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AIRCRAFT NOISE EFFECTS ON CULTURAL RESOURCES: REVIEW OF TECHNICAL LITERATURE

Carl E. Hanson, Kenneth W. King, Mary Ellen Eagan, Richard D. Horonjeff

HMMH Report No. 290940.04-1
September 1991

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Prepared for:
National Park Service, U.S. Department of the Interior
NPS-dsc Contract No. CX-2000-0-0025
Work Order No. 4

HARRIS MILLER MILLER & HANSON INC.

Consultants in Noise and Vibration Control

NPOA Report No. 91-3
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FORWARD

This report is the first of three products prepared under Work Order No. 4, Contract No. CX-2000-0-0025, dated July 16, 1990. The scope of work required a review, critique and analysis of the scientific literature to assess the nature and probable magnitude of the potential effects of aircraft overflights on historical and cultural resources in the National Park System. Excluded under this work order are such items as historical or cultural context or setting.

Separate from this report are two other products:

1. A report on recommendations and rationale for further research in specific areas necessary to assess the effects of aircraft overflights on historical and cultural resources and measures to mitigate the most important adverse effects.

2. An annotated bibliography of the literature reviewed.

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EXECUTIVE SUMMARY

This report summarizes the available literature on aircraft noise-induced vibrations of structures, with a focus on damage to historical and cultural resources. For purposes of preservation, the term "damage" in this context refers to the threshold level of the onset of a permanent effect. An important effect of aircraft noise may be the initiation of cracks in the surfaces of structures. This apparent insignificant event can be the first step to further damage in the long term by the forces of nature.

Most of the available literature stems from research on the effects of sonic booms conducted by the U.S. Air Force, the National Aeronautics and Space Administration and the Federal Aviation Administration. These studies conclude that sonic booms present very substantial risks to structures within the area of their influence. Methods of estimating probabilities of damage to historical and cultural resources have been developed.

In contrast, very limited information has been obtained on the response of structures to subsonic aircraft and helicopters. Measurement programs have been conducted which conclude there is normally a minimal risk of damage to structures from low-flying subsonic jet aircraft and small helicopters. However, a recently-developed prediction method places a statistical estimate on the probability of noise-induced damage to prehistoric structures and other cultural resources from low overflights of multi-engine bombers and large helicopters. A ranking of the risks of damage is included in Table 4.1 of this report. Among the structures most susceptible to damage are parts of wood-frame historic houses and prehistoric buildings with intact roofs.

Perhaps the most significant finding from the literature review is the potential damage risk from helicopters. The noise characteristics of helicopters are such that they tend to excite nearby structural elements at their resonance frequency, causing low frequency vibrations, rattle, and in some cases, damage. The sound pressure is greatest at structures in the plane of the main rotor, such as could be the case for a helicopter approaching a cliff dwelling. This subject is worthy of further investigation.

Four representative cultural resources administered by the National Park Service were reviewed according to available models for probability of damage from either subsonic or supersonic aircraft.

Each of the four experienced some risk of damage from overflights, including:

> Fort Jefferson National Monument: Fragile mortar may be susceptible to damage from sonic booms.
>
> White Sands National Monument: Flat roof with viga construction is susceptible to damage from helicopter noise.

San Antonio Mission National Historic Park: Masonry buildings with intact roofs are in the very high risk category for sonic booms, low-flying subsonic multi-engine bombers, and heavy (greater than 20,000 lbs.) helicopters.

Chaco Culture National Historic Park: Rubble-core adobe walls are somewhat susceptible to damage from helicopter noise.

Mitigation measures for aircraft noise-induced vibration effects found in the literature are based on maintaining a clear zone between the vibration-sensitive receivers and aircraft operations that may cause damage. Definition of what distance constitutes a "clear zone" is lacking in the literature, although one study identified 50 feet to avoid damage from helicopter noise to a fragile structure at Mesa Verde and another study identified 500 feet as a minimum to avoid "rattle" in wood frame houses from helicopter noise. Mitigation is another area where more information should be developed.

1. INTRODUCTION

This report presents a review of the existing scientific literature concerning aircraft noise-induced damage to structures, with a focus on historical structures and cultural resources. Both short term and long term effects have been observed and recorded in attempts to quantify the relationship between cause and effect and to establish criteria. Prediction models developed from these studies enable the estimation of probabilities of damage from aircraft operations and the specification of mitigation measures. In this report, every effort is made to preserve the results and opinions of the referenced authors. Summaries of the best available methods for the evaluation of damage to historical and cultural resources are provided. An annotated bibliography of referenced sources follows in a separate document.

1.1 Overview of Aircraft Noise Effects on Cultural Resources

Aircraft noise is of concern to communities in the vicinity of airports, primarily due to annoyance from interference with activities around the home or interference with speech in schools and offices. However, an additional concern is the suspicion that high noise levels are causing damage to structures. The literature referenced throughout this report contains a wide variety of claims. Resonant vibrations of building elements are commonly experienced during aircraft overflights, reportedly causing walls to vibrate, windows to shake and hanging bric-a-brac to rattle. There have been claims of nails popping out of siding and interior walls, and chandeliers falling due to aircraft noise-induced vibrations. Helicopter overflights have caused windows to rattle and houses to shake. Sonic booms have been blamed for window shattering and cracks developing in plaster walls. The public perception is that all this vibration must result in damage -- maybe not immediately, but in the long term. In fact, it is this very concern that drives this study: cracks develop in houses, buildings, and all structures as they age. When buildings are *very* old, they take on additional value: they become cultural resources and are often irreplaceable. Thus, any form of damage is a threat to such an irreplaceable resource - and if aircraft noise causes damages, then a way must be found to prevent such exposure.

Prompted by this concern, Congress required the National Park Service in Public Law 100-91, Section 1 (C) to conduct research which "shall provide information and an evaluation regarding...injurious effects of overflights on the ...historical and cultural resources for which such units were established." These resources include historical and archeological structures, including sites on the National Register of Historic Places and National Landmarks, and under certain circumstances, archeological sites and artifacts and cultural resource objects inside structures. Historical or cultural context or setting are also addressed under Public Law 100-91, but are excluded from consideration under this work order. Issues of human detection and annoyance are not part of this study. Consequently, the literature review for this work order is focused on the physical response of structures and objects to airborne noise.

1.2 Extent of Literature on Aircraft Effects on Cultural Resources

This report is a review of the existing literature pertaining to the potential for short term and long term damage to sites and structures from operations of aircraft. The search procedure was carried out as follows. Prior surveys of literature in this field were conducted during recent research programs sponsored by the U.S. Air Force and others (Sutherland, et al., 1990; Sutherland, 1990; Haber and Nakaki, 1989). This study used the bibliographies resulting from these studies as a starting point. Relevant primary sources were retrieved for detailed study and application to the specific structures and objects associated with cultural resources. Additional key references from some of these documents were obtained. Bibliographies from key journals, such as the Journal of the Acoustical Society of America and the Journal of Sound and Vibration, were reviewed. A computerized search of literature was undertaken to supplement the published bibliographies. The search was conducted using the DIALOG Information Services' databases on the topic of aircraft noise-induced vibration effects on cultural resources. The following databases were included in the search: NTIS; DISSERTATION ABSTRACT; ENVIROLINE; TRIS; AVERY ARCHITECTURE INDEX; FEDERAL RESEARCH IN PROGRESS and the GPO DATABASES (Files 66 and 166). The concepts searched were vibration damage of historic buildings, sonic boom effects on buildings, vibration-triggered avalanches, helicopter sound pressures measured at ground level and infrasound effects on buildings. Particular types of construction such as adobe and viga construction were also searched as well as particular authors on the subjects. Finally, collaboration with key researchers in the field yielded additional work in progress or unpublished reports which were found to be relevant to the subject.

Studies of aircraft noise effects on structures have been prompted by more than Congressional interest. The Environmental Impact Assessment process carried out for proposed military training routes and supersonic operations areas must address the potential for damage to cultural resources in order to respond to public concern regarding potential damage. Consequently, there is a need to establish guidelines for the evaluation of claims of damage caused by aircraft overflights. The bulk of the literature has been generated from the following sources:

- Sonic boom research sponsored by the U.S. Air Force under the Noise and Sonic Boom Impact Technology Program (This program is current. Sonic boom research has recently restarted after a nearly ten year hiatus since the late '70's.);

- Sonic boom research by the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) during the middle 1960's (This testing program continues to serve as the basis for current research.);

- Environmental impact assessments conducted by the U.S. Air Force for proposed military training routes for subsonic and supersonic aircraft;

- Measurements of aircraft noise-induced vibration of buildings conducted by NASA in the vicinity of rocket launch sites;

- Measurements of airborne and ground-borne effects of blasting by the Bureau of Mines and Atomic Energy Commission;

- Measurements of vibrations of archeological ruins from aircraft noise and other seismic events by various researchers from the U.S. Geological Survey, the U.S. Air Force Geophysics Laboratory and others.

The literature covers a wide range of topics relating to effects on all types of structures and building elements subject to high noise levels from aircraft operations. A subset of these structures could be considered historical and cultural resources. A review of the types of structures to be considered in this study appears in Section 2, with detailed consideration of those likely to be significantly affected in Section 4. Section 2 also includes background information and a definition of effects, both long term and short term, a review of the thresholds of effect and estimation procedures involving the key factors which influence the effects. Section 3 includes a discussion of the aspects of aircraft overflights which cause the most significant effects. Section 4 focuses on the types of historical structures and other cultural resources subject to the most significant effects. Finally, Section 5 covers any recommended measures that have been identified to mitigate potential adverse effects of aircraft overflights. All references used as primary sources are listed in Section 6. Some of the primary sources include extensive literature surveys (e.g., Sutherland, 1990; Sutherland, et al., 1990; Haber and Nakaki 1989); key references were checked when they were judged to hold important information relevant to cultural resources; others were considered to be incorporated in the author's review by reference.

2. EFFECTS ON HISTORICAL AND CULTURAL RESOURCES

The term "adverse effect" has special meaning when used in association with historical properties. For example, the definition put forth in The National Historic Preservation Act of 1966 states: "An undertaking is considered to have an adverse effect when the effect on a historic property may diminish the integrity of the property's location, design, setting, materials, workmanship, feeling or association." Covered in this review are physical effects (presumably included in the above definition as "design" and "materials"), but not subjective effects such as setting, aesthetics, feeling or association. This section defines "effects" for the purposes of this review, and summarizes observed and predicted effects from aircraft noise on all structures, not necessarily only historical and cultural resources. Thresholds for determining significant effects are also reviewed and interpreted in the context of application to historical and cultural resources of the National Park System.

2.1 Observed Effects - All Structures

In order to understand the effects of aircraft noise on structures, it is necessary to have a grasp of basic terminology. The following discussion introduces the terms used in this report in a summary of the interaction between sound and structures.

Airborne sound[1] at a single point is a disturbance in the ambient pressure of the atmosphere. A steady-state sound is a continuous fluctuation over a long period of time, whereas a transient sound is only temporary. Rapid fluctuations are distinguished from slower ones by the number of times per second they occur, or their frequency, measured in Hertz (Hz). One Hz equals one cycle per second. Sound may be made up of a combination of many frequencies. When sound is analyzed, it is common to break it up into its component frequencies such that the sound pressure at each frequency is displayed in a spectrum, typically ranging from 16 Hz to 20,000 Hz, the range of human audibility. The magnitude of pressure oscillation is measured in terms of pounds per square inch (psi) in the English system and Pascals (= one Newton per square meter) in the International system of physical units. In fact, the effective magnitude of the pressure fluctuation is expressed in terms of either the peak pressure, its highest value, or the root mean square (rms) pressure, a measure of the energy of the sound. The range in magnitude of the sound pressures commonly experienced in our environment is very great; the ratio of sound pressures from the loudest sounds (close to a jet engine) to the quietest sounds (threshold of hearing) is as much as a million to one. As a result, acousticians use a logarithmic quantity described in terms of decibels to simplify the numbers and bring them into a more manageable range. For example, the one million to one range in pressures thereby shrinks to a range of 120 decibels.

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[1] The words "sound" and "noise" can be used interchangeably for the purposes of this report. Sometimes "noise" is referred to as "unwanted sound," implying an attitudinal differentiation, but the physical phenomena are identical.

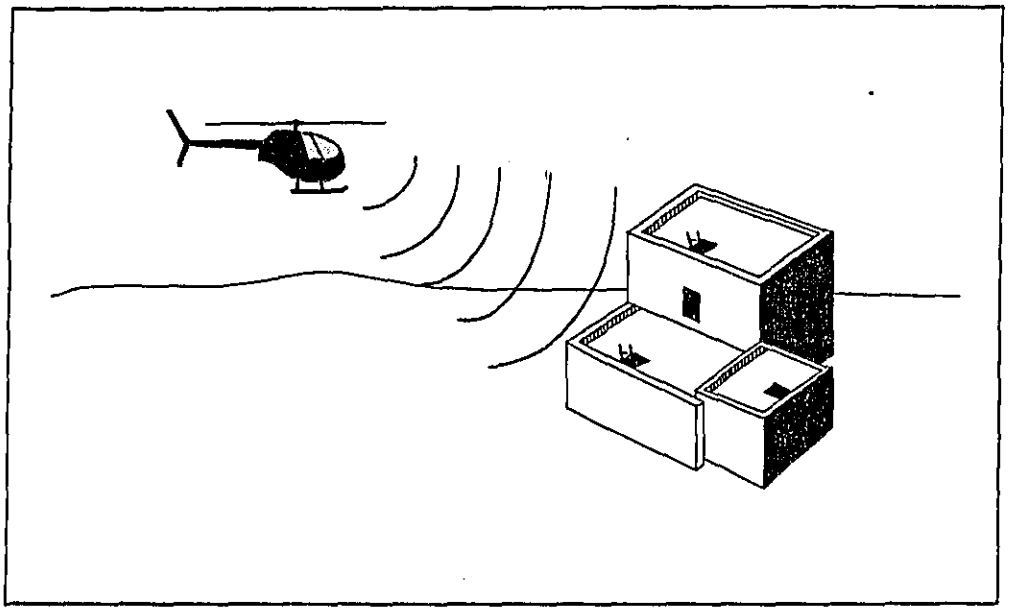
An intrinsic characteristic of sound is that it travels in waves, with a speed (sound speed) that depends on the density of the air. These waves contain energy (sound energy), and when they encounter a structure, part of the energy is transferred to the structure and part is reflected. How much of the sound energy is transferred depends on how easily the surfaces of the structure are set into motion in compliance to the shape of the sound wave. A technical term for this compliance is **admittance**, a measure of how much motion in the surface is generated by a given pressure. The motion of the surface is generically called **vibration** and is usually expressed in terms of the velocity. Consequently, the units of admittance are velocity divided by the pressure (e.g., in/sec/psi). Sometimes the motion of the surface is expressed in terms of **acceleration** with the units of inches per second per second (in/sec^2), or very commonly in terms of the acceleration due to gravity, g, where one "g" equals 386 in/sec^2. As in the case of sound pressure, vibration is expressed in terms of either the peak velocity (or acceleration) or the rms velocity (or acceleration). Also as in the case of sound pressure, vibration is characterized by its frequency.

A structure exposed to sound pressure waves will respond (**dynamic response**) by bending of its surfaces and distribution of the energy to other parts of the structure without major physical effects. However, the construction of structures and especially the dimensions and material characteristics of structural elements (walls, windows, roofs, etc.) makes them particularly compliant at certain frequencies, called **resonant frequencies**. At these frequencies the vibrations of the surface can be very great, limited only by material characteristics. One of the more important characteristics limiting the motion at resonance is **damping**, a measure of how much energy a material or a structure can dissipate. When the resulting bending motion is too great for the material to accommodate, it will fracture.

Aircraft noise is generated by the propulsion system and airflow over the airframe. Aircraft flying faster than the speed of sound generate an intense pressure wave called a sonic boom in addition to the propulsion and airframe noise. The noise-generation characteristics of each aircraft type is discussed later in Section 2.4.

Thus, aircraft noise impinging on a building, as illustrated in Figure 2.1, or other structure or artifact may result in any of a number of observable physical effects. In descending order of amplitude they are: permanent displacement, visible motion, feelable vibration and audible re-radiated sound. The only lasting of the foregoing physical effects is permanent displacement, a failure of a structural element which occurs whenever the peak stress induced by the pressure loading exceeds the material strength. Such a failure is commonly called "damage," a term with multiple implications depending on the circumstances in which it is used. For example, "cosmetic damage" has an entirely different connotation than "structural damage." The former is associated with visible cracks in non-structural members, while the latter may involve large cracks in structural members with resulting reduction in load-carrying capacity. However, as shown in Section 2.4.2 below, neither can be neglected since in some ancient structures, the incidence of cosmetic damage may have serious effects in the long-term. Most authors refer to the threshold of effect as "damage", even though the occurrence of damage may simply be hairline cracks which may be indistinguishable from cracks generated by other causes. Some of the types of aircraft and non-aircraft damages are described in the following sections.

Figure 2.1 Aircraft Sound Wave Impinging on a Historical Site



2.1.1 Observed Damage from Aircraft Noise

Aircraft noise, especially sonic boom excitation, has been blamed for damage in structures. Much of the research was done during tests conducted in the mid-1960's. Some of the effects cited in the literature are as follows:

> Cracked Plaster: Cracks in surface plaster from overflights of supersonic aircraft were the leading damage claim item in the Greater St. Louis area and were the second-leading claim for Edwards Air Force Base tests according to U.S. Air Force files (Clarkson and Mayes, 1972; Hershey and Higgens, 1976). Sonic booms have resulted in documented widening of existing cracks in an adobe wall (Sutherland et al., 1990). Plaster has the highest breakage probability of the structural elements considered by Hershey and Higgins (1976).

Broken Windows: Cracked glass is also a leading damage claim item resulting from sonic boom exposure, and it is currently the only recognized property damage in the U.S. Air Force's planning guidelines (USAF). It has the second highest probability of damage from sonic booms of the structural elements considered by Hershey and Higgins (1976). Overflights of heavy helicopters have been the source of window damage (Sutherland, 1990).

Roof Tile Failures: Old roofs, especially those with slate or ceramic tiles with corroded nails, slip as a result of sonic boom overpressures (Haber and Nakaki, 1989).

Bric-a-Brac Breakage: Small items on shelves vibrate and fall off; pictures fall from interior walls as a result of sonic boom overpressures (Hershey and Higgins, 1976).

Plaster Dust Fall: Sonic boom shook a house under observation and caused noticeable dust to fall from the edges of the ceiling (Brown and Sutherland, 1990).

Chimney Dust Fall: Sonic boom overpressures in the range of 0.5 to 2 psf have caused soot to fall from previously unswept chimneys (Haber and Nakaki, 1989).

Avalanches and earth slides: Although the probability of triggering an avalanche or landslide by aircraft noise is small, there have been reports of sonic booms triggering unstable snow fields and earth slides. Sutherland et al. (1990) gives a few references, including one with a credible observation by a National Park ranger of a slide triggered by a sonic boom.

Damage attributed to aircraft overflights is often difficult to quantify due to a lack of before- and after documentation. Cracks in interior surfaces are especially difficult to document (Sutherland et al., 1990). The factors which influence the ability to observe and record cracks in structures during a research program are (Wiggins, 1965):

1. Frequency of observation;
2. Objectivity of observers;
3. Maintenance of the same observers throughout the program;
4. Rotation of observers to randomize their effect;
5. Application of positive crack recording methods;
6. Analysis of data on crack length times number of cracks; and
7. Correlation between cracking data from exposure and pre-exposure time periods.

2.1.2 Observed Damage from Other Causes Unrelated to Aircraft Noise

Sutherland et al. (1990) point out, care must be taken in appraising claims of damage, since there can be many causes that result in the same visible result. Structures are exposed to many transient forces, such as those associated with temperature and humidity variations, thunder storms, high winds, blasting operations, and door slamming. Many of these environmental effects can be sufficient to cause damage of the same magnitude as that from aircraft noise. A list of reasons for damage in structures which have nothing to do with exposure to sonic booms was prepared by Wiggins (1965):

1. Ratio of inside to outside surface and air temperatures;
2. Range of inside and outside humidity (i.e., temperature and humidity influence the amount of shrinking of wood frame members which is a major source of cracking of interior surfaces);
3. Intensity, duration and direction of wind;
4. Differential settlement of building foundation;
5. Room volume, wall and ceiling area;
6. Orientation of walls to solar heat input;
7. Type of skin, frame, exterior materials and interior finish;
8. History of patching; and
9. Presence of water leaking from pipes onto building structure.

Sutherland (1990) reported levels of mid-wall velocities of typical wood-frame houses due to human activities such as walking, jumping, door slams and nail pounding. He then compared these levels to estimates for subsonic military overflights and found the human activities to cause greater vibrations than all but heavy helicopter overflights. Other comparisons of non-aircraft causes of vibration in structures included highway vehicles and trains, seismic activity and weather changes. In the cases of highway vehicles and trains vs. overflights, the comparisons were made for prehistoric masonry/stone buildings (See Table 2.1). Aircraft overflights, especially multi-jet bombers and both heavy and light helicopters, tended to result in higher vibration levels than the surface transportation sources. Wind loading was found to induce substantially higher stresses in windows than would be caused by subsonic aircraft overflights, with the possible exception again of heavy helicopters.

Table 2.1 Comparison of Measured or Estimated Values for Wall Velocity of Typical Prehistoric Masonry/Stone Buildings Due to Highway or Railroad Traffic with Estimates for Vibration from Military Training Route (MTR) Flights[(1)] (Source: Sutherland, 1990)

	Highway/ Railroad Traffic	------------MTR Flights[(2)]------------				
		Fighters	Bombers	Cargo	Helicopters	
					Heavy	Light
Peak Wall Velocity Mean Values (in/sec)	0.05 - 0.15[(3)]	0.11	0.36	0.09	5.1	0.29

(1) For building directly under flight path.
(2) Mean estimates for each category of aircraft for prehistoric masonry/stone structures, no roof.
(3) Range of measured or estimated values.

2.2 Categorizing Historical and Cultural Resources

The National Park Service administers vast tracts of land containing natural resources and cultural resources. In order to determine the extent of effects on cultural resources, it is necessary to estimate the range of structures and objects that may be exposed to aircraft noise that fall into this category. Sutherland, et al. (1990) provides a categorization used by the USAF for structures exposed to sonic booms. Cultural resources include structures not normally inhabited, prehistoric structures, ruins, and archeological sites; these have been categorized as "unconventional" structures. Cultural resources also include inhabited dwellings and commercial buildings that are considered to be historical; these are considered to be "conventional" structures. Perhaps the overriding definition covering all of the foregoing types of sites is that they are, in part or in whole, irreplaceable.

Sutherland's list of "unconventional" structures was developed from two sources:

- the relative frequency of types of structures cited in public hearings associated with the environmental impact assessments for supersonic operating areas, and

- professional judgment of the types of structures to be located near military training routes and supersonic operating areas.

The latter step was necessary because the former list was not considered to be sufficiently general to provide a completely valid selection criteria for the study of sonic boom effects on all unconventional structures. Sutherland's list of unconventional structures is shown in Table 2.2.

The difference between "conventional" structures and "unconventional" structures as defined for the sonic boom program is irrelevant to the National Park Service's interest. For example, whether a historic building is inhabited ("conventional" structure) does not change the effect of damage from aircraft noise. Consequently, for the purposes of this review, Table 2.2 contains the universe of structures to be considered even though it is labeled "unconventional structures." Some of them, such as the radio telescope, water tanks and utility buildings are unlikely to be considered cultural resources. Slide areas, both snow and soil, are included because of the secondary damage they could inflict if triggered in the vicinity of an otherwise protected cultural resource.

Table 2.2 List of Unconventional Structures Considered in Sonic Boom Study by Sutherland, et al. (1990)

No.	Type of Structure	Type of Construction
1	Historic Buildings (1)	Masonry, Stone
2	Historic Buildings (1)	Brick
3	Historic Buildings (1)	Adobe
4	Historic Buildings (1)	Wood Frame, Plaster Interior
5	Historic Buildings (1)	Wood Frame, Wood Interior
6	Historic Buildings	Covered Wood Bridge
7	Prehistoric Structures (2)	Masonry, Stone
8	Prehistoric Structures (2)	Adobe
9	Geological/Archeological Sites(3)	Stone Caves/Rock Formations
10	Water Tanks	Metal/Stone (above ground)
11	Wells	Masonry (below ground)
12	Slide Areas - Avalanche	Snow on Steep Slope
13	Slide Areas - Soil	Soil on Steep Slope
14	Utility Buildings of All Types	Concrete Block
15	Utility Buildings of All Types	Wood Frame
16	Utility Buildings of All Types	Metal Frame
17	Radio Telescopes	Metal Frame

(1) More than 50-100 years old (roof intact)
(2) Early American habitation/ceremonial sites (roof missing)
(3) May contain petroglyphs or other Early American art

The list, as taken directly from Sutherland, includes key elements of historical and cultural resources. It becomes comprehensive by expanding to include combinations of entries. For example, prehistoric Anasazi structures are made of a wide variety of adobe materials and combinations of adobe and stone. The footnote reference to "other Early American Art" most likely includes pictographs and other rock art, as well as historic inscriptions. Moreover, not only caves, but also some of the adobe structures, have a mud plaster sheen with Early American Art (e.g., Cliff Palace on Mesa Verde).

2.3 Observed Aircraft Noise Effects on Cultural Resources

Documented observations of aircraft noise effects on cultural resources are rare. Those found in literature are included in this report, especially in Section 2.4. Nevertheless, public concern for the potential of damage is high, based on the frequency of public comments on Draft Environmental Impact Statements for USAF supersonic operating areas (Sutherland, et al., 1990). Without documentation it appears that many of these concerns for damage from aircraft noise are based on rumor. Among the many causes of damage to a cultural resource, aircraft noise is listed as one of the possible causes. Because many cultural resources are generally remote and uninhabited, much is left to speculation with regard to damage.

Even when observed, some damage occurs very slowly and accumulates only over a long period, such that the effects may not be readily noticeable. For example, in a series of controlled measurements in a historic, adobe building in White Sands during sonic boom tests, observers noticed no major changes in cracks in the interior adobe surface; however, careful measurements of one of the cracks showed that nearly every sonic boom produced a slight widening of the crack (Sutherland, et al., 1990). During the same investigation, observers noticed dust falling from the edges of the ceiling as a result of sonic booms.

Another study actually documented the cumulative crack growth in plaster on wood lath surfaces in a two-story structure over a period of several weeks of sonic boom exposure. The results showed steady increase in crack length, with each sonic boom event, with a dramatic increase when the overpressures reached a critical value (Clarkson and Mayes, 1972). Surface cracks in adobe structures are often observed, and, as discussed in Section 2.4.2, may result in long term damage to the structure due to moisture intrusion.

2.4 Short Term and Long Term Effects

Aircraft noise effects on structures are noticed either immediately (short term effects) or after many exposures. Immediate or short term effects are generally noticed after a substantial noise event generates significant vibrations in a structural element. Long term effects are generally related to low level events that have a cumulative effect, like the cumulative crack growth example above, or they may be related to the long term consequences *initiated by* single events.

2.4.1 Short Term Effects

The obvious "short term effect" is when a building element suffers immediate displacement, with broken surface or increased crack length. For noise to be the source of immediate damage, the pressure levels must be extremely high, such as in a sonic boom, or the frequency must coincide with one or more of the natural frequencies of the structure. Damage claims for cracked surfaces, broken windows and broken bric-a-brac have resulted from single sonic boom events during periods of testing in populated areas (Clarkson and Mayes, 1972) and broken windows have resulted from overflights of helicopters (Sutherland, 1990).

A short term, catastrophic event is possible if a resonance of a highly unstable wall is excited. King et al. (1985) measured natural frequencies and damping of walls at eight prehistoric structures at Chaco Culture. A follow-up visit a year later revealed that some of the walls with very low damping had fallen (King, 1990). Since the walls were not observed during the interim period, the cause for failure is unknown. However, King surmised that vibration, either ground-borne or air-borne, could have generated the necessary force.

2.4.2 Long Term Effects

Cumulative effects of repeated noise exposure are not as easy to document as short term effects, for the reason that some of the damage observed in a structure will be due to naturally occurring forces over time. Materials and structures expand and contract due to changes in temperature, humidity, wind loads, foundation settlement and human activity. Consequently it is difficult to determine when an observed damage is the sole result of a particular source. Haber and Nakaki (1989) reported on several surveys regarding the relative importance of environmental effects vs. sonic booms at low overpressures. For example, Wiggins revisited a White Sands site seven years after the completion of extensive sonic boom tests, and concluded that natural deterioration had a far greater influence on the observed cumulative damage than did sonic booms. Moreover, Haber and Nakaki (1989) point out that the evidence for cumulative damage in glass and plaster from exposure to repeated sonic booms at low overpressures is weak. They found it to be potentially very important, however; in using their recommended model to make damage prediction, they found that the dominant contributors to the estimated number of damaged building elements are the preweakened elements. Recommendations for further investigation of cumulative damage effects on glass, plaster and bric-a-brac were in the conclusion of their report.

There is some evidence that long term effects of noise exposure could result in damage. For example, the reason preweakened glass has a higher probability of damage may be related to extension of small cracks under continued exposure. Glass may be preweakened by stress raisers (nails, glazing points, or any other object which may abrade or impact the glass) which may initiate cracking. Furthermore, measurements by Sutherland, et al. (1990), in which sonic booms caused continued crack widening and plaster dust to fall from the ceiling, lend credence to the possibility of cumulative damage. Long term effects appear as: (1) fatigue effects after extensive exposure, (2) moisture damage initiated by cosmetic cracks in exterior surfaces and (3) gradual erosion of surface materials from repeated events.

Fatigue effects in walls have been documented by the Bureau of Mines in a two-year study of the effects of vibrations from blasting on a specially-made house in the path of an advancing coal mine (Stagg, 1984). The first crack was observed in a gypsum board wall after 56,000 cycles, the equivalent of 28 years of shaking by blast-generated ground motions of 0.5 in/sec (12.7 mm/sec), twice a day. Sutherland (1990) estimated that structural elements could experience as many as 80 million cycles of loading at their resonance frequencies from exposure to aircraft operations along defined military training routes over a 50-year period. This large number could lead to significant reduction in material strength.

Moisture damage can be the second phase of a deteriorization process initiated by surface cracking. Though only cosmetic, surface cracks admit moisture which may weaken the underlying structure, thus setting in motion a natural chain of events leading to premature structural damage. King (1990) describes a case in which moisture damage resulted in the flaking of exterior adobe surfaces at the base of a wall in Casa Grande, a Hohokam structure in Phoenix, Arizona. He demonstrated by experiment that vibrations from traffic in a nearby parking lot could initiate the surface cracks needed to admit moisture.

Erosion damage from wind and precipitation can occur once the exterior surface has been compromised. For many adobe mud-plastered walls, the loss of the exterior surface also results in invasion of additional moisture into the interior, thereby weakening the structural core. Once the core is weakened, wind or additional acoustic loadings can compromise the integrity of the structure.

When such an affected structure constitutes an irreplaceable resource, any of the foregoing certainly qualify as adverse effects. Because aircraft noise has the potential of initiating some of these long term effects it qualifies as a contributor to the degradation over time of historical structures.

2.5 Factors which Influence Effects

Several researchers have developed prediction methods for estimating the occurrence of damage from aircraft noise. Sutherland, et al. (1990) listed the factors which influence the magnitude of the dynamic loading and stress response of structures and hence influence the occurrence of damage from sonic booms:

- Magnitude of peak pressure of sonic boom;
- Wave form and duration of pressure pulse from sonic boom;
- Direction of arrival of sonic boom relative to building surface;
- Relative rigidity (or impedance) of surface exposed to sonic boom;
- Presence and position of nearby reflecting surfaces, including the ground;
- Total number of booms experienced (i.e. the effect of cumulative exposure);
- Dynamic response characteristics of the structure, including its resonant frequencies, mode shape, damping, location of walls on outside or inside of structure, and presence of windows or doors; and
- Structural strength of the material at the time of exposure to the sonic boom.

Each item on the list could be extended to all aircraft noise events, not only sonic booms. As discussed in Section 2.6.1, Sutherland's model for damage from subsonic aircraft contains essentially the same elements as the one for sonic booms (Sutherland, 1990).

2.6 Methods for Predicting Response of Structures

Methods for the estimation of response of structures to excitation from noise emitted by aircraft have been proposed by many researchers. Sonic booms have been the primary focus of these methods, many of which are empirically-based with a significant amount of background data. Until very recently, there has been very limited information on the response of structures to noise from low altitude subsonic flights. This section summarizes the available models for both supersonic and subsonic overflights.

2.6.1 Structural Response Models

The prediction models discussed in this section for structural damage from acoustic loadings incorporate the following steps:

1. Define the characteristics of acoustic excitation;
2. Specify the propagation characteristics;
3. Define the effective sound pressure on the structure;
4. Estimate the vibration response of structural elements;
5. Determine the stresses in the structure due to vibration;
6. Compare these stresses to material rated ultimate stresses; and
7. Assess damage based on potential exceedence of ultimate stress.

Sutherland (1990) developed a comprehensive statistical model to allow systematic estimates to be made of the probability of damage to a wide range of structural types from subsonic aircraft on military training routes. This is the first comprehensive model for subsonic aircraft-induced damage prediction which incorporates essentially all of the foregoing steps.

Sutherland's model is the first simple empirical model for the low frequency noise from subsonic military aircraft, including helicopters, caused by wake and trailing vortex fields. This is the source of the low frequencies which cause resonant structural vibrations leading to potential for damage. An important contribution of Sutherland's report is an approach for the estimation of sound pressures at the fundamental helicopter blade passage frequency.

This model parallels the sonic boom models, described below, with the major difference in that the acoustic pressure excitation is considered to last longer than that from a sonic boom. This results in a slightly different dynamic response model than that for sonic boom excitation.

Two recent studies associated with the U.S. Air Force's Noise and Sonic Boom Impact Technology Program provide definitions of the reaction of structures to aircraft noise, especially to high intensity sounds associated with sonic booms. Sutherland et al. (1990) evaluated potential damage to unconventional structures by sonic booms; Haber and Nakaki (1989) focused on conventional structures. Both reports contained thorough literature reviews on their respective subjects. Haber and Nakaki found twenty models for assessing the effects of sonic booms on structures. However, they found one particular model by Hershey and Higgins (1976) to be a good baseline for further development for the prediction of the statistical probability of damage to conventional structures over a wide area of sonic boom exposure. Since there was no prior model for unconventional structures, Sutherland developed an approach to be used for uninhabited historical buildings.

Both studies were designed to provide the definition of input data for a new microcomputer based planning aid, called ASAN (Assessment System for Aircraft Noise), under development for the U.S. Air Force Noise and Sonic Boom Impact Technology program. In this program, damage estimates are developed based upon predicted ground surface levels of sonic booms and the geographical distribution of the conventional structures in an affected area by assessing the probability that the pressure applied to the building elements will exceed their capacity. Damage assessments are expressed in terms of the *probability* of damage to windows, ceilings, plaster walls and bric-a-brac over a wide-spread area.

In another field, but still related to the issue of sound pressure effects on structures, the Bureau of Mines developed an estimation procedure to assess the structure response and damage produced by airblast from surface mining (Siskind, et al., 1980). This model, like the ones developed for sonic booms, is based on empirical results from an extensive data base. This report concludes that airblast-produced structural responses (peak velocities) tend to be less than those produced by sonic booms by almost one-half. Clarkson and Mayes (1972) also observed this fact, quantified as a ratio of 1 to 1.8 and suggested that it is probably due to the fact that a blast generates only a short-duration pulse containing one pressure peak, whereas the sonic boom, with time durations two to five times greater, has two peaks, one positive and one negative, which may occur in phase with the structural response. Thus, both duration and pulse pattern have been identified as important to the excitation of the structure at its resonance frequencies.

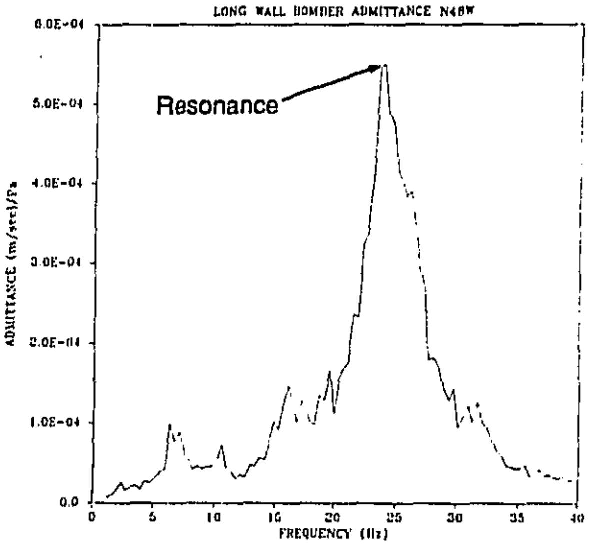
2.6.2 Structural Admittance Functions

Siskind's report includes tables of measured responses of structures from impulsive noise sources (airblasts and sonic booms). Instead of response being expressed in terms of vibration velocity (in/sec), it is expressed in terms of a normalized velocity (in/sec/psi), which is actually an overall "admittance," defined as the ratio of velocity of a structural element to the imposed pressure. Although not particularly highlighted in the Bureau of Mines report, this approach may be a new tool for use in predicting the sensitivity of particular structures to sound pressures. For example, by knowing the admittance function for the flat roof of a historic site, one can predict how much it will vibrate when exposed to noise from an aircraft overflight.

Battis (1983, 1988) used admittance functions to define the response of fragile archeological structures to aircraft noise, both subsonic and supersonic. An example is shown in Figure 2.2, where the measured admittance function of a wall during subsonic aircraft overflights clearly demonstrates a natural frequency near 25 Hz. The measurements were taken at the Anasazi Long House Site, near Kayenta, AZ. He also tried a low-cost method for estimating admittance functions using shotgun blasts, but concluded the method was inadequate for long massive walls.

Sutherland's (1990) approach includes a solid basis for the estimation of admittance functions. He develops an empirical model for structural response using mobility, a transfer function which uses acceleration response instead of velocity. Although most structures are too complex to enable a reliable prediction of responses over wide frequency ranges, it is generally recognized that significant damage potential exists only where the incident sound waves contain significant energy in frequencies close to the structure response natural frequencies. Consequently, the models may only need to be accurate in a limited frequency range. The admittance function, or mobility function, could be a very useful tool in defining the response of structures to sound pressure loadings. Further research needs to be done before this approach could be considered reliable. However, it may be worth further development to expedite inventories of large numbers of sensitive structures.

Figure 2.2 Sample of a Measured Admittance Function of the Wall of a Prehistoric Structure (Source: Battis, 1988)



2.7 Thresholds of Effect

The term "damage" has a wide variety of meanings depending on the level of concern. Concern for the preservation of historical structures or cultural resources calls for the definition of a threshold related to the onset of a permanent effect. Investigators of aircraft-noise induced vibration generally use the term "damage" for any response above a predetermined threshold level. Damage criteria have been proposed for different types of structures by various organizations and researchers.

2.7.1 Summary of Criteria

A summary of criteria as surveyed by Sutherland is shown in Table 2.3. Most of the criteria are in a range which varies by a factor of about ten, from a minimum of about 0.05 inches per second to 0.5 inches per second, depending on the frequency range, the type or the historical importance of the structure. In many cases it is assumed that criteria established for ground vibration applies to the structure as well, but it depends on the type of structure and the pressure loading waveform. For example, in one case, an assumed amplification of a factor of 20 between the base and the top of very fragile prehistoric towers at Hovenweep National Monument resulted in an effective criterion for quasi-steady state vibration of 0.004 inches per second as a criterion for damage, which is one-twentieth of the ground vibration criteria of 0.08 inches per second (King and Algermissen, 1987). As discussed in Section 2.6.1, the waveform of a sonic boom has been found to cause response of approximately 1.8 times greater than a shorter impulsive airblast. As a result, Sutherland, et al. (1990) suggest that it is not unreasonable to decrease the thresholds developed for airblasts by a factor of 1.8 when applied to sonic booms.

Table 2.3 Criteria for Maximum Structural Displacement and Velocities to Avoid Damage to Prehistoric, Historic, Sensitive and Conventional Structures (Source: Sutherland, 1990)

Reference	Type of Structure	Frequency Range, Hz	Criteria Displacement (inches)	Criteria Velocity in/sec
King and Algermissen, 1985	Prehistoric (Chaco Canyon)	1-20		0.08 (1)
King, et al., 1987	Prehistoric (Hovenweep)	1-10		0.004 (2)
Saurenman, et al., 1982	Historic/Sensitive			0.04 (1)
Konon and Schuring, 1985	Historic/Sensitive	<10 Hz		0.25 (1)
		>40 Hz		0.5 (1)
German DIN 4150 (3)	Ancient ruins and historic buildings			0.08 (2)
	Buildings with visible damage/cracks in masonry			0.16 (2)
	Buildings in good condition with possible cracks in plaster			0.32 (2)
	Industrial and concrete structures without plaster			0.4-1.56 (2)
Australian Standard (3)		<15	0.008	(2)
		>15		0.75 (2)
U.K. (3)	(Blasting only)			0.4-1 (2)
	(Steady state vibration)			0.2 (2)
Ashley (3)	Ancient and historic monuments			0.3 (2)
	Housing in poor repair			0.47 (2)
	Good residential, commercial and industrial structures			1.0 (2)
	Welded gas mains, sewers, engineered structures			2.0 (2)
Esteves (3)	Historical monuments, hospitals, very tall buildings			0.1-0.4 (4)
	Current construction			0.2-0.8 (4)
	Reinforced construction (e.g., earthquake resistant)			0.6-2.4 (4)
Siskind et al., 1980a	Wood frame (plaster interior)	<2.7	0.03	
		2.7-10		0.50
		10-40	0.008	
		>40		2.0

(1) Peak velocity of structure
(2) Peak velocity of ground at base of structure
(3) As cited in Siskind, et al., 1980b
(4) Range of velocity for ground varying from incoherent loose soil (lowest velocity) to coherent hard soil or rock

2.7.2 ISO Standard

The International Organization for Standardization (ISO) proposed limits for vibration levels related to damage to buildings. A summary of the 1976 draft standard ISO/TC 108/SC 2/WG3 appears in the CHABA Report (CHABA, 1977). The proposed standard provides descriptions of phases of damage which can occur, and then relates these phases to actual vibration levels. The various damage phases are:

Category 1: Threshold Damage

> *Threshold damage* consists of visible cracks in non-structural members such as partitions, facings, plaster walls (e.g. loose mortar between tiles, etc.). As a guideline visible cracks may be taken as those of a width of 0.02 mm.

Category 2: Minor Damage

> *Minor damage* consists of visible cracks in structural members such as masonry walls, beams, columns, slabs and no serious reduction in load-carrying capacity.

Category 3: Major Damage

> *Major damage* consists of large permanent cracks in non-structural and structural members; settlement and displacements of foundations which may result in reduction of load-carrying capacity.

The proposed standard recommends different frequency ranges depending on whether the whole building is affected (shock, quarry blasting, and steady vibration of whole buildings - frequency range from about 1 Hz to about 100 Hz) or just parts of the building are affected (steady vibration of floors and walls - frequency range from about 10 Hz to about 100 Hz). The measurement quantity recommended for shock is the vector sum of the maximum velocity (v_R) along a set of orthogonal axes. The maximum velocity along an axis is that measured at any time during an event. With the foregoing measurement quantities, the limiting values associated with the three damage categories are as follows:

Category of Damage	Range of v_R for Onset of Damage
1. Threshold Damage	3 to 5 mm/sec (.12 to .2 in/sec)
2. Minor Damage	5 to 30 mm/sec (.2 to 1.2 in/sec)
3. Major Damage	100 mm/sec (4 in/sec)

2.7.3 Other Criteria

Threshold damage criteria have been proposed by various researchers in the field. King et al. (1985) recommend 2.0 mm/sec (0.08 in/sec) particle velocity over the frequency range of 1 to 20 Hz including a factor of safety for the upper limit for induced motions in Chaco Canyon archeological structures. They point out that the governments of Germany, Great Britain and Sweden have adopted maximum ground motion for historic buildings and sites at 2 mm/sec (0.08 in/sec), 2.5 mm/sec (0.1 in/sec) and 2 mm/sec (0.08 in/sec), respectively. Researchers at Bureau of Mines identify a value of 0.5 in/sec (12.7 mm/sec) for threshold damage from airblasts (Stagg, 1984; Siskind et al., 1980a); Battis (1988) adopted a vector sum velocity of 1.3 mm/sec (0.05 in/sec) for a bandwidth of 1 to 40 Hz as conservatively "safe for ancient structures".

Investigations of the structural motion environment in the vicinity of rocket launchpads by the U.S. Air Force Geophysics Laboratory (AFGL) have identified "levels of concern" for application to rocket launch areas only. These levels are much higher than those in criteria for damage considered applicable to cultural resources (Battis, 1985).

2.7.4 Criteria for Potential Damage of Museum Objects

There are no established criteria for noise-induced damage effects on bric-a-brac, artifacts and museum objects because of the wide variety of shapes, materials and mountings found in a given location. One study determined the probability of breakage of bric-a-brac based on claims data and observations of damage during sonic boom tests (Hershey and Higgins, 1976). These researchers concluded that the probability of bric-a-brac breakage is generally less than for window glass during sonic boom exposure. No data were presented about how the breakage occurs, although in one of their illustrative examples the authors imply that in general objects break by falling or overturning. Many museum objects are displayed (or stored) on shelves or hung on walls. Consequently, damage could result from the object "walking" off the shelf or rattling against the wall. Criteria for onset of "rattle" have been determined by the Bureau of Mines as a wall acceleration of 0.5 g, with a range of 0.1 g to 1.0 g (Siskind et al., 1980a). Complaints about rattling begin to occur when airblasts generate approximately 0.1 g to 0.2 g in interior walls. Wall-hung objects, such as pictures or plaques, can rattle against the wall at even lower acceleration levels, ranging from .02 g to .13 g depending on the angle between wall and hanging object (Hubbard, 1982). No particular frequency range has been established for the onset of "rattle," although it can be assumed that it will occur when the midwall vibrates at its natural frequency. Using the average midwall natural frequency of 16 Hz for conventional structures measured by the Bureau of Mines (discussed below), the velocity associated with the onset of rattle, acceleration level of 0.02 g, is 0.08 inches per second. This velocity happens to agree with King's criterion for threshold damage at Chaco Canyon.

None of the reports in this literature survey discussed the possibility of a free-standing, or buried, object suffering damage by exposure to aircraft noise induced vibrations. Hershey and Higgins, 1976, rate the breakage potential to be less than window glass, however.

2.7.5 Specifying Frequency Range of Criteria

The important fact emerging from these studies is that in establishing a threshold for damage, or minimum effect, it is necessary to specify the frequency range over which the criterion applies. It is generally agreed that criteria established for frequencies corresponding to those from airblasts, such as the well-known Bureau of Mines damage level of 2 inches per second for frequencies greater than 40 Hz, is inadequate for assessing damage from pressure loadings with significant energy in lower frequencies associated with structural resonances (Konon and Schuring, 1985). The greatest probability of damage occurs when the structure is excited at its resonance frequency. Structural resonant frequencies tend to be below 40 Hz for conventional structures. Siskind et al. (1980a) measured responses to airblasts of 55 buildings and found natural frequencies of the entire structure and interior midwalls to be an average of 7 Hz and 16 Hz, respectively.

A similar range of frequencies has been measured at archeological ruins. At Chaco Culture National Historical Park King measured building natural frequencies ranging from 6 Hz to 19 Hz, depending on the height of the standing walls (King et al., 1985). Brumbaugh (1985) measured resonance frequencies ranging from 18 Hz to 26 Hz for short (2.5 ft to 3.5 ft) limestone block walls in the Pt. Sublime Anasazi ruins. The conclusion is that in establishing thresholds for effect related to historical structures and cultural resources, the criteria should be specified for the frequency range which includes the fundamental natural frequencies of building structural elements, generally below 40 Hz.

3. ASPECTS OF AIRCRAFT OVERFLIGHTS WHICH CAUSE THE MOST SIGNIFICANT EFFECTS

3.1 Noise Effects

Sutherland's list of factors which influence the magnitude of the dynamic loading and stress response of structures, described in Section 2.5, can be slightly modified for application to all sound pressures incident on structures, whether or not they are sonic booms. The modified list follows:

1. Magnitude of sound pressure incident on the structure;
2. Wave form (i.e., frequency spectrum) and duration of sound pressure;
3. Total number of events experienced (i.e., cumulative exposure);
4. Direction of arrival of sound waves relative to building surface;
5. Presence and position of nearby reflecting or screening surfaces, including the ground but not including vegetation;
6. Admittance of structure to sound pressure waves. This is a measure of the dynamic response characteristics of the structure, including its resonant frequencies, mode shapes, damping, location of walls on outside or inside of the structure, and presence of windows or door; and
7. Structural strength of the material at the time of exposure.

The first four items are related to the characteristics of the aircraft generating the noise. Sound levels of aircraft are well documented for the purposes of noise certification by the Federal Aviation Administration and for the purposes of source data for noise prediction models. However, the noise prediction models used for military or civilian airports, NOISEMAP and INM, respectively, use A-weighted sound levels, not sound pressure spectra, the second factor on the list above. References with sound spectra for aircraft in flight are rare. The following section discusses typical sound spectra from of the types of aircraft likely to be involved in overflights lands administered by the National Park Service.

3.2 Sound Pressures Generated by Aircraft Operations

Noise characteristics of aircraft as perceived on the ground depend on many factors, some of which include:

1. Aircraft type: jet, propeller, helicopter, rocket;
2. Speed regime: subsonic, supersonic, motionless (hovering);
3. Operational mode: accelerating, level flight, climbing, hovering, take off, landing;
4. Aircraft performance characteristics: power level, flap setting, exhaust direction;

5. Atmospheric effects: wind gradient, wind direction, wind speed, temperature gradient, humidity; and
6. Distance: aircraft altitude, slant distance, flight track.

It would be a monumental task to develop a statistical expression corresponding to the models discussed in Section 2.6 for all possible configurations of aircraft operations for all of the cultural resources under the purview of the National Park Service. Consequently, this review focuses on the aircraft noise characteristics which can be related to structural response known to have a potential for damage.

3.2.1 Sound from Jet Aircraft

Supersonic Flight. Some jet-propelled aircraft are capable of supersonic speeds. A supersonic overflight generates a sonic boom which is characteristically represented by an "N-shaped" time history of pressure above and below the ambient (Figure 3.1). The term, "overpressure" refers to the pressure above the ambient (the baseline in the figure). The upper peak of the "N" is described as the peak overpressure. The overpressure is generally followed by an "underpressure" which makes the sonic boom an especially effective exciter of structural response (e.g., a push, followed by a pull). Haber and Nakaki (1989) provide a clear description of the characteristics of sonic booms. Ground level overpressures are affected by the size, speed and altitude of the aircraft. The magnitude of the overpressure increases with aircraft weight and size, and decreases with distance; a typical military fighter will generate maximum overpressures between 1 and 5 pounds per square foot. The speed effect is less definitive: at low (supersonic) speeds the overpressure increases with speed, but at higher speeds, overpressure actually decreases with speed. Durations of the sonic booms depend on the aircraft length and the distance between the aircraft and the receiver. Durations for sonic booms from fighters are typically from 50 to 150 milliseconds, while they can last up to 300 milliseconds for bombers. The frequency spectrum associated with an ideal N-wave of 100 millisecond duration shows a fundamental peak near 5 Hz, with considerable energy continuing to frequencies above 250 Hz (Figure 3.2). It is this low frequency energy content which excites many structural elements at their resonance frequencies.

In some cases, either atmospheric effects or special aircraft maneuvers can produce enhanced overpressures (e.g., 20 pounds per square foot) and variations of the basic N-wave will be received on the ground - either a spikey "U-shaped" wave or more rounded. Near the edges of the sonic boom trace on the ground, the waves change to a more rounded wave with a wide variety of shapes and overpressures possible.

Figure 3.1 Representative Sonic Boom "N-wave" Time History (Source: Sutherland, 1990)

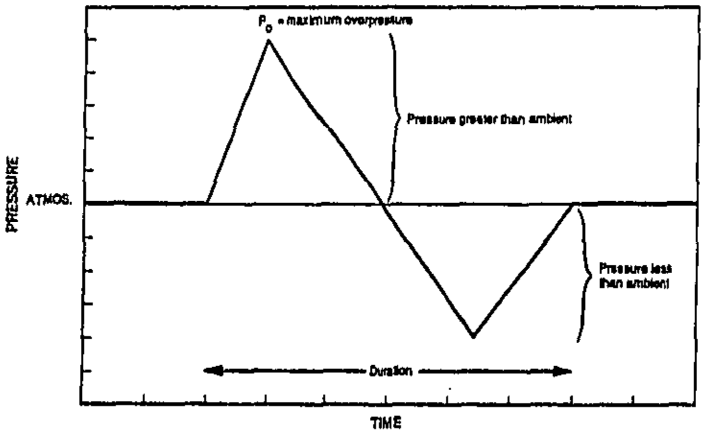
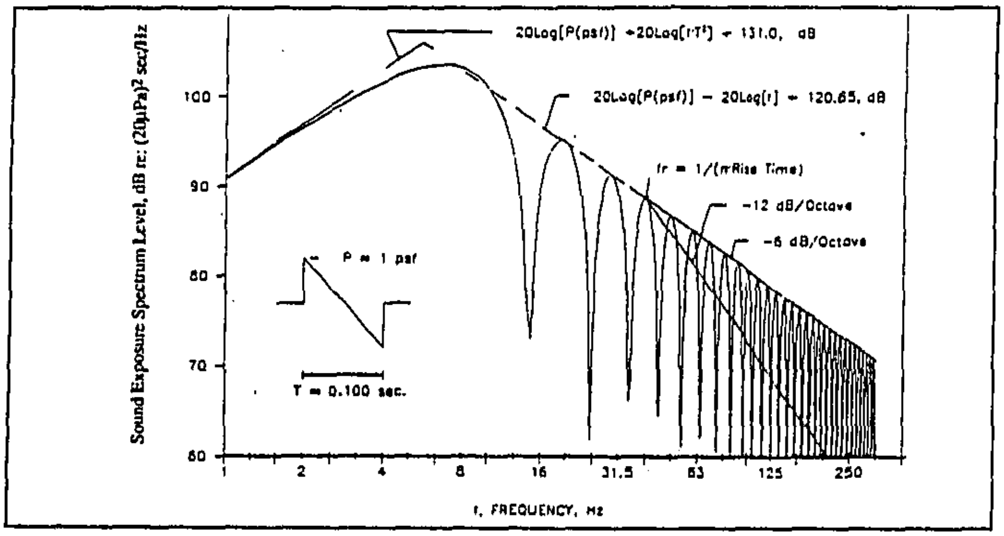


Figure 3.2 Representative Frequency Spectrum for Sonic Boom "N-wave" with Duration of 0.1 Second (Source: Sutherland, 1990)



In summary, the chief aspects of sonic booms that tend to cause damage are as follows:

1. Wave form is impulsive, with a "push-pull" forcing function;
2. Wave contains a great deal of energy;
3. Frequency spectrum of wave has considerable energy at a broad range of frequencies, including those associated with typical natural frequencies of structures; and
4. Wave covers a broad area, thereby being able to excite entire structures.

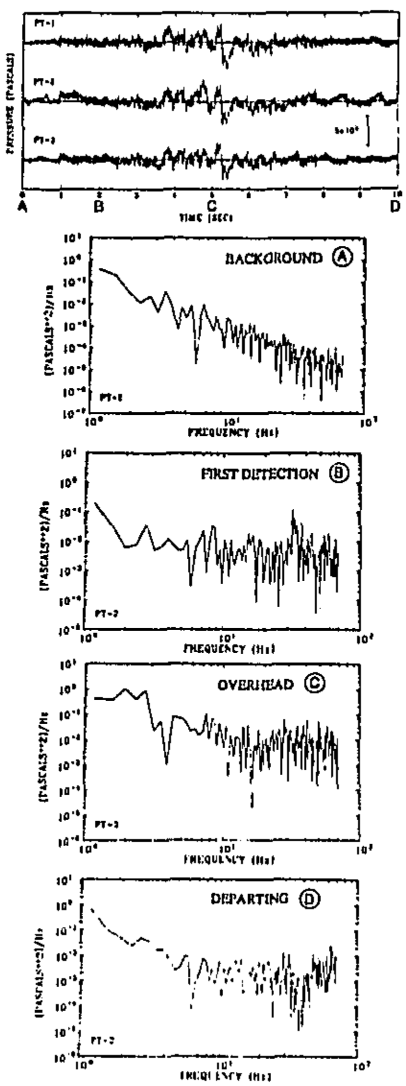
Subsonic Flight. Most noise exposure from jet-propelled aircraft is from overflights at subsonic speeds. A wide variety of sound pressure levels and spectra can result from this condition. Sutherland (1990) provides a model for acoustic pressure excitation including engine noise, lift pulse (the momentary pressure increase on the ground when an aircraft passes overhead), and the low frequency aircraft wake and trailing vortex pressure fields. Most important for structural response, according to Sutherland is the low frequency range below 50 Hz. Sutherland found a relationship for this low frequency sound pressure based on the fifth power of the airspeed, the wing area and the inverse square of the slant distance. This is the first time such a relationship has been confirmed for aircraft in "clean" flight configurations. Previous airframe noise estimates have been made based on measurements under landing operations when the aircraft is in "flaps-down" condition. Sutherland's low frequency data agree with those measured by Battis in the study at Long House.

Perhaps most relevant to this survey is the measurement program by Battis at Long House, an Anasazi Indian site built around A.D. 1300 near Kayenta, Arizona (Battis, 1988). He measured pressure signatures from B-52 overflights during low and close overflights of this large, subsonic aircraft. In order to describe the character of the sound, he broke the pressure signal into four elements: ambient conditions, distant approach of the aircraft, near closest approach, and departure, marked as points labelled A, B, C, and D respectively, on the time history shown in Figure 3.3 (Battis, 1988). He then analyzed the pressure signal to obtain the power spectral density estimate at the four points in the time history. Figure 3.3A shows the spectral estimate of the pressure background noise prior to the overflight, demonstrating a classical roll-off of wind noise with frequency. Figure 3.3B is the power spectral density estimate of the signature just after detection, showing an increase in sound energy above 30 Hz. On approach, the dominant noise sources are the engine compressor and the aerodynamic sound generated by the air frame.

The spectrum shown in Figure 3.3C , when the aircraft is closest to the receiver, shows additional sound pressure in the frequency range of 2 to 70 Hz, which Battis believes may be associated with the dynamic pressure of the turbulent wake of the aircraft. Finally, the spectrum for the departing aircraft shows a persistent higher frequency signal (above 30 Hz) from the jet noise, Figure 3.3D. In some cases, the departure sound was detectable for 50 seconds or more after the B-52 had passed.

The maximum sound pressure level measured by Battis (1988) during 15 overflights was 113.3 dB, associated with a flight at 400 mph at altitude 600 feet above ground level. This corresponds to a sound pressure of 9.25 pascals, which is equivalent to a wind gust of 8 mph.

Figure 3.3 Analysis of Time History of a B-52 Overflight (Source: Battis, 1988)



Typical Pressure
Time History
At Three Coterminal
Pressure Transducers

A. Background spectrum shows wind noise.

B. Spectrum of aircraft just after detection; dominated by engine compressor and airframe. (f > 30 Hz)

C. Spectrum for aircraft overhead; pronounced low frequency pulse (2 to 70 Hz) consistent with turbulent wake of aircraft.

D. Spectrum for departing aircraft; dominated by engine jet noise. (f > 30 Hz)

Wesler (1978) measured low-frequency noise (frequencies between 16 Hz and 125 Hz) from long-range subsonic aircraft (707, 747, DC-10) as well as from the Concorde Supersonic Transport operating at subsonic speeds. He concluded that low-frequency aircraft noise may induce sympathetic vibrations in structures located near aircraft flight paths, but he did not discuss the probability of damage.

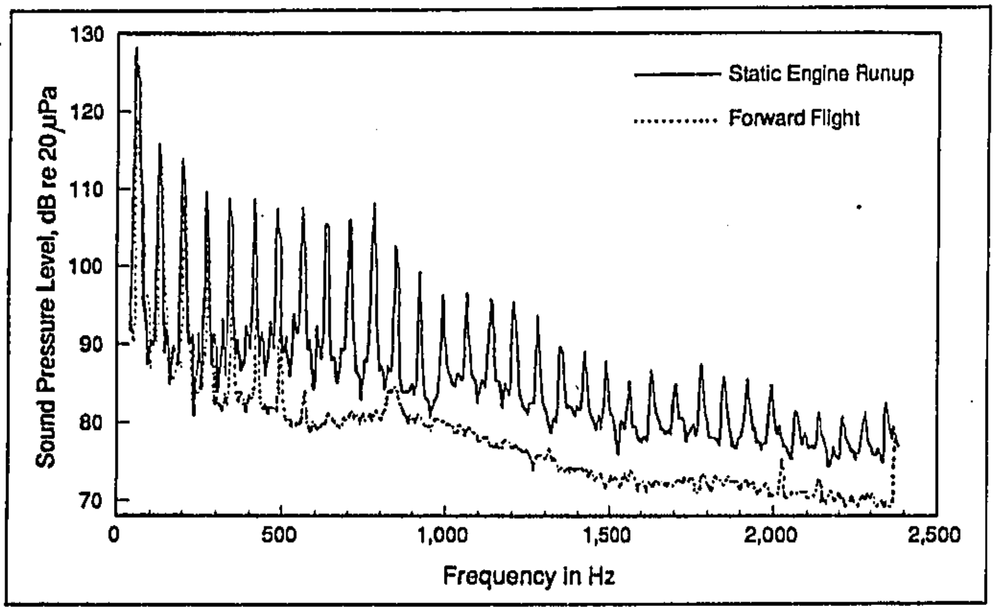
In summary, the chief aspects of subsonic sound waves that may cause damage are as follows:

1. Wave form is broad band noise forcing function;
2. Wave can contain much energy, but only if aircraft are on a close approach;
3. Frequency spectrum of wave has considerable energy at a broad range of frequencies, including those associated with typical natural frequencies of structures; and
4. Wave covers a broad area, thereby being able to excite entire structures.

3.2.2 Sound from Propeller Aircraft

Noise from propeller aircraft rarely reaches the pressure levels attained by jet aircraft. However, a propeller does have the characteristic of a series of almost pure tones in its frequency spectrum arising from periodic disturbances of the air by the propeller (Figure 3.4). The fundamentals of this discrete frequency noise is at the frequency with which blades pass a point, or is the number of blades times the revolutions per second. For the small aircraft noise spectrum shown in Figure 3.4, the fundamental is 70 Hz. For most large aircraft this blade rotational rate is about 100 Hz, which, although it sounds like a low frequency to a human observer, is actually well above the natural frequency of most structures. Hence, the damage potential from this type of aircraft is minimal. The magnitude of the sound pressure increases with the tip speed of the propellers, especially the higher harmonics of the blade rotational rate.

Figure 3.4 Sound Spectrum of a Typical Propeller Aircraft



3.2.3 Sound from Helicopters

As will be discussed later in Section 4.2, helicopter noise has a potentially great risk of causing damage to cultural resources. Because this noise source may play a very important role in this analysis, it is worth gaining an in-depth understanding of the various components of helicopter noise.

The sound field produced by helicopters is complex, both in the number of sound generating mechanisms as well as the directional and spectral characteristics of each mechanism. The recounting of a familiar helicopter overflight helps illustrate the point. As the aircraft approaches the observer the familiar "wop-wop-wop" sound produced by the main rotor is frequently heard. Also heard is a more or less constant buzzing sound produced by the tail rotor. Engine noise may also be audible, particularly if the aircraft is turbine powered (as opposed to piston powered); the high pitched whine from the turbine will likely be noticed. After the aircraft passes overhead and is heading away, the sound of the main rotor is less pronounced, but the tail rotor and engine noise may still be heard. The engine noise may change however in that the compressor whine becomes less audible.

The foregoing description illustrates several points. First, the helicopter produces noise from several sources. Second, each source is directional in nature; that is, the sound level depends on the direction the aircraft is heading with respect to the observer. Third, each source produces noise in unique ranges of the frequency spectrum (some produce high pitched sounds, some produce low pitched sounds). Since structural response to noise is limited to the frequency region of 50 Hz and below, it is important to identify the helicopter sources which produce sound energy in this region and to identify the conditions under which the observer will experience them.

Figure 3.5 shows contributions of the various helicopter noise sources to the frequency spectrum. The vertical axis of the graph shows the sound level in decibels, but the scale is intended to show relative levels of the various contributing sources, not absolute levels (actual sound levels would likely be considerably higher than those inferred from the graph). The horizontal axis shows the frequency in Hertz.

Figure 3.5 confirms the overflight experience described in the preceding paragraphs: the dominant noise sources are the main rotor noise, the tail rotor noise, and the powerplant and transmission noise. The main rotor dominates the low frequency end of the spectrum, the tail rotor produces noise in the mid-frequency range, and engine and gear train noise is found mostly at the higher frequencies. The most important message to be obtained from this figure is that the main rotor dominates the noise spectrum below 50 Hz (with some minor contribution from the tail rotor). Hence, from a structural response perspective, the main rotor becomes the focal point for further discussion of helicopter sound generating mechanisms.

There are basically two important sound generating mechanisms involving the main rotor, and both produce energy at the same distinct points in the frequency spectrum. These points are the fundamental blade passage frequency (the number of revolutions per second of the main rotor multiplied by the number of blades) and higher multiples of this frequency. For example, if the rotor is turning at the rate of 360 revolutions per minute, this is the same as 6 revolutions per second. If this rotor has 3 blades, the fundamental frequency will be 6 x 3 = 18 Hz. Thus, the frequency spectrum will contain acoustic energy at 18, 36, 54, 72, 90 Hz and additional higher harmonics (all multiples of 18 Hz).

The most commonly heard mechanism results in the familiar "wop-wop-wop" sound of an approaching helicopter. The generic term for this sound is "blade slap", but the mechanism is blade vortex interaction (BVI). The BVI sound is generated by one blade hitting the swirling air vortex produced by the preceding blade. The aircraft must be in forward motion for BVI to occur, and its directional characteristics generate maximum sound pressures in front of the aircraft and at angles below the plane of the main rotor.

The sharp cracking sound produced by BVI is rich in higher harmonics of the blade passage frequency, and these harmonics make the sound quite audible. However, it is the inaudible infrasonic region, not the audible part of the sound spectrum which contributes to structural excitation. And, there is no strong evidence suggesting that the apparent loudness of blade slap is necessarily a reliable indicator of the low frequency, infrasonic energy present in the signal.

To address the low frequency region of BVI, Sutherland (1990) determined a relationship between low frequency (5 to 40 Hz) sound pressure and a number of flight characteristics for measurements under low-flying helicopters. He indicates the low frequency rotor noise from helicopters is expected to vary directly as an "effective" area of the rotor disk, inversely as the square of the distance from the rotor, and as the fifth power of the "effective" helical velocity of the rotor blade. The "effective" area of the rotor disc is defined by 80% of the rotor radius, a point commonly used in modelling noise from propeller blades. Similarly, the "effective" helical velocity is the vector sum of the tangential velocity at that point on the blade and the forward airspeed of the helicopter. The fifth power of velocity is related to aerodynamic noise caused by wakes and vortex pressure fields.

While generally useful for most overflight situations, Sutherland's relationship potentially underpredicts low-frequency acoustic loads in situations where helicopters approach a structure whose elevation above ground level is the same as the aircraft. Cliff dwellings, such as those shown pictorially in Figure 3.6, are an example of this type of situation.

Figure 3.6 illustrates the second main rotor noise generating mechanism, "thickness noise". Thickness noise radiates from the main rotor in a fairly narrow angular window of plus or minus 10 degrees from the main rotor plane. (Brentner, 1991). Therefore, it is rarely heard or measured by observers on flat terrain unless the aircraft is very low to the ground and a relatively long distance away. Inside a structure this noise generating mechanism is most often detected by a low level of window or structural rattling. In contrast to BVI, thickness noise is generated regardless of whether the aircraft is in forward motion.

Finally, thickness noise energy is concentrated at the main blade passage frequency and is usually greater in amplitude than that generated by blade slap at this frequency. Hence, a helicopter in the vicinity of cliff structures potentially exposes the structure to relatively high intensity, low frequency noise during the entire time it is at the same elevation as the structure regardless of whether it is in forward motion.

Quantifying the sound levels of thickness noise for specific helicopters is difficult, however. The major body of literature on helicopter noise spectra covers only the audible range of 25 to 10,000 Hz (Newman et al, 1984). Since these data were collected for purposes relating to human audition, the frequency spectrum only extends down to 25 Hz. Thus, the main rotor fundamental is not included in the data. In addition, most of these data were obtained during helicopter overflights, and as such are unlikely to include thickness noise energy in any part of the recording time history. The National Aeronautics and

Space Administration (NASA) has developed a computer based prediction model for thickness noise (Brentner, 1986) and has done some limited verification work. Data for a variety of aircraft types do not appear to be available in the general literature at the time of this writing.

For the sake of completeness, one final loading phenomenon should be mentioned. Since the main rotor supports the helicopter, and the air beneath it supports the rotor, there is a slowly time-varying pressure on the ground know as the "lift pulse." The magnitude of the pressure is dependent on the weight of the helicopter and the duration depends on the speed of the aircraft as it passes by the observer or structure. The lift pulse does not produce an audible sound because all of the energy is contained in the infrasonic frequency region below the normal range of human hearing. Sutherland (1990) dismissed this pressure as a cause for concern because it is comparable to that produced by a light gust of wind.

In summary, thickness noise is potentially one of the most important acoustic loading phenomena for cultural resources. Unfortunately, measurement data for this phenomenon is not reported in the open literature and Sutherland's (1990) BVI prediction model is likely to understate loads for thickness noise. Therefore, further investigation of thickness noise source levels would seem warranted.

Figure 3.5 Typical Narrow Band Sound Spectrum Shape of Helicopter Noise (Source: Richards and Mead, 1968)

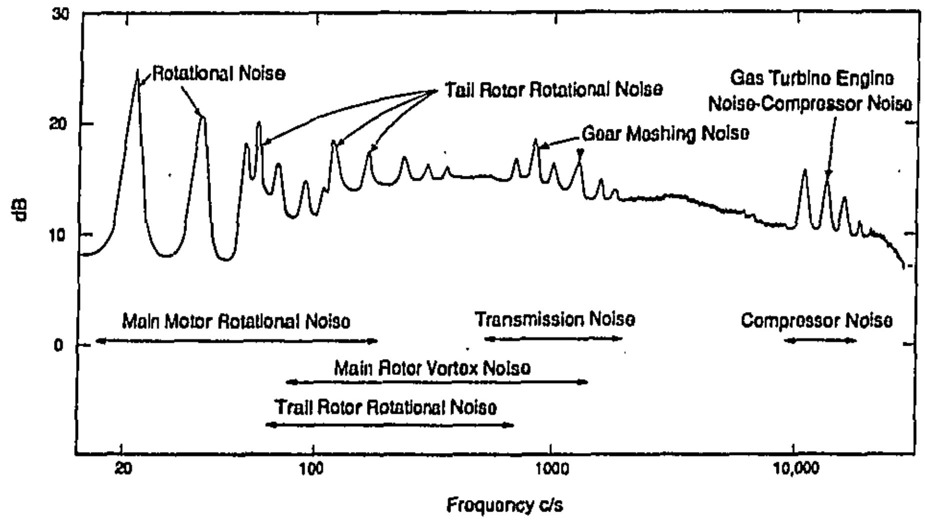
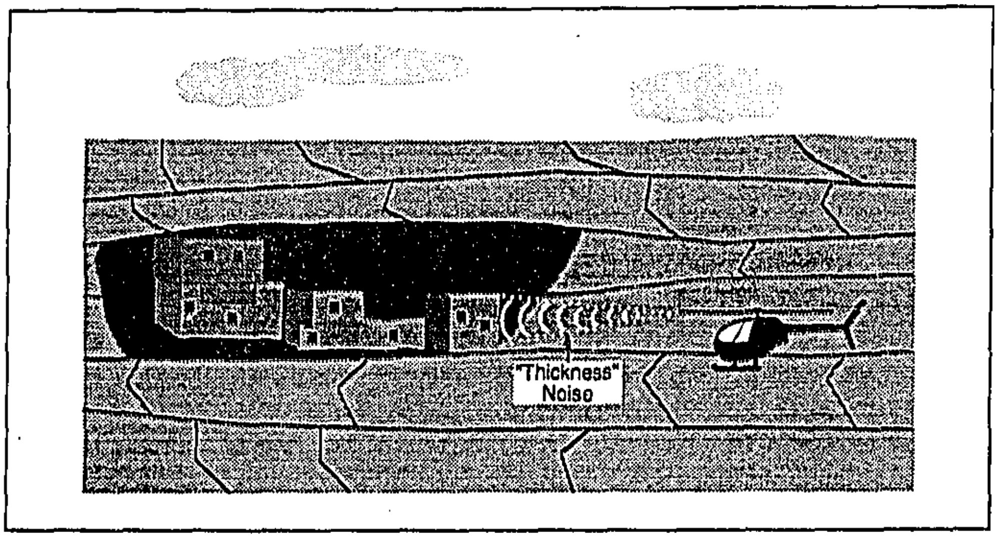


Figure 3.6 Sketch of a Helicopter at the Same Level as a Cultural Resource



3.2.4 Rocket Noise

Another aircraft noise event of significance, although rare and site specific, is the launching of a rocket. Measurements of the vibro-acoustic environments in the vicinity of launchpads at the Kennedy Space Center and Vandenberg AFB have shown that the nearby landform can have a focusing effect for increasing sound energy exposure at nearby facilities (Battis, 1985). Several of the "levels of concern" identified in Section 2.7 have been found to be exceeded at facilities adjacent to launchpads, none of which are currently considered to be cultural resources.

4. CULTURAL RESOURCES SUBJECT TO AIRCRAFT NOISE EFFECTS

This section gives examples from the literature which document aircraft noise effects that pertain directly to historical structures and cultural resources. Differentiation between "conventional structures" and "unconventional structures" is based on the standard definition used in the US Air Force Sonic Boom Study (Sutherland, et al., 1990).

4.1 Conventional Historical Structures

Many National Park Service structures could be classified as conventional; these include office buildings, commercial buildings, and residences that are normally inhabited on a daily basis. Usually these structures are located in populated areas where the presence of aircraft is controlled for reasons of safety and community annoyance. Conventional structures located in remote areas, however, may be subject to aircraft noise from air combat training maneuvers, military training routes, low level flight and helicopters. Helicopters may frequently fly near conventional structures at tourist attractions. Because these buildings are inhabited on a daily basis, they are subject to the loads placed on a structure by normal use which are in excess of those caused by most aircraft overflights, as discussed in Section 2.1.2. The exceptions are pressure loading from sonic booms, the adverse effects of which are discussed in detail by Haber and Nakaki (1989), and overflights of heavy helicopters, as discussed by Sutherland (1990).

4.2 Unconventional Structures

In accordance with Sutherland's definition, unconventional structures are those not normally inhabited or used for routine commerce (Sutherland et al., 1990). As described in Section 2.2, this category covers a wide range of structures administered by the National Park Service, many of which are valued historical and cultural resources considered irreplaceable. The fact that they are uninhabited means that they are not continually subjected to human activity, except by tourists and occasional ceremonies. In some cases they may be exceptionally fragile due to their age and natural degradation from environmental effects, or from prior vibro-acoustic exposure.

King (1989) believes the effects of tourist foot traffic and ceremonial dancing to be well out of the frequency ranges of interest for structural resonances. He measured vibrations of a fragile stone wall of an ancient ceremonial site (kiva) in Chaco Canyon caused by activities of ceremonial dancers. The wall natural frequency was 12 Hz, but measurable vibrations (presumably from drum sounds) occurred no lower than 18 to 20 Hz. Footsteps of dancers would be 4 Hz or less, well below the 12 Hz resonance.

Footsteps of most site visitors would occur at even lower frequencies, 1 Hz or less. He concluded that vibrations from neither the ceremonial dancing nor the site visitors posed a threat to the structures.

The designs of many historical structures lend themselves to potential damage from airborne pressure waves. The quarter wavelength of a sound wave is a standard measure of the distance over which sound pressure is well-correlated. For the frequency range of 10 Hz to 20 Hz corresponding to a helicopter fundamental rotor frequency, the quarter wavelength ranges from 26 feet to 14 feet.[2] This length is comparable to the dimensions of roof elements of old Pueblo dwellings, which averaged 12 feet by 20 feet (Yue, 1986). (The smaller dimension was limited by the difficulty to obtain long tree trunks for use as "vigas", the main supporting members for the flat roofs.) This means that when exposed to a helicopter sound a typical pueblo roof with this dimension would be exposed to an oscillating pressure field that is nearly uniformly distributed over the surface.

Helicopter Effects

In an attempt to quantify the potential for damage of antique buildings subject to helicopter noise, King measured the response of a flat roofed adobe house of viga construction at Mesa Verde from noise of controlled helicopter passbys (King, 1991). He found the greatest roof response to occur at 13 Hz, with a second peak at 27 Hz, corresponding to the fundamental and first harmonic of the main rotor. These frequencies were in the likely range of the natural frequencies of the roof. King estimated that the motion of the flat roof could lead to excessive corner stresses and to cracking in the vicinity of the viga supports. His measurements did not include sound pressure incident on the roof. From his vibration measurements, he concluded that damage from this type of structure could be avoided by maintaining a clear zone of at least 50 feet for hovering overhead. He measured greater vibration levels on the roof when the helicopter was hovering off to the side of the site than when hovering overhead. Moreover, blade slap did not increase structural response at resonance frequencies. This study provides the best evidence that there could be damaging pressure loads from helicopters on fragile antique structures and it is caused by thickness noise and not blade slap.

Sutherland (1990) calculated a very high risk of damage to prehistoric sites from overflights of heavy helicopters (greater than 20,000 lb) on military training routes. He attributed this high risk situation to the very high sound levels in the same low frequency range at which structural fundamental resonance frequencies occur. As discussed in Section 3.2.3, the sound pressure in the plane of the main rotor is even greater than below the helicopter, which could exacerbate the damage potential for structures level with low-flying aircraft.

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[2] Frequency times wavelength equals the speed of sound; hence, a frequency of 10 Hz and a typical sound speed of 1100 ft/sec yields a wavelength of 110 ft. One-quarter of the wavelength is 28 feet. The corresponding quarter wavelength associated with 20 Hz is 14 feet.

In contrast, another researcher measured helicopter noise on the Point Sublime Anasazi site in Grand Canyon National Park and failed to find any response in stone walls with natural frequencies of 18 Hz to 26 Hz (Brumbaugh, 1985). However, the reported helicopter noise spectrum showed a maximum at 50 Hz and no frequency components below 30 Hz. It is not clear why the energy from the fundamental frequency of the main rotor was not detected, although the explanation may be related to frequency limitations in the instrumentation used. The signal from the tail rotor may have been in the range reported, but it is unlikely that the lightly loaded tail rotor would have generated the maximum pressure in a helicopter spectrum.

In a study of vibration and rattle effects of helicopter noise, Schoemer (1985) identified distances within which significant rattle occurred in a conventional frame house from noise from a military helicopter (UH-1). In his experiment, he determined that slant distances within 500 feet virtually ensured high levels of helicopter noise-induced vibration and rattle. These effects virtually disappeared for slant ranges beyond 1000 feet. The results of Schoemer's study have implications for the potential for breakage of museum artifacts on shelves, which is related to rattle in Section 2.7.4.

Sonic Boom Effects

Wyle Laboratories conducted extensive measurements during sonic boom exposure on an adobe house, the George McDonald ranch house, designated a National Historical Monument in the White Sands Missile Range (Sutherland, et al., 1990). As described in Sections 2.1.1 and 2.3 above, several indicators of damage were observed. Cracks in the adobe walls of the ranch house were found to widen with the incidence of each sonic boom.

4.3 Susceptibility to Damage

Two prediction models estimated the probability of damage for historical structures and cultural resources from sonic booms and from military overflights (Sutherland, 1990; Sutherland, et al., 1990). Table 4.1 gives the rank order and probability of structural damage from aircraft noise for selected cultural resources from the two Sutherland reports. The leading risk category for low overflights of heavy helicopters is a historic wood frame house with plaster interior walls, where the probability of damage is 2.6. Probabilities greater than one mean that damage is highly likely in this case. The lowest risk category, landslide areas, is less than one millionth of a percent.

In general, the table shows that historic structures of wood frame construction with plaster walls and old windows have the highest susceptibility to damage. Also at high risk are masonry/stone structures with intact roofs. The reason for the extremely high probability of damage from helicopters is discussed in Section 4.2.

Table 4.1 Ranking and Probability of Structural Damage from Aircraft Noise (taken from Table 6-7 of Sutherland, et al 1990, and Table 26 from Sutherland 1990)

Type of Structure	Sonic Boom*		Subsonic Jet Bomber**		Heavy Helicopter***	
	Rank	Prob.	Rank	Prob.	Rank	Prob.
Historic Sites						
Windows, old	6	0.16	2	0.06	2	1.5
Wood frame, plaster	3	0.49	3	0.04	1	2.6
Wood frame, wood panels	8	0.053	7	0.002	7	0.3
Adobe	12	0.037	10	0.0002	8	0.2
Masonry, stone	13	0.0017	13	1E-08[c]	13	0.002
Brick	2	0.62	9	0.0004	10	0.2
Prehistoric Sites						
Masonry/Stone - roof intact	4	0.38	1	0.06	3	1.3
Adobe - roof intact	5	0.27	4	0.01	5	0.6
Masonry/stone - no roof	9	0.046	5	0.01	6	0.5
Adobe - no roof	10	0.044	8	0.0009	9	0.2
Seismically-sensitive Areas						
Avalanche - loose snow	1	0.92	6	0.007	4	1.1
Early American pictographs,petroglyphs, caves	11	0.043	11	8E-05	11	0.03
Avalanches - slab	7	0.096	12	9E-06	12	0.02
Landslide areas	14	4.6E-05	14	7E-15	14	1E-06

*Probability of damage per boom for level supersonic corridor flights
**Probability of damage occurring in one structure lying within ±1.56 miles of nominal military training route track centerline.
***Probability of damage occurring in one structure lying within ±0.4 miles of nominal military training route track centerline.

[c] Scientific notation for the number 0.00000001, or 1×10^{-8}

4.4 Four Examples Provided By NPS

Four cultural resource sites were selected as examples of the range of types of National Park structures likely to be affected by aircraft noise:

1. White Sands National Monument, New Mexico;
2. San Antonio Missions National Historic Park, Texas;
3. Chaco Culture National Historic Park, New Mexico; and
4. Fort Jefferson National Monument, Florida.

A summary of the characteristics of each of the sites is shown in Table 4.2. Without actual overflight characteristics, it is difficult to predict the probability of damage from overflights. However, the following discussion focuses on the characteristics of the primary structures at each site that could make them susceptible to aircraft noise damage based on the assumptions of the Sutherland (1990) and Sutherland, et al., and Goerner (1990) models.

<u>White Sands National Monument</u>: "adobe - roof intact"

The administration building and museum were built in the 1930's of adobe brick walls covered with a stucco layer. An improved adobe brick material was developed for the construction. Roofs are asphalt but are of viga construction in a Pueblo revival style. This structure falls into Sutherland's category of "adobe - roof intact." Among the building's features that make it vulnerable to damage are:

- Flat roof with viga construction susceptible to helicopter noise,
- Glass windows susceptible to sonic booms and helicopter noise,
- Artifacts on shelves susceptible to sonic booms and helicopter "rattle."

Stuccoed adobe is subject to surface cracks from sonic boom exposure. It is estimated that the probability of damage is 0.4% per boom at a peak overpressure of 2 psf (a minor boom) and 20% per boom at 8 psf (a significant boom).

<u>San Antonio Missions</u>: "masonry / stone - roof intact"

These four churches and their outlying buildings were built in the period of 1740 to 1780. The church roofs are vaulted but the outlying buildings are flat-roofed viga construction. These structures are now within the urban area of San Antonio, Texas, and subject to the usual environmental effects of an urbanized area. Among these building features that make them vulnerable to damage from aircraft noise are:

- Masonry/stone buildings with intact roofs are very high risks for all three types of aircraft noise - sonic booms, low subsonic jets and heavy helicopters. (The susceptibility of vaulted roofs is unknown.)
- Flat roofs and viga construction of outlying buildings are susceptible to helicopter damage.
- Windows are susceptible to sonic booms and helicopter noise.
- Church objects and artifacts on shelves are subject to helicopter "rattle."
- Pictographs on adobe walls are subject to sonic boom damage.

Chaco Culture National Historic Park: "masonry/stone - no roof"

Chaco Culture is a series of Anasazi villages built in the 11th and 12th centuries. The villages were built of well-fitted stone with rubble cores and originally covered with a smooth skin of adobe mud. The adobe mud has long-since gone, the roofs are gone, but many of the walls are standing. Wooden lintels are preserved in some cases.

King (1985) documented the natural frequencies and damping factors of many of the walls in this park. The natural frequencies occur over a range of 6 to 18 Hz, which make these walls susceptible to the helicopter fundamental frequency of the main rotor. According to the prediction models, these structures are subject to damage from aircraft noise as follows:

- Sonic boom: low to medium risk of damage; masonry/stone structures with no roofs rank 11th in Table 4.1.
- Helicopter: medium risk of damage from heavy helicopters.
- Subsonic jets: medium risk of damage from low-flying heavy aircraft.

Fort Jefferson National Monument: "brick masonry"

This fort, out at the end of the Florida Keys, was built during the Civil War era. The outer walls are massive structures with thick walls typical of a fortification. Smaller buildings are located within the fort, including a lighthouse made of iron. Ordinarily a brick structure is a high risk for sonic boom damage according to the prediction model. This is due to the fragility of the mortar on old brick dwellings. It is not clear whether this would be the case in the walls of the fort, although long term effects of damage from cracking mortar may come about from the forces of nature, especially in the harsh seacoast environment. Glazing of the lighthouse could be at high risk from all aircraft noise sources.

Table 4.2 Construction Characteristics of Cultural Resources

Site	Fort Jefferson National Monument, Florida	White Sands National Monument, New Mexico	San Antonio Missions National Historic Park, Texas	Chaco Culture National Historic Park, New Mexico
Approx. Date of Construction	1860's	1930's	1740 to 1780	11th and 12th century
Size of Main Structures of Interest	Fort is hexagonal-shaped with four 476' walls and two 324' walls that are 45' high, and vary in depth from 14 feet at their base to 5 feet at their crown	The Administration and Museum Building is approximately 100' by 90', and is of Pueblo Revival Style.	Four churches, ranging in size from 25' by 65' to 92' by 53'. Also remains of Indian quarters.	The structures of interest are many kivas and multi-story pueblos which have as many as 500 rooms. Exact dimensions not given.
Wall Construction Type	brick masonry	stuccoed adobe	Churches of limestone/sand stone with lime mortar. Indian quarters of sandstone with stone or adobe interior walls.	Rubble-cored with exterior and interior veneer of well-shaped stones. Generally 1.5 to 3 m high, although some are more than 5 m.
Roof Construction Type	flat terreplain, 26' across, 1/2 mile circumference with lead flashing for waterproofing	asphalt roof of viga construction	Churches vaulted. Indian quarters have flat earthen roofs, of viga construction.	masonry, sandstone, adobe
Glass windows	Some	Yes	Yes	No
Artifacts or Display items	Yes	Yes	Yes	Yes

Sources: National Register of Historic Places Inventory - Nomination Forms
King, 1985 for Chaco Culture.

5. MITIGATION MEASURES

This section summarizes mitigation measures found in the literature for damage to historical structures and cultural resources caused by aircraft noise. In general, mitigation measures are designed to restrict aircraft operations which are predicted to have significant risks of damage. Much of the effort in this field has been focused on the method to predict effects, leaving application and specification of mitigation up to the user. A few cases exist where an author recommends a specific mitigation measure.

5.1 Mitigation of Effects of Sonic Booms

Mitigation for the effects of sonic booms has two elements:

(1) avoid sensitive structures in the carpet of the sonic boom, or
(2) limit the sonic boom overpressures below a threshold level.

Two statistical models have been developed to predict the probability of damage given characteristics of conventional structures and unconventional structures, but they do not specify mitigation measures to avert damage (Haber and Nakaki, 1989; Sutherland, et al., 1990). The calculation procedures of these reports could be used, however, to develop mitigation measures by determining limits on the areas of supersonic air combat maneuvers, given the location of sensitive structures. The U.S. Air Force plans to use the information from these reports for an automated environmental planning aid being developed as part of the Noise and Sonic Boom Impact Technology program. The National Park Service may benefit from the work. In order to use these models, a complete inventory of sensitive structures, categorized according to location, type and condition, would be required. Emphasis should be given to the types of structures that rank high in susceptibility to damage (Table 4.1).. Any structure where the probability of damage is high from sonic booms should be identified and if located in a known air combat maneuver or military training route made known to the U.S. Department of Defense (e.g. U.S. Air Force Office of Noise and Sonic Boom Impact Technology). Otherwise the likelihood of exposure to sonic booms is minuscule.

5.2 Mitigation of Effects of Subsonic Operations

Mitigation measures for the effects of low-flying subsonic aircraft, including helicopters, are related to operational restrictions to maintain a sufficient distance between the noise source and sensitive structure. Sutherland (1990) recommends that *areas with prehistoric structures with intact roofs* be avoided for military training routes using subsonic jets, especially heavy bombers. Likewise, he emphasizes that routes for heavy helicopters should be carefully planned to avoid *most types of structures*, an outcome of his prediction of a high risk of damage from the low frequency sound pressures generated by the main rotor blades.

Other studies suggested restrictions on helicopter operations as mitigation measures. Schoemer (1985) recommends maintaining a separation distance of at least 500 feet, and preferably 1000 feet, between the UH-1 helicopter and conventional structures to avoid significant rattle. As described in Section 2.7.4, rattle may be related to damage to museum artifacts. To prevent damage to any prehistoric structure, King (1991) recommends a clearance of at least 50 feet for a helicopter hovering overhead, with a greater, but undefined, distance recommended for hovering off to the side of cliff dwellings.

Although a specific set of mitigation measures does not emerge from the limited number of cases reported above, it is clear that researchers have recognized the need for maintaining some kind of clear zone between identified sensitive structures and aircraft operations. This warrants further research to develop applicable procedures to the cultural resources maintained by the Park Service.

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