken to be 0.5 sec and the successive values of $f(j)$ during each 0.5 sec period are used to calculate the long-term mean square S by

$$S = \frac{1}{n} \sum_{j=1}^{n} f(j) \quad .$$

Since $n = T/\tau$, with $T = 0.5$ sec and $\tau = 10$ msec, then $n = 50$. For each period of 0.5 sec, the quantity $\bar{T}$ is calculated as shown above.

The quantity $10 \log \bar{T} = x$, is used in conjunction with a transfer function to obtain the impulse correction, Δ_{NPL}. Δ_{NPL} is proposed as an addition to L_{PNT} values, at 0.5 sec intervals, before calculating L_{EPN}. The transfer function first suggested is

$$\Delta_{NPL} = k\,(x - x_o) \quad , \quad \text{in dB},$$

where x is $10 \log \bar{T}$ for the signal, x_o is $10 \log \bar{T}$ for A-weighted white noise, and k is approximately 0.6. In this formulation, Δ_{NPL} is limited to a maximum of 6 dB, and Δ_{NPL} is zero for $x \leq x_o$. A later formulation reduced k to equal 0.3.[9]

5.4 Aerospatiale, Δ_A

This method was proposed by the French firm, S.N.I. Aerospatiale. As presented by d'Ambra and Damongeot,[11] the method incorporates sensitivity to pulse shape, pulse amplitude (crest factor), and pulse repetition rate, all combined into one impulse correction. In this method, the helicopter noise signal is passed through an A-weighting filter followed by a low-pass filter with a 2500 Hz cutoff. The signal is then digitized, without detection, at a 5000 Hz sampling rate. N samples of V_i (proportional to sound pressure) are taken every 0.5 sec and the quantity CI (coefficient d' impulsivite) is computed as

$$CI = \frac{\frac{1}{N} \sum_{i=1}^{N} V_i^4}{\left[\frac{1}{N} \sum_{i=1}^{N} V_i^2\right]^2}$$

This quantity is used to derive a correction factor, Δ_A, from the transfer function:

$$\Delta_A = 1.14\,(CI - 3) \quad .$$

A subsequent version was proposed in terms of $\log_{10}$ CI and can be expressed as

$$\Delta_A = -6.875 + 13.75 \log CI \quad ,$$

where $o \leq \Delta_A \leq 5.5$.[9] If perceived noisiness is considered as the base unit, Δ_A is added to the L_{PNT} values, in each 0.5 sec interval, before computing L_{EPN}.

5.5 International Standardization Organization, Δ_{ISO}

This method was recommended by Working Group 2 (TC43/SC1) of the International Standardization Organization (ISO),[10] based in Geneva, Switzerland. It was recommended to Working Group B of the Committee on Aircraft Noise (CAN) of the International Civil Aeronautical Organization (ICAO). However, the method was never finally adopted by ICAO, which chose instead not to incorporate any impulse correction for helicopter noise.

The method is based upon the Δ_{NPL} correction, but with the specification of sampling parameters that make it very close to the Δ_A correction. In the ISO version, the short sampling time, τ, is defined as $200\,\mu$sec, which corresponds to the 5000 Hz digitizing rate of the French Δ_A computation scheme. In this version, the sampling rate itself is set at 5000 Hz. Thus, in the Δ_{NPL} formulation, $m = 1$ and $f(j) = V_i^2$, the square of the sampled value. Consequently,

$$S = \frac{1}{n} \sum_{i=1}^{n} V_i^2 = \frac{1}{N} \sum_{i=1}^{N} V_i^2 \quad ,$$

since n, the number of short-term integration periods, becomes the same as N, the number of samples in the long-term integration period. Likewise,

$$S^2 = \left[\frac{1}{N} \sum_{i=1}^{N} V_i^2 \right]^2 \quad .$$

By multiplying out the expressions in the equation defining $\bar{T}$ and by using the above relationship, it can be shown mathematically that

$$\bar{T} = \left[\frac{\sum_{i=1}^{N} v_i^4}{N \left[\frac{1}{N} \sum_{i=1}^{N} v_i^2 \right]^2} \right] - 1 = \left[\frac{\frac{1}{N} \sum_{i=1}^{N} v_i^4}{\left[\frac{1}{N} \sum_{i=1}^{N} v_i^2 \right]^2} \right] - 1 \ .$$

When the above equation is compared with that defining CI according to the Δ_A method, the Δ_{NPL} and the Δ_A methods are seen to be related in a simple manner,

$$\bar{T} = CI - 1 \ .$$

Thus the Δ_{ISO} method represents a true compromise between the English and the French proposals as far as the computation of the internal impulse correction is concerned. The different sampling parameters do necessitate a somewhat different transfer function, however. In the case of Δ_{ISO},

$$\Delta_{ISO} = 0.8 \ (x - 3) \ , \quad \text{in dB} \ ,$$

where $x = 10 \log \bar{T}$, with the limitation that

$$0 \leq \Delta_{ISO} \leq 5.5 \text{ dB} \ .$$

For larger values of x, Δ_{ISO} is held constant at 5.5 dB.

5.6 Crest Level, Δ_{CL}

This method was proposed by the American delegation to ISO, and exists in several versions. As presented by Galloway,[9] this method has the advantage of being implemented with only analog instruments, avoiding the necessity to digitize the signal. The simplest approach obtains the difference between the maximum peak A-weighted sound level and the maximum A-weighted sound levels that occur during the helicopter flyover, irrespective of when these maxima occur. These values may be conveniently obtained with an impulse sound level meter having a "peak hold" feature, and can be expressed as a crest level in decibels.

An alternate method is to obtain a value for the crest level in each 0.5 sec interval of the signal. This can be accomplished with a sound level meter by actuating the peak hold reset each 0.5 sec with the same timing signal that is used to generate the one-third octave spectrum readout in an L_{EPN} analysis. The peak level in each 0.5 sec interval can be easily measured by means of an analog-digital converter on the output of the sound level meter. With most instrumentation, the A-weighted sound level in each 0.5 sec interval is obtained from the normal one-third octave spectrum analysis used in the L_{EPN} computations.

These two forms of Δ_{CL} are sometimes denoted CL_M and $CL_{0.5}$. The transfer function for applying them to base psychoacoustic measurement units involves direct application of the obtained crest level minus a constant for white noise (about 12 dB). Thus $\Delta_{CL} = CL - 12$, which can be added to each 0.5 sec interval in the case of computations of L_{EPN}.

5.7 Repetition Rate, Δ_R

This method was proposed by the American delegation to ISO as an additional feature that could be added to any of the other impulse corrections in order to take account of the repetition rate of the helicopter impulses. In work reported by Galloway,[9] a regression analysis was made on human response data to helicopter blade slap with different repetition rates for the separate impulses. The regression analysis resulted in an impulse correction based on repetition rate that could be added directly to L_{EPN} values. It is defined for helicopter sounds as

$$\Delta_R = 0.74 + 0.20\ \gamma_o ,$$

where γ_o is the pulse repetition rate.

5.8 Izumi Method, Δ_{75A}

This method was presented in a paper by Izumi.[12] The method is based upon a regression equation that describes a convex three-dimensional surface relating the major parameters found by the author to be important in noisiness judgments of repetitive impulsive noises. This surface is part of what the author calls "The Perceived Noisiness Model of Periodically Intermittent Sounds 75-A", which is summarized by the following formula:

$$\Delta_{75A} = 6 \log_{10} BTF + (10 \log_{10} \gamma_o + 10)(1 - e^{-15 T_{off}}) .$$

Here BTF = burst time fraction, or on-time/on + off-time, γ_o = repetition rate in pulses per second; and T_{off} = off-time in seconds. Some of the input parameters for this method are different from those used in the other methods. The Δ_{75A} method requires accurate definition of the pulse geometry, in particular the duty cycle of the pulse train. Such measurements are not typically reported in psychoacoustic experiments on helicopter noise and may be difficult to realize given the nature of actual helicopter blade-slap pulses. Thus, while of considerable interest, the Δ_{75A} impulse correction has not been computed for the majority of the collected pool of empirical psychoacoustic data.

5.9 Constant Correction, Δ_C

This method is proposed in ISO R1996, titled "Procedure for Describing Aircraft Noise Around an Airport".[13] It simply calls for a constant correction or penalty of +5 dB for any impulsive-type sound, where impulsivity is left loosely defined. The impulse correction is of one all-or-none sort, with a single number to be applied to all impulsive sounds that pass the "impulsivity" criterion, irrespective of the degree of impulsiveness or repetition rate.

6.0 EXPERIMENTAL RESULTS

Many psychoacoustic experiments have been conducted concerning people's reactions to the unique properties of helicopter noise. The present review examines 34 of them. The studies are listed in alphabetical order by the first author's name in Tables 1 through 4. These tables provide abbreviated information about important features of each experiment. Table 1 gives a profile of who conducted the study, i.e., the experimenter(s), and who served as listeners, i.e., the participants. Table 2 describes the physical stimuli that were presented. Table 3 gives the psychophysical procedures employed. Finally, Table 4 outlines the results of the investigation. The remainder of this section presents a short summary of each study, also in alphabetical sequence.

6.1 Ahumada and Hersh

Ahumada and Hersh[14] investigated the detectability of 10 Hz pulse trains with identical Fourier series amplitudes presented over earphones. Variations in phase were applied to a train of 10 msec simulated helicopter rotor pulses with an envelope maximum for the amplitude spectrum of 100 Hz. In a two-alternative forced choice detectability task, four observers were not able to detect any differences between pulses that had altered phase relations. Thus phase relations did not appear to be an important factor in the detection of helicopter impulses, and presumably in the above-threshold perception of them as well.

6.2 Berry, Fuller, John, and Robinson, 1

Berry *et al.*[5] conducted an experiment with recorded samples of impulsive helicopter noise. Eleven different recorded samples of helicopter noise were *a priori* assigned by the experimenters to categories of high, moderate, and slight degrees of impulsiveness. Twenty research participants compared various pairings of these sounds for relative annoyance in a free acoustic field. The participants did not base their annoyance judgments on the relative impulsiveness of the sounds, but rather on other ill-defined features of the stimulus. Thus, with recorded samples, no discrimination of impulsiveness was observed in annoyance judgments, and no impulse correction was needed.

6.3 Berry, Fuller, John, and Robinson, 2

Berry *et al.*[5] investigated the effect of pulse width and crest level on annoyance judgments of helicopter blade slap presented in a free field. Single-cycle sine wave pulses were superimposed on a shaped noise chosen to simulate the continuous portion of a

Table I

Studies and Participants

STUDY						PARTICIPANTS						
No.	Author	Year	Variable	Place	Publication	Number	Age	Sex	Paid	Screened	Trained	Sampling
1.	Ahumada	1979?	Phase	Stanford		4			2 Staff		2 Highly	
2.	Berry 1	1979	Impulsiveness	NPL	NPL	20			Yes & Staff			
3.	Berry 2	1979	Pulse Width & Crest Level	NPL	NPL	31		4M, 27F	Yes & 3 Staff			
4.	Berry 3	1979	Crest Level vs. Overall L	NPL	NPL	20		3M, 17F	Yes & 2 Staff			
5.	Crosse	1960	Peak Level	Nat. Gas Turbine	Journal	1009	10-70					Show Visitors
6.	d'Ambra	1978	Crest Level & Repetition	Aerospatiale	NASA	60				Audiol.		
7.	Fidell	1981?	Pulse Width & Repetition	BBN		4			Yes			
8.	Galanter	1977	Crest Level	Columbia	ASA Meeting	40				Audiol.		
9.	Galloway	1977	Crest Level & Repetition	BBN	BBN	20	18-32	10M, 10F		$\pm$20 dB of ISO	Some	College Students
10.	Izumi	1977	Temporal Pattern	Muroran	Journal	7 8	20s	7M 7M, 1F		Audiol.	Highly	Students & Staff
11.	Klumpp	1978	Impulsiveness	NOSC	NOSC	19 9	21-52 19-27	14M, 5F 4M, 5F	Staff Yes	Most Audiol.	50 Items	Staff & Students
12.	Lawton	1976	5 Parameters	NASA	NASA	40	19-63	20M, 20F		20 dB	3 Trials	
13.	Leverton	1972	Slap vs. No-Slap	ISVR	NASA							
14.	Leverton	1976	Slap vs. No-Slap	Westland	Westland	20	18-35		Staff		50%	

Table I (Continued)

STUDY						PARTICIPANTS						
No.	Author	Year	Variable	Place	Publication	Number	Age	Sex	Paid	Screened	Trained	Sampling
15.	Leverton	1978	Tail Rotor	Westland	NASA							
16.	MAN	1975	V/STOL vs. CTOL	MAN	FAA	35	20-59	15M, 20F		Audiol.	Previous Experim.	
17.	Munch	1973?	Crest Level	Sikorsky	NASA							
18.	Ollerhead P	1982	Methodology	Loughborough		40						
19.	Ollerhead M	1982	Types & Operations	Loughborough		36-40	19-23	50%M				College Students
20.	Ollerhead R	1982	Methodology	NASA		80	Mean 34	20M, 60F	Yes			Local Residents
21.	Patterson	1977	Types & Operations	USAARL	USAARL	25	18-46	5M, 20F		$\pm$20 dB ANSI		
22.	Pearsons	1967	Helicopter Type	BBN	FAA	21	17-23	13M, 8F		$\pm$20 dB $\pm$50		College Students
23.	Powell 1978	1978	5 Parameters	NASA	NASA	40	19-63	20M, 20F		20 dB	3 Trials	
24.	Powell* 1980	1980	Phase	NASA		30						College & Older
25.	Powell 1981	1981	Types & Operations	NASA	NASA	91	18-72	11M, 80F	Yes	Audiol.	One Flyby	Local Residents
26.	Powell	1982	Crest Level & Repetition	NASA	NASA	48			Most	Audiol.	3 Trials	Local Residents

* Conducted by Ahumada, reported by Powell.

Table I (Continued)

STUDY						PARTICIPANTS						
No.	Author	Year	Variable	Place	Publication	Number	Age	Sex	Paid	Screened	Trained	Sampling
27.	Robinson	1961	VTOL vs. CTOL	NPL	Journal	570			Staff			Staff
28.	Shepherd	1978	Types & Operations	Bionetics	NASA	32			Yes	Audiol.		Local Residents
29.	Southwood	1976	Crest Level	Westland	Westland	19 20	Most 20-30	18M, 1F 20M	Staff	No	Some	Staff
30.	Southwood	1979	Slap vs. No Slap	Westland	Westland	20						
31.	Stent	1978	Crest Level & Repetition	Westland	Westland	20 21	18-35 19M, 2F	20M	Staff			Staff
32.	Sternfeld	1978	Crest Level	Boeing	NASA	25	21-36	15M, 10F	Contrib.	Audiol.		Civic Group
33.	Sternfeld	1974	Proposed V/STOL	Boeing	NASA	28	21-34	22M, 6F	Contrib.	20 dB		Civic Group
34.	Williams	1980	Types & Operations	Westland	Westland	40	Approx. 20-45	20M, 20F			12	

Table 2

Stimuli

		HELICOPTER SOURCE			BROADBAND				IMPULSIVE			
No.	Author	Signal	Type	Flight	Spectrum	Level	Duration	Rise/Fall	Spectrum	Crest Level	Width	Repetition
1.	Ahumada	Synthetic	N/A	N/A	White Noise	$L_{SP} = 85$	1 sec		100 Hz max.	$d' = 13.1-19.9$		10 Hz
2.	Berry 1	Recorded	5	5 Hover 6 Flyby	11	$L_A = 74-78$ dB	10-15 sec		11	$\Delta_{NP} = 8-23$ dB		
3.	Berry 2	Synthetic	Wessex	Hover	Shaped Noise	$L_{AS} = 70-80$ dB	10 sec	0.5 sec	1-Cycle Sine	10-20 dB	200-800 Hz	10 Hz
4.	Berry 3	Synthetic	Wessex	Hover	Shaped Noise	$L_{AS} = 70-80$ dB	10 sec	0.5 sec	1-Cycle Sine	10-20 dB	400 Hz	10 Hz
5.	Crosse	Synthetic	N/A	N/A	CTOL Jet	Peak L_{SP} = 85-95 dB	4 sec	0.2 sec	Amplitude Modulation	Modulation Depth=8dB	50% Duty Cycle	4-12 Hz
6.	d'Ambra	Mixed Recorded	Several	70-148 kt.	Real	$L_{PN} = 90-100$ dB			Mixed Recorded	12-20 dB		10-35 Hz
7.	Fidell	Synthetic	N/A	N/A	Pink Noise	Threshold	0.5 sec		Sine, Square, Triangle		100 Hz-1 kHz	5-100 Hz
8.	Galanter	Recorded	B-347 UHI-G	3 Modes For Each	6	$L_A = 83-95$ dB			6	18.5-26.8 dB		11-25 Hz
9.	Galloway	Synthetic & Recorded	6	5 Level 3 Approach	8 Recorded 2 Shaped	L_{EPN}=80dB	10 sec	0.5 sec & 2 dB/sec	8 Real 13 Sine	$\Delta L = 15-30$ dB	138-250 Hz	11-30 Hz
10.	Izumi	Synthetic	N/A	N/A	None	$L_A = 70$ dB	0.25-1 sec	10-80msec	Intermittent Pink	30 dB >Backgr.	16-950msec	1-4 Hz
11.	Klumpp	Recorded	4	Various	70 Real	$L_A = 50-90$ dB	7 sec	0.5 sec	35 with Bladeslap	Hi >15 dB Lo <12.5dB		
12.	Lawton	Synthetic	36	Hover	Shaped Noise	$L_{SP} = 65-80$ dB	10 sec	0.5 sec	Sine Bursts	15-25 dB	1-3 Cycles 200-400 Hz	8-20 Hz
13.	Leverton	Recorded	5		Real				Recorded			
14.	Leverton	Synthetic & Recorded	15	Hover and Flyby	Real		30 sec		9 Simulated 2 Recorded			

Table 2 (Continued)

		HELICOPTER SOURCE			BROADBAND				IMPULSIVE			
No.	Author	Signal	Type	Flight	Spectrum	Level	Duration	Rise/Fall	Spectrum	Crest Level	Width	Repetition
15.	Leverton	Synthetic & Recorded										
16.	MAN	Recorded & Synthetic	4	2 Takeoff 7 Approach	33	L_A = 57-73 dB	5-45 sec		9 Recorded 7 Simulated	Half had Slap	House-Filtered	
17.	Munch	Recorded	6	Various	9	L_{SP} = 97-116 dB			4 Impulsive	9-19 dB		
18.	Ollerhead P	Recorded	Various	Various	33	L_A = 68-97 dB	17-207 sec					
19.	Ollerhead M	Recorded	16	Mostly Flyby	89 VTOL 30 CTOL	L_A = 68-93 dB			16 Impulsive			
20.	Ollerhead R	Recorded	16	Mostly Flyby	63 VTOL 30 CTOL	L_A = 68-93 dB			13 Impulsive			
21.	Patterson	Live	9	12 Maneuvers	Live	Integ.L_A = 79-96 dB			Live			
22.	Pearsons	Recorded	5		8	L_A = 79-90 dB	3-16 sec	100 msec				
23.	Powell 1978	Synthetic	36	Hover	Shaped Noise	L_{SP} = 65-80 dB	10 sec	0.5 sec	Sine Bursts	15-25 dB	1-3 Cycles 200-400Hz	8-20 Hz
24.	Powell * 1980	Synthetic	N/A	N/A	None	L_A = 89-95 dB	3-12.5 sec		4	Δ_{ISO} = -0.3-10.5 dB		10-20 Hz
25.	Powell 1981	Live	OH-58A 204B	Flyby	Various				3 Levels			
26.	Powell	Synthetic	N/A		None	L_{SP} = 68-80 dB	6 sec		Pulse Trains	3.2-19.3 dB		10-115 Hz

* Conducted by Ahumada, reported by Powell.

Table 2 (Continued)

		HELICOPTER SOURCE			BROADBAND				IMPULSIVE			
No.	Author	Signal	Type	Flight	Spectrum	Level	Duration	Rise/Fall	Spectrum	Crest Level	Width	Repetition
27.	Robinson	Recorded	3	Various	4 VTOL 1 CTOL	L_{SP} = 82-102 dB	4 sec	0.1 sec	2 Impulsive			
28.	Shepherd	Recorded	OH58A 204B	Flyby		L_A = 72-90 dB				3 Levels		
29.	Southwood	Synthetic			White Noise & Wessex	L_A = 60-80 dB		0.1 msec	Single Sine	40 dB Range	250 Hz	15.7 Hz
30.	Southwood	Recorded	B204B	3 RPM Values	Notch-Filtered	L_A = 78 99 dB	10-15 sec		Real			
31.	Stent	Synthetic			Wessex	L_A = 80 dB		Sharpened	1-Cycle Sine	11-17 dB	167-667 Hz	10-40 Hz
32.	Sternfeld	Mixed Recorded			3 Shaped Noises	L_A = 60 dB			Simulated	Adjustable: 10-34 dB		10-30 Hz
33.	Sternfeld	Synthetic	Proposed VSTOL		Simulated	L_A = 52-74 dB			Simulated			
34.	Williams	Synthetic & Recorded	4	Flyby & Hover	11 Recorded & Simulated				6 Simulated 5 Recorded			

Table 3

Procedure

		STIMULUS PRESENTATION			PSYCHOPHYSICS						
No.	Author	Source	Surround	Calibration	Descriptor	Method	Standard	Trials	Groups	Precision	Theory
1.	Ahumada	Earphones			Detectability	2AFC	None				Signal Detectability
2.	Berry 1	Loudspeaker	Free		Annoyance	Paired Comparisons	Crossed				Torgerson
3.	Berry 2	2 Loudspeakers	Free		Annoyance	Paired Comparisons	Crossed				Torgerson
4.	Berry 3	Loudspeaker	Free		Annoyance	Paired Comparisons	Crossed				Torgerson
5.	Crosse	Loudspeaker	Theatre	±2.5 dB	Disturbance	Paired Comparisons	Crossed		21 Seats	±1 dB	
6.	d'Ambra				Annoyance	Paired Comparisons	Non-Impulsive			±1.3 dB	
7.	Fidell	Loudspeaker	Free		Detectability	2AFC	None	PEST			Signal Detectability
8.	Galanter	Loudspeaker	Living Room		Annoyance	Magnitude Estimation	CTOL Jet				
9.	Galloway	Loudspeaker	Free		Annoyance	Paired Comparisons	S-61 Non-Impulsive	PEST		±1 dB	
10.	Izumi	Loudspeaker	Semi-Reverb.	RT = 0.06 sec NR = 28	Loudness & Noisiness	Paired Comparisons	Steady Pink	8	3-4		
11.	Klumpp	Loudspeaker	Studio	Freq.Resp. ±5 dB	Annoyance	Magnitude Estimation	Bus	1	7-19		
12.	Lawton	Loudspeaker	Auditorium		Annoyance	10-Point Scale	None	2		Non-Signif. Test-Retest	
13.	Leverton	Loudspeaker	3		Loudness & Annoyance	Adjustment	Non-Impulsive				
14.	Leverton	Earphones			Intrusion or Annoyance	Adjustment	Non-Impulsive				

Table 3 (Continued)

		STIMULUS PRESENTATION			PSYCHOPHYSICS						
No.	Author	Source	Surround	Calibration	Descriptor	Method	Standard	Trials	Groups	Precision	Theory
15.	Leverton				Annoyance?						
16.	MAN	Loudspeaker	Semi-Reverb.		Annoyance Acceptability	Magnitude Estimation	USASI Noise			± 3 dB	
17.	Munch				Annoyance		Various				
18.	Ollerhead P	Earphones			Noisiness & Annoyance	11-Point Scale & Adjustment	Several			± 1 dB	
19.	Ollerhead M	Earphones		Std.Dev. ± 2 dB	Annoyance	11-Point Scale	T-28 Airplane		6	± 1.5 dB	
20.	Ollerhead R	Earphones & Loudspeakers	Living Rm. + Theater	Std.Dev. ± 4 dB	Annoyance	11-Point Scale	T-28 Airplane		5		
21.	Patterson	Live	Outdoors		Acceptability	Magnitude Estimation	C-47 Aircraft				
22.	Pearsons	Loudspeaker	Free		Noisiness	Paired Comparisons	DC-8 and Simulated		6	Std.Dev. 5.4 dB	
23.	Powell 1978	Loudspeaker	Auditorium		Annoyance	10-Point Scale	None	2		Non-Signif. Test-Retest	
24.	Powell * 1980	Earphones			Annoyance	11-Point Scale	None				
25.	Powell 1981	Live	Outdoors & Indoors		Noisiness	5-& 11-Point Scales	None		15-40		
26.	Powell	Loudspeaker	Free	Ambient $L_A = 15$ dB	Annoyance	11-Point Scale	None				

* Conducted by Ahumada, reported by Powell.

Table 3 (Continued)

	STIMULUS PRESENTATION			PSYCHOPHYSICS						
No. Author	Source	Surround	Calibration	Descriptor	Method	Standard	Trials	Groups	Precision	Theory
27. Robinson	3 Loud-speakers	Semi-Reverb.	± 5 dB	Loudness & Disturbance	Paired Comparisons	Crossed	1	10	± 1 dB	
28. Shepherd	Loudspeaker	Simulated Room		Noisiness	11-Point Scale	Crossed		2		
29. Southwood	Earphones			Intrusiveness or Annoyance	Adjustm.	Non-Impulsive			± 4 dB	
30. Southwood	Earphones				Adjustm.	Non-Impulsive				
31. Stent	Earphones			Annoyance	Adjustm.	Non-Impulsive				
32. Sternfeld	Earphones	Control Room		Annoyance	Adjustm. & Rating	Shaped Noise		Single	3-6 dB	
33. Sternfeld	Loudspeaker	Office Trailer	± 2 dB	Annoyance	9-Point Scale	None		6		
34. Williams	Earphones			Noisiness	Tolerance, Adj.,& Rating	Non-Impulsive				

Table 4

Results

		MAJOR FINDING		IMPULSE CORRECTION				REPETITION CORRECTION		HELICOPTER CORRECTION	
No.	Author	Variable	Effect	Needed	Unit	Crest Level	Amount	Needed	Amount	Needed	Amount
1.	Ahumada	Phase	No	N/A							
2.	Berry I	Impulsiveness	No	No							
3.	Berry 2	Pulse Width & Crest Level	Yes	Yes			5 dB				
4.	Berry 3	Crest Level vs. Overall L	Yes	Yes	Δ_{NPL} or Δ_A	20 dB	5 dB				
5.	Crosse	Peak Level	Yes	No				No	0 dB	Yes	Peak L_{PN}
6.	d'Ambra	Crest Level & Repetition	Yes	Yes	Δ_{ISO}		6 dB	No	0 dB		
7.	Fidell	Pulse Width & Repetition	Yes	Yes	d'		Up to 10 dB	Yes	-1 to -2 dB		
8.	Galanter	Crest Level	Yes	No						Yes	2-3 dB
9.	Galloway	Crest Level & Repetition	Yes	Yes	A		7 dB	Yes	3 dB		
10.	Izumi	Temporal Pattern	Yes	N/A				Yes	3 dB		
11.	Klumpp	Impulsiveness	Yes	Yes	L_A		2 dB				
12.	Lawton	5 Parameters	Yes	Yes	L_A	25 dB	2 dB	Possibly	?		
13.	Leverton	Slap vs. No Slap	Yes	Yes	L_A		6 dB				
14.	Leverton	Slap vs. No Slap	Yes	Yes	L_A	20 dB (250 Hz)	6 dB				

Table 4 (Continued)

		MAJOR FINDING		IMPULSE CORRECTION				REPETITION CORRECTION		HELICOPTER CORRECTION	
No.	Author	Variable	Effect	Needed	Unit	Crest Level	Amount	Needed	Amount	Needed	Amount
15.	Leverton	Tail Rotor	Yes	Yes			6 dB				
16.	MAN	V/STOL vs. CTOL	Yes	No			Negative			Yes	-2 dB
17.	Munch	Crest Level	Yes	Yes	SENEL	20 dB	12 dB				
18.	Ollerhead P	Methodology	No	N/A							
19.	Ollerhead M	Types & Operations	Yes	No						Yes	-2 dB
20.	Ollerhead R	Methodology	Minor	No						Yes	-2 dB
21.	Patterson	Types & Operations	Yes	No						Yes	2 dB
22.	Pearsons	Helicopter Type	Yes	No						No	0 dB
23.	Powell 1978	5 Parameters	Yes	Yes	L_A	20 dB	3 dB	Possibly	?		
24.	Powell * 1980	Phase	Yes	N/A							
25.	Powell 1981	Types & Operations	Yes	No			Negative			Yes	-2 dB
26.	Powell	Crest Level & Repetition	Yes	Yes	L_{PN}		Up to 13 dB	Yes	1.5 to 3 dB		

* Conducted by Ahumada, reported by Powell.

Table 4 (Continued)

		MAJOR FINDING		IMPULSE CORRECTION				REPETITION CORRECTION		HELICOPTER CORRECTION	
No.	Author	Variable	Effect	Needed	Unit	Crest Level	Amount	Needed	Amount	Needed	Amount
27.	Robinson	VTOL vs. CTOL	Yes	No						No	0 dB
28.	Shepherd	Types & Operations	No	No						No	0 dB
29.	Southwood	Crest Level	Yes	Yes	L_A	20 dB	6 dB				
30.	Southwood	Slap vs. No-Slap	Yes	Yes	L_A		5-8 dB				
31.	Stent	Crest Factor & Repetition	Yes	Yes	L_A	20 dB	7.5 dB	Possibly	-3 dB		
32.	Sternfeld	Crest Level	Yes	Yes	L_C		5 dB ?	Possibly	?		
33.	Sternfeld	Proposed V/STOL	Yes	No						No	0 dB
34.	Williams	Types & Operations	Yes	Yes	L_A		8.5-9 dB				

Wessex helicopter noise spectrum. The sine waves ranged from 200 to 800 Hz and had a repetition rate of 10 Hz and a crest level of 10 or 20 dB. Thirty-one participants compared various combinations of the above parameters as well as combinations with the shaped noise alone. When unidimensional psychophysical annoyance scales were applied to the data obtained, the resulting annoyance scale values showed good agreement with the progression of impulsiveness from non-impulsive to a crest level of 10 dB to one of 20 dB. Thus crest level did play a significant role in determining annoyance judgments, although in this experiment pulse width did not yield such an orderly relationship. In some cases, longer pulses were judged more annoying than shorter ones.

6.4 Berry, Fuller, John, and Robinson, #3

Berry et al.[5] examined the trade between impulsiveness and level in a psychoacoustic study employing free-field listening to simulated sounds. Single-cycle 400 Hz sine wave pulses were superimposed at a 10 Hz rate on a continuous noise shaped like that from a Wessex helicopter. Crest levels of 10 dB and 20 dB were incorporated into signals with overall A-weighted levels of 70, 75, and 80 dB. In this way, twenty observers could compare various combinations of crest level and overall level for relative annoyance. From the results, a unidimensional annoyance scale was constructed. An orderly trade between crest level and overall level was obtained and permitted the calibration of other data obtained by the same authors in terms of relative levels. For a crest level of 20 dB, an impulse correction of about 5 dB would be indicated. Several impulse corrections were evaluated. Δ_{SA} was generally insensitive and inadequate, and Δ_{WHL} was sensitive, but exhibited wide variability with the spectral peak of the impulse component. By contrast, Δ_{A} and Δ_{NPL} were moderate and well-behaved predictors of annoyance.

6.5 Crosse, Davidson, Hargest, and Porter

Crosse et al.[15] undertook a large-scale psychoacoustic experiment in conjunction with an air show. An impressive sample of 1,009 attendants at the show participated in listening tests where they compared the disturbance of simulated helicopter-type sounds while listening in a semi-reverberant room. The signals were amplitude modulated samples of CTOL jet takeoff noise that were modulated at between 4 and 12 Hz with a 50 percent duty cycle and a peak sound pressure level between 85 and 95 dB. The modulation depth was 8 dB and the rise time was 0.2 sec, yielding an impulsive sounding signal. Instantaneous peak sound pressure levels, and by implication instantaneous peak perceived noise levels, were excellent predictors of the equal disturbance judgments made by the listeners. Furthermore, these judgments were not affected by the repetition (modulation rate) or the overall level. Thus, instead of an impulse correction, the authors recommend the use of instantaneous peak perceived noise level for the measurement of helicopter noise.

6.6 d'Ambra and Damongeot

d'Ambra and Damongeot[11] report a psychoacoustic study where recorded helicopter impulses were electronically mixed with recorded helicopter broadband noise. This approach permitted the manipulation of several largely independent parameters in an extremely realistic acoustic stimulus. Overall levels varied from L_{PN} = 90 dB to 100 dB, crest levels varied from 12 dB to 20 dB, and repetition rate varied from 10 Hz to 35 Hz. Sixty-two listeners made paired comparison judgments, comparing a synthetically mixed signal with the non-impulsive noise that served as its broadband component. Judgments were also collected with some real recorded helicopter signatures. The results indicated that anywhere from 0 to 7 dB had to be added, either to the perceived noise level, or to the effective perceived noise level, to reflect the annoyance of the impulsive noises. This amount did not change with repetition rate. Thus an impulse correction is recommended, but no repetition correction. Of the various impulse corrections evaluated, Δ_{ISO} gave the best correlation with the psychoacoustic data.

6.7 Fidell and Horonjeff

Fidell and Horonjeff[16] studied the detectability of single-cycle sine, triangular, and rectangular pulses of varying repetition rate (5 to 100 Hz) and fundamental frequency (100 Hz to 1 kHz) imbedded in a white noise background. Four listeners detected faint signals of this type in a free acoustic field. Both repetition rate and pulse width had a systematic effect on the signal-to-noise ratio necessary for detection. The minimally detectable signals tended to have a high fundamental frequency (1 kHz) and an intermediate repetition rate (20 to 40 Hz). Both the fundamental frequency (pulse width) and different waveform shape could be accounted for by applying the Theory of Signal Detectability to the basic data obtained. Although these authors measured detectability of low-level impulses, they argue that a relationship exists between detectability and annoyance. Accordingly, the relative annoyance of a given sound can be predicted to a large degree from its relative detectability, i.e., highly annoying sounds tend to be more readily detectable. In this way, the data have implications for helicopter rotor noise:

1. Differences of the order of 10 dB may exist in impulsive wavetrains of equal annoyance and of equal total energy, but varying repetition rates and pulse widths.

2. Designs for minimum annoyance may be guided by the obtained relationships between repetition rate and pulse width.

Naturally, these data tend to support the need for both an impulse and a repetition correction.

6.8 Galanter, Popper, and Perera

Galanter et al.[17] conducted an experiment where forty participants gave magnitude estimates of the annoyance of recordings of several CTOL jet aircraft and two different kinds of helicopters in a semi-reverberant room. They obtained a 4 to 5 dB penalty for the helicopter noise relative to the CTOL jet noise in terms of the A-weighted sound level needed for equal annoyance. For effective perceived noise level, they report a similar penalty of 4 to 5 dB, but their data seem to support only about 2 to 3 dB. In terms of A-weighted sound level, a progressive increase in estimating annoyance was observed with increasing crest levels (18.5 to 26.8 dB). Conversion to effective perceived noise level (estimated by D-weighted level) eliminated these differences. Thus effective perceived noise level was found to be an adequate predictor of the annoyance due to helicopter sounds of differing impulsiveness, without any additional corrections. However, an impulse correction might be warranted when comparing VTOL with CTOL aircraft.

6.9 Galloway

Galloway[9] evaluated several correction factors to account for helicopter impulsiveness in annoyance judgments. Twenty listeners compared the annoyance of recorded helicopter sounds and simulated helicopter sounds to a standard non-impulsive helicopter (S-61) in a free field. Some stimuli were steady state (simulating hover) while others were time-varying (simulating approach and level flight). His results indicated that effective perceived noise level underestimated the human response to impulsive noise signals by 7 to 8 dB. Various impulse corrections were tested to find which one would reduce this discrepancy to a minimum. None of the traditionally proposed corrections (Δ_{NPL}, Δ_A, and Δ_{CF}) satisfactorily reduced the scatter in the data below a chance level, when all the stimuli were considered. When only recorded helicopter stimuli were considered, Δ_A performed adequately. However, repetition rate proved to be a powerful variable. Thus a considerable improvement could also be achieved by applying a correction for repetition rate, Δ_R. When combined with this repetition rate correction, all of the proposed measures became statistically significant. Thus both an impulse correction and a repetition correction were endorsed.

6.10 Izumi

Izumi[12] conducted two experiments on the loudness and the noisiness of repetitive impulsive sounds with different temporal patterns (duty-cycles and repetition rates). He used the method of paired comparisons with interrupted bursts of pink noise serving as impulsive sounds, and a steady pink noise serving as the standard. In the first experiment, seven participants judged pairs of sounds both in terms of loudness and noisiness while seated in a semi-reverberant room. Relative loudness and relative noisiness both varied in an orderly fashion with duty cycle (burst time fraction) and repetition rate. However, there was a consistent and significant difference between the loudness and the noisiness reponses, with noisiness showing larger impulse corrections. The second experiment employed only noisiness instructions and had one additional participant. It was designed to further quantify and refine the relationships obtained in the first study. The results were presented as a three-dimensional surface that showed relative burst level, or the difference between the impulsive and non-impulsive signals, as a function of both burst-time-fraction and repetition rate. A quantitative model and an accompanying formula were developed and validated based upon: (1) energy summation; (2) positive startle caused by the intermittency; and (3) negative startle caused by temporal masking. The model clearly points toward the need for a repetition rate correction, although some of the repetition rates investigated were lower than those commonly associated with helicopter rotor noise.

6.11 Klumpp and Schmidt

Klumpp and Schmidt[18] conducted two psychoacoustic experiments on blade slap noise recorded from four types of helicopters. Seventy samples of helicopter noise were *a priori* rated as to the amount of blade slap present: 35 without, 9 weak, 11 moderate, and 15 heavy. Two groups of listeners (altogether 28 people) each heard the helicopter sounds in a semi-reverberant room. The method of magnitude estimation was employed to register an annoyance response with the recorded noise from a city bus serving as the standard or reference sound. The results revealed an A-weighted level difference of from 1.4 to 2.2 dB between equally annoying helicopter noises with and without blade slap. When the seventy sounds were reclassified according to a crest level criterion (above or below 15 dB) to separate blade-slap from no-blade-slap groups, the difference between the groups was 2.5 dB for equal annoyance. A small subset of five participants also judged the recorded helicopter sounds as if heard inside a house. In this case, all the sounds were filtered in a manner that simulates the transmission loss of a typical house. Again, a penalty of approximately 2 dB was obtained for helicopter samples containing appreciable blade-slap noise. Thus an impulse correction of 2 dB was recommended for periods when blade slap is present.

6.12 Lawton

Lawton[19] simulated blade-slap noise by superimposing 1- to 3-cycle sine waves on a continuous shaped broadband noise background. Forty listeners estimated the annoyance of the simulated helicopter noises on a 10-point scale while seated in a semi-reverberant room. Five parameters were varied simultaneously: (1) the number of cycles in a single pulse; (2) the frequency of the sine waves; (3) the impulse repetition rate (8 to 20 Hz); (4) the sound pressure level of the continuous noise (65 to 80 dB); and (5) the idealized crest level of the impulses (15 to 25 dB). All five parameters exhibited a significant effect upon annoyance ratings, but the sound pressure level of the continuous noise and the idealized crest level exhibited a much stronger effect than the other variables. Idealized crest level is defined as the ratio of the peak of the impulses alone to the rms of the background alone, instead of the ratio of the peak of the impulses plus background to the rms of the background alone. Thus an impulse correction would certainly be endorsed by these data, and possibly a repetition rate correction as well.

6.13 Leverton

Leverton[20] reported on some psychoacoustic experiments to determine the increase in loudness and annoyance associated with helicopter blade slap. A small sample of listeners was asked to adjust the loudness of a "banging" and "non-banging" helicopter, as recorded out of doors, until they were perceived as equally loud. The stimuli were presented to the listeners in three acoustic environments: (1) outdoors away from walls; (2) in a semi-reverberant lounge; and (3) in a reverberant office. In each of these three environments, the "banging" helicopter required an A-weighted sound level penalty of 6, 7, or 8 dB, respectively, to achieve equal loudness with the "non-banging" one. In a second experiment, light music was played as a background (L_A = 77 dB) in the semi-reverberant lounge, and annoyance, instead of loudness, matches were obtained. On the average, the "non-banging" helicopter was adjusted to a level 6 dB above that of the "banging" helicopter, again indicating a 6 dB penalty in terms of A-weighted sound level.

6.14 Leverton and Southwood

Leverton and Southwood[10] reported an experiment where fifteen recordings of helicopter noise were played over earphones to twenty observers. These recordings had been a priori classified as to impulsiveness: none, marginal, mild, and severe. Δ_{WHL} appeared to follow the growth in impulsiveness implied by this classification scheme. The experiment was conducted to relate the levels of helicopter noise adjusted to equal intrusiveness or annoyance to the crest level as measured by the Δ_{WHL} method. The data suggested that the Δ_{WHL} impulse correction would be useful. The proposed correction had a lower cutoff at a crest level of 11 dB, where it was set to zero, and rose linearly through an impulse correction of 6 dB for a crest level of 20 dB, but had no limit.

6.15 Leverton, Southwood, and Pike

Leverton et al.[21] report preliminary psychoacoustic tests using real and simulated recorded samples of helicopter noise with varying degrees of rotor blade slap and tail rotor noise. Rotor blade slap was accounted for rather well by the Δ_{WHL} impulse correction. Moreover, a parallel correction was observed describing another penalty due to pronounced tail rotor noise. Tail rotor noise correction could add another A-weighted sound level penalty of 4 dB. This second correction for tail rotor noise presumably could not be accounted for by the tone correction scheme for effective perceived noise level. However, since the crest level of tail rotor noise is typically less than that of main rotor blade slap, with appropriate adjustments for the L_{EPN} tone correction cutoff, the single Δ_{WHL} impulse correction may suffice for both.

6.16 MAN—Acoustics and Noise, Inc.

MAN-Acoustics and Noise, Inc.,[22] investigated possible differences in the human response to CTOL, VTOL, and STOL aircraft. Thirty-three recorded and simulated aircraft sounds (nine recorded helicopters) were judged for annoyance (magnitude estimation with a USASI noise reference). The sounds were also judged for acceptability on an absolute binary scale. Thirty-six observers listened in a semi-reverberant room after the signals had been electronically filtered to simulate the expected spectra inside a home. The results indicated that perceived noise level overstimated the annoyance of helicopters relative to CTOL aircraft (about 2 dB). The addition of a tone correction reduced the obtained variability somewhat, and the addition of a duration correction reduced it markedly, to the point where effective perceived noise level could serve as an adequate predictor of annoyance. Thus no impulse correction would be justified, and if it were, the correction would be negative. However, the sounds in this study were all passed through an electronic house filter, which increased the rise time of any impulsive blade slap present in the signal.

6.17 Munch and King

Munch and King[23] conducted a preliminary test to investigate the relationship between crest level and the perception of blade slap. Nine recorded helicopter noise samples were evaluated by the investigators themselves. These samples were classified as to the existence and degree of blade slap and were equated in judged annoyance to the recorded noise from a series of reference aircraft. The results indicated A-weighted level penalties of 6 to 13 dB for crest levels from 14 to 21 dB. Below a crest level of 13 dB, the authors felt that there was no appreciable blade slap present, but for higher crest levels an impulse correction seemed appropriate.

6.18 Ollerhead P

In this section and in the two sections to follow, Ollerhead[24] reports an interlocking series of psychoacoustic experiments. Altogether there were five pilot studies (P), one main experiment (M), and three replications (R). In the five pilot studies, forty research participants heard various recorded helicopter and aircraft sounds through earphones. Many of these stimuli were tape recordings of the same sounds that Powell[25] had presented live by means of actual helicopter and airplane flyovers in the field. In most cases, the participants rated the sounds on an 11-point noisiness scale, although some participants also made level adjustments.

In one pilot experiment, the listeners rated 33 test sounds relative to a reference sound (T-28 airplane), which itself was presented at eight different sound levels. This experiment permitted the establishment of a relationship to convert average noisiness rating scores (0 to 10) into equivalent relative noisiness ratings in dB. Such a conversion proved possible with a standard error of the mean of about ± 1 dB. Certain test sounds were purposely repeated at different times throughout the experiment, and these all produced satisfactory consistency in noisiness ratings. In another experiment, approach sounds were presented in their full long-duration versions and again in versions truncated at their 10 dB-down points. The results indicated that the early approach period before the first 10 dB-down point makes no measurable contribution to the judged noisiness or annoyance of the entire event. Further pilot experiments explored changes in the verbal instructions given to the research participants; some versions emphasizing duration, others not; and some versions using "noisiness" and others using "annoyance" as the descriptor for the response being scaled. An additional experiment compared the results obtained with the 11-point noisiness scale with those obtained by the method of adjustment, using the same research participants. The rating method proved to be highly correlated with the method of adjustment. It also proved to be stable and insensitive to changes in verbal instructions. Overall, the pilot studies confirmed the suitability of the psychoacoustic methods proposed for a large-scale main experiment.

6.19 Ollerhead M

Ollerhead[24] conducted a major psychoacoustic experiment to investigate the need for a helicopter impulse correction with a sufficiently large number of recorded helicopter and CTOL sounds to constitute a sample of good size. Between 36 and 40 participants listened to 89 helicopter and 30 CTOL sounds over earphones. The participants rated them on an 11-point annoyance scale with a T-28 aircraft noise serving as the standard. The 89 helicopter sounds were further divided into two classes of less-impulsive and more-impulsive, on the basis of a 4 dB criterion for the Δ_{ISO} impulse correction. Perceived annoyance ratings were obtained from the participants for all these sounds, and the results were plotted against nine different commonly used measurement scales. In general, all time-integrated scales incorporating a duration correction were considerably superior as predictors of annoyance than those scales that did not have a duration correction. Tone corrections yielded minor improvement. The impulse corrections (Δ_{ISO} and Δ_{CF}) did little to improve the scales to which they were applied. In fact, the impulse corrections tended to counteract the beneficial effects of the duration correction. When compared with CTOL sounds, the helicopters were overrated by about 2 dB. In summary, if duration is accounted for in the traditional manner (+3 dB/doubling), the results of this study do not support further impulse corrections or penalties being added to effective perceived noise level or other time-integrated measures.

6.20 Ollerhead R

Ollerhead[24] reported several psychoacoustic experiments designed to replicate some aspects of his main experiment, which employed 119 different aircraft sounds. These replications were conducted: (1) with earphones but at a higher level; (2) in the Interior Effects Room (IER), a semi-reverberant simulated living room located at the NASA-Langley Research Center; and (3) in the Exterior Effects Room (EER), a semi-reverberant lecture theatre also located at NASA-Langley. Eighty research participants gave annoyance ratings on an 11-point scale to three-quarters of the recorded aircraft sounds employed in the main experiment. On the whole, the higher level earphone tests tended to corroborate the lower level earphone results of the main study. This replication did point toward slight improvement in predicting annoyance as emphasis was shifted toward the low frequencies.

The IER results revealed the same approximately 2 dB overrating of helicopter sounds relative to CTOL sounds, but this time the duration correction did not yield any significant improvement in the predictive abilities of the various scales. The EER results were quite similar, except that some improvement was observed when the duration correction was applied. In both loudspeaker experiments (IER and EER), the magnitude of the impulse correction practically vanished, presumably as a result of poor pulse reproduction and room reverberation. Nevertheless, the more-impulsive and less-impulsive helicopters were still rated much the same as when their impulsiveness was present in the earphone experiments. These findings provide evidence that the increased level and duration consequent to impulsiveness may be sufficient to account for helicopter blade slap without the need for a separate impulse correction.

6.21 Patterson, Mozo, Schomer, and Camp

Patterson et al.[26] conducted a psychoacoustic experiment with actual live helicopter flyovers. Nine helicopters executed 12 prescribed maneuvers for 25 listeners who rated the acceptability of the noises produced on a magnitude estimation scale. The standard or modulus sound was a C-47 aircraft. Spectral analyses of the noise produced by each flyby were used to calculate 21 predictors of annoyance. In general, A-weighted sound level, D_2-weighted sound level, and effective perceived noise level performed the best. For the case of L_A, on the average the entire collection of helicopter sounds was rated as more annoying than the C-47 aircraft by about 2 dB. However, no specific correction for blade slap was found. Crest level proved unable to account for the difference between heavy blade slap flybys and those with no blade slap. A modified crest level where the RMS value was measured between impulses provided a somewhat better distinction, but proved unwieldy to use. Likewise, the ratio of energy below 250 Hz to the high-frequency energy in the spectrum, as well as a collection of numerical weights applied to each one-third octave band, yielded some improvement but were also impractical.

6.22 Pearsons

Pearsons[27] investigated the noisiness of eight different recorded samples of helicopter noise in a paired comparison experiment using the recorded noise from a DC-8 and simulated jet aircraft noise as standards. Twenty-one participants judged the relative noisiness of the stimuli in a free field. The results were most accurately portrayed by perceived noise level, followed by N-weighted and A-weighted sound level. Duration and tone corrections did not improve predictability of the relative noisiness of the helicopter sounds. In fact, the duration correction increased the calculated mean difference between the standard and comparison sounds and increased the variability as well. A possible explanation of this result may lie in the shape of the flyby envelope of a helicopter relative to that of a jet aircraft. Whereas the jet aircraft envelope increases at an almost uniform rate, the helicopter envelope increases more gradually at first and then more rapidly just before reaching its maximum.

6.23 Powell, 1978

Powell[28] reported some further analyses of the data of Lawton.[19] First he determined that perceived noise level provided the best overall correlation with the human response data. Given L_{PN} as the appropriate frequency weighting for helicopter noise measurements, the contribution of the five parameters in Lawton's experiment could be evaluated relative to the changes in L_{PN} produced by each parameter. Although each parameter had a significant effect upon judged annoyance, each parameter produced a similar change in L_{PN}. Only the addition of an A-weighted crest level correction produced a slight but significant improvement in predictive ability. The amount of the correction was a function of Δ_{CF}, but most of this correction could be accounted for in L_{PN} changes. The regression equation describing the Δ_{CF} function was similar to that obtained by Sternfeld and Doyle[29] but with a somewhat steeper slope in the present case. This difference in slope could be due to differences in experimental procedure: whereas Lawton employed loudspeakers that could induce whole-body vibration, Sternfeld and Doyle used earphones that were restricted to auditory simulation. In summary, a correction for impulses was implied, but no evidence was found for a repetition rate correction.

6.24 Powell, 1980

Powell* reported an experiment conducted by Ahumada, where the latter essentially replicated earlier results on the effects of phase using an 11-point annoyance scale instead of a detectability task. A total of thirty observers took part in three experiments. They listened over earphones to pulse trains with repetition rates of 10 and 20 Hz. The pulse trains were modified in phase, but maintained the same Fourier series amplitudes. This time the results were somewhat different from those obtained earlier: the two less-impulsive sounds (random phase) were rated significantly more annoying than the two more-impulsive sounds (sine and cosine series). In the three experiments, the difference between these two types of pulse trains ranged from 2.7 to 4.5 dB. The conclusion was that a measure based solely on the amplitude (crest level) of the impulsive sound might not be adequate.

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* Powell, C.A., "Psychoacoustic Research Progress Report", Working Group B, ICAO Meeting, October 6-8, 1980.

6.25 Powell, 1981

Powell[25] conducted two field tests with live helicopter and airplane operations. Two helicopters (OH-58A and 204-B) produced varying amounts of blade slap noise by changing flight characteristics. In addition, a T-28 single-engine propeller airplane was used as a non-helicopter reference sound. Ninety-one observers gave noisiness judgments on two different scales. The observers sat either outdoors or inside a house near the aircraft operations. The results revealed that the sample of observers judged the noise from the less-impulsive helicopter as more noisy than the noise from the more-impulsive helicopter (about 1 to 2 dB difference). Neither the Δ_{ISO} nor the Δ_{CF} impulse corrections produced any significant improvement in the ability of L_{EPN} to predict the noisiness of the helicopter samples. A series of verbal category scales, including such descriptors as "thumping", "slapping", and "hammering", was found to be related to the noisiness judgments of the observers, but not to any of the impulse corrections examined in the study. Furthermore, when indoor versus outdoor listening were compared, the outdoor judgments were less variable and displayed more difference among aircraft types.

6.26 Powell and McCurdy

Powell and McCurdy[6] investigated the effects of varying both crest level and repetition rate on the annoyance judgments of 48 listeners. The participants heard computer-generated simulated pulse trains presented in a free field as they rated the sounds on an 11-point scale in two separate experiments. Crest levels were varied from 3.2 to 19.3 dB, and repetition rates were varied from 10 to 115 Hz. The results indicated that annoyance increased with increasing repetition rate to a maximum L_{EPN} penalty of 4 dB, over and above other corrections that were applied. The uncorrected effect of repetition rate was more on the order of L_{EPN} penalties of 5 to 12 dB. Annoyance also increased with crest level to a maximum L_{EPN} penalty of 13 dB, but this effect was found to be somewhat dependent upon overall level. A-weighted sound level predicted annoyance responses with less error than any of the other noise measures examined, and the inclusion of the Δ_{ISO} or Δ_{CF} impulse corrections did not generally improve predictability for the different measures. Annoyance responses were, however, highly correlated with the frequency of the perceived dominant one-third octave band. Thus a new frequency weighting was devised to account for this effect. The new weighting was modified at the low frequencies so that it fell somewhere between the D-weighting and the A-weighting curves. This modified weighting yielded a significant improvement in predictability.

6.27 Robinson and Bowsher

Robinson and Bowsher[30] report an experiment involving 570 participants who judged the loudness and disturbance of recorded aircraft sounds by the method of paired comparisons. They presented combinations of four VTOL sounds and one CTOL jet sound in a free acoustic field. Various calculation procedures for predicting loudness and disturbance were applied to the stimuli, and the average errors were assessed under conditions of perceptual equality. The various calculating schemes ranked as follows in closeness of prediction: Zwicker phons, perceived noise level, A-weighted sound level, Stevens phons, and overall sound pressure level. Since only a small advantage was found for Zwicker phons over perceived noise level, and since the latter is in more widespread use for aircraft, it was surmised that L_{PN} is the most appropriate measure to predict helicopter noise, producing errors of only 1 to 2 dB.

6.28 Shepherd

Shepherd[31] employed recorded samples of the same helicopter and propeller aircraft noises used by Powell[25] in his earlier field study. Thirty-two participants sat in a semi-reverberant room and rated the recordings on the same 11-point noisiness scale as Powell had used. Thus the present experiment served as a partial replication in the laboratory of Powell's field experiment. The results generally confirmed the field study. The relative noisiness judgments for the two studies showed statistically significant correlation ($r = 0.66$), indicating reasonable agreement between the results of the two experiments. The laboratory study revealed that neither of two proposed impulse corrections, Δ_{ISO} and Δ_{CF}, produced significant improvement in prediction ability, just as had been found in the field test. The comparison of the noisiness of the two helicopters was in the same direction for both studies: the less-impulsive OH-58A generally was judged more annoying than the more-impulsive 204-B; however, the trend was not statistically significant in the laboratory case.

6.29 Southwood and Pike

Southwood and Pike[32] conducted several experiments with simulated and recorded helicopter impulses. About 20 listeners adjusted the intrusiveness or annoyance of various test sounds presented through earphones until they matched the recording of a non-impulsive Wessex helicopter, which served as a standard. The simulated test sounds were single-cycle sine waves of 250 Hz fundamental frequency presented at a repetition rate of 13.9 Hz. In a separate experiment, an impulsive Chinook CH-47A helicopter recording was also adjusted against the same standard. The results of the experiment with simulated pulses showed that an impulse correction of from 0 dB to 6 dB was recommended over crest level range from 11 dB to 20 dB, where crest level is defined as in Δ_{WHL}. In the case of the Chinook versus Wessex recorded helicopter experiment, the more-impulsive Chinook helicopter seemed to warrant about a 6 dB penalty relative to the Wessex, as opposed to the implied negative correction found by Berry et al.[5] for the same two craft.

6.30 Southwood

Southwood[33] employed three of the helicopter noise samples from a Bell B204-B recorded by Powell[25] during his field study, and the recorded noise of a Wessex helicopter. The three impulsive Bell helicopter sounds were presented as recorded by Powell and also as modified through a "notch filter" that removed up to 12 dB between 800 and 2000 Hz. The filtered sounds had the sharp transients largely eliminated just prior to passage overhead. Twenty observers listened over earphones and adjusted the Bell helicopter sound until it was perceptually equal to the Wessex sound, which had a maximum A-weighted sound level of 80 dB. The results revealed that the blade slap-dominated signal was underestimated by an A-weighted sound level of between 5 and 8 dB, or an effective perceived noise level of between 2 and 5 dB. These laboratory results conflict with those obtained by Powell in the original field study, where the impulsive helicopter was judged less noisy. No consistent difference was observed in the results for the unfiltered and the filtered signals – the latter having less of the sharp impulses just before the overhead position. Thus an impulse correction is suggested which is not a function of the relatively brief overhead pulses that sometimes occur.

6.31 Stent and Southwood

Stent and Southwood[34] conducted two psychoacoustic studies with simulated pulses combined with a recorded Wessex helicopter sound. The pulses were single-cycle sine waves with fundamental frequencies from 167 Hz to 667 Hz and repetition rates from 10 to 40 Hz. A total of 41 participants listened over earphones and adjusted the simulated impulsive sounds until they were of equal annoyance to a recorded Wessex hover sound. The results showed an A-weighted penalty of about 5 dB for a crest level of 17 dB and an A-weighted penalty of about 7.5 dB for a crest level of 20 dB. The corresponding penalties in terms of perceived noise level were 3 dB and 4.5 dB, respectively. No statistically significant differences in the appropriate penalty were found for different repetition rates, although the mean penalties did show a trend toward a slight minimum at a repetition rate of about 25 Hz, dropping from about 8 dB to about 4 dB for A-weighted sound levels.

6.32 Sternfeld and Doyle

Sternfeld and Doyle[29] investigated simulated helicopter sounds using the method of adjustment with 25 listeners. The impulsive and broadband component of each signal was derived from recordings of actual helicopter sounds modified to account for the earphone transducer. The impulse component and the broadband component were electronically combined to form a simulated blade-slap stimulus, with the listener having control over the amount of the impulse component that was added. Thus the listener actively participated in the creation of the combined impulsive-plus-broadband sound, while the broadband background spectrum of the combination served as the reference sound. The listener added enough impulsive sound to the broadband sound to make an annoyance match. The results showed that annoyance matches were a function of both level and impulsiveness, the latter being measured in terms of C-weighted sound level and idealized crest level. Regression equations were developed for both measures of impulsiveness, in terms of both A-weighted sound level and perceived noise level. For L_A, the crest level correction yielded a correlation coefficient of 0.960, while the L_C correction yielded a correlation of 0.894. For L_{PN}, the corresponding correlation coefficients were 0.931 and 0.911, respectively. Remaining inconsistencies in the data seemed to be attributable to an effect of repetition rate which did not appear in the method of adjustment results, but did appear in separate verbal ratings.

6.33 Sternfeld, Hinterkeuser, Hackman, and Davis

Sternfeld et al.[35] investigated the simulated noises from two proposed new 60-passenger aircraft systems – a tandem rotor VTOL and a turbofan STOL. In addition, the recorded flyby noise from a jet CTOL aircraft was included. Their experiment incorporated several unusual features:

1. The 28 participants were housed in groups of 6 people in a trailer outfitted at one end like a work space and at the other end like a rest space. They rated the sounds on a 9-point annoyance scale first at the work end (two hours) and then at the rest end (one hour).
2. The participants were engaged in normal, meaningful activities while they listened to the sounds over loudspeakers. At the work end they performed their own work-related reading and paperwork tasks. At the rest end they watched television, played cards, read, and conversed.
3. The duration of the individual flyovers and the intervals between flyovers were representative of a range that might be expected to occur during commercial operation of the proposed aircraft, from 6 to 48 operations per hour.

4. Natural ambient backgrounds of two types of recorded traffic noise were provided instead of artificial quiet laboratory conditions.

Thus the simulation of an appropriate psychological context for conducting the study was far above average. The results showed that the STOL noise was judged more annoying than the VTOL noise in terms of both perceived noise level and A-weighted sound level. However, the difference largely disappeared when a duration correction was applied, yielding effective perceived noise level and duration-corrected A-weighted level. Exposure to a high repetitive density of operations (e.g., 48 per hour) did not increase the annoyance judgment of each individual sound, even though the total exposure was described as unacceptable in separate questioning. Furthermore, temporal variations in the background traffic noise also had no effect upon the participant's ratings.

6.34 Williams

Williams[36] conducted a psychoacoustic experiment with earphones to evaluate various recorded and simulated helicopter sounds, including some with varying degrees of tail rotor noise. Forty listeners judged the noisiness of the helicopter sounds by three different methods: (1) adjustment to an absolute "just noisy" criterion; (2) rating on an 11-point noisiness scale; and (3) adjustment to equal noisiness with a standard non-impulsive helicopter (Wessex). The results showed that A-weighted impulse correction of the order of 8.5 to 9 dB are necessary for main rotor blade slap, and of the order 6 dB for tail rotor noise. Higher corrections were produced by women than by men, and by recorded sounds than by simulated sounds. The method of adjustment produced less variable results than either of the other two methods. Thus, not only was a blade-slap impulse correction endorsed, but a possible tail rotor noise correction was also introduced.

7.0 SYNTHESIS OF RESULTS

The 34 studies reviewed in the previous section exhibit certain trends in indicating those variables that might be important to providing a psychoacoustic foundation for measurements of helicopter noise. In increasing order of apparent importance they are phase relations, tail rotor noise, repetition rate, CTOL versus VTOL differences, and crest level.

7.1 Phase Relations

Only two of the studies systematically manipulated the phase relations among the various Fourier frequency components of the impulsive waveform that constitutes helicopter blade slap. Ahumada and Hersh[14] found no effect of phase on the perception of simulated helicopter impulses. Powell's* report of another experiment by Ahumada gives a 2.7 to 4.5 dB penalty to the less-impulsive random phase sounds, when compared with the more-impulsive sine and cosine phase-related sounds. The first experiment investigated detectability of faint sounds and may not be relevant to annoyance judgments. The second experiment represents more relevant annoyance judgments and could have important implications for impulse corrections to helicopter noise. Phase is closely related to the sharpness or rise time of impulsive waveforms, and rise time has been alluded to as having importance in the perception of blade slap (see Southwood and Pike[32]). If this single study reported by Powell is taken by itself and related to some of the crest level experiments in Tables 1 to 4, the results would support a negative impulse correction. However, since there is only one experiment, and since different complex phase relations are inevitably involved in the impulse signatures for different helicopters, as regards the present review, the effects of phase *per se* will be considered to be inconclusive and accounted for in other stimulus parameters, namely helicopter type and operations.

7.2 Tail Rotor Noise

Only two of the studies systematically investigated the human response to the noise from tail rotors on certain helicopters. Leverton *et al.*[21] found that an impulse correction of about 4 dB was needed to account for tail rotor noise, while Williams[36] observed a 6 dB tail rotor correction. However, both studies found that a still greater correction was needed for main rotor blade slap. Thus tail rotor noise, even at its worst, is of secondary

* Powell, C.A., "Psychoacoustic Research Progress Report", Working Group B, ICAO Meeting, October 6-8, 1980.

importance to main rotor blade slap. For this reason, Williams has suggested that a main rotor impulse correction would be sufficient to account for both. Although recognized as an important source of noise from the viewpoint of physical acoustics (see Section 3), tail rotor noise may be regarded as a secondary characteristic of the acoustic spectrum from the viewpoint of human response. In addition, some helicopters, primarily twin main rotor types, do not have tail rotors. When helicopters do exhibit prominent tail rotor noise, as in the physical measurements of Leverton et al., this tail rotor noise generally appears above the other noise components during an early portion of the flyby, more than 10 seconds before the maximum level is reached. Yet Ollerhead[24] has shown that acoustic events in the early time-history of helicopter flybys are not very important determinants of judged noisiness. Thus, for the purposes of the present review, tail rotor noise will be considered of lesser importance and will be handled conceptually as another variation in helicopter type and operation.

7.3 Repetition Rate

It has been suggested that the repetition rate of the individual pulses that constitute helicopter blade slap may be important in the overall human response to helicopter noise. Of the 34 studies reviewed in the present paper, ten of them investigated the repetition rate parameter in some systematic manner. These ten studies, and their outcomes with regards to repetition rate, are shown in the next to the last two columns in Table 4, labelled "Repetition Correction". In terms of the tabulated outcomes alone, two studies indicate that no repetition correction is warranted, four studies indicate that a possible but weak repetition correction might be needed, while four studies indicate that some sort of quantitative repetition correction is required. This over-simplified summary would tend to support the need for a repetition rate correction on the basis of simply tallying votes. Yet, because the repetition rate corrections are not all in the same direction, an average for the amount of the correction is only about 0.7 dB. Thus a closer examination of each study is required in order to make a more astute evaluation.

Crosse et al.[15] found no repetition rate effect, with over 1,000 research participants, but they used artificial modulated CTOL noise bursts to simulate helicopter blade slap. Thus it is not certain that the stimuli in their experiment represented a sufficiently close approximation to actual helicopter noise as heard in the field. d'Ambra and Damongeot[11] reported no significant effect of repetition rate over the range from 10 to 35 Hz in rather carefully controlled psychoacoustic experiments with more realistic helicopter sounds. Thus their study should be considered as providing rather strong evidence against the need for a repetition rate correction.

Some studies provided only weak or inconclusive evidence for a repetition rate correction. Lawton[19] and Powell[28] scrutinized the same data from a multivariate experiment, simultaneously exploring the effects of five different variables. They both report statistically significant effects of repetition rate on annoyance judgments, but two other variables exhibited a much stronger effect. Over a range from 8 to 10 Hz, the effect of repetition rate was only 0.3 points on a 9-point annoyance rating scale, with the higher repetition rate being judged slightly more annoying. In further treatment by Powell, no clear separation of the data by repetition rate was provided in a regression analysis approach. Likewise, Stent and Southwood[34] also found a marginal effect of repetition rate. Their data revealed a vague U-shaped trend in the necessary impulse correction over the repetition range from 10 to 40 Hz, with a minimum at about 25 Hz. The A-weighted penalty for impulsiveness dipped from about 8 dB at 10 Hz, to about 4 dB at 25 Hz, and rose again to about 8 dB at 40 Hz. This trend was not statistically significant, however. Finally, Sternfeld and Doyle[29] found no evidence for a repetition rate correction in the main body of their psychoacoustic data collected by the method of adjustment. But, when less precise verbal category scales and a verbal checklist of adjectives (e.g., "booming", "slapping", "thumping", "burring", "thudding", etc.) were employed, weak qualitative evidence for a possible repetition rate correction emerged.

Four studies do present concrete evidence that a repetition rate correction might be needed. Fidell and Horonjeff[16] found a U-shaped function relating the detectability of impulsive sounds to the repetition rate of the impulses. Similar to those obtained by Stent and Southwood, the functions for single-cycle sine waves of low fundamental frequency obtained by Fidell and Horonjeff showed a minimum at repetition rates of 20 to 30 Hz and a range of variation of about 2 to 4 dB. But Fidell and Horonjeff investigated low signal level detectability, which may not be relevant to annoyance judgments. Thus the results of the Fidell and Horonjeff study are difficult to compare quantitatively with annoyance and noisiness experiments conducted by other investigators. Galloway[9] presents the strongest evidence for a repetition rate correction. He also shows about a 3 to 4 dB shift in the necessary impulse correction with a change in repetition frequency from 10 Hz to 25 Hz. However, unlike the data of Stent and Southwood and those of Fidell and Horonjeff, the results presented by Galloway are in the opposite direction. The necessary impulse correction grows with repetition rate, at about 3 dB with each doubling of the rate.

The results obtained by Izumi[12] could possibly be used to extend the repetition rate range, since Izumi varied repetition rate from 1 to 8 Hz, while Galloway investigated the range from 10 to 25 Hz. For noisiness judgments, Izumi found that an increasing impulse correction was needed with increasing repetition rate, and that the slope was again about 3 dB for each doubling of the repetition rate. The absolute magnitudes of the impulse corrections at the transition repetition rate region from 8 Hz (Izumi) to 10 Hz (Galloway) are different, however, for the two studies. Izumi reports about an 8.5 dB correction at 8 Hz, whereas Galloway shows about a 3 dB correction at 10 Hz. Thus the Izumi data do not represent a direct extension of the Galloway data down to lower frequencies. The discrepancy is probably due to differences in methodology between the two studies. Powell and McCurdy[6] also show an increasing impulse correction with increasing repetition rate. Depending upon the particular experiment, repetition rate variations from 10 Hz to 115 Hz produced changes in predicted L_{EPN} impulse corrections of between 5 and 12 dB. These correspond to approximate growth rates of between 1.5 and 3 dB per doubling of the repetition rate.

In summary, four studies reported significant effects of repetition rate. One was not considered relevant to annoyance-type judgments. The data for the remaining three are shown in Figure 5, which portrays the estimated necessary impulse correction as a function of the impulse repetition rate. (The data of Powell and McCurdy have been shifted up by adding 6 dB to account for the D-weighting curve.) Although each of the three studies indicates a positive slope within the context of that particular study, when the data from all the studies are plotted together on a single set of coordinates, considerable scatter is observed. However, when the data of Izumi are excluded, a clear relationship does appear to exist.

Methodologically, it is of interest to note that all ten studies which included concrete statements for or against the necessity of a repetition rate correction employed primarily electronically synthesized helicopter-like acoustic stimuli, or electronic modifications of natural tape-recorded helicopter sounds. None of them presented exclusively natural helicopter noises, either live or tape recorded, to their listeners. There is a distinct possibility that the inclusion of synthesized stimuli in listening tests with helicopter noise can yield exaggerated psychoacoustic effects of the independent variables under investigation. The use of only artificial helicopter noise stimuli maximizes the chances of obtaining possibly exaggerated or misleading psychoacoustic data. The exact nature of this methodological problem and possible reasons for it are explained in Section 7.6. Suffice it to say here that, on the whole, the collection of these ten studies concerning repetition rate may have a somewhat higher probability of producing a Type I error in the Bayesian sense of hypothesis testing: there really is no effect of repetition rate on annoyance judgments, but the studies indicate that such an effect does exist. Moreover, taken as a whole, this body of data presents several other problems which make it difficult to endorse a repetition rate correction:

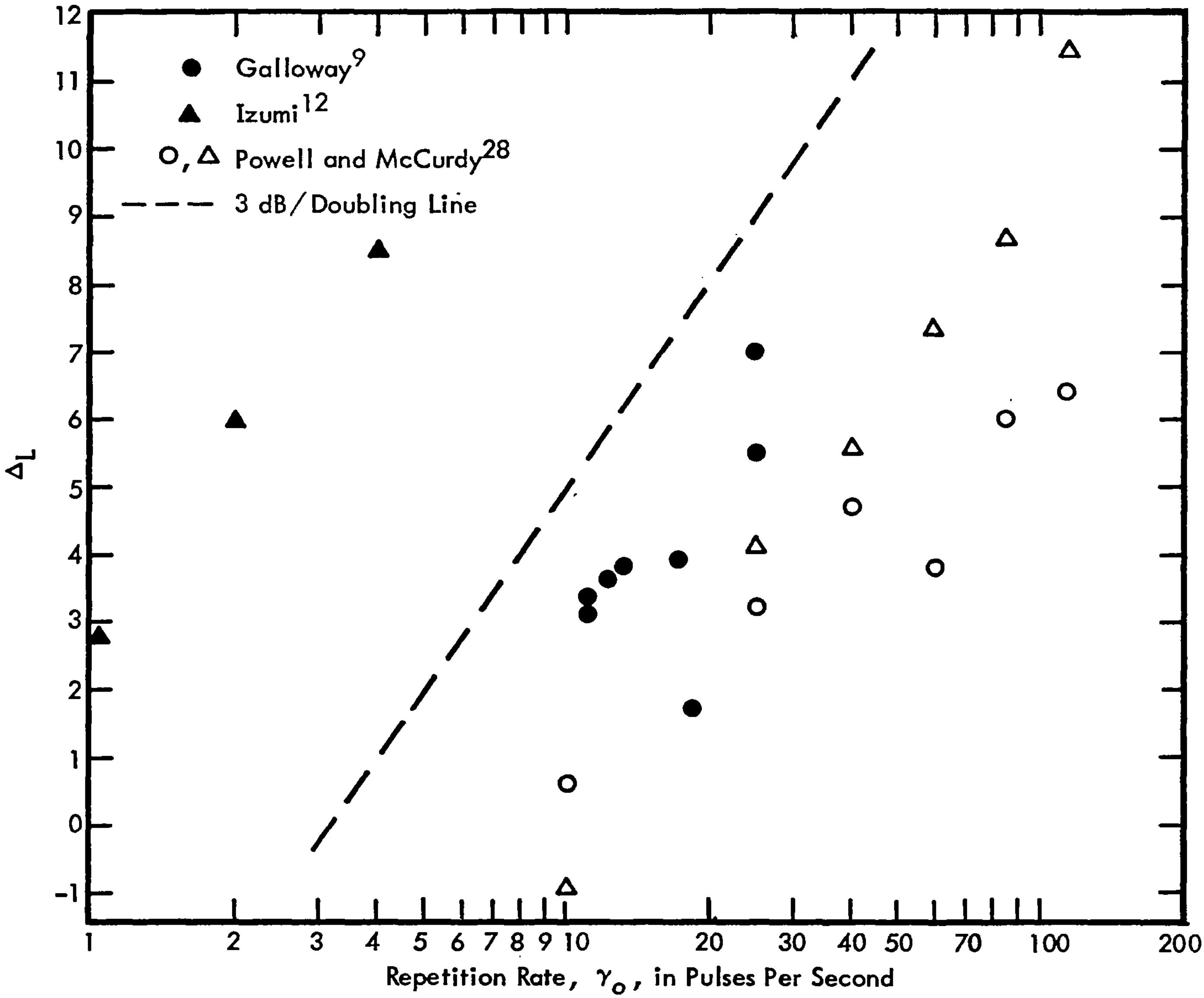

Figure 5. Composite Data Showing the Necessary Impulse Correction, Δ_L, as a Function of Repetition Rate, γ_o.

1. The large degree of variability among the three studies showing the strongest effects;

2. The contradictory findings as to the direction of the repetition rate correction among all eight studies indicating any repetition rate correction at all; and

3. The one important study showing no effect (d'Ambra and Damongeot).

Finally, a limited analysis of the potential effect of repetition rate was made on some of the results of Ollerhead.[24] The data on 15 of his test signals, displayed in Appendix C of his report, were used to determine repetition rate, which varied from about 12 to 28 Hz for that sample. There was little or no correlation between a possible impulse correction inferred from his data and the repetition rate.

Thus the conclusion drawn from the present review is that repetition rate can exert a possible, as yet inconclusive, effect upon psychoacoustic measurements of helicopter noise. However, for present purposes repetition rate cannot be considered as an important variable.

7.4 CTOL Versus VTOL Differences

Most researchers agree that the noise from helicopters, or VTOL aircraft, sounds different than the noise from other types of airplanes (CTOL aircraft). The CTOL aircraft that have been most studied consist primarily of large turbopropeller and jet passenger planes. Although people might confuse some helicopter flyovers with those of certain smaller propeller-driven craft, for the most part people can readily discriminate helicopter noise from the noise of other airplanes. The presence of any noticeable blade slap would almost certainly result in a listener recognizing the sound as emanating from a helicopter. Just because people can easily discriminate VTOL noise from CTOL noise does not necessarily mean, however, that the two kinds of noise would be judged as different with regards to "annoyance", "noisiness", "intrusiveness", or some other dimension of human aversion. Thus, although VTOL noise may sound different from CTOL noise, the question still remains as to whether VTOL noise should be measured differently or not.

Of the 34 studies reviewed, 11 of them are relevant to the generic question of whether helicopters as a class should have a single-number correction applied to measurements of their noise relative to CTOL aircraft. The majority of the experiments listed in Tables 1 to 4 did not employ any noises from CTOL aircraft as stimuli, and so were eliminated because they cannot directly answer the question. A few studies were eliminated because they were primarily methodological pilot studies and their data only tended to agree with the results of the main empirical studies that were included. The 11 experiments that did employ CTOL sounds, either as reference stimuli or intermingled with other helicopter stimuli, are shown in the last two columns of Table 4, labelled "Helicopter Correction". The first study, that of Crosse et al.,[15] cannot be easily evaluated along with the others. A non-conventional type of measurement, peak L_{PN}, was employed, and sufficient information is not given to convert this unusual unit to one with which quantitative comparisons can be made among the various other studies.

All of the remaining 10 studies report some sort of frequency-weighted or perceived noisiness average level, for the most part corrected for duration, primarily L_{EPN}. For each study, the last column of Table 4 shows the recommended single-number impulse correction to be added to measurements of the noise from VTOL aircraft, as a class, irrespective of variations among helicopter types and operating parameters. Two studies indicate an impulse correction of about +2 dB, four studies indicate about -2 dB, while four studies indicate 0 dB. Overall, the case for a generic impulse correction for all helicopter noise does not look good. When one considers that two of the -2 dB recommended corrections were reported by Ollerhead in rather similar studies, the average comes out to very nearly 0 dB (-0.2 dB, to be exact). Thus, from the present review, a generic measurement correction is not warranted for helicopters as one type of aircraft, compared to CTOL aircraft as another. This is not to say that different helicopters may not still vary among themselves as regards the perceived annoyance or noisiness of the sounds that they produce. It does imply, however, that, as a class of aircraft, helicopters should not be rated any differently from CTOL aircraft for their noise output, when measured in terms of L_{EPN}.

7.5 Crest Level

The single variable that has received the most attention with regards to impulse corrections for helicopter noise is the crest level of the signal or some variation thereof. With the exception of four studies that primarily concentrated upon phase relations, repetition rate or methodological concerns, the remaining 30 studies listed in Tables 1 to 4 either directly or indirectly manipulated the crest level of the signal. In some cases the crest level was under the experimenter's direct control through the use of synthetic electronically generated signals. In other cases, tape recorded samples of helicopter noise with differing degrees of impulsiveness were selected as stimuli by the experimenter. In these instances, the crest levels of the various helicopter noise samples were chosen to be quite different. The 30 studies that did employ varying degrees of crest level are indicated, along with their outcomes, in columns 5 through 8 of Table 4, labelled "Impulse Correction". A simple binary tally of the results reveals that 18 studies supported the need for an impulse correction based upon crest level, and 12 did not. The various amounts of the impulse correction suggested in Table 4 (column 8) correspond to signals with rather large crest levels, about 20 dB in most cases (column 7). Thus, for a helicopter noise with a crest level of 20 dB, one could take an average across all the positive estimates of the required impulse correction (column 8). This average impulse correction correction would be about 6.5 dB, computed by taking the mean of the 18 entries in column 8 where a positive impulse correction was found. However, as in the case of repetition rate, before reaching a possibly premature conclusion concerning the importance of crest level, a more detailed examination of these studies is warranted.

Most of the proposed impulse correction methods that are related to some variation of a crest level measurement, Δ_{SA}, Δ_{WHL}, Δ_{NPL}, Δ_{A}, Δ_{ISO}, and Δ_{CL}, incorporate some sort of impulse correction transfer function, i.e., the amount of impulse correction to be added to the basic measurement of helicopter noise as a function of a crest level-derived physical measurement. Thus the elaboration of a functional relationship between the perceptually required impulse correction and the crest level in the stimulus is a central theme in most of the 30 studies that address the crest level problem. As a result, several researchers have attempted to display on common coordinates the data from all the relevant studies in order to examine the form that such a composite function might take. Unfortunately, because of a plethora of different experimental approaches, possible relevant psychoacoustic measurement units, and candidate impulse corrections, this has not been easy to accomplish. The data are often simply not compatible, and a limited composite is the best that can be achieved. One such limited composite function, presented by Williams and Leverton,[8] is shown in Figure 6. The data displayed are from Berry et al.[5] (NPL), Leverton and Southwood[10] (Westland), d'Ambra and Damongeot[11] (Aerospatiale), Galloway[9] (BBN), and Leverton, Southwood, and Pike[21] (WHL T/R), representing only a small subset of all the data that might have been displayed. Even with this small number of studies, the ordinate in Figure 6, Δ_L , or the perceptually required impulse correction, involves some questionable mixing of units. Nevertheless, despite the considerable scatter, a general trend of growth in the required impulse correction with increasing crest level can be found. Many of the data from the remaining 13 studies which endorse a crest level-based impulse correction would probably fall in the general vicinity of the plotted data points. By contrast, some of the data from the remaining 13 studies (for example, those of Klumpp and Schmidt,[18] Lawton,[19] and Powell[28]) show a maximum impulse correction of only 2 to 3 dB. These latter data would be likely to fill out the lower right-hand corner of the graph, if it were convenient to plot them on these coordinates.

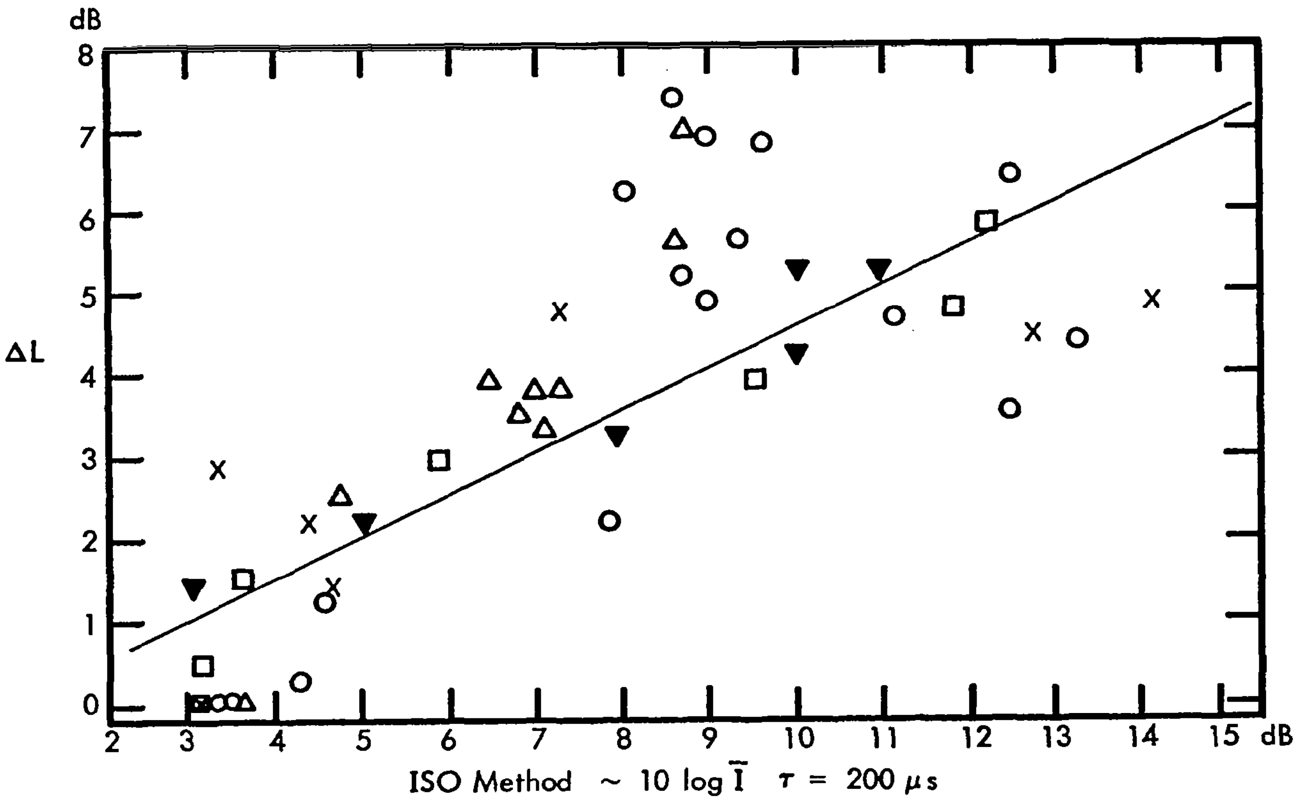

Figure 6. Composite Data Showing the Necessary Impulse Correction, Δ_L, as a Function of 10 log $\bar{I}$, From Williams and Leverton.[8] (Key to Data Source: X : NPL; □: Westland; O: Aerospatiale; Δ: BBN; ▼: WHL T/R.)

So far the discussion has centered around those studies which have supported a crest level-based impulse correction. However, there are 12 studies which have produced empirical evidence against the need for such an impulse correction. In fact, in many of these cases the implied impulse correction was negative. Pearsons[27] and Robinson and Bowsher[30] found that L_{PN} performed well in reflecting people's reactions to tape recordings of helicopter noise. Berry et al.[5] and Galanter et al.[17] found that no crest level impulse correction was needed for recordings of helicopter noise; instead L_{EPN}, which incorporates both a tone correction and a duration correction, was sufficient to describe the data. MAN-Acoustics and Noise, Inc.,[22] also used tape recordings of actual helicopter noise, along with simulations of other aircraft noise, while Sternfeld et al.[36] employed carefully synthesized VTOL and STOL sounds. In both experiments no evidence for a crest level impulse correction was found, and L_{EPN} could adequately describe the data. Likewise, Crosse et al.[15] dispensed with an impulse correction based upon a crest level concept, since their data better supported a peak effective perceived noise level measurement. In the Crosse et al. experiment, although an impressive sample of over 1,000 people participated, the acoustic stimuli were modulated bursts of jet takeoff noise, which may not have been representative of actual helicopter sounds. Thus these data may not be relevant.

Patterson et al.[26] and Powell[25] conducted the only experiments using the field method with live helicopter sounds as stimuli. In many respects, these two experiments represent the epitome of realism and simulation among the 34 studies reviewed in the present paper. Neither experiment substantiated the need for any crest level impulse correction for helicopter noise. In fact, Powell's data showed a more-impulsive helicopter to be less noisy than a less-impulsive one. When considered as a pair, these two studies complement each other from a methodological viewpoint as well. Whereas Powell sampled only two types of helicopters, Patterson et al. employed 9 different helicopters executing 12 different maneuvers. Whereas Patterson et al. sampled only 25 listeners, Powell employed a more substantial sample size of 91 people in his experiments. Furthermore, the findings of Powell's field study were carefully replicated and independently verified by two different investigators, Ollerhead[24] (pilot study) and Shepherd.[31] These two laboratory validation experiments presented tape recordings of the actual sounds heard by the listeners in Powell's field experiment. They obtained essentially the same results, the first using earphones and the second using loudspeakers. Thus, with respect to face validity and cross-validation, the results of these two field studies should be weighed heavily in evaluating the need for a crest level impulse correction.

The series of experiments conducted by Ollerhead[24] should also receive considerable weight. This program of research embraces nine separate interlocking experiments that exhibit uncommon methodological and empirical cross-checks. The effects of variations in stimulus presentation, psychophysical methods, verbal descriptors, etc., were all tested to ensure a maximum of cross-coupling in the data obtained. From the standpoint of the number of stimuli presented, of the 34 experiments reviewed in the present paper, these experiments conducted by Ollerhead represent the most ambitious sampling of aircraft sounds: 89 helicopter noises and 30 CTOL noises in a single experiment. Some of the overall conclusions drawn from this series of experiments were: (1) that no crest level impulse correction was needed; (2) that the duration and tone corrections inherent in the L_{EPN} calculating algorithm are sufficient to rate helicopter sounds; and (3) that helicopter sounds tended to be overrated as to their annoyance by about 2 dB when compared with CTOL sounds.

Taken together, the Patterson et al. and Powell field studies, their attendant replications, and the carefully laid-out Ollerhead experimental series represent the best examples of experimental methodology in practically all of the important categories of Tables 1 to 4. With the exception of the two studies that were conducted in conjunction with an airshow, Crosse et al.[15] and Robinson and Bowsher,[30] Powell and Ollerhead employed the largest samples of research participants. This is in addition to the most realistic stimulus presentation method and the largest number of different helicopter sounds. Thus the consistent disavowal of an impulse correction in all of these studies must be taken seriously.

7.6 Resolution

Although, according to the taxonomy presented in Tables 1 to 4, the most impressive studies are aligned against a crest level-based impulse correction, there are some excellent experimental results supporting the notion. Of the 18 studies that endorse an impulse correction, several stand out as fine examples of psychoacoustic research. Then why the discrepancy in results? The source of this discrepancy may lie in the methodologies and approaches selected by the experimenters. The 30 studies that address the issue of a crest level impulse correction were separated into those studies that endorsed such a correction and those that did not. These classifications were further partitioned in various ways according to the methodologies employed in the various experiments. For example, one partitioning was according to the method of stimulus presentation: live, free-field, semi-reverberant field, or earphones. Another was according to the psychophysical technique of measuring people's responses: comparison, adjustment, or rating method. Still a third was according to the verbal descriptor employed: "annoyance" or "noisiness". If each study was considered to be a single score, the resulting contingency tables showed no statistically significant relationships between the experimental methodology employed and the outcome of the experiment, as regards the need for a crest level based impulse correction.

One methodological distinction did appear to offer more promise of showing such a relationship. That distinction was between natural and synthesized sound stimuli. An important decision that must be made in designing any psychoacoustic experiment on helicopter noise is whether to use natural helicopter sounds, either presented live in the field, or tape recorded in the field and reproduced under laboratory conditions. The alternative is to use artificial electronically synthesized sounds. The relative advantages and disadvantages of using synthesized helicopter sounds are enumerated in Section 4.1.6.

In Table 5, 29 of the 30 studies that address the problem of a crest level impulse correction are partitioned according to whether they employed natural helicopter stimuli or synthesized stimuli, and according to whether an impulse correction was indicated by their data, or no impulse correction was indicated. The rationale for partitioning the studies was straightforward in most cases. The separation into those groups that supported a crest level impulse correction and those that did not was simply by the entries in column 5 of Table 4, just as in Section 7.5, with one exception. The study by Leverton et al.,[21] which endorsed the impulse correction, could not be included in Table 5 because of insufficient specification of stimulus presentation methods in the report. That is why Table 5 shows 17 studies in favor of an impulse correction and 12 against it, whereas Section 7.5 gives 18 for and 12 against. Otherwise, the four remaining studies that were eliminated are the same ones that were eliminated in Section 7.5. These four studies, listed in the insert at the lower right of Table 5, were not included for the same reasons given earlier, i.e., they concentrated upon other variables.

Classification according to stimulus material, natural or synthesized, was accomplished by inspection of column 3 of Table 2, labelled "Helicopter Source". Here "synthetic" signals were obvious to classify, and "recorded" and "live" signals were classified as "natural stimuli". There were a few special cases, however. Four studies (Galloway,[9] Leverton and Southwood,[10] MAN-Acoustics and Noise, Inc.,[22] and Williams[36]) employed a combination of synthetic and recorded signals. These studies were classified according to whether the majority of the signals presented were synthetic or recorded, as indicated in column 10 of Table 2. Two studies employed what has been called "mixed recorded" stimuli in the nomenclature of the present review. d'Ambra and Damongeot[11] and Sternfeld and Doyle[29] started out with recorded samples of helicopter noise which

Table 5

Classification of Studies Addressing
Crest Level Impulse Correction Question

NATURAL STIMULI — IMPULSE CORRECTION

Study No.	Authors
11.	Klumpp and Schmidt
13.	Leverton
17.	Munch and King
	TOTAL = 3

NATURAL STIMULI — NO IMPULSE CORRECTION

Study No.	Authors
2.	Berry _et al._, 1
8.	Galanter _et al._
16.	MAN-Acoustics and Noise, Inc.
19.	Ollerhead, M
20.	Ollerhead, R
21.	Patterson _et al._
22.	Pearsons
25.	Powell, 1981
27.	Robinson and Bowsher
28.	Shepherd
	TOTAL = 10

SYNTHESIZED STIMULI — IMPULSE CORRECTION

Study No.	Authors
3.	Berry _et al._, 2
4.	Berry _et al._, 3
6.	d'Ambra and Damongeot
7.	Fidell and Horonjeff
9.	Galloway
12.	Lawton
14.	Leverton and Southwood
23.	Powell, 1978
26.	Powell and McCurdy
29.	Southwood and Pike
30.	Southwood
31.	Stent and Southwood
32.	Sternfeld and Doyle
34.	Williams
	TOTAL = 14

SYNTHESIZED STIMULI — NO IMPULSE CORRECTION

Study No.	Authors
5.	Crosse _et al._
33.	Sternfeld _et al._
	TOTAL = 2

NOT INCLUDED

1.	Ahumada and Hersh
10.	Izumi
15.	Leverton _et al._
18.	Ollerhead P
24.	Powell, 1980

they electronically separated into an impulsive component and a continuous component. Then they electronically mixed these two components back together in varying proportions to create a wider range of helicopter sounds than is likely to occur in nature. Since this approach eliminated some of the natural constraints on the possible impulsive/ continuous combinations that would be likely to occur in real helicopter noise observed in the field, these two studies were classified as having "synthesized" as opposed to "natural" stimuli. Similarly, Southwood[33] engaged in electronic manipulation of recorded helicopter sounds by applying a "notch" filter to attenuate some of the middle frequency components of helicopter blade slap. Although listed in column 3 of Table 2 as coming from a "recorded" helicopter source, the artificial electronic manipulation executed by Southwood was classified under "synthesized" as opposed to "natural" stimuli. Thus the governing principle for classification is the degree of constraint over acoustic parameters imposed by natural helicopter designs and operations. Electronic manipulations or simulations that go beyond these constraints are considered "unnatural" or "synthetic".

Inspection of Table 5 shows a strong relationship existing between the type of stimulus employed and the outcome of the psychoacoustic study as concerns the need for a crest level impulse correction. Studies employing natural stimuli tend to reject an impulse correction, whereas studies employing synthesized stimuli tend to endorse it. If all of the 29 studies in Table 5 are given equal weight, a simple statistical test confirms the obvious conclusion that the type of stimulus and the need for an impulse correction are significantly related ($\chi^2 = 12.26$, 1 df, $p < 0.01$). There are two possible reasons for this relationship.

First, as mentioned earlier, those experiments employing synthesized stimuli are likely to include combinations of acoustic parameters that do not occur in nature. Some of these acoustic parameters may have important psychoacoustic effects upon the annoyance or noisiness responses of people. However, they may be so combined by the natural physical constraints of real helicopter operations that their effects are compensatory, i.e., one parameter always offsets the other. This is, after all, similar to the argument that has been made by Ollerhead[24] and Powell:[25] with natural helicopter stimuli, either presented live or via tape recordings, the combined duration, spectrum, and level changes that accompany helicopter blade slap are sufficient, within the context of L_{EPN} measurements, to account for the human response to impulsive versus non-impulsive helicopter noise. The presence of blade slap, in and of itself recognized as contributing to increased annoyance, produces changes in other acoustic parameters that can compensate for or account for the increased annoyance caused by the presence of the blade slap. Altering the natural constraints among the acoustic parameters by electronic tampering can destroy this compensatory mechanism.

A second possible reason for the observed relationship between the type of stimulus and the need for an impulse correction is the existence of a bias that sometimes occurs in this sort of psychophysical testing. In Section 4.2.4, the fundamental response underlying all 34 psychoacoustic experiments on helicopter noise was shown to be that of discrimination. Even when stimuli are perceptually matched for "equal annoyance" or "equal noisiness", they are still discriminably different on other dimensions. The purpose of the verbal descriptor is to restrict the participant's response. However, when one considers the exquisite sensitivity of the human observer, the contrivance of artificial psychoacoustic experiments where carefully administered amounts of impulsiveness may be interjected by electronic means can militate against the experimenter in the following manner.

In many of the experiments using synthetic sounds, the listener hears a reference non-impulsive helicopter stimulus and a series of test helicopter stimuli composed of that same identical non-impulsive reference helicopter sound with a few different levels of impulses added to it. The danger exists in having this sort of experimental design too transparent to the participant who, despite the invoking of certain abstract verbal descriptors, is under a strong tacit motivation to please the experimenter and not to appear inconsistent. If sound A is that of a non-impulsive helicopter, and sound B is sound A-plus-impulses, to the listener, sound B must somehow be greater than sound A, for sound B is sound A plus something. Despite the verbal instructions exhorting the listener to pay attention only to the relative "annoyance" of the sounds, since the listener can readily discriminate that something has been added to the second sound, the listener may presume that the second sound must be louder and therefore more annoying than the first sound. The participant may perceive this, even if the impulses really exert some sort of soothing influence on the sound complex and actually make the combination less annoying. The experimenter obviously added something to the stimulus, and the listener wants to please the experimenter and not to respond in an inconsistent manner. In short, if the participant can discriminate among the stimuli, he will tend to discriminate among them, even if this discrimination is of no real consequence to his relative aversion for the sounds. Those psychoacoustic experiments which employ natural helicopter stimuli are less prone to encountering this sort of psychophysical bias, since they rarely have the luxury of careful, progressive, and wide variation of parameters. They usually present randomly scattered combinations of stimulus parameters that vary on many dimensions at the same time. With natural stimuli, typically the listener has considerably more difficulty in trying to second-guess the experimenter.

Thus two possible reasons have been offered for why those studies that employed natural stimuli tended to find no impulse correction and those that employed synthesized stimuli did find an impulse correction. These reasons may explain why the majority of the studies in Table 5 follow the general relationship. An examination of the five studies in Table 5 which do not uphold this general relationship might prove revealing as exceptions to the rule. Of the three investigations which used natural stimuli and supported an impulse correction, two of them (Leverton[20] and Munch and King[23]) were only pilot studies, possibly conducted with the experimenters themselves serving as the listeners, for no information is given on the number or kind of research participants who took part in the experiments. By contrast, the study conducted by Klumpp and Schmidt[18] represents a substantial psychoacoustic investigation. These researchers employed a rather incongruous reference sound, that of a city bus; but this should not have seriously affected the results. They did, however, only indicate the need for a modest impulse correction of 2 dB. On the other side of the issue, two studies which employed synthesized stimuli did not support an impulse correction. As mentioned earlier, the investigation of Crosse et al.[15] used modulated jet takeoff noise as a simulation for helicopter impulses. When compared with the acoustically more faithful simulations used in most of the other studies, the perceptual realism of this stimulus may certainly be questioned. Furthermore, the classification of the Crosse et al. study according to whether it does or does not support a crest level impulse correction is open to interpretation. By a strict interpretation, Crosse et al. recommend a peak L_{PN} measurement instead of a crest level measurement. However, one could argue that using a peak L_{PN} measurement for helicopter noise, and using a time-averaged L_{PN} measurement for CTOL aircraft noise, at least conceptually, represents an operation similar to making a perceptually adjusted crest level determination. In a similar manner, the experiment of Sternfeld et al.[36] possesses unusual features. As regards the stimulus parameters investigated, these researchers concentrated on overall level and spectrum shape as independent variables. They did not independently manipulate the crest levels of their stimuli. Furthermore, they employed an extremely realistic simulation of the psychological context for obtaining laboratory psychoacoustic data. Their superior psychological modeling of actual meaningful listening situations would make their study more resistant to the intrusion of a psychophysical bias for second-guessing the experimenter. Thus, for four of the five studies that do not uphold the general relationship, special circumstances may explain why they stand as exceptions.

In summary, the question of whether or not a crest level-based impulse correction is needed in the measurement of helicopter noise resulted in a close vote: 18 studies in favor and 12 against. However, counted among the 12 negative votes were some of the most carefully designed and realistically executed psychoacoustic experiments of all the 34 studies reviewed. Practically all those studies that employed natural helicopter noise stimuli, either live or tape recorded, found that no impulse correction was needed. Conversely, practically all those studies that employed electronically modified helicopter noise or electronic simulations of helicopter noise found that an impulse correction was needed. Thus the outcome of the experiment is to some degree a function of the design of the psychoacoustic test and the methodology employed. In operational terms, the answer obtained depends upon the question asked. One question is: Can one construct a psychoacoustic experiment with helicopter-like sounds such that people will respond to the crest level of the acoustic signals? The answer is yes. People are sensitive to differences in the crest level or degree of impulsiveness in sounds. If one isolates the variable of crest level and systematically manipulates it, people will likely discriminate these changes in the stimulus and will respond to them in a systematic way. This is not to say, however, that this seemingly systematic response necessarily represents changes in the actual annoyance experienced or in some other psychologically meaningful feature of importance or of consequence to the listener. The other question is: Are differences in crest level important determinants of the negative reactions that people might have upon hearing actual helicopter sounds in their natural environments? The answer is probably no. Those psychoacoustic experiments that presented a wide variety of natural helicopter sounds, both live and recorded, under conditions that most nearly simulated actual listening environments, both acoustically and psychologically, practically all showed no effect of crest level on annoyance or noisiness judgments of the sounds.

8.0 CONCLUSIONS

The present paper reviewed 34 psychoacoustic experiments on the human response to helicopter noise. Certain variables emerged as being of possible importance in providing a psychoacoustic foundation for measurements of helicopter noise. Of particular interest were those variables which could be incorporated as possible corrections for impulsive blade slap. The importance of five factors was assessed:

1. Phase Relations — The effects of varying the phase relations among the Fourier frequency components constituting helicopter blade slap have not been well researched. Of the 34 studies reviewed, only two related to this problem, and their results were contradictory. Thus, at present, phase relations are not considered to be an important variable.

2. Tail Rotor Noise — Certain helicopters produce a distinct noise that emanates from the tail rotor. Tail rotor noise may have some effect upon the overall human response to helicopter noise, but it is not well understood, and its effect is probably secondary to that of main rotor blade slap. Of the 34 studies reviewed, only two addressed this issue. Both suggested that tail rotor noise can likely be accounted for in whatever manner is devised for main rotor blade slap. Therefore tail rotor noise is considered to be a secondary factor of relatively little importance.

3. Repetition Rate — The repetition rate of the individual noise pulses that make up helicopter blade slap has been suggested as an important determinant of the human response to helicopter noise. Ten of the 34 studies reviewed investigated the repetition rate parameter to some degree. Two studies indicated that no repetition rate correction was needed, four provided weak evidence of a possible relationship, while four supported such a correction. Contradictory evidence concerning the direction of the effect, considerable variability in the data supporting the effect, and certain possible methodological drawbacks make the definition of a useful functional relationship extremely difficult. Consequently, for the present, repetition rate is not considered to be an important variable. Measurements of L_{EPN} should be adequate to account for differences in repetition rate.

4. CTOL Versus VTOL Differences — Some researchers have suggested that a single-number penalty should be applied to all helicopter noise in order to account for blade slap, irrespective of differences in helicopter type and operations. Eleven of the 34 studies reviewed addressed this question: two

suggested a +2 dB penalty, four suggested a -2 dB penalty, and four suggested no penalty (one study deleted). When properly adjusted for the specifics of each study, the average correction came out to be very nearly 0 dB. Thus, as a class, helicopters should not be measured differently from other aircraft.

5. Crest Level — Most of the 34 studies reviewed (30 to be exact) either directly or indirectly investigated possible impulse corrections for helicopter noise based on crest level types of measurements. Of these, 18 studies supported the need for a crest level based impulse correction, and 12 did not. But this small majority in favor of a crest level type correction was offset by some of the larger scale and more realistically executed experiments aligning themselves against such a correction. Methodological considerations provided an exit from this dilemma. Practically all those studies that reported the need for a crest level impulse correction employed electronically synthesized or electronically modified examples of helicopter noise. These electronically created sounds represented many variations of helicopter noise that do not occur in nature. Furthermore, such artificial simulation experiments are susceptible to certain possible psycho-physical biases. Conversely, practically all those studies that reported no need for a crest level impulse correction employed natural helicopter stimuli, presented either live or by tape recordings. These experiments often involved large samples of realistic helicopter noises under conditions that most nearly simulated actual listening environments. For this second group of studies, in practically all instances, the tone and duration corrections already inherent in the L_{EPN} measurement scheme could adequately handle impulsive helicopter blade slap. Therefore, as concerns the possible negative reactions of people actually exposed to helicopter operations, the conclusion is that crest level, or one of its derivative measurements, is not an important factor to consider as the basis for an impulse correction.

In summary, a careful analysis of the evidence for and against each factor reveals that, for the present state of scientific knowledge, none of these factors should be regarded as the basis for a significant impulse correction. The commonly used method of measuring effective perceived noise level, L_{EPN}, with its inherent corrections for tonal components and exposure duration, is adequate for measuring helicopter noise as well. Thus, at present, there is apparently no need to measure helicopter noise any differently from other aircraft noise.

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16. Abstract

A detailed review of 34 studies indicated that several factors or variables might be important in providing a psychoacoustic foundation for measurements of the noise from helicopters. These factors are phase relations, tail rotor noise, repetition rate, crest level, and generic differences between conventional aircraft and helicopters. Particular attention was given to the impulsive noise known as blade slap. A careful analysis of the evidence for and against each factor reveals that, for the present state of scientific knowledge, none of these factors should be regarded as the basis for a significant noise measurement correction due to impulsive blade slap. The current method of measuring effective perceived noise level, L_{EPN}, for conventional aircraft appears to be adequate for measuring helicopter noise as well. Thus there is apparently no need at present to measure helicopter noise any differently from other aircraft noise.

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